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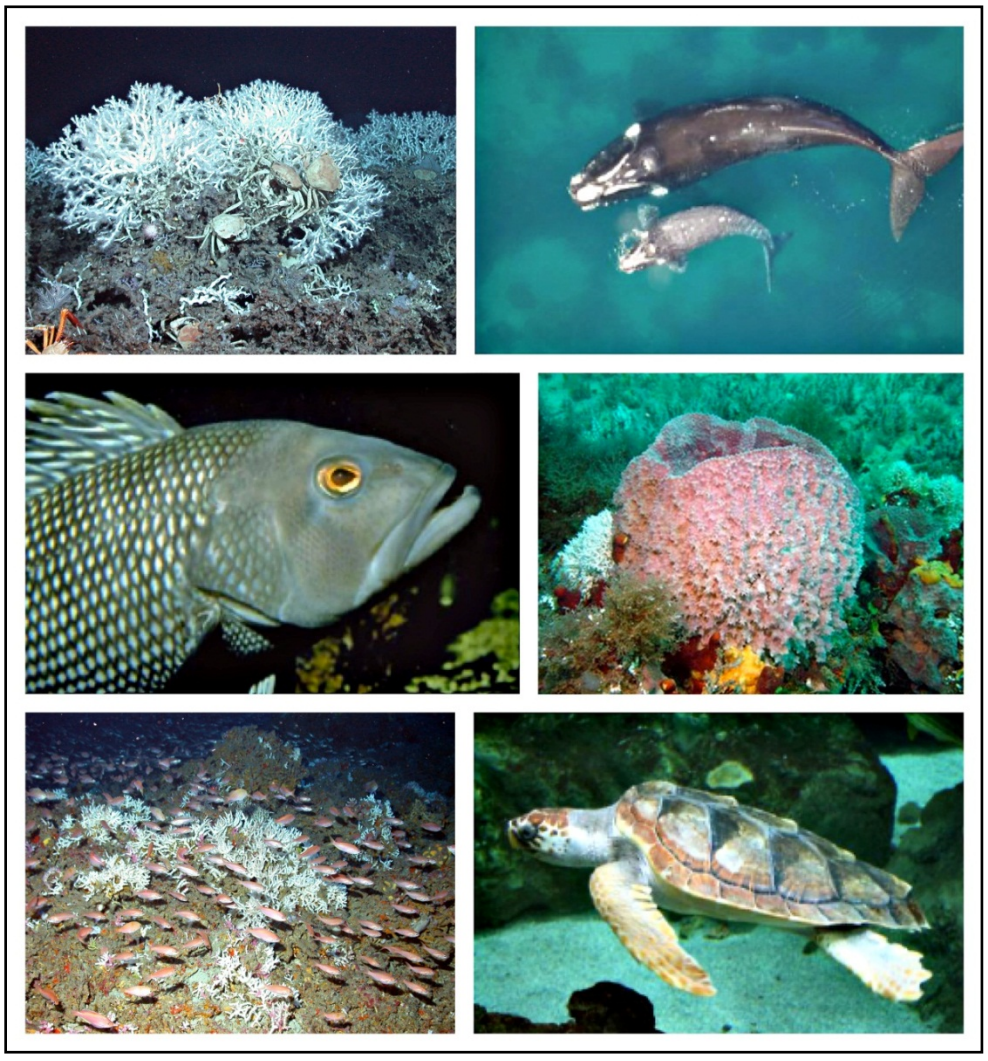
South Atlantic Information Resources: Data Search and Literature Synthesis



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South Atlantic Information Resources: Data Search and Literature Synthesis

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Jacqueline Michel

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ACRONYMS AND ABBREVIATIONS

ACCSP	Atlantic Coastal Cooperative Statistics Program
ADCP	acoustic Doppler current profiler
AFDW	ash-free dry weight
AOU	apparent oxygen utilization
API	American Petroleum Institute
ASL	above sea level
AVHRR	advanced very high resolution radiometer
AWEA	American Wind Energy Association
AWOIS	Automated Wreck and Obstruction Information System
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
BSR	Bottom Simulating Reflector
C	carbon
CbPM	carbon-based production model
CETAP	Cetacean and Turtle Assessment Program
CHAPC	Coral Habitat Areas of Particular Concern
cm	centimeter
COADS	Comprehensive Ocean-Atmosphere Data Set
COD	chemical oxygen demand
COST	Continental Offshore Stratigraphic Test
CRRC	Coastal Response Research Center
CZCS	Coastal Zone Color Scanner
DAPA	diaminopimelic acid
dB	decibels
DDT	dichlorodiphenyltrichloroethane
DIN	dissolved inorganic nitrogen
DO	dissolved oxygen
DOC	dissolved organic carbon
DOE	US Department of Energy
DOM	dissolved organic matter
DON	dissolved organic nitrogen
DPS	distinct population segment
DSDP	Deep Sea Drilling Project
EEZ	Exclusive Economic Zone
EFH	essential fish habitat
EMF	electromagnetic field
EORR	Experimental *Oculina* Research Reserve
ESA	Endangered Species Act
ESP	Environmental Studies Program
EWS	Early Warning System
FAD	fish aggregation devices
FL	fork length
FLEX	Fall Experiment

GABEX	Georgia Bight Experiment
gams	general additive models
GRNMS	Gray's Reef National Marine Sanctuary
GW	gigawatt
HAPC	Habitat Areas of Particular Concern
HPLC	high-performance liquid chromatography
Hz	hertz
IBA	Important Bird Area
IGSF	Inshore Gulf Stream Front
IOOS	Integrated Ocean Observing System
L	liter
LiDAR	Light Detection And Ranging
LME	large marine ecosystems
m	meter
μM	micromolar
Ma	millions of years
MARMAP	Marine Resources Monitoring Assessment and Prediction Program
MPA	Marine Protected Area
MRA	Marine Resource Assessment
mg	milligram
mg/L	milligrams per liter
MMPA	Marine Mammal Protection Act
MMS	Minerals Management Service
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Marine Protected Area
MSL	mean sea level
Mt	metric ton
MW	megawatt
NADP	National Atmospheric Deposition Program
NASG	North Atlantic Subtropical Gyre
NCDC	National Climatic Data Center
NDBC	National Data Buoy Center
NEIC	National Earthquake Information Center
NEP	National Estuarine Program
NERR	National Estuarine Research Reserve
ng	nanogram
nM	nanomole
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NODC	National Ocean Data Center
NODE	Navy Operating Area Density Estimate
NOS	National Ocean Service
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
NWR	National Wildlife Refuge

NWS	National Weather Service
NURP	National Undersea Research Program
OBIS-SEAMAP	Ocean Biogeographic Information System -Spatial Ecological Analysis of Mega-vertebrate Populations
OCA	*Oculina* Closed Area
OCS	Outer Continental Shelf
ODMDS	Ocean Dredged Material Disposal Site
OGSF	Offshore Gulf Stream Front
OHAPC	*Oculina* Habitat Area of Particular Concern
OSWinD	Offshore Wind Innovation and Demonstration
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCL	precaudal length
PEIS	Programmatic Environmental Impact Statement
pM	picomoles
POC	particulate organic carbon
POM	particulate organic matter
PON	particulate organic nitrogen
ppt	parts per thousand
RCOOS	Carolinas Regional Coastal Ocean Observing System
ROSS	Reconnaissance Offshore Sand Search
RPS	Renewable Portfolio Standards
RRT	Regional Response Team
SAB	South Atlantic Bight
SABSOON	SAB Synoptic Offshore Observational Network
SAFMC	South Atlantic Fishery Management Council
SCSPA	South Carolina State Ports Authority
SEAMAP	Southeast Area Monitoring and Assessment Program
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEDAR	Southeast Data, Assessment, and Review
SEEP	Shelf Edge Exchange Processes
SEFSC	Southeast Fisheries Science Center
SERDP	Strategic Environmental Research and Development Program
SGD	submarine groundwater discharge
SHPO	State Historic Preservation Office
SL	standard length
SMZ	Special Management Zones
spp.	species
SPREX	Spring Experiment
TDS	total dissolved solids
TEU	twenty-foot equivalent unit
TL	total length
TOC	total organic carbon
T-S	temperature-salinity
TSHD	trailing suction hopper dredges
µg	microgram

UML	upper mixed layer
UNCW	University of North Carolina-Wilmington
USACE	US Army Corps of Engineers
USCG	US Coast Guard
USEPA	US Environmental Protection Agency
USGS	US Geological Survey
USWTR	Undersea Warfare Training Range
WBM	water-based drilling muds
WEC	wave energy converter
WIS	Wave Information Studies
WMA	wildlife management area
WNAW	Western North Atlantic Water
yd^3	cubic yards

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The South Atlantic Planning Area extends between the North Carolina-South Carolina border to Palm Bay, Florida (Figure 1.1) and covers 54.34 million acres. This area has unique physical oceanography, physiography, and zoogeography; numerous valuable fisheries; and a pristine coastal and marine environment. The continental shelf reaches 130 kilometers (km) at its widest point off Georgia. The coastal region is dominated by barrier islands that progressively decrease in length toward the head of the Georgia Bight, which has the highest tides of the US Atlantic coast south of Maine. The Santee River is the largest river along the US Atlantic coast and forms the Santee Delta. In South Carolina, 42% of the coastline is preserved open coast (Kana, 1988). In Georgia, over 80% of the coastline (ten of the thirteen barrier island groups) is undeveloped.

The Bureau of Ocean Energy Management (BOEM) 2007–2012 Outer Continental Shelf (OCS) oil and gas leasing program does not include any lease sales for the South Atlantic Planning Area. Oil and gas leases for 106 blocks in the area were issued in 1978, 1982, and 1983. Six exploratory wells and one Continental Offshore Stratigraphic Test (COST) well were drilled in this planning area. As of 2011, there are no active leases in this area. In 2008, the South Carolina General Assembly established the South Carolina Natural Gas Exploration Feasibility Study Committee to examine the feasibility of natural gas exploration off the coast of South Carolina. The Committee recommended that the state consider the development of an offshore natural gas industry, but only when BOEM executes a five-year plan that includes natural gas exploration off the South Carolina coast (South Carolina Natural Gas Exploration Feasibility Study Committee, 2009).

Of the offshore renewable energy sources (wind, ocean current, and wave), wind has the greatest potential for development in the South Atlantic Planning Area within the next several years. Ocean current and wave energy technologies are being explored in other regions where their resource potential is greater. Wind maps for South Carolina and Georgia show that there are areas with sufficient wind speed, water depth, and distance to shore for potential offshore wind energy development in these two states. Wind energy becomes feasible with annual average wind speeds greater than 7 meters/second at 90 meters (m) above the surface. At this time, there are insufficient data to map the wind energy potential off northern Florida (Swartz et al., 2010).

There are initiatives in South Carolina and Georgia to develop offshore wind. In March 2009, a project was launched by the Palmetto Wind Research Project, a collaborative project by Santee Cooper (a public utility), Coastal Carolina University, and the South Carolina Energy Office to study the possibilities of generating wind energy off the South Carolina coast. As of May 2011, this project had completed preliminary wind mapping (the strongest, closest-to-shore winds are in the northern part of the state), deployment of coastal anemometers and six offshore buoys along two transects, high-level environmental checks, a preliminary design of an offshore meteorological tower off the mouth of Winyah Bay, and a conceptual design for a demonstration-scale offshore wind farm of up to 20 wind turbines 6.5–8 km off the mouth of Winyah Bay. The demonstration wind farm is planned to produce 40 megawatts (MW) of electricity. In May 2011, BOEM announced the establishment of a task force with the federal,

state, local, and tribal governments in South Carolina to facilitate intergovernmental communications regarding OCS renewable energy activities.

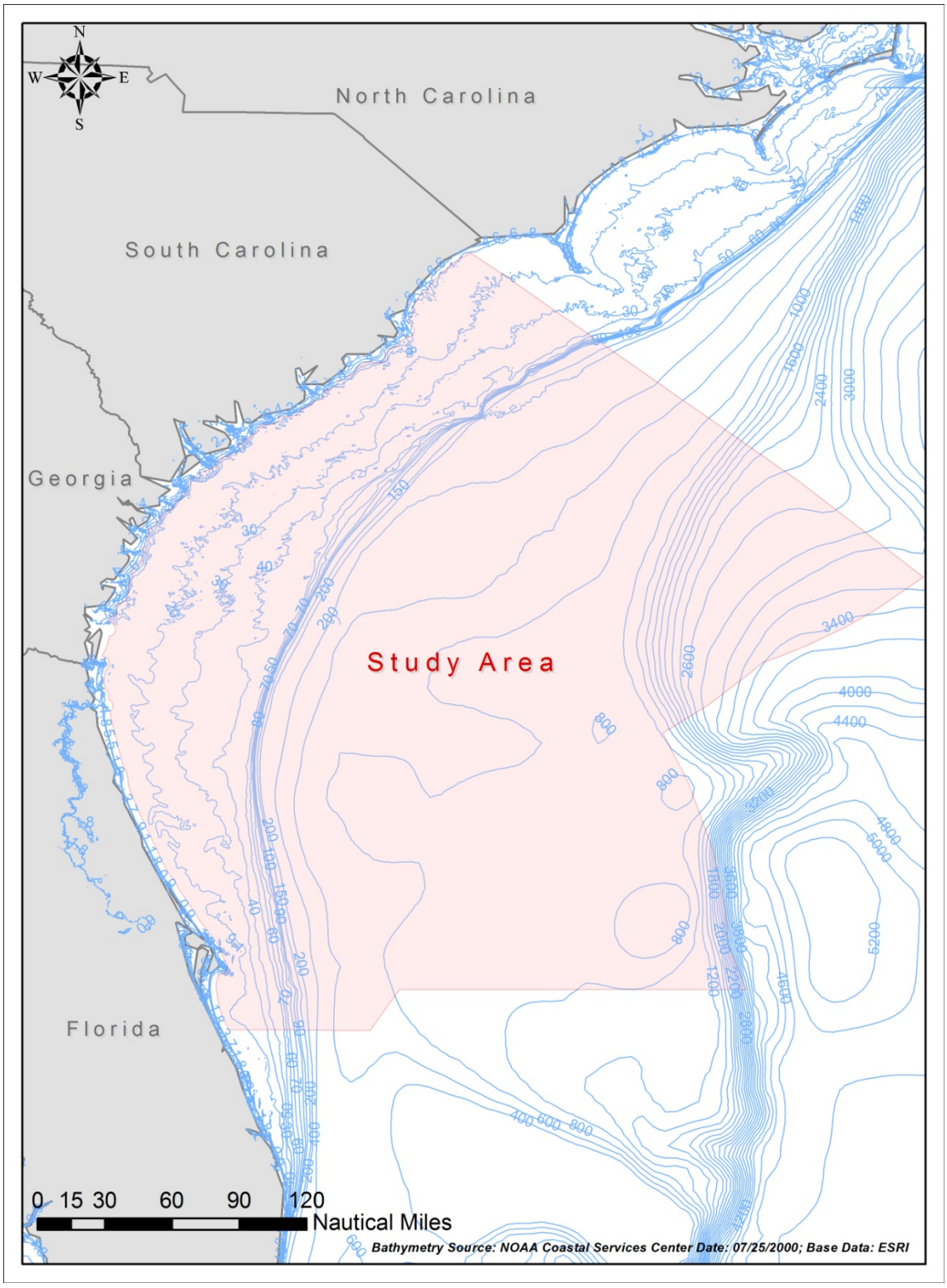

Figure 1.1 Study area for the South Atlantic Planning Area.

Georgia Tech and Southern Company jointly completed an offshore wind feasibility study and are evaluating the feasibility of a small (10 MW) demonstration project off Tybee Island, Georgia. As of December 2011, Southern Company had submitted an application for a federal lease to construct meteorological towers off the Georgia coast to collect data for assessing the potential for offshore wind generation. Georgia Tech has three active wind monitoring stations and the Georgia Wind Working Group is facilitating wind development in the state.

The sand and gravel resources in the OCS of the South Atlantic Planning Area have been leased for beach nourishment in both South Carolina and Florida. Since 1997, over 3 million cubic yards (yd^3) of sand have been conveyed for shoreline protection and restoration in the Myrtle Beach, South Carolina area, and Folly Beach, South Carolina may require OCS sand resources in the near future. The Charleston Offshore Dredged Material Disposal Site may be used to provide 4.5 million cubic meters (m^3) of fill for the Marine Container Terminal at the South Carolina State Ports Authority. Since 1995, over 11 million yd^3 of OSC sand has been conveyed for use along the South Atlantic Planning Area in Florida, and new projects are proposed in Flagler, Volusia, and St. Johns counties.

In summary, in the South Atlantic Planning Area offshore wind energy development is being actively pursued in South Carolina and Georgia. There is some potential for offshore gas exploration and development in the future, but it will depend on many factors. OCS sand and gravel resources will likely be targeted for development, mostly in South Carolina and Florida. Therefore, the sections on the potential impacts of OCS development projects focus on wind, oil and gas, and sand and gravel.

1.2 STUDY OBJECTIVES

The last major study of the physical oceanography of the South Atlantic OCS was conducted for the Minerals Management Service in the early 1980s (Atkinson et al., 1985). Between 1977 and 1991 the US Department of Energy (DOE) sponsored research in the area. This DOE work was complemented by a number of additional research projects sponsored by the National Science Foundation, US Environmental Protection Agency, the National Oceanic and Atmospheric Administration, and others, which addressed specific processes or components of the system. However, the DOE-supported research was the major interdisciplinary, multi-institute project to be initiated to address shelf processes. The Marine Minerals Program has conducted studies of specific borrow sites in South Carolina and Florida. In 2008, the US Navy completed a comprehensive compilation of data and literature concerning natural resources (with emphasis on marine mammals and sea turtles) found in the Charleston-Jacksonville Operating Area (Department of the Navy, 2008). Clearly, there is a need for a new synthesis with the following objectives:

- To develop comprehensive literature syntheses of the environmental and human aspects of the South Atlantic Planning Area; and
- To update the understanding of the ecological communities, dominant physical oceanographic and other processes that drive the shelf and deep-sea ecosystems, and the potential sensitivities of the area.

The project had the following long-term goals:

1. Provide a synoptic organization of existing knowledge;
2. Synthesize the knowledge into functional relationships;
3. Identify information gaps in need of further study;
4. Present data for planning and management of BOEM's offshore activities in the area; and
5. Update existing information databases.

1.3 STUDY METHODS

1.3.1 Literature Search

Research staff at Research Planning, Inc., Industrial Economics, Inc., Clemson University, and Applied Science Associates, Inc. performed literature searches for each individual discipline included in the project. The disciplines included were: Areas of Special Concern; Biological Oceanography, divided into Plankton Communities, Benthic Resources, Fish and Fish Habitats, Marine and Coastal Birds and Bats, Sea Turtles, and Marine Mammals; Chemical Oceanography; Geological Oceanography; Physical Oceanography; Research and Development Technology; and Social and Economic Sciences.

Initial "first cut" searches were conducted, compiled, and submitted to the Principal Investigators (PIs) responsible for writing the section associated with that particular discipline. The PIs, as experts in their respective fields, exercised their best professional judgment to determine the appropriateness of each article. Efforts were made to specifically narrow the scope of the synthesis review to literature that would provide a high value on each of the specified disciplines. The PIs also helped identify additional information sources, such as selected peer-reviewed articles, gray literature, reports, unpublished theses and dissertations, and spatial information. The literature was downloaded from online sources, requested from peers, State, and Federal agencies, acquired through academic library resources, or provided by each of the PIs. In all cases, efforts were made to include articles specific to the geography of interest, although in a few instances relevant articles outside the study area were also considered. Individual citations were re-evaluated to select the articles most relevant to each of the resources in the study area, the South Atlantic Bight, and the potential impacts of offshore renewable energy development.

The primary databases used in literature searches included the following:

- U.S.D.A. National Agricultural Library (NAL, or Agricola
- CAB Abstracts
- CSA Environmental Pollution and Management Database
- GEOBASE
- Google Scholar
- US Census Bureau
- US Geological Survey Publications Warehouse
- Social SciSearch via Web of Science
- Web of Science

Internet searches included, but were not limited to, a variety of governmental and academic websites such as:

- Atlantic States Marine Fisheries Commission
- Bureau of Ocean Energy Management Environmental Studies Program Information System (ESPIS)
- Florida Fish and Wildlife Commission
- Florida Museum of Natural History
- Georgia Department of Natural Resources
- National Sea Grant Library
- National Oceanic Atmospheric Administration Library
- Skidaway Institute of Oceanography
- South Carolina Department of Natural Resources
- South Atlantic Fishery Management Council

The literature compilation was completed and the first review draft of the report was submitted in October 2011. At the request of BOEM, Chapter 12 was updated with 2010 census data, and a second review draft was submitted in April 2012, with only minor additional literature synthesis. Since that time, there have been only editorial changes to the report. Therefore, the literature is current mostly as of October 2011.

1.3.2 Annotated Bibliography

All cited references were compiled in an electronic annotated bibliography using Reference Manager® software. Each discipline was included as a separate database as a subset of the master database. Each record in the database contained the complete citation, a short summary (up to 250 words) and keywords, written by the Research Associates. In addition, PDF files of non-copyrighted articles were attached to the appropriate records. Links to online PDFs were also included as appropriate. Reference Manager® can be queried by searching on: name, title, authors, date, publisher, journal/periodical, keywords, abstract, or any combination thereof. The databases are listed below with the number of records in each. Combined, the databases contain 2,980 records.

1. Biological Oceanography
    a. Benthic Resources, 849 records
    b. Fish and Fish Habitats, 454 records
    c. Marine and Coastal Birds and Bats, 305 records
    d. Marine Mammals, 150 records
    e. Plankton Communities, 215 records
    f. Sea Turtles, 101 records
2. Chemical Oceanography, 222 records
3. Geological Oceanography, 270 records
4. Physical Oceanography and Air-Sea Interactions, 230 records
5. Social and Economic Sciences/Areas of Special Concern/Research and Development Technology, 184 records

1.3.3 Geospatial Data

The deliverables of this project included data and metadata on the spatial extent covered in the studies cited in the report. Spatial data were created, compiled, and organized in accordance with the *Proposed Spatial Component Development Procedures* document submitted to BOEM on 31 January 2011. All spatial files were organized by discipline and have a corresponding record in the Reference Manager® database, also separated by discipline. Due to the multi-disciplinary nature of the project, some records may appear in several databases and also in corresponding spatial files. Eight spatial files were created that correspond to each of the Reference Manager® databases. No spatial data were created for the Social and Economic Sciences, Areas of Special Concern, and Research and Development database. More detailed descriptions of the methods for generating the shapefiles are included with the spatial data deliverable.

1.4 Structure of the Report

This report is divided into chapters that cover the entire range of topics for each resource areas. Each chapter is designed to stand alone; therefore, each chapter includes a detailed table of contents, lists of figures and tables, and list of references cited in that chapter. The chapter headings include descriptions of the resource in the South Atlantic Planning Area, discussion of the potential impacts of OCS development including oil and gas, sand and gravel extraction, and renewable energy (with emphasis on wind energy development), and a summary and identification of data gaps in that resource area with regard to OCS development in the region. The final chapter is a summary synthesis that discusses the unique characteristics of the South Atlantic Planning Area, key seasonal patterns, ecological relationships, and data gaps.

1.5 References

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CHAPTER 2: GEOLOGICAL OCEANOGRAPHY

2.1 BATHYMETRY AND PHYSIOGRAPHY

The continental shelf along the US Atlantic coast is a classic passive tectonic (Atlantic-type) margin resulting from a long history of continental rifting, crustal subsidence, and sedimentary deposition. An important transition on the Atlantic margin occurs off South Carolina, Georgia, and north Florida from the clastic terrigenous sediment dominated shelf-slope-rise margin of the middle and north Atlantic to the steep-sided carbonate platforms of the Bahamas. The landward curve of the US Atlantic margin between Cape Fear and Cape Canaveral is often referred to as the South Atlantic Bight (SAB) and inherits its shape from the Southeast Georgia Embayment, a deep underlying geological structure formed during the continental rifting that produced the Atlantic Ocean Basin (Dillon and Popenoe, 1988). The South Atlantic Planning Area is a subset of the SAB, in that it starts at the North Carolina/South Carolina border. Within the South Atlantic Planning Area, the continental margin has an unusual two-tiered shelf with relatively narrow upper shelf to depths <100 m, and a very wide lower shelf (average depth ~800 m) that is triangular in plan view which drops off along a steep escarpment into a thick continental rise sedimentary section (Figure 2.1). The two-tiered physiography developed as a result of the changing patterns of sediment deposition controlled by the strong ocean currents through the area. As a result, the physiography of the study area can be divided into three main provinces: the modern coast and shoreface, the upper shelf known as the Florida-Hatteras Shelf, and the lower shelf, known as the Blake Plateau.

2.1.1 The Modern Coast and Shoreface

The modern coastline and shoreface is a mesotidal, mixed-energy to tidal-dominated environment with the greatest tidal range in Georgia, near the center of the bight. As a consequence of the variation in tidal energy and relatively uniform sediment sources, a general overall symmetry exists within the South Atlantic Planning Area described by Hayes (1994) from shore-welded barriers and Pleistocene-cored mainland beaches near the fringes of the study area to increasingly large estuaries and wider backbarrier marshes toward the center. The majority of the shoreline near the center of this area consists of Holocene-Pleistocene barrier islands backed by salt marsh between major estuaries. Most barriers are drumstick shaped as a result of wave refraction around ebb-tidal deltas creating local reversals in longshore drift (Hayes, 1979). Two types of estuaries are bar-built (or lagoonal) and coastal plain estuaries (e.g., Dame et al., 2000).

Hayes (1994) defined five coastal compartments that describe the variation of shoreline-building processes across the study area (Figure 2.2). From Cape Fear, North Carolina to North Inlet, South Carolina, the shoreline consists of Pleistocene welded barriers and mainland beaches. Seaward, the inner shelf has low relief and a thin, patchy veneer of surficial sand that is generally thickest adjacent to tidal inlets (Baldwin et al., 2006). From North Inlet to St. Helena Sound, South Carolina regressive, mixed-energy barrier islands make up the majority of the coastline along with delta-front barrier islands. The inner shelf here has more relief due to ebb-tidal shoals and the detached sand ridges of the delta of the Santee/Pee Dee river system, the largest fluvial delta on the US east coast, is in this compartment. Cape Romain retreated from the presently submerged Santee/Pee Dee delta

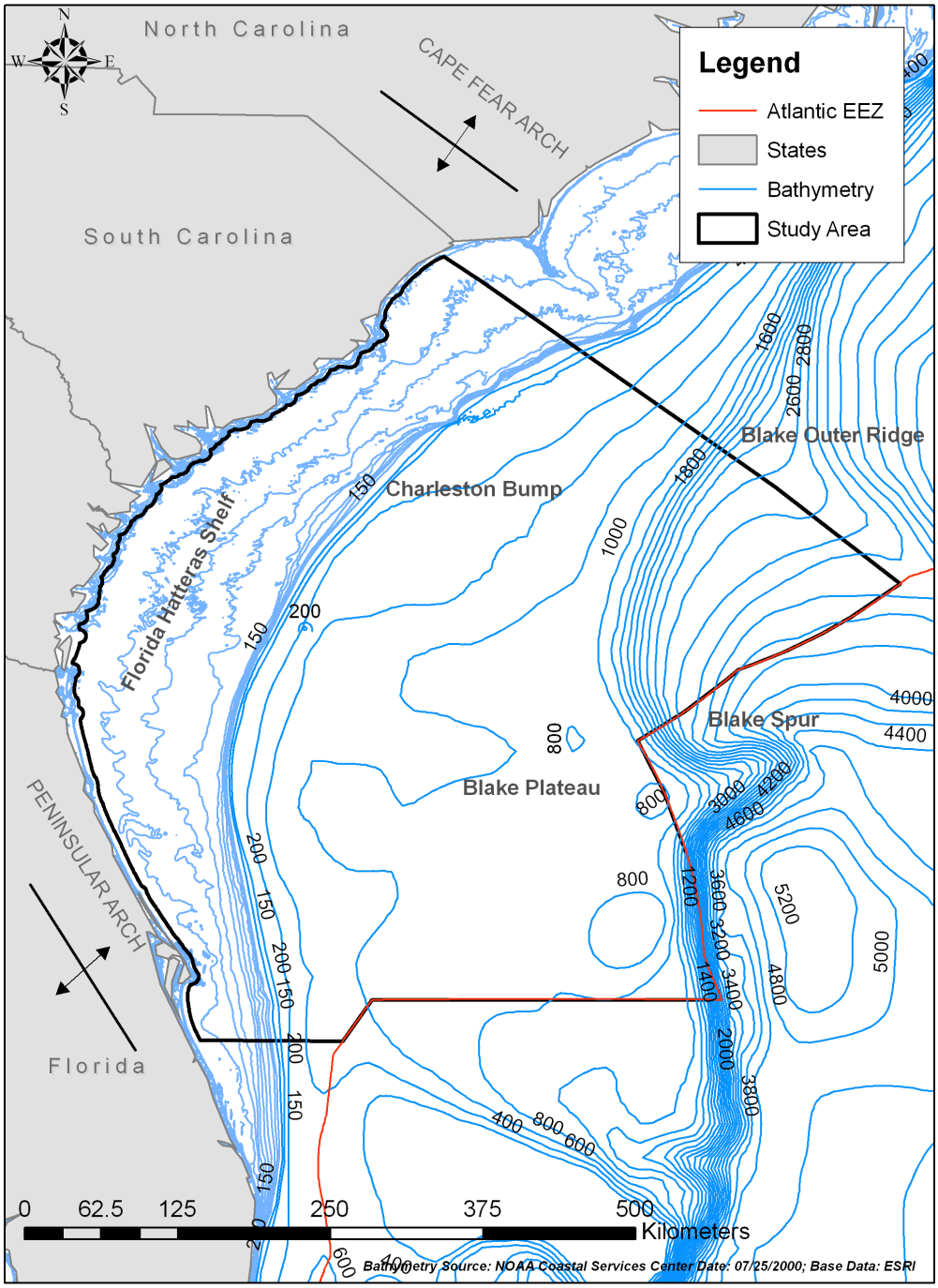

Figure 2.1 Bathymetry and major physiographic features of the South Atlantic Planning Area. Depth contours are labeled in meters below mean sea level.

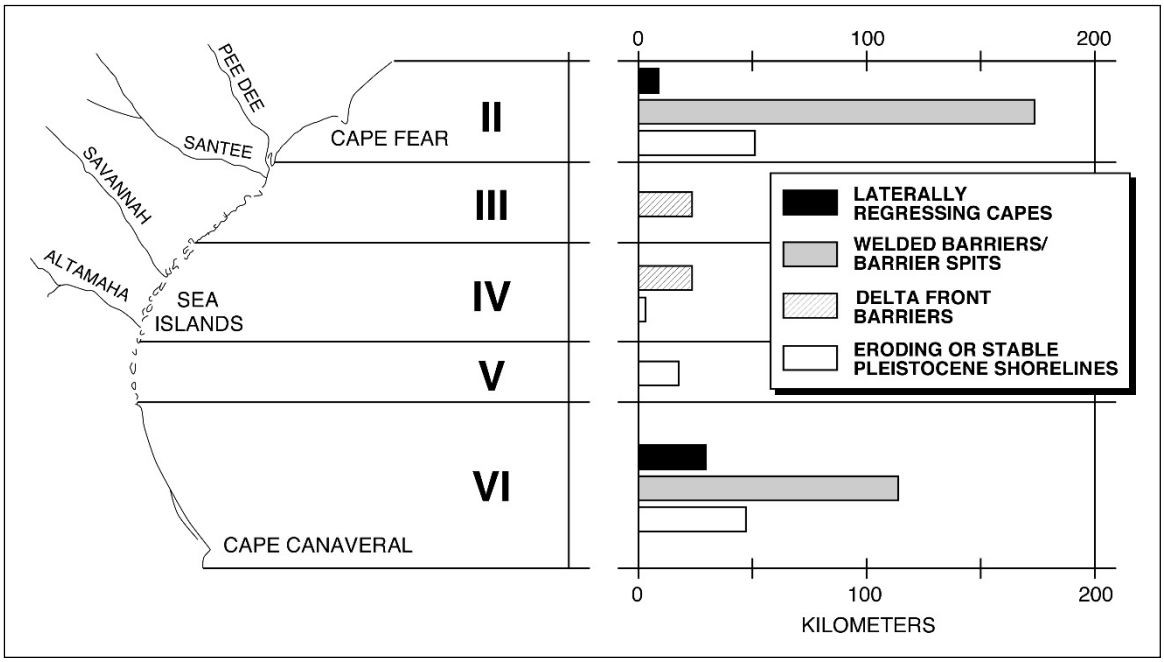

Figure 2.2 Shoreline compartments from Cape Fear to Cape Canaveral (on left panel) and the classification of shoreline within each compartment by total length (on right panel) (modified from Hayes, 1994).

and now deposits sand overlying marsh and estuarine deposits (Hayes, 1994). From St. Helena Sound, South Carolina to St. Simons Sound, Georgia the shoreline is dominated by sea islands surrounded by large estuaries with extensive backbarrier marsh and tidal flat environments. These sea islands consist of remnants of Pleistocene beach barrier sediment on the landward side and Holocene beach ridges on their seaward edge. The compartment from St. Simon's Sound, Georgia to St. John's River, Florida consists of large drumstick barrier islands. The last compartment to the south, extending from St. John's River to Cocoa Beach, Florida, consists of welded barrier islands, transgressive wave-dominated barrier islands, and Pleistocene mainland beaches with the laterally regressive Cape Canaveral making up 12% of this compartment. Offshore, sand ridges and shoreface-attached sand sheets are a very common morphological feature in the southern two compartments, and these are overlain inshore by ebb-tidal deltas, mostly between St. Simon's and St. John's rivers.

2.1.2 The Florida-Hatteras Shelf and Slope

The Florida-Hatteras Shelf (Upper Shelf) extends the entire length of the South Atlantic Planning Area and beyond to the south along Florida as a carbonate platform (Dillon and Popenoe, 1988). The shelf is 100 km wide in the northern end of the study area, becoming progressively wider until it reaches 130 km at its widest point off Georgia before narrowing again to ~60 km wide off Cape Canaveral (Figure 2.1). The shelf has relatively flat bathymetric surface, with surface relief primarily consisting of linear sand ridges and megaripples (Gardner et al., 1996; Reid et al., 2005). A few small erosion structures relict from the last sea-level lowstand, such as channels, barriers, and mounds, generate moderate relief (<8 m) in the offshore zone (Pilkey et al., 1981). Lithoherms and bioherms with relief ranging from a few meters to tens of meters are common along the outer edge of the shelf (Reed, 2002). The shelf is essentially a continuous extension of

the lower coastal plain sediments of South Carolina and Georgia, with most geological formations traceable back to the Appalachian fall line (Figure 2.3) (Colquhoun, 1995). The shelf break occurs at ~80 m water depth, followed by a gentle short slope down to the Blake Plateau.

The Florida-Hatteras Slope is a rather featureless surface compared to most continental slopes elsewhere on the Atlantic margin. It is devoid of any large submarine canyons or slump scars south of 33°N latitude (Figure 2.1). The Florida-Hatteras Slope dips seaward at 4–6 degree over most of its length (Figure 2.4) and is typical of continental slopes globally. The slope drops from ~80 m to ~400 m below sea level before the slope gradient flattens again upon reaching the level of the Blake Plateau.

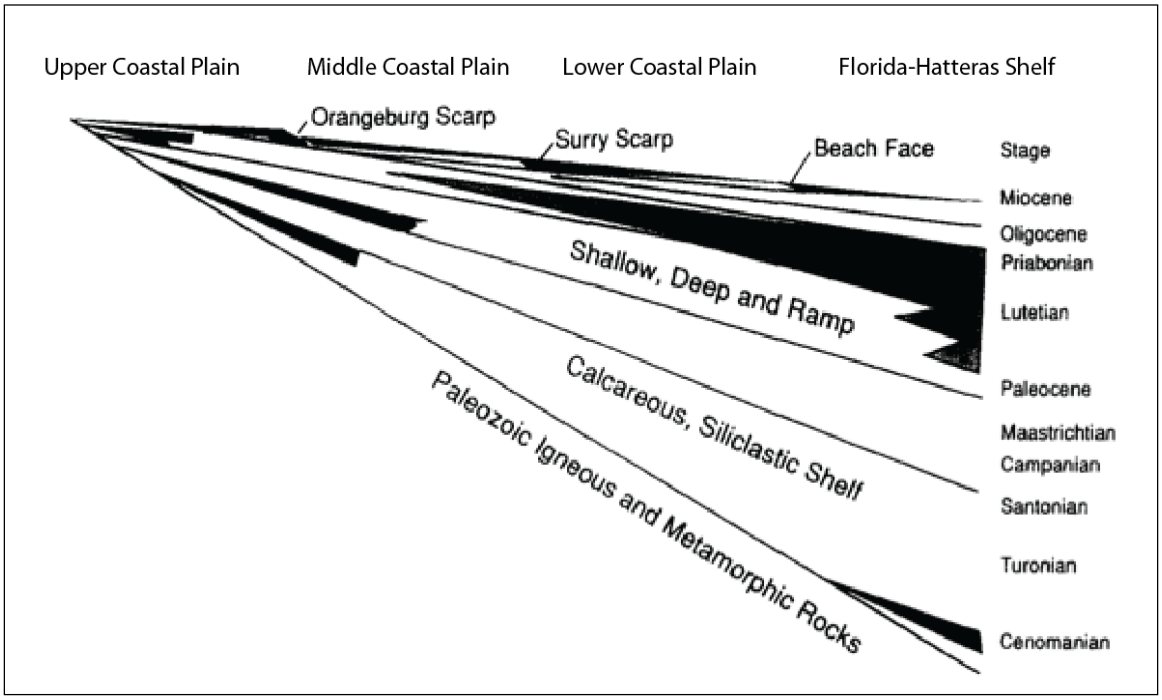

Figure 2.3 Onshore-offshore stratigraphic dip model showing unconformities and major sequences of deposition between depositional stages from Late Cretaceous to Modern. Carbonate and siliclastic shelf depositional unit sequences are indicated by dark areas (modified from Colquhoun, 1995).

2.1.3 The Blake Plateau

The Blake Plateau is the largest, most dominant physiographic feature in the South Atlantic Planning Area with a ~800 km^2 surface area in an approximately triangular shape. The Blake Plateau extends from its convergence with the Florida-Hatteras Shelf at the latitude of Cape Fear, North Carolina in the north down to its ~400 km wide base near the latitude of Cape Canaveral, Florida in the south. The Bahamas Bank lies just south of the Blake Plateau across a deep channel. The plateau lies at an average depth of ~800 m within a range of 400–1,200 m, dipping very slightly overall to seaward (Figure 2.1).

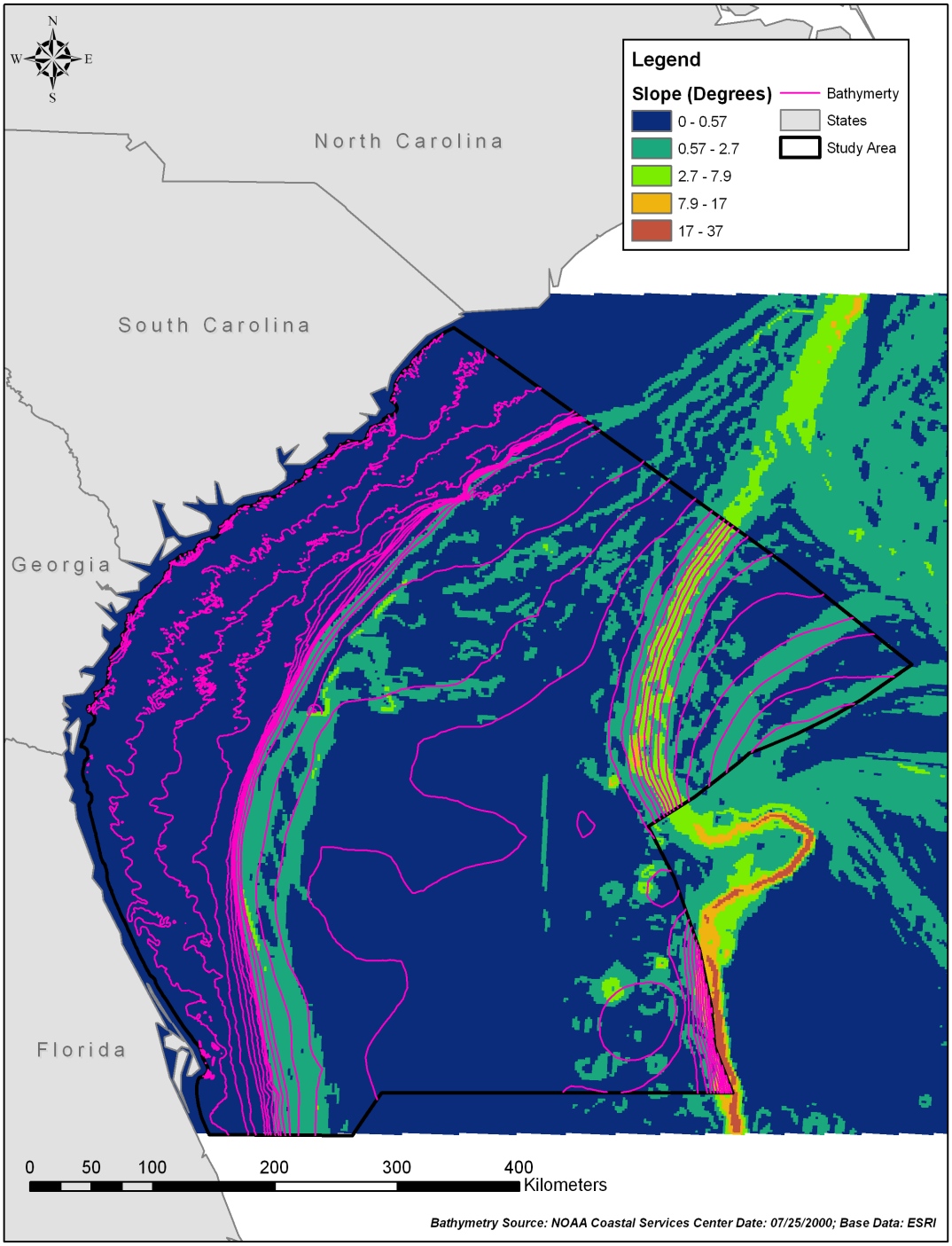

Figure 2.4 Surface slope gradient of the South Atlantic Planning Area, derived from bathymetry in Figure 2.1.

The plateau is thought to be a subsided part of the formerly continuous continental shelf in the SAB. At the onset of the Florida Current, sediments deposited landward of the current have formed the present Florida-Hatteras Shelf; the current has prevented deposition on its seaward side. On-going sediment starvation and subsidence of the outer shelf below and seaward of the Florida Current formed the Blake Plateau (Dillon and Popenoe, 1988).

Although some sediments were deposited on the outer Blake Plateau as late as the Miocene, since that time, the Gulf Stream has prevented most deposition over the plateau and has scoured the bottom in many parts of the plateau removing Neogene age sediment (Gardner et al., 1996). GLORIA imagery shows that much of the surface of the Blake Plateau has a bright reflection in acoustic backscatter, indicating that it lacks a covering of unconsolidated sediment (Figure 2.5). Extensive areas covered by manganese nodules or a phosphate-manganese pavement (Dillon and Popenoe, 1988). Unconsolidated sediments collect in large scoured valleys, scour holes, or in the lee of truncated strata or high relief produced by reef-building corals. The distribution of the sediments on the surface of the Blake Plateau is currently not mapped in detail, although there are few regional compilations from seismic data (e.g., Popenoe et al., 1982; Popenoe, 1980, 1984). A number of circular depressions over 150 m deep are visible in GLORIA images near 31°N, 78°30'W (EEZ-SCAN, 1991). These holes resemble sinkholes, although they also may be caused by bottom scour (Gardner et al., 1996). As the current scours the inner Blake Plateau, it also nourishes deep-water bioherms that form reefs with up to 50 m of relief on the western side of the plateau and up to 150 m of relief on the eastern side (Reed, 2002; Paull et al., 2000).

The Blake Escarpment marks the transition from intermediate depths (1,000–2,000 m) to oceanic depths (5,000 m) off the southern Blake Plateau off Florida. The Blake Escarpment is a very steep undersea cliff; it rises 3 km at an average slope of 40 degrees (Figure 2.4). The Blake Escarpment was initially thought to be structurally controlled; however, more recent evidence points to an erosional origin combined with previous reef development (Paull and Dillon, 1980). This process places the origin of the Blake Escarpment back in Oligocene time (Paull and Dillon, 1980). Although just outside the study area, the Blake Spur is a salient of the Blake Plateau that extends northeastward by 50 km from the northern part of the main plateau (Figure 2.1). North of the Blake Spur, the slopes are more gentle, and influenced by sediment deposited in the Blake Outer Ridge (Figure 2.4). Just to the south of the Blake Spur is a zone of the Blake Escarpment that is cut by submarine canyons and contains at least one large collapse deposit at approximately 29°15'N (Gardner et al., 1996). Such evidence is consistent with on-going undercutting by deep currents as suggested by Paull and Dillon (1980) and Land et al. (1999).

The Blake Outer Ridge extends 200 km southeastward from the Florida-Hatteras Shelf north of the Blake Plateau (Figure 2.1). The study area boundary runs very near the bathymetric axis of the ridge so that the southeastern half of the ridge is within the study area. Blake Outer Ridge is a fine-grained contourite deposit associated with sediments deposited by the Western Boundary Undercurrent. The elongate shape and peaked profile has a surface relief of up to 1,000 m, and it is thought to be 1,000–2,500 m thick. The Blake Ridge surface slopes down from 2,500 to 5,000 m water depth. Megaripples and the heads of slumps associated with methane hydrates cut into its seaward edge (Hornbach et al., 2008). The Cape Fear Slide, just northeast of the study area, is the largest known submarine slide deposit on the US Atlantic coast (Twichell et al., 2009).

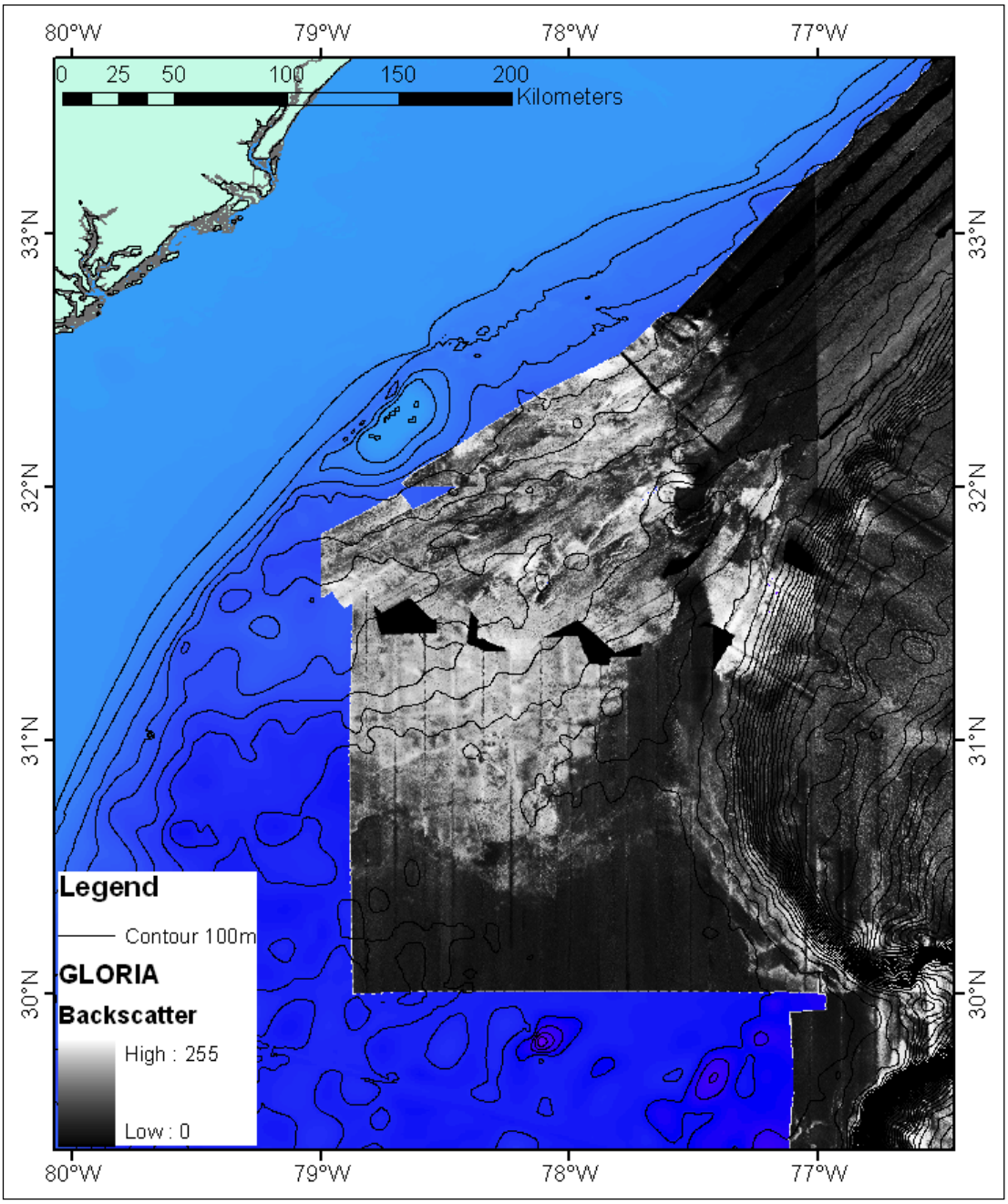

Figure 2.5 GLORIA side-scan sonar backscatter of the northern Blake Plateau. Most of the Plateau is high backscatter (light) suggesting an indurated surface. Black lines are bathymetric contours.

The Charleston Bump is a rocky outcrop at the northern corner of the Blake Plateau (31°30'N and 79°W) that shoals rapidly from over 700 m to a minimum 400 m depth (Popenoe, 1994). Popenoe and Manheim (2001) provide a detailed review of the geology and origin of the Bump, including its effect on physical and biological oceanography of the vicinity. The bump consists of a large knoll with smaller ridges running perpendicular to the flow of the Gulf Stream current. The Charleston Bump forms where the edges of the Carolina Trough and Blake Plateau Basin form a right angle bend that leaves an abrupt basement high (Popenoe and Manheim, 2001). Differential subsidence associated with the termination of the Blake Spur Fracture Zone against continental crust is responsible for the uplift of the Bump (Dillon and Popenoe, 1988). The Bump is important in the South Atlantic Planning Area because it is one of the few hard-bottom features with significant relief, which causes an offshore deflection of the Gulf Stream current and induces eddies and upwelling in the local area.

2.2 GEOLOGICAL STRUCTURES

2.2.1 Deep Depositional Basins

In the study area, two main depositional basins, the Blake Plateau Basin and Carolina Trough, developed as a result of continental rifting that produced the Atlantic Ocean (Figure 2.6). Evidence from magnetic anomalies and seismic reflection profiles indicate that these basins overlie the thinned continental crust at the edge of the Atlantic ocean-continent transition (Austin et al., 1990). These basins consist of one large triangular pull-apart delimited to the north by the Cape Fear Arch and to the south by the Peninsular Arch of Florida (Dillon et al., 1978). The sedimentary fill for these basins is delimited landward by the fall line in the Piedmont zone of the Appalachians (Colquhoun, 1995).

2.2.1.1 Blake Plateau Basin

Based on ages of synrift sedimentary rocks and basalt flows (Lanphere, 1983), it is believed that rifting began opening the Blake Plateau basin probably in late Early Jurassic (~184 million years ago [Ma]) and ended with the shift to seafloor spreading that coincides with the Blake Spur Magnetic Anomaly age of 170 Ma (Klitgord and Schouten, 1986). The basement rocks of the basin are Paleozoic crystalline metamorphic rocks and Jurassic igneous rocks with some sedimentary rocks (Dillon and Popenoe, 1988). The depth to basement at the postrift unconformity reaches a maximum of 14 km (Figure 2.6) (Dillon and Popenoe, 1988). Landward, the basement slopes gradually upward toward present-day Georgia to form the Southeast Georgia Embayment. The Blake Plateau Basin is fairly equant in plan view at about 300 km north-south x 300 km east-west. It underlies almost the entire study area (Figure 2.6).

Pinet and Popenoe (1985) interpreted the geologic history since Middle Cretaceous time based on 4,700 km of seismic reflection profiles. Three progradational clinoform sequences believed to consist of clastic sediment were deposited through the Cretaceous (Figure 2.7, top). Three thin units of Paleocene, Eocene-Oligocene, and post-Oligocene age are composed primarily of deep-water limestone. The Gulf Steam limited the deposition on the Blake Plateau in the Cenozoic, scouring the surface and creating numerous erosional unconformities in the seismic stratigraphy, producing the modern deep-water, sediment-starved environment.

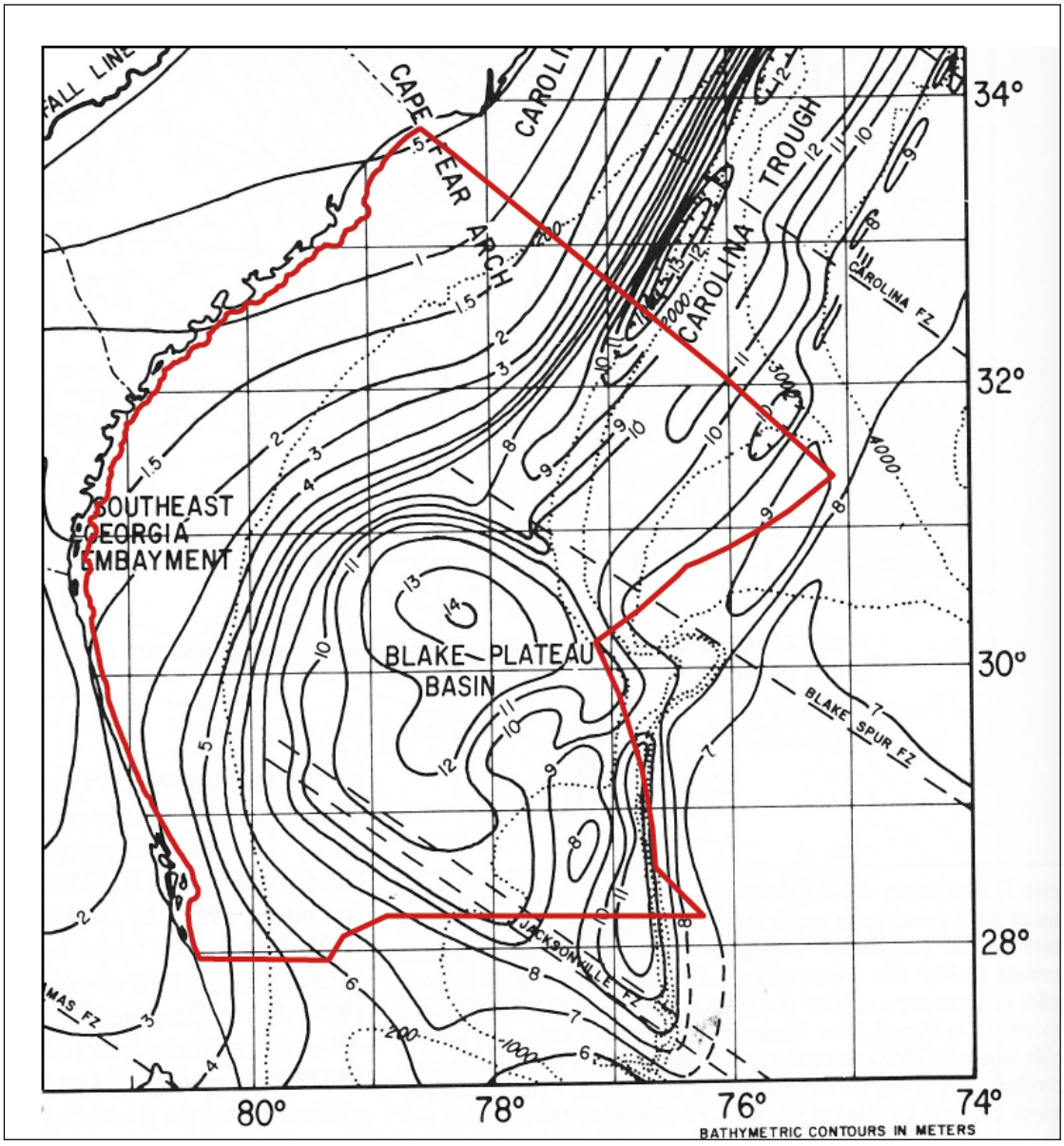

Figure 2.6 Depth to postrift unconformity (assumed to be Mesozoic basement) of the South Atlantic study area and adjacent areas (after Dillon and Popenoe, 1988). Solid lines show the depth to basement in km. Dotted lines show the bathymetric contours in meters. Bold red lines show the boundary of the study area.

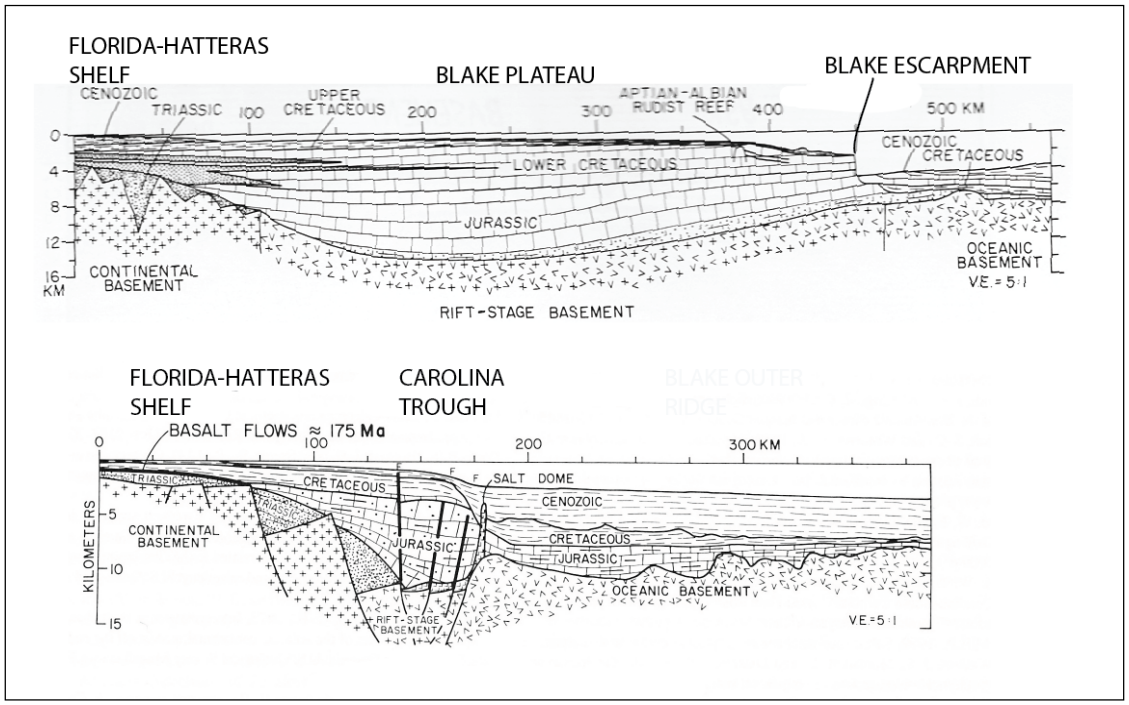

Figure 2.7 Idealized cross-sections through the Blake Plateau (top) and Carolina Trough (bottom) structural basins showing the fill. Carbonate is depicted in a brick pattern and siliclastic is shown as stippled or dashed, following the usual geologic conventions (modified from Dillon and Popenoe, 1988).

2.2.1.2 Carolina Trough

Only the southernmost part of the Carolina Trough extends into the study area (Figure 2.6). The rifting responsible for opening the Carolina Trough probably began at the same time as the Blake Plateau was formed but ended earlier, before the Blake Spur Magnetic Anomaly dated at approximately 175 Ma (Dillon and Popenoe, 1988). Unlike the Blake Plateau Basin, the Carolina Trough is narrow (50–100 km wide) and long (>300 km) although at 13 km deep (Figure 2.6) it is nearly as deep as the Blake basin (Hutchinson et al., 1983; Poag and Valentine, 1988). The Carolina Trough has a steep fault-bounded side to landward and a more gently sloping basement to seaward (Sheridan et al., 1988) (Figure 2.7, bottom). In the Early to Middle Jurassic, evaporite precipitation of varying amounts occurred near the southern end of the Carolina Trough (Dillon et al., 1983). The trough currently contains a line of 27 salt diapirs along its seaward side, including the large Cape Fear and Blake Ridge Diapirs, as a result of the evaporite deposition during this early stage of trough development (see Section 2.2.3).

2.2.2 Helena Banks Fault Zone

The Helena Banks Fault is the only major tectonic fault that runs through the study area that also appears to have been active through the Cenozoic (Idris and Henry, 1995). The Helena Banks Fault is mapped as a zone of en echelon, left-lateral strike-slip faults that are ~25 km offshore; it extends from at least Dewee's Island in the north to the North Edisto River inlet to the south (Behrendt and Yuan, 1987). The fault has little to no seafloor expression at the current resolution of seafloor mapping in the area, but it does displace sub-seafloor seismic reflectors by 1 m at a

depth of 10 m below the seafloor, and by ~500 m at 5 km depth below the seafloor (Behrendt and Yuan, 1987). The fault appears to be a reactivated normal fault, originated during continental rifting, that is seated in Cretaceous strata (Idris and Henry, 1995). Many small antithetic faults are associated at depth with the Helena Banks Fault, but the antithetic faults are probably associated with the initial stage of normal faulting and are unlikely to have been recently active. The US Geological Survey National Earthquake Information Center (USGS NEIC) catalog places a few minor earthquakes along offshore structures associated with the Helena Banks Fault Zone since 1980, suggesting that it remains an active zone of slip. No other known active tectonic structures occur on the shelf.

2.2.3 Salt Domes

Most of the South Atlantic Planning Area has no evidence of evaporite deposition, except for the Carolina Trough at the northern boundary of the study area. A line of 27 salt diapirs extends along the seaward side of the Carolina Trough from 32 to 35°N along the ~3,000 m depth contour offshore (Popenoe, 1984). The diapirs occur in a range of sizes. One of the largest is the Blake Ridge Diapir, located at the south end of the Carolina Trough and within the boundaries of the study area (Dillon and Popenoe, 1988).

2.2.4 Tertiary Basement Antiforms

There is some evidence that the Tertiary basement structures on the Florida-Hatteras Shelf control the position and migration of barrier islands and the Quaternary stratigraphy, particularly along the central South Carolina inner shelf (Harris et al., 2005; Kindinger et al., 1997; Baldwin et al., 2006). Idris and Henry (1995) noted that several of these highs have an antiformal morphology but an erosional origin from the subaerial exposure of the shelf during sea-level lowstands since Miocene time. In Florida, the basement highs are associated with the karstification of the carbonate bank during the late Oligocene to early Miocene sea-level low stands that makes up the shelf (URS and CPE, 2007). The extent of the influence of these basement highs on the migration of major coastal plain rivers (e.g., Baldwin et al., 2006) and barrier island formation (e.g., Harris et al., 2005) is still mostly speculative.

2.3 HYDROGEOLOGY OF THE SOUTH ATLANTIC BIGHT

Throughout the study area, particularly from approximately Hilton Head and south, the offshore extension of the Floridan Aquifer is the primary source of submarine groundwater. The Floridan Aquifer is a group of Tertiary limestone units bounded by low permeability units of either clay or marl that provide an artesian freshwater supply in Florida, coastal Georgia, and parts of South Carolina. Kohout et al. (1988) summarized the hydrologic properties of this aquifer from drilling studies done on the Florida margin off Fernandina Beach (Tenneco Well) and a line of JOIDES Deep Sea Drilling Project (DSDP) holes extending farther seaward, three AMCOR wells off South Carolina and one off Georgia, and the COST GE-1 well off Georgia. Salinity profiles in the JOIDES test wells are typical for a freshwater aquifer that underlies a low-permeability confining unit. The wells off South Carolina show more typical Ghyben-Herzberg profiles suggesting the lack of upper confinement. A series of submarine freshwater springs are located where the Ocala Limestone section of the Floridan Aquifer is exposed at the seafloor off north Florida (e.g., Crescent Beach Spring, 4 km off Crescent Beach, Florida). Saltwater is intruding

the Floridan Aquifer from St. Augustine south to Cape Canaveral (Kohout et al., 1988). Karstification (dissolution of limestone by groundwater) occurred during the late Oligocene to early Miocene sea-level low stands. Karst that developed in early Tertiary limestones from St. Simon's Sound to Cape Canaveral produces subsurface local stratigraphic deformation in the form of folds and sags that have up to 100 m of subsurface relief (Meisburger and Field, 1975; Popenoe et al., 1984). This karst topography probably controls much of the physical processes on the Florida shelf, and strongly influences the groundwater flow regime off of Florida. Farther north, it is probable that filled fluvial paleochannels serve as conduits for freshwater offshore, and thus play an important role in shelf hydrogeology.

2.4 SEDIMENTARY STRATIGRAPHIC FRAMEWORK

The offshore stratigraphy of the South Atlantic Planning Area including the Blake Plateau and Florida-Hatteras Shelf is summarized in Dillon et al. (1985), Dillon and Popenoe (1988), Popenoe (1990), and Colquhoun (1995). The stratigraphic framework is largely based on interpreted seismic reflection data tied to offshore wells and onshore data. Figure 2.7 presents a simplified summary of the fill in these two basins. On the shelf, the COST well is important for the stratigraphic control it provides at depth (Scholle, 1979). Several shallow penetration wells by the USGS, JOIDES, and Atlantic Slope Project provide the most widespread stratigraphic control (Charm et al., 1969; Poppe, 1981; Hathaway et al., 1979; Dillon and Popenoe, 1988 and references therein). The DSDP has drilled a few deeper holes on the Blake Spur (DSDP 390 and 392) and the Blake Outer Ridge (DSDP 102, 103, 104, and 533). There are about fifteen stratigraphically sampled wells in total; only five of these penetrated Cretaceous rocks (Dillon and Popenoe, 1988).

Based mostly on seismic profiles (Austin et al., 1990; Idris and Henry, 1995; Colquhoun, 1995; and work reviewed in Dillon and Popenoe, 1988), it is believed that the base of the sedimentary column lies unconformably on the Jurassic-Paleozoic basement. Early sedimentary layers, mostly Cretaceous and earlier, have a slight landward dip, which rotates to flat-lying and slightly seaward in the Cenozoic, moving upward through the stratigraphic layers.

A thick section of Jurassic strata composed of terrigenous to shallow marine sedimentary deposits reflects the rapid subsidence early in the history of the basins. These are overlaid by carbonate-platform deposits that formed landward of reefs or banks that, from Late Jurassic to Early Cretaceous, grew near the eastern edge of the Blake Plateau Migration of the coastline across this area produced cyclical deposits of siliclastic and carbonate sediments that form the bulk of the sedimentary fill in the Blake Plateau Basin and Carolina Trough. The lower Cretaceous consists of marine and non-marine sediments, including red and gray sandstone, minor limestone, anhydrite, pyrite, glauconite, and coal. Because of subsidence and rising sea levels, by the Late Cretaceous, reef growth ended along the eastern edge of the Blake Plateau Basin. Deposition at this time was a mix of deep-water sediments such as chalks and marls deposited across the platform areas. Onset of the Gulf Stream current in early Eocene caused scour on the Blake Plateau. Continued sediment deposition landward of the current produced the Florida-Hatteras Shelf. Flat-lying beds of sand-sized sediment mixed with calcareous shell fragments compose the top layers of Eocene-Recent sediments.

Recent, more-detailed local studies have filled in some of the gaps in knowledge about the uppermost stratigraphy along the inner shelf. Detailed stratigraphic studies that link the basement geologic structures to modern deposition and the coastal sedimentological framework are available for Myrtle Beach to Winyah Bay, South Carolina (Baldwin et al., 2006), Isle of Palms to Seabrook Island (Harris et al., 2005), and northeast Florida (URS and CPE, 2007 and related database). Currently, the Georgia coast and South Carolina between Winyah Bay and Charleston lack this level of detailed offshore geological study.

Baldwin et al. (2006) present a detailed seismic stratigraphic model of the inner shelf of Long Bay extending from Little River, North Carolina to Winyah Bay, South Carolina. Their model links tectonic patterns revealed in the basement structures to modern shelf processes on this shoreface-attached barrier part of the coast. Internal antiform and synform structural features were identified in the Cretaceous basement, indicating north-south compression that may be related to the formation of the Cape Fear Arch. Antiforms were truncated or incised by now-filled fluvial paleochannels. Baldwin et al. (2006) suggest the locations of the paleochannels may be partly controlled by extension-related fracturing of the strata at the crests of the folds, making them preferential sites for fluvial incision and channel development. In the sub-bottom data from Long Bay, South Carolina, fluvial paleochannels are common and take the form of large channels carved into underlying continental shelf deposits. These paleochannels are most likely the results of Piedmont and Coastal Plain rivers cutting into subaerially exposed units during sea-level low stands, or small channels with less continuity across the shelf, interpreted as tidal creeks or smaller inlets (Baldwin et al., 2006). Erosion associated with sea-level fluctuations eroded much of the Tertiary section and yielded a mappable upper boundary interpreted to represent an erosional surface formed during the last marine transgression (Baldwin et al., 2006). Sediment associated with paleochannel systems has been reworked by modern hydrodynamic processes into a patchy distribution of shoreface-attached and -detached ridges that contain most of the sand in the system (Baldwin et al., 2006).

Harris et al. (2005) describe the influence of the near-surface stratigraphic units, the internal stratigraphic architecture of those units, and the geomorphology of the region from Charleston to St. Helena Sound, South Carolina. They focus on the effect on surficial sedimentary cover and the development of the coastline of Folly, Kiawah, and Seabrook islands. This area is the center of the classic drumstick-type barrier island chain (Hayes, 1979). Harris et al. (2005) describe three major stratigraphic depositional systems within the seafloor and near-surface deposits beneath their study area: (1) Tertiary strata deposited at the Early Tertiary shelf edge; (2) Miocene and Pliocene strata preserved as infill sequences of low stand-incised valleys and isolated local basins; and (3) Quaternary barrier beach and shelf complexes composed of paralic deposits (sediments deposited on the landward side of a coast). Harris et al. (2005) also find evidence for incised paleochannels of Quaternary age cutting into Tertiary consolidated sediment similar to those found to the north by Baldwin et al. (2006). The Folly and Kiawah Tertiary basement antiforms underlie the islands for which they are named, with major tidal inlets, paleochannels, and paleovalley systems generally parallel to these major underlying stratigraphic highs and lows (Harris et al., 2005). In this area, the underlying structure controls Quaternary sediment deposition by emplacing most sand through the major drainage systems in the Tertiary lows and thinning between the islands.

2.5 HARD-BOTTOM AREAS

Hard bottom or hard ground refers to those areas of seafloor where soft sediment is absent so that a lithified substrate, typically Miocene-Cretaceous sedimentary rock units, are exposed at the surface. Comprehensive reviews of the data on hard-bottom areas were compiled as part of the Southeast Area Monitoring and Assessment Program (SEAMAP). The resulting reports were published by Van Dolah et al. (1994) for South Carolina and Georgia and by Perkins et al. (1997) for Florida. In addition to those major reports, a few local studies have been done (e.g., Baldwin et al., 2006; Hunt, 1974; Kendall et al., 2005; Denny et al., 2005; Harris et al., 2005; Kindinger et al., 1997). There are many deep-water coral reefs along the base of the Florida-Hatteras Slope and on the Blake Plateau that are technically hard bottom.

The SEAMAP project compiled data for the Florida-Hatteras Shelf (to <200 m depth) for the South Atlantic Planning Area and forms the most comprehensive database of hard-bottom areas for the study area. Data for the SEAMAP synthesis were derived from a wide variety of sources rather than a single, designed study. Only 28% of the 1x1 arc-minute grid cells in the study area contain any data. The clustered nature of the spatial distribution in the raw data records means that the number of records poorly reflects the distribution of hard-bottom area. Van Dolah et al. (1994) noted that the data tend to be drawn from fisheries studies of reef or hard-ground areas.

SEAMAP has compiled 11,534 records of bottom type off South Carolina, 3,886 off Georgia, and 37,417 records off Florida (ASMFC, 2001). Approximately 50% of the records are hard bottom or possible hard bottom (51% in South Carolina, 58% in Georgia, 48% in Florida). When the data are divided into 1x1 minute bins in South Carolina, approximately 30% of the bins contain hard bottom (Van Dolah et al., 1994). However, almost half the data come from the Long Bay (i.e., Myrtle Beach) area and nearly another one-third from the Charleston region.

2.5.1 Hard Bottom on the Inner Shelf (Depth <20 m)

Henry and Giles (1980) reported that hard bottom occurred as one of three types of features: (1) low-relief hard ground, (2) moderate relief ridges, or (3) shelf-edge reefs. The SEAMAP studies did not attempt to differentiate these types, but a few other studies were locally more detailed. Gray's Reef, a National Marine Sanctuary offshore Georgia, is a set of NE-SW trending ridges of ~2 m relief and composed of dolomitized sandy biomicrite (Kendall et al., 2005; Hunt, 1974). Hard bottom in Long Bay, between Myrtle Beach and Pawley's Island, South Carolina, consists of outcroppings of marl ledges (Baldwin et al., 2006). Off Charleston, hard-bottom areas consist mainly of low-relief (0.3 m) outcropping ledges of limestone conglomerate (Continental Shelf Associates, 1979). The overall pattern of hard-bottom distribution is patchy throughout the inner shelf.

2.5.2 Hard Bottom on the Outer Shelf (Up to 80 m)

Ridges of algal rock, built by calcareous algae and bryozoans, or coquina rock, parallel the shelf break of the Florida-Hatteras Shelf in water depths of 50–80 m (Emery and Uchupi, 1972). The ridges are common but discontinuous across South Carolina and Georgia, but change in nature near the south end of the study area. Most outer shelf ridges are low relief (<5 m), but rarely can be up to 10 m high (Continental Shelf Associates, 1978). At the southern end of the study area in central Florida, various types of high-relief, hard-bottom areas, such as *Lophelia* mounds, karst

features, and outcropping ledges, extend into the study area and are associated with the Oculina Banks, a Marine Protected Area just south of the study area, (Reed, 2002).

2.5.3 Hard Bottom Off-shelf: Blake Plateau and Ridge

The surface of the Blake Plateau has a patchy accumulation of sediments because it is scoured by the Gulf Stream. A hard-bottom pavement of phosphorite and manganese covers most of the surface of the Blake Plateau between 30-32°N (Popenoe, 1984). The pavement occurs between 600–800 m depths in the area of maximum scour by the Gulf Stream. The pavement forms a continuous surface except where it is cut by deep pits formed by limestone solution or bottom currents. In deeper water (700-–1,000 m), where less scour occurs, ferromanganese nodules cover large areas of the plateau (Popenoe, 1984). These nodules appear to have formed over phosphatic gravel cores derived from phosphate-rich Oligocene to Miocene age deposits (Milliman et al., 1972). The only large, continuous area of sand on the inner Blake Plateau lies north of 33°N in the lee of the Charleston Bump. The Blake Outer Ridge is surfaced entirely by unconsolidated sediment that ranges from silt to mud (Dillon and Popenoe, 1988).

Deep-water (>200 m) coral reefs are common in the South Atlantic Planning Area. The most well-studied sites are the Stetson Reef and Savannah Lithoherms, although numerous small reef patch sites can be found across the Blake Plateau (Reed, 2002; Paull et al., 2000). Stetson Reef is comprised of over 200 pinnacles along the eastern Blake Plateau, in depths of 600 m to over 800 m, that are very steep and up to 150 m high. Submersible dives on these structures reveal that they are composed of *Lophelia* rubble with colonies of live *Lophelia* at the top (Reed, 2002). A number of mounds, described as lithoherms formed by deep-water *Lophelia* trapping sediment with typically 10–50 m relief, are found at the base of the Florida-Hatteras Slope (Paull et al., 2000). Reed (2002) suggests that these isolated coral mounds extend south to form a continuous band of deep-water *Lophelia* mounds that could contain as many as 40,000 individual mound structures along the base of the slope between Savannah and Miami. Additional study is needed to define the extent and distribution of this deepwater reef setting.

2.6 SURFICIAL SEDIMENTS

2.6.1 Sediment Types

This section addresses the composition and texture of unlithified surface sediments found in the South Atlantic Planning Area. Milliman et al. (1972) and Pilkey et al. (1981) summarize the results of several sampling expeditions and most of the important studies up to about 1980. Since that time, local studies focused on the upper shelf have added analyses related to offshore sand resources as described in Section 2.6.3. Records of sediment type were also viewed in the usSEABED database (Reid et al., 2005).

The Florida-Hatteras Shelf surface is covered almost entirely by a sheet of sand (Knebel, 1981) that is made up of moderately well-sorted, medium-grained, subarkosic to orthoquartiztic sand (Milliman et al., 1972). The subarkosic to orthoquartzitic composition of the sands indicates the weathered sources and the long transport path of sediment carried by the southern Piedmont rivers. A band of arkosic sand along the Florida-Hatteras Slope contains significantly more feldspar than either the landward shelf or the modern fluvial sources, indicating that it is possibly

derived from mid-Tertiary formations locally underlying the sediment (Hathaway et al., 1979). The most abundant heavy minerals in the sands are staurolite and epidote (Milliman et al., 1972; Van Dolah et al., 1994). Pockets of coarse-grained sand to gravel occur on the Blake Plateau (Figure 2.8). Silt and clay cover the Florida-Hatteras Slope off northern Florida, forming one of the few major exceptions to the ubiquitous sand sheet (Figure 2.8).

South of Cape Hatteras, sediments begin to contain abundant calcium carbonate. However, terrigenous sedimentation strongly influences local variations in carbonate abundance (Figure 2.9). Input of terrigenous sediments from the major rivers from the Pee Dee to Savannah reduces carbonate to 15% of the deposits (Milliman et al., 1972). This fraction increases to up to 50% off northern Florida. Mollusks are the primary component of the inner shelf carbonate fraction. Encrusting coralline algae deposits are common on the outer shelf, and hermatypic corals are increasingly common offshore and southward. Ooids can be found everywhere south of Onslow Bay, but are only texturally important off Florida.

On the Florida-Hatteras Slope, glauconite comprises up to 95% of the non-carbonate component of sediment. Glauconite grains are probably derived from local outcrops of mid-Tertiary sedimentary rocks, as indicated by their dark coloration and other factors (Milliman et al., 1972). Phosphorite typically constitutes 2% or less of the shelf sediment (Luternauer and Pilkey, 1967). Highly localized pockets of phosphorite and manganese on the inner part of the Blake Plateau coincide with local outcrops of Cretaceous and Tertiary strata.

The preponderance of carbonate, glauconite, and phosphorite on the Florida-Hatteras Slope and the inner Blake Plateau, in association with outcrops of Cretaceous or Tertiary rocks, suggests that most glauconite and phosphorite sediments are residual rather than authigenic (e.g., Milliman et al., 1972; Dillon and Popenoe, 1988). This indicates that no net sedimentation has occurred in these areas since the mid-Tertiary.

2.6.2 Thickness of Surficial Sediment

Acoustic measurements (i.e., seismic) are the most efficient way to determine the thickness of what can be a highly variable, mobile, surface sediment layer. Vibracore and drill cores are also useful as direct measurements. Popenoe (1984) and Popenoe et al. (1982) provide a regional review of sediment thickness on the outer shelf based on widely spaced seismic lines. Surficial sediment is thin or absent over most the Blake Plateau (Figure 2.5). The Blake Outer Ridge has a relatively thick mobile sediment layer that consists of several tens of meters of muddy silt (Hornbach et al., 2008).

The overall distribution of surficial sediments on the inner shelf are largely the result of the thin and discontinuous nature of Pleistocene and Holocene sediments, but large volumes of quartz sand are found in low relief seafloor features. Adjoining areas of the shelf often contain surface sediments deposited at different times and under contrasting environmental conditions (Pilkey et al., 1981; Meisburger and Field, 1975, 1976).

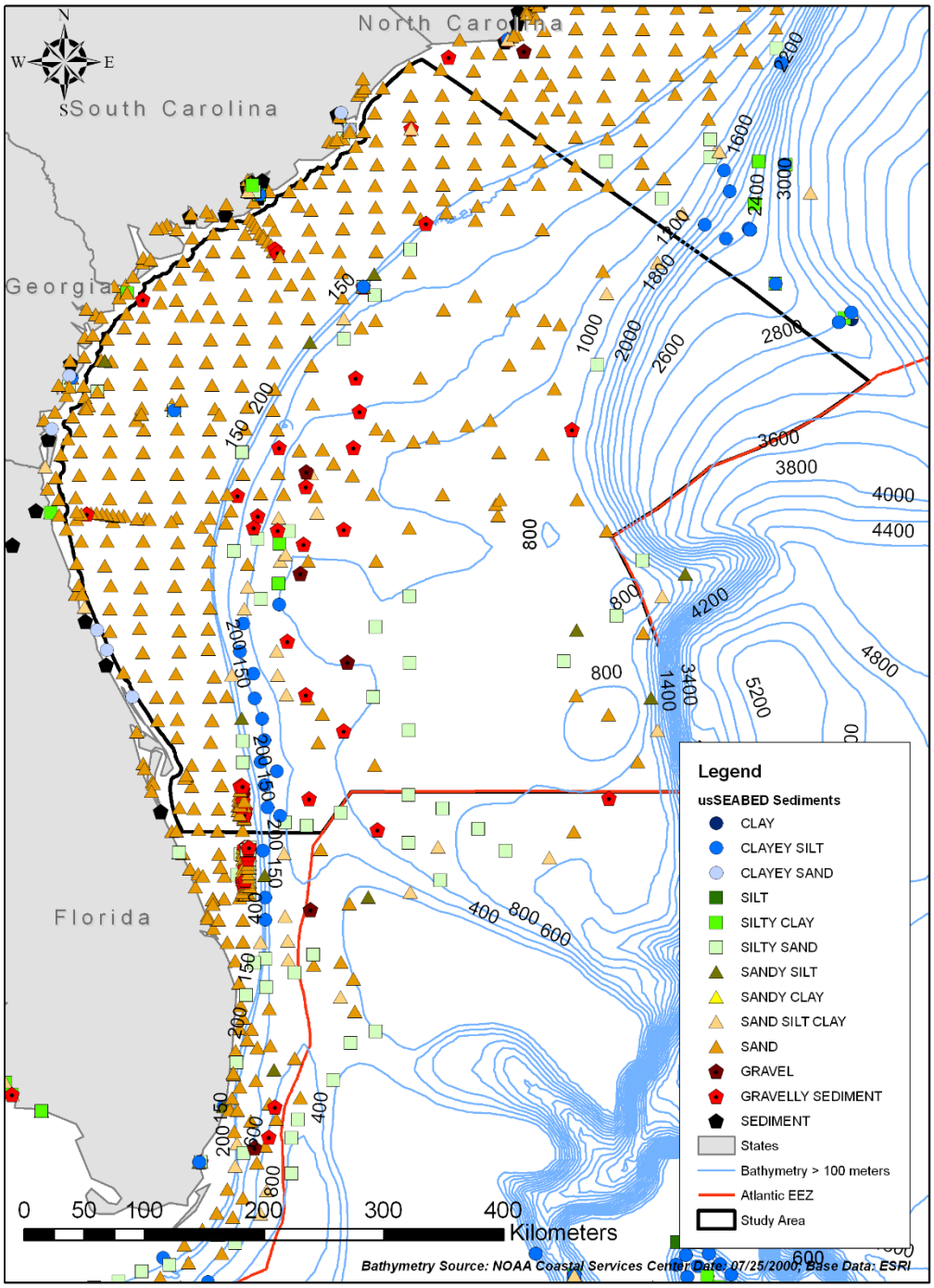

Figure 2.8 Surface sediment grain size data from usSEABED compilation (2005) for the study area and adjacent areas.

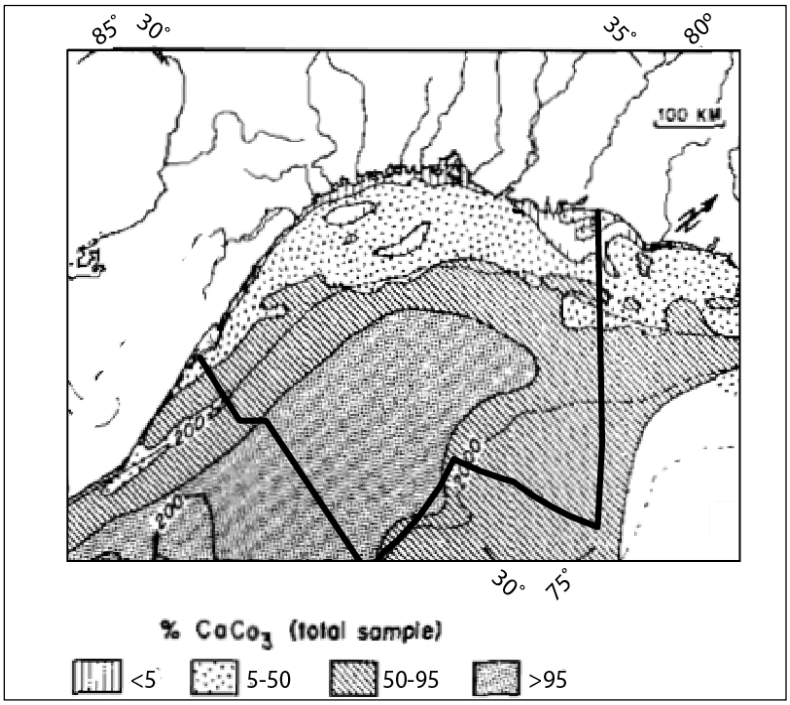

Figure 2.9 Calcium carbonate as a percentage of the sample in surface sediments with study area limit shown in bold solid line (modified after Milliman et al., 1972).

On the Florida-Hatteras Shelf, the upper sediment layer tends to be thinner than 4 m, except locally where it fills paleochannels and can be more than twice as thick (Pilkey et al., 1981). Sediment off of northern South Carolina is very patchy, with numerous exposed areas of indurated sedimentary rock but locally up to 6 m thick (Figure 2.10A). Most of the thicker sediment accumulations consist of paleochannel fill. Off central South Carolina, in the Charleston area, the sand layer at the coastline tends to be most continuous, with more patchy distribution farther offshore; however, there are some places with thicker deposits, again, filling paleochannels (Harris et al., 2005; Gayes et al., 1998) (Figure 2.10B). Farther south, the surface sand sheet becomes more pervasive, although it remains thin. Wright et al. (1998) found a <2 m thick clean sand layer near Hilton Head, and this thin cover extends south into Georgia (Foyle et al., 2004).

Thickness and spatial distribution of lithologic units on the Florida shelf are organized by Meisburger and Field (1975) into three primary patterns. Most of the shelf from the Georgia border with Florida to Jacksonville is covered by fine- to medium-grained quartz sand deposits that are up to 1 m thick, but range up to 2 m thick in some places. Off Fernandina and Jacksonville, the quartz sand deposits are up to 3 m thick and more uniform in lateral extent (URS and CPE, 2007). Approaching Cape Canaveral, the surficial sand sheet on the shelf is characterized by fields of linear, northeast-trending sand ridges typically a few meters thick and containing medium-grained, well-sorted sand that is similar to sand along the present shoreline (URS and CPE, 2007). Studies by Meisburger and Field (1975) indicate the presence of sand sheets up to 2 m thick and linear ridge-like shoals >2 m thick off Fort Pierce and Cape Canaveral and south of Daytona Beach.

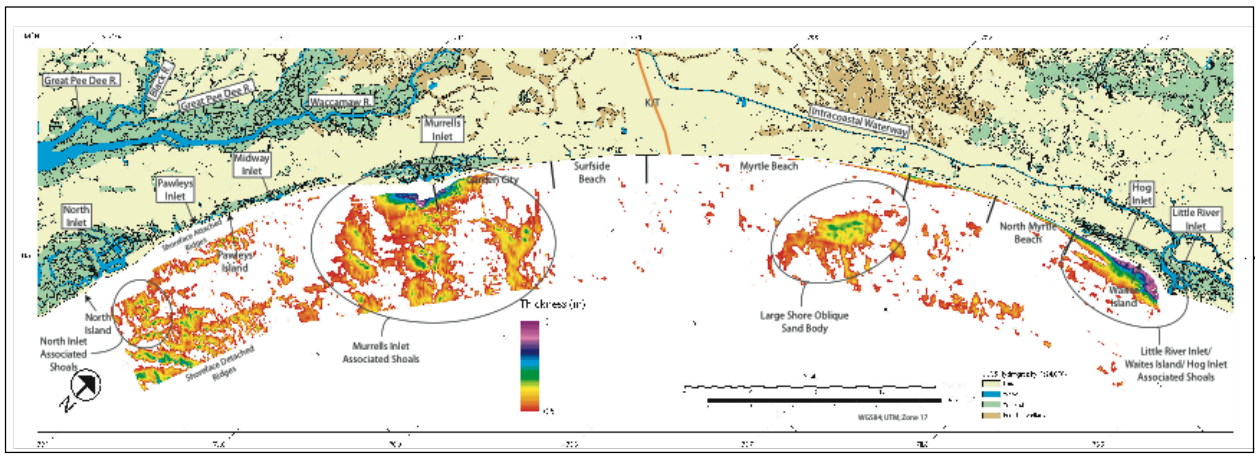

Figure 2.10A Sediment isopach map showing Holocene sediment thickness derived from chirp seismic data in Long Bay, South Carolina (from Baldwin et al., 2004).

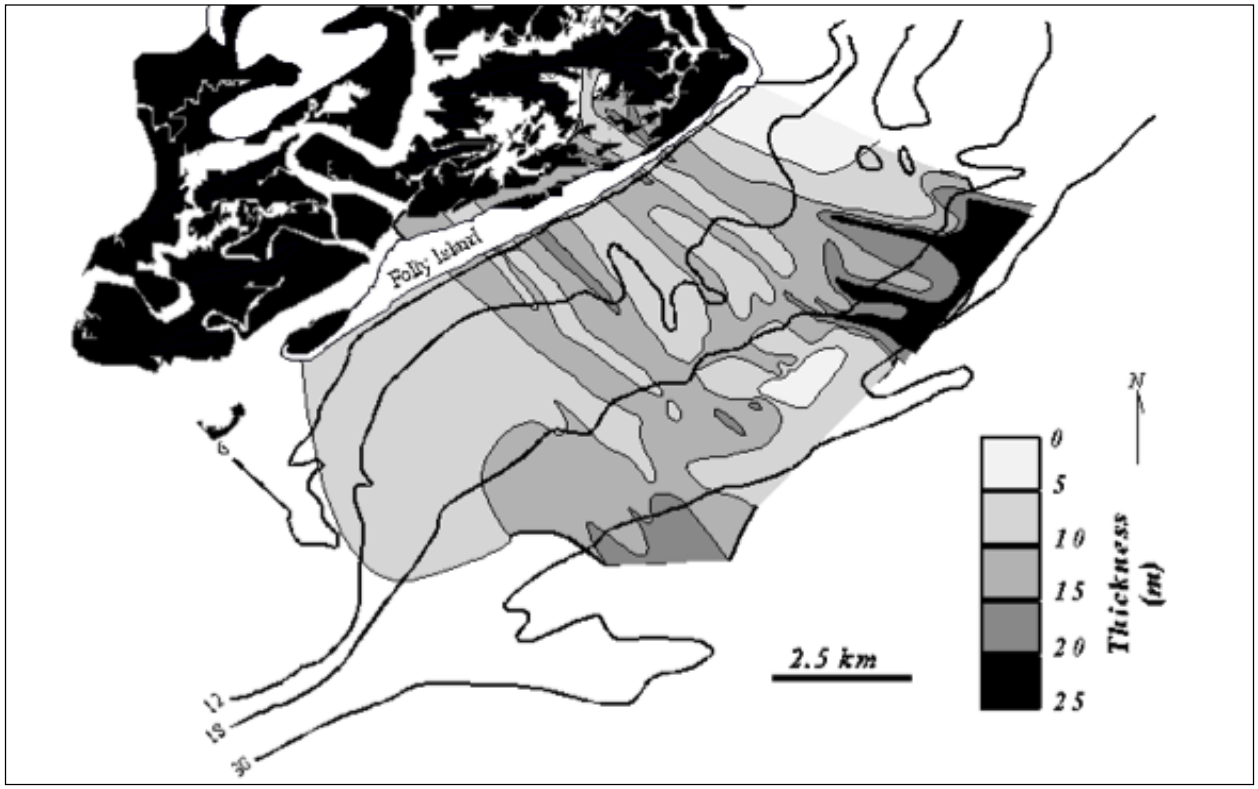

Figure 2.10B Sediment thickness isopach of Quaternary deposits off Folly Island. Bathymetric contours are in feet below mean sea level (from Gayes et al., 1998).

2.6.3 Sand and Gravel Resources

The South Atlantic Planning Area contains large sand deposits that can be sources of material for beach nourishment, coastal protection, and other public and private projects. Several federal and

state agencies have responsibility for decisions related to sand resources. Additional resources are located in state waters adjacent to the OCS planning area; an overview of these resources is presented to give a more comprehensive picture of the regional resources. On the present transgressive coastline, the estuaries, sounds, and inlets function efficiently as sediment traps for sand moving into the coastal zone. This occurs because fluvial base-level rise, in response to the ongoing sea-level transgression, creates more accommodation space than available sediment supply can fill. More than 70% of the available Holocene sand in the coastal system is now stored in well-developed ebb-tidal deltas which act as temporary sediment sources and sinks (Hayes, 1994). Thus, little new sand-sized sediment is reaching the shelf from either rivers that drain the Piedmont (such as the Pee Dee and Savannah Rivers) or Coastal Plain rivers (such as the Edisto and St. John's Rivers). In the South Atlantic Planning Area, sand bodies preserved on the shelf that were or could be targets for sand borrow sites include: (1) active and inactive estuarine entrance shoals (e.g., off St. Helena Sound, South Carolina); (2) large ebb-tidal deltas off tidal inlets (e.g., South Edisto River Inlet, South Carolina); (3) delta lobes deposited at lower stands in sea level (e.g., Santee Delta, South Carolina); and others (Hayes and Nairn, 2004). Filled paleochannels are a promising source of sand in the South Atlantic Planning Area because they are common and can be large (Gayes and Ealy, 1995). Because mixed sand and fines of silt and mud often fill such channels, detailed exploration will be required to locate channels filled by clean sand.

The Florida-Hatteras Shelf along northeast Florida between Fernandina Beach and Cape Canaveral contains abundant sediments that have accumulated in a variety of settings. Sand resources on the shelf of north Florida beyond the 3-mile limit are now relatively well known due to the Reconnaissance Offshore Sand Search (ROSS) project and its online searchable database on nearshore and coastal data in Florida (URS and CPE, 2007). The largest potential sand resources are in St. Johns County (28×10^9 m^3) and Volusia County (21.6×10^9 m^3), which together take in about 612,924 hectares of seafloor. Significant potential sand resources are also associated with Duval County (13.5×10^9 m^3), Flagler County (9×10^9 m^3), and Nassau County (6.2×10^9 m^3) (URS and CPE, 2007). Bank shoals, flat-topped bodies of irregular outline and low relief, occur throughout the area and often are mantled by quartz sand up to one meter deep. Some bank shoals show promise as sand sources, such as the shoal located 9.7 km offshore from Jacksonville and St. Augustine where the sand volume is estimated by Meisburger and Field (1975) to be on the order of 177.9×10^6 m^3. Deposits off Ormond Beach and Marineland are estimated to contain about 46×10^6 m^3 and 30×10^6 m^3, respectively (URS and CPE, 2007). A buried channel of the St. Johns River contains reasonably clean, medium- to coarse-grained quartz sand under a shallow overburden. Linear shoals, such as those lying off Amelia Island, may contain thick sand accumulations. A sand ridge near St. Augustine, for example, is estimated to contain at least 5.3×10^6 m^3 of sand in a layer 1.2–1.8 m thick (URS and CPE, 2007). Four potential sand resource sites were identified offshore of Brevard County near Cape Canaveral with three of these containing numerous sand shoals (medium-to-coarse sand ridge deposits with maximum shoal relief was on the order of 5–6 m, and average shoal relief was about 2–3 m) with the largest extractable sand volume up to 13×10^6 m^3 just south of the cape (Hammer et al., 2005). These shoals are associated with Cape Canaveral, one of the largest cuspate forelands in the world, formed of relict sand deposited during brief Plio-Pleistocene marine transgressions (Field and Duane, 1976).

Wright et al. (1998) reported the potential sand resources based on high-resolution seismic profiles, surface sediment grab samples, vibracores, and compiled previous studies off of Hilton Head, South Carolina. They concluded that Gaskin Banks is the best source of sands in the area. Surface sediment grain-size analysis indicates higher percent sand values (>95%) on Gaskin Banks and seaward of the banks in deeper water to the south than elsewhere in the vicinity (Wright et al., 1998). Their high-resolution seismic data indicates the layer of sand continues seaward to the limit of their study area as a thin (<2 m) unit.

Offshore Folly Beach, South Carolina sand deposits have been studied in detail for use in local beach nourishment projects. The area offshore the northern half of the island contains thick sand deposits where a channel system incised the shelf during marine regressions (Harris et al., 2005). In incised low-stand channels, sediment depth may reach a depth of 15–20 m below seafloor (Gayes and Ealy, 1995). The ebb-tidal delta at Stono Inlet at the southern end of Folly Beach represents an additional and potentially massive reserve of sand for Folly Beach (Gayes et al., 1998). Similar ebb-tidal delta shoals have been used as sand sources for beach nourishment projects elsewhere in South Carolina at Edisto, Hilton Head, and Seabrook islands (Van Dolah et al., 1998). Areas off Stono Inlet and Lighthouse Inlet have large sand reservoirs but were not targeted for further study because they were not suitable resources due to their status as environmentally sensitive areas. Tertiary units comprised of calcareous marl outcrop ~8 km off Folly Beach (depth >10 m) and several poorly developed sand ridges have formed in their lee. The sand source that was used for the 1993 nourishment of Folly Beach was located behind Stono Inlet in the Folly River; the post-dredging recovery is documented in Van Dolah et al. (1998). In the area off Edisto Island, the Tertiary deposits form an undulating surface with basement highs very close to or at the sea floor. No significant paleochannels are seen to incise the Tertiary strata, and no significant thicknesses of Quaternary age sediments are seen in the seismic data from the inner shelf offshore of Edisto Island (Gayes et al., 1998). The large shoal complex within the ebb-tidal delta of the South Edisto River Inlet is the most promising source of sand (Gayes et al., 1998) and has been used for beach nourishment (Van Dolah et al., 1998).

Wright et al. (1998) describe the sand resources off Pawley's Island, South Carolina as interpreted from high-resolution seismic, side-scan sonar data and 96 vibracores. They found thin sediment cover (<2.4 m, typically <0.9 m) over the entire study area, with the thicker sediment deposits occurring within bathymetric highs located to the southeast of Pawley's Island. Grain size was lower and carbonate content was higher in the offshore surficial sands than in the natural beach sands on Pawley's Island. Seismic profiles revealed possible thicker deposits of sediment underneath bathymetric highs to the southeast of Pawley's Island up to 0.3 m thick, and some potential borrow sites of poorer quality were identified to the north and to the east. In this case, the filled paleochannels do not appear to contain useable sand.

Van Dolah et al. (1998) studied six sand borrow sites from the southern half of the South Carolina shoreline. The borrow sites described share a geologic setting as shoals a few kilometers offshore. Off Hilton Head Island, Gaskin Banks, 3.7 km offshore near the center of the island, and Joiner Bank, nearshore close to the mouth of Port Royal Sound, were dredged. The Edisto Island, Hunting Island, and Seabrook Island beach nourishment projects obtained material from nearshore shoals less than 3 km from the shoreline. These shoals contain clean sands near the surface, and they represent highly suitable resources for beach nourishment

projects. However, some of the sites contain muddy lenses at depth that could limit the amount of usable sand to ~1 m thickness near the top of the shoal. In South Carolina state waters, most of the sand borrow areas that have been dredged to date range in size from approximately 5–84 hectares; they have dredged to depths 3 m or more below the existing seafloor (Van Dolah et al., 1998). Van Dolah et al. (1998) report infilling of these dredge cuts in 5.5–11.8 years with variable sediment grain sizes, although McCoy et al. (2010) found replacement of sediment in OCS borrow areas off Myrtle Beach, South Carolina up to 65% after one year post-dredging. Long-term sand resource potential is highest in the highly mobile sediment areas where refilling by relatively clean, beach-compatible sand was observed (Van Dolah et al., 1998; McCoy et al., 2010).

Fewer studies of sand resources have been conducted on the Georgia coast; nearshore sand borrow sites have been adequate for past needs. The Georgia coastline is low-lying and depositional, with Pleistocene and Holocene sediments deposited in barrier islands, salt marshes, a number of large estuaries (called sounds), and two rather small river deltas blanketing an irregular topography eroded during low stands of sea level during the Pleistocene epoch. With a spring tidal range of 2.5 m, Georgia has very large ebb-tidal deltas that contain large amounts of clean sand (Foyle et al., 2004).

2.7 SEDIMENT TRANSPORT

2.7.1 Sediment Sources

Important rivers bringing new sediment into the coastal system are the Pee Dee, Santee, Savannah, Altamaha, and Cape Fear rivers (Hayes, 1994; Morton and Miller, 2005; McCarney-Castle et al., 2010). St. John's River in Florida is not a significant source of sediment to the shelf, and its contribution is usually not considered. In the past century, the dams installed on the Santee and Savannah reduced these rivers' sediment contributions to a very small input. Coastal plain rivers deliver only reworked sediments from the alluvial fill accumulated in stream valleys that were cut in the last sea-level lowstand. Rivers have low runoff but high suspended load. More recent studies (McCarney-Castle et al., 2010) of riverine input used a parameterized watershed-scale model to examine the fluvial input to the southeastern US. Their results indicate that, since the placement of the reservoirs, total sediment supply to the coastal zone has decreased by approximately 55%. The mean annual suspended sediment load transfer rate was estimated as 6.2 metric tons per year (Mt/yr) during the period 1680–1700, which corresponds to pre-European settlement conditions. Deforestation and agricultural activities of the European settlers led to an increase of sediment input to 15.04 Mt/yr, before dam construction. Because of dam trapping, the current sediment discharge rates were estimated at 5.2 Mt/yr. McCarney-Castle et al. (2010) argued that the Savannah and Santee rivers discharge significantly less sediment today, compared with pre-European fluxes, but that the Pee Dee River sediment discharge has not changed significantly (Figure 2.11). Mass conservation arguments suggest that this material escapes the estuaries during freshet events; dredging activities do tend to interrupt the natural sediment transport path. The majority of fine-grained sediment is being trapped on salt marshes (Murphy and Voulgaris, 2006 and references therein), and the majority of the coarser sediment is accumulating on the ebb-tidal deltas that trap much of this sediment on the inner shelf (Hayes, 1994; Blake et al., 2001; Brynes and Hiland, 1995; Barnhardt et al., 2009).

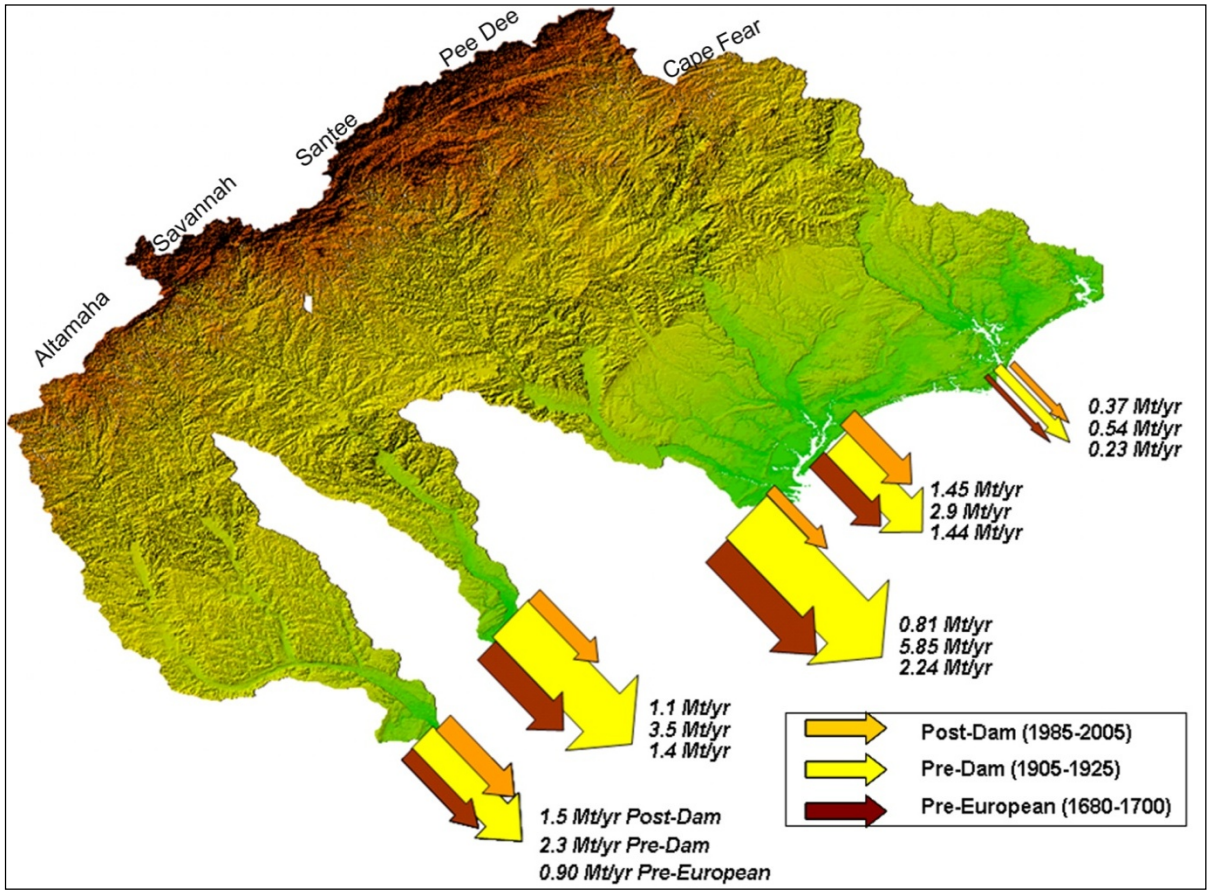

Figure 2.11 Sediment input from major rivers along South Atlantic Planning Area margin (modified from McCarney-Castle et al., 2010).

2.7.2 Nearshore Sediment Transport

Generally, the center of the South Atlantic Planning Area receives most of its sand supply from rivers and ebb jets (Hayes, 1994). Near the margins of the study area, along-shore and possibly natural offshore sources contribute sediment; shoreline erosion is a greater concern. Relict deltaic sand-lobes on the mid-shelf deposited during lowstands may contribute to the sediment supply at the coastline in a few areas of the South Atlantic Planning Area (e.g., Bull's Island; Hayes, 1994).

More studies have addressed coastal sediment transport on the beaches, along the coastline, and in shallow (<11 m depth) waters. A good early review of the research into sediment transport along the coastlines is given by Hayes (1994) for the overall region, with additional overviews by Frey and Howard (1988) for Georgia and Hayes (1977) for South Carolina. Sediment transport along the coast is predominately north to south, and increases from 150,000 m^3/yr near Myrtle Beach, South Carolina to over 500,000 m^3/yr at Cape Canaveral, Florida (Hayes, 1994). More recently the analysis of beach-profile and coastal erosion data (Gayes et al., 2003) suggested that erosion of the beach and shoreface along the Grand Strand (north part of South Carolina) removes approximately 104,000 m^3/yr of sediment. On the other hand, detailed

modeling and analysis of existing data (Work et al., 2004 and references within) at Folly Island, South Carolina showed a southward net sediment transport of 95,000 m^3/yr.

A detailed study of coastline erosion along the barrier-island-dominated middle part of the South Carolina coast extending from Bull Island to Seabrook Island was carried out by Kana and Gaudiano (2001). Using volumetric sediment changes derived from coastline position analysis from various maps and other data sources, they concluded that the long-term mean erosion rate is approximately 200,000 m^3/yr, after correcting for the temporal effect of beach replenishment projects. However, it was noted that this long-term coastal erosion rate is highly variable from location to location, and sometimes the same location is undergoing alternating periods of erosion and accretion. This is particularly the case for areas in the vicinity of tidal inlets and associated ebb deltas because the play an important role in coastal sediment transport.

The impact of the increased tidal energy in the South Atlantic Planning Area creates ebb-tidal deltas with a seaward-protruding arcuate shape that produces a local reversal of longshore current on the down-drift side of the delta (Hayes, 1979). As a consequence of the current reversal in the lee of the tidal delta, much of the longshore littoral sediment is trapped at the northern end of the barrier islands, widening the northern end while the southern end erodes. Hayes (1979) coined the term "drumstick barrier" to describe the resulting island morphology. In his review, Hayes (1994) finds very little evidence that hurricanes or other extreme events exert much influence on the morphology or sedimentology in the study area.

Gaudiano and Kana (2008) showed that in the mixed wave and tidal energy setting of South Carolina, sediment mobility and coastal erosion are episodic processes controlled mainly by the movement of sand bodies that detach from ebb-tidal deltas, move onshore, and attach to the coast downstream to the inlet. This process, called "shoal bypassing," is responsible for movement of significant volumes of sand. Analysis of this process from nine tidal inlets in South Carolina showed that mean periodicity of shoal bypassing and volume are closely related to tidal prism. The period is a minimum of 4.5 years for smaller inlets with an addition of a year for each additional 26×10^6 m^3 of ebb-tidal delta volume. This movement of sediment in the nearshore through shoal bypassing represents, on average, 0.6–6.6% of the total ebb-tidal delta volumes.

In the southern part of the area adjacent to Cape Canaveral, Florida, large shoals, ridges, and channels are found along the shelf surface, extending from the shoreface to about 12 km offshore. Surficial sediment on the shelf in this region is well-sorted, medium-to-coarse quartzose calcareous sand that is presently being reworked and redistributed in the form of large ridges, shoals, and irregular banks. Brynes et al. (2004) estimated net longshore sand transport along the east coast of Florida as being quite variable, decreasing from approximately 460,000 m^3/yr at Fernandina to about 270,000 m^3/yr near Cape Canaveral, which is a much higher rate than that identified for the northern part of the region.

2.7.3 Shelf Sediment Transport

On the inner shelf, at depths less than 20 m, the surficial sand sheet consists of relict sediment, largely not reworked (Pilkey et al., 1981). The exception is modern outflow channels (or scour depressions) that run perpendicular to the shoreline (Duane and Stubblefield, 1988). Large shore-perpendicular, linear-rippled scour depressions that contain deposits bearing strong textural and

shape affinities to sands from the modern beach and surf zone off north-central Folly Beach have been proposed as a potential conduit for the transport of nearshore sands to the inner shelf off of Folly Beach (Gayes et al., 1998). However, subsequent work (Gutierrez et al., 2005; Murray and Thieler, 2004) has shown that these features are mainly the results of alongshore, wind-driven flows that dominate in the study area.

Direct observations of active sediment transport on the shelf are relatively limited in the study area. The total of sediment transport measurement studies are listed in Table 2.1 and shown in Figure 2.12. A field experimental study carried out during the period 6 July–20 August 2001 aimed at providing data and some insight on sediment mobility in the vicinity of the permitted disposal zone within the Charleston Ocean Dredged Material Disposal Site (Voulgaris, 2002). Data from a bottom boundary layer tripod, including turbulence due to the combined action of waves and currents and sediment remobilization and transport, were used to drive a 1-D sediment resuspension and transport model. It was found that wind-driven circulation is most important in controlling sediment transport on the inner shelf. Winds enhance bottom steering through wave-driven resuspension of bottom sediments. At the same time, wind-driven flow transports the resuspended sediment along the direction of the mean current. Sediment transport directions and magnitudes in this site were highly correlated with wind data; this suggests that meteorological data can be used as a first-order approximation of near-seabed transport (Voulgaris, 2002; Wren et al., 2010). The primary directions of wind-driven flows in the Charleston area are NE and SW, in response to the local wind climate and the wind-generated alongshore flows.

Table 2.1.
Locations and periods of deployments of benthic boundary layer tripods for the study of sediment transport processes in the region

Station ID	Latitude	Longitude	Deployment	Recovery	Depth (m)	Source
A	32° 33.7'N	78° 39.5'W	5 Feb. 1978	13 April 1978	44.0	(1)
			13 April 1978	13 July 1978		
			13 July 1978	15 Nov. 1978		
B	31° 05.3'N	80° 28.8'W	6 Aug. 1978	8 Sep. 1978	30.0	
C	31° 06.8'N	80° 10.6'W	5 Feb. 1978	11 April 1978	47.0	
D	32° 32.5'N	78° 37.5'W	13 July 1978	13 Dec. 1978	86.0	
n/a			6 July 2001	20 Aug. 2001	9.0	(2)
Site 6	33° 41.41′N	78° 45.61′W	29 Jan. 2004	23 April 2004	10.6	(3)
Site 7a	33° 43.35′N	78° 46.75′W	29 Jan. 2004	23 April 2004	10.6	
BF0607	31o 22.35'N	80o 33.69'W	26 June 2007	20 Aug. 2007	28.0	(4)
BF0807	31o 22.34'N	80o 33.67'W	26 Aug. 2007	10 Oct. 2007	28.0	
BF1107	31o 22.38'N	80o 33.68'W	18 Nov. 2007	19 Feb. 2008	28.0	
BF0408	31o 22.41' N	80o 33.59'W	17 April 2008	11 June 2008	28.0	
BF0908	31o 22.41' N	80o 33.56'W	26 Sep. 2008	10 Dec. 2008	28.0	
Sources are: (1) Butman et al. (1980); (2) Voulgaris (2002); (3) Sullivan et al. (2006). (4) Voulgaris (unpub. data).						

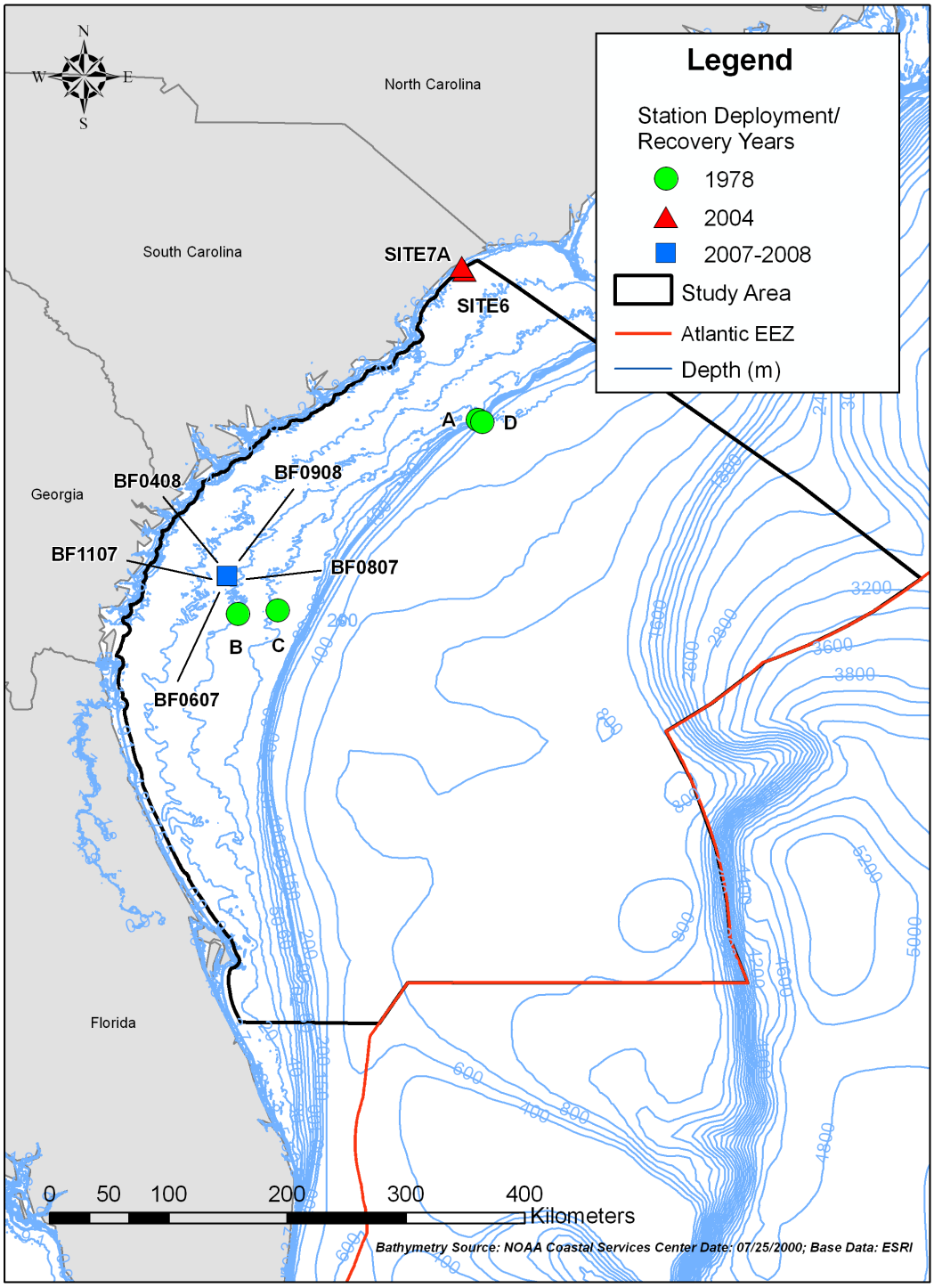

Figure 2.12 Locations of benthic boundary layer tripods for the study of sediment transport processes in the region that are listed in Table 2.1.

Similar conclusions were extracted from hydrodynamic measurements that were carried out at six locations in the Long Bay, South Carolina area for periods exceeding 30 days (Gutierrez et al., 2005). Also, an extensive hydrodynamics and sediment transport measuring program was carried out from October 2003 to April 2004 at eight sites in the inner continental of Long Bay off the city of Myrtle Beach, South Carolina. This latter project was led by the USGS and involved the deployment of bottom-mounted, instrumented tripods collecting data on waves, currents, bed morphology (ripples), and suspended sediment concentrations at water depths of 7–11 m (Sullivan et al., 2006). These data were augmented by wind measurements from nearby stations and analyzed to assess sediment transport processes on the inner continental shelf (Warner et al., 2012). The results of this USGS study show that, locally, wind energy correlates strongly with peaks in wave energy and that sediment mobilization occurs only under increased near-seabed stresses due to storm-induced wave activity. Tidal-driven currents alone are not sufficient to mobilize sediment. A combination of wind-driven surface currents and near-bottom circulation during wave events was found to dictate the direction and magnitude of sediment transport within Long Bay (Warner et al., 2012). The direction and magnitude of sediment transport on the inner continental shelf are influenced by the different patterns of storms that pass through the southeastern US–tropical cyclones and cold and warm fronts (Figure 2.13). Based on direct measurements Warner et al. (2012) showed that, under cyclone (hurricane or tropical storm) conditions, winds initially come from the northeast shifting to the northwest generating strong waves and mean flows generally directed toward the south, driving a net sediment flux toward the southwest. Under cold-front conditions, the wind initially blows out of the southwest and then shifts to the northeast. The generation of higher waves when the wind blows from the southwest leads to more sediment resuspension, which results in a net northeast sediment flux during the passage of cold fronts. When a warm front passes through Long Bay, the wind starts blowing out of the northeast and turns to the southwest. Due to increased wave activity for southwesterly winds, net inner-shelf sediment flux is to the northeast, as it is during the passage of cold fronts. Overall, it is concluded that the duration, magnitude, and frequency of the different storm types dictate the long-term sediment flux in the region, cold fronts and warm fronts produce northeast-directed net sediment fluxes, and tropical cyclones generally drive sediment to the southwest.

Additional data on sediment transport are available from a benthic boundary layer tripod and a stationary imaging sonar at 26 m water depth off the Georgia coast (Savidge et al., 2008). Continuous monitoring of the seabed using acoustic imaging at 26 m water depth (Voulgaris and Morin, 2008) was used to monitor sea-bed changes over a one-year period at the mid-continental shelf off the coast of Georgia. The mean particle size of the seabed is 450 microns, and the tidal currents on the site have a speed of up to 45 centimeters per second (cm/s). Despite the higher tidal currents in this site, compared to the study off South Carolina, less sediment movement was detected, mainly due to the higher fraction of coarse-grain sizes present at the Georgia study site. Only during periods of storm activity was sediment motion detected and that was mainly when the wave height and period were sufficient for the waves to feel the bed.

Sediment studies from the 1970s (Butman et al., 1980) were carried out in deeper water, ranging from 40–85 m depth (see Table 2.1 and Figure 2.12). As these studies revealed, the lack of penetration of wave energy to the seabed inhibits continuous seabed sediment mobilization

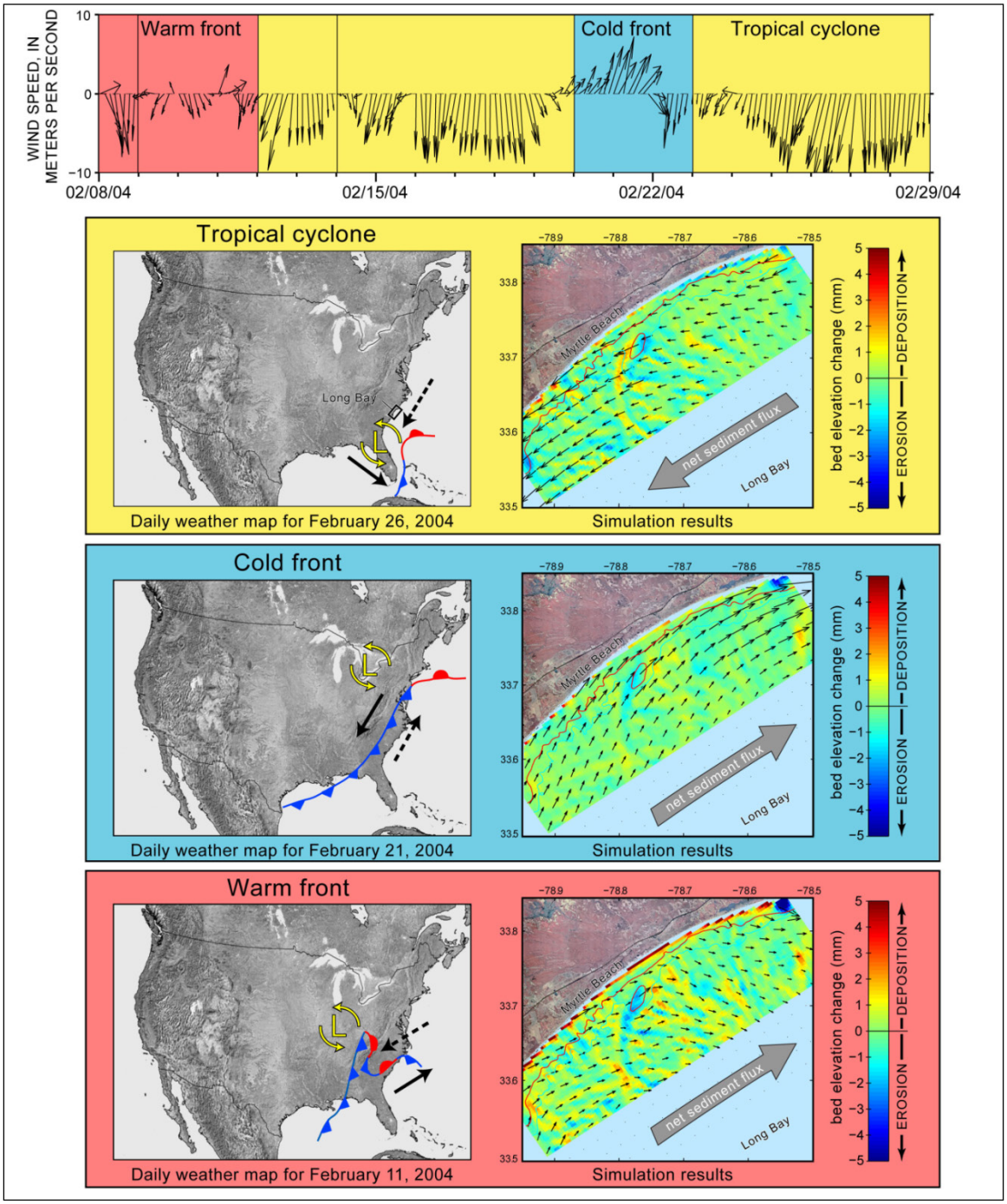

Figure 2.13 The front system types found in the region, and preliminary model results of associated sediment transport due to waves and currents. (from Barnhardt et al. 2009).

and transport. However, Gelfenbaum and Noble (1993) found a gradual net deposition of 20 cm during July–September, 1978, followed by net erosion of 5 cm until November 1978, at a tripod 100 km offshore Charleston in 85 m water depth. The largest flow events they recorded occurred at subtidal time scales (Noble and Gelfenbaum, 1992; Gelfenbaum and Noble, 1993). During these periods, erosion occurred in a series of punctuated events associated with Gulf Stream filaments passing the tripod (Gelfenbaum and Noble, 1993). Photographs from the tripod revealed changes in the seabed from biologically produced mounds and tubes to a smooth/streaked texture associated with periods of erosion (Gelfenbaum and Noble, 1993).

As evidenced from the work described above, the Gulf Stream current has a strong effect on the sediment dispersal within the study area. This current is responsible for shaping the modern outer continental shelf, including preventing sediment deposition on the Blake Plateau and depositing the contourite that forms the Blake Outer Ridge. The Blake Escarpment is a result of this current's erosion of the seaward edge of the Blake Plateau. As a consequence, sediment accumulates only in the lee of seabed features that block the current, such as the Charleston Bump.

The slope of the Florida-Hatteras Shelf lacks submarine canyons, an indication that the main direction of sediment flow is along the shelf rather than cross-shelf (Field and Pilkey, Pilkey and Field, 1972). Sand ripples along the shelf are consistent with the direction of modern current flow, and likely reflect on-going transport in the direction of major present-day ocean currents rather than relict structures (Uchupi, 1968). On the shelf in water depths over 20 m, the sand material is relict but the lack of fossil carbonate fraction in the sediments indicates dissolution that comes through extensive reworking (Duane and Stubblefield, 1988). The absence of sedimentary structures, such as storm layers or cross bedding, suggests extensive bioturbation of the sand sheet (Knebel, 1981).

2.8 GEOHAZARDS

2.8.1 Limestone Solution

Thick sections of limestone occur across the study area, deposited from late Cretaceous through Oligocene time. The subaerial exposure of areas of the shelf, mainly during late Oligocene through Miocene, permitted extensive limestone dissolution by acidic freshwater during these periods (Popenoe et al., 1982). A regional upwarp of the Floridan Aquifer centered in the vicinity of Jacksonville, Florida, exposes the top of the Ocala Limestone and allows sinkholes to form in this area (Meisberger and Field, 1976; Kohout et al., 1988). Popenoe et al. (1984) report that collapse features are widely scattered across the shelf off northeast Florida. Red Snapper Sink (Figure 2.14) is the largest of these collapses; it is ~120 m diameter and ~150 m deep and rooted in Cretaceous limestone (Spechler and Wilson, 1997). Karstic collapses have not been reported north of Florida on the Florida-Hatteras Shelf.

Several karstic collapse structures occur on the eastern edge of the Blake Plateau (Pinet et al., 1981). Similar features on the subaerial carbonate platform of Florida are associated with large cavern systems. These collapses are associated with the sedimentary growth fault, at the eastern edge of the Blake Plateau, which has a 1 m throw in the upper 10 m of seafloor (Folger, 1988). It

is a steeply east-dipping fault that has been active in association with the movement of diapirs of Jurassic salt (Dillon et al., 1983).

2.8.2 Gas Hydrates

The Blake Ridge Hydrate Province is one of the largest concentrations of methane hydrate on Earth (Holbrook et al., 1996). The hydrates in this area produce a Bottom Simulating Reflector (BSR) on seismic records that is very distinctive. Early seismic mapping of the South Atlantic shelf revealed an extensive BSR (e.g., Popenoe, 1984). The Blake Ridge Hydrate Province has since been reported by the USGS (e.g., Popenoe, 1984; Dillon et al., 1993; 1994; 1998), the NRL (Gettrust et al., 2004), and DOE in cooperation with NSF (e.g., Holbrook et al., 1996).

Hydrates underlie only a small part of the South Atlantic Planning Area, where the Blake Ridge meets the Blake Plateau (Figure 2.14). However, this is only the southwest corner of the hydrates which underlie virtually the entire Blake Outer Ridge and extend northward along the Carolina Trough to Cape Lookout (Dillon et al., 1994). Areas of seafloor deformation and sediment wavefields clearly correlate with an unstable BSR (Hornbach et al., 2003).

Concentrations of hydrates are a hazard to drilling and can lead to blowouts during drilling, although seismic "bright spots" associated with free gas phases in the subsurface can provide advance warning for drillers (Folger, 1988). Naturally escaping free gas can also trigger slides and mass wasting; this process is suggested to have played a role in the Cape Fear Slide (Hornbach et al., 2008). A number of smaller slump scarps are seen on the southwest Blake Outer Ridge (Popenoe et al., 1982). These slumps overlie the Blake Ridge Diapir and coincide with a BSR, the two triggering mechanisms noted for the Cape Fear Slide (Hornbach et al., 2003). This is the only place in the study area where mass wasting is visible at the seafloor.

2.8.3 Faulting

The Helena Banks Fault Zone runs through the area off Charleston (Figure 2.14). Helena Banks appears to be an active fault, although it has very little throw in Quaternary sediments. The fault has very little expression in the seafloor bathymetry and a displacement of ~1 m at a 10 m depth below the seafloor. Behrendt et al. (1981) suggest that the fault movement is mainly strike-slip, and perhaps this accounts for the small amount of throw associated with the fault plane. No other faults are obvious on the shelf. The central South Carolina coastal plain has a record of on-going seismicity, including the 1886 Charleston earthquake whose epicenter was on the lower coastal plain (Behrendt et al., 1981). No earthquakes have been uniquely identified with the Helena Banks Fault, although the NEIC catalog does list a few offshore earthquakes in the vicinity. The probability of a major earthquake on the Helena Banks Fault is unknown. Faulting is often a trigger for other geohazards, such as slumping and tsunamis. However, none of these are reported in association with the history of the Helena Banks Fault.

2.8.4 Mobile Sediment

The greatest hazards due to unstable slopes occur at steep areas by rapid down-slope transport of sediment. The relatively flat surface of the shelf and slope devoid of any large canyon features argue against a significant hazard for the Florida-Hatteras Shelf. A few slumps and minor

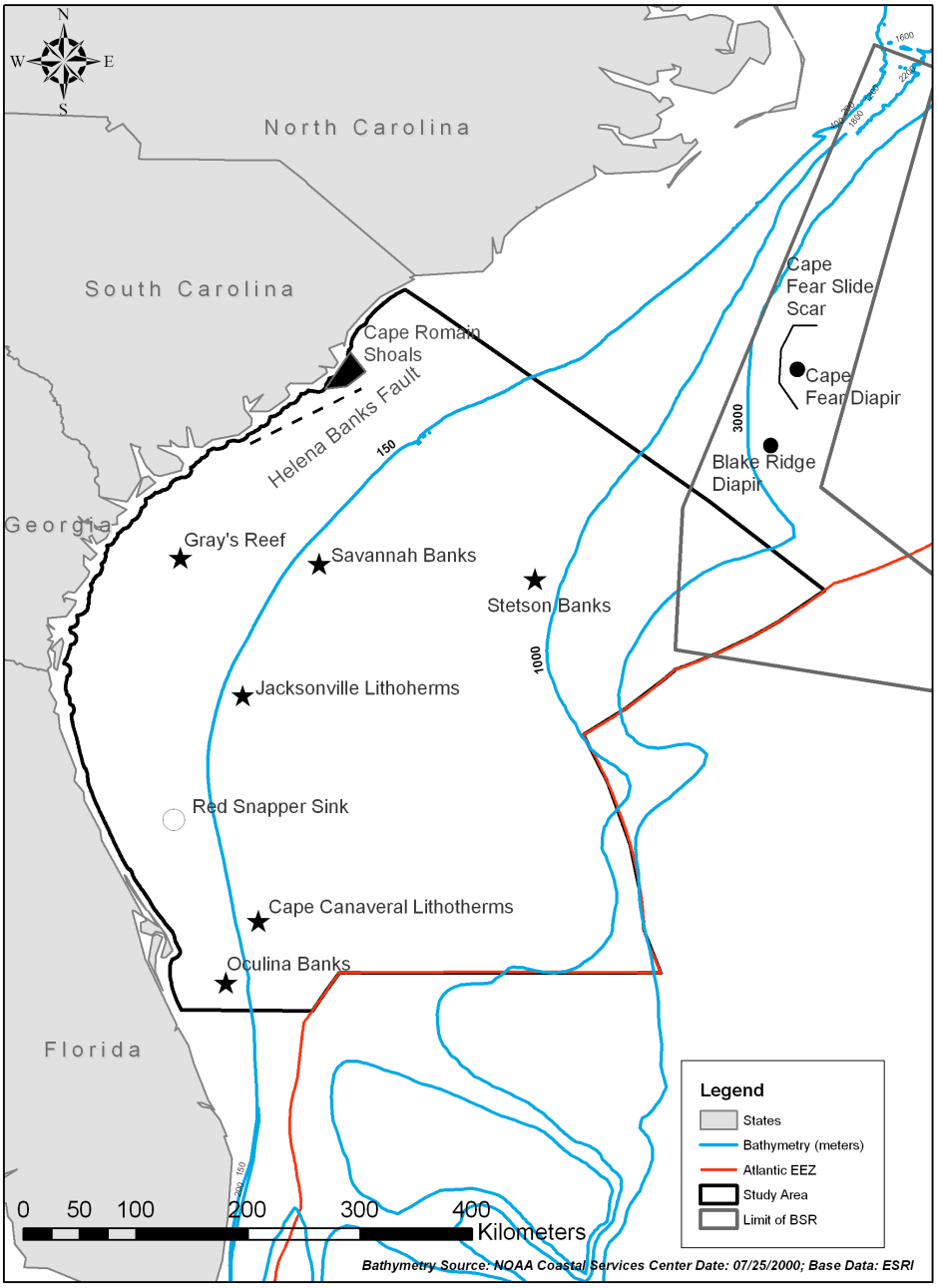

Figure 2.14 South Atlantic Planning Area hazards discussed in the text (after Popenoe, 1994) and major named coral banks (after Reed, 2002).

canyons cut the Florida-Hatteras Slope north of 33°N. Gardner et al. (1996) report one large slump at 29.5°N. Sand wave fields occur off of Cape Romain and in several smaller areas off Cape Canaveral (Popenoe et al., 1982). These are similar to sand wave fields that occur off most major capes on the US Atlantic coast. Migrating sediment in these areas may pose a hazard to seafloor structures by scour or erosion. Elsewhere, the relatively thin sediment veneer of shelf sands (e.g., Pilkey et al., 1981) is unlikely to threaten large-scale structures.

2.9 POTENTIAL IMPACTS OF OCS DEVELOPMENT ON GEOLOGICAL OCEANOGRAPHY

2.9.1 Oil and Gas Exploration and Development

The main impacts of concern related to geology from oil and gas exploration and production are to the surficial geology and sediments. These are the substrates that are habitat for benthos and exchange the most material with the overlying ocean. Seismic and sonar surveying are two standard methods of exploration for oil and natural gas resources. As non-invasive methods, seismic and sonar exploration will have no effect or impact on geological resources in the area.

Drilling into the seafloor impacts the physical state of the seafloor and may alter the subsurface rock properties. For offshore exploratory and production wells, most of these impacts concern waste products from drilling operations (Shinn et al., 1993). Drilling produces "cuttings," small bits of rock ground by the drill that are usually found mixed with a drilling fluid, which is typically a water-based mud composed of fresh or salt water, barite, clay, caustic soda, lignite, lignosulfonates, and water-soluble polymers. Under certain conditions, a synthetic-based drilling fluid or mud is used, typically an olefin or ester.

Discharges of cuttings and drilling fluid can result in heavy metals and debris disturbing several acres around a borehole. Drilling muds typically contain barite as a weighting agent (Shinn et al., 1993). In addition, the materials used in the mud are typically taken from onshore sites and can contain minerals and compounds foreign to the seafloor environment. Water-based muds and cuttings, and cuttings that have been wetted by synthetic-based muds, may be discharged under current permitting requirements, which include toxicity testing.

There may be concerns about the potential impacts of drilling on freshwater springs associated with karst (limestone) formations, patch reefs, and other hydrogeological features. No scientific studies that addressed these concerns were identified; however, this issue would be considered in environmental impact statements associated with permitting.

The range of impacts from producing oil wells may include disruption to seafloor sediment transport processes from construction of offshore rigs, laying pipelines across the seafloor and shoreline, and local alteration in the substrate from long-term rig operation. From producing wells, the introduction of new types material to the seafloor, such as shell mounds, drilling mud and cutting, and debris, can affect sediment characteristics. Bomkamp et al. (2004) reported shell mounds below producing platforms in southern California that were up to 8.5 m high and 84 m across, creating hard substrate habitat in an otherwise soft-bottom habitat. Continental Shelf Associates (2006) documented mapped debris and cuttings within 1–3 km of exploration and production platforms in about 1,000 m of water on the continental slope in the Gulf of Mexico. However, studies have shown that the magnitude of these kinds of debris piles decrease over time (Shinn et al., 1993).

Undiscovered, technically recoverable resource estimates for oil and gas reserves based on Minerals Management Service (MMS) 2006 assessment data (Figure 2.15) show peak values in 200–800 m water depth. This region includes the edge of the Florida-Hatteras Shelf and the inner Blake Plateau. Both of these areas have patch reefs and exposed hard-bottom areas that could be

affected by waste from drilling. This slope area is less susceptible to changes in cohesion of surface sediment because the existing sediment has a larger fraction of silt and mud. However, this area also contains many of the shelf-edge patch reefs that could be susceptible to inundation by mud or cuttings discharged from a drill site. Currently this is a very stable slope with no evidence for large-scale slumping or significant mass wasting, and drilling is unlikely to trigger mass wasting.

No drilling is active on the Blake Plateau, but studies of the impacts from drilling activities along Georges Bank should provide insight into impacts expected in a similar offshore shelf and plateau environment. Neff et al. (1989) estimated that a total of approximately 9,200 Mt of drill cuttings and approximately 5,000 Mt of drilling fluid solids containing 3,000 Mt of barite and 1,500 Mt of bentonite clay were discharged to Georges Bank during the drilling of eight exploratory wells at water depth of ~100 m. There was a 10–20% increase in the fine-grained sediment, and a correlated increase in metals in the sediment associated with the drilling (Neff et al., 1989). Cuttings were directly detected in seafloor samples within a 200 m radius of the Georges Bank exploratory wells and 150 m radius of similar exploratory well off New Jersey (Neff et al., 1989).

2.9.2 Sand and Gravel Extraction

Geologic impacts of marine mining result from activities in the coastal zone where combined wave and current energy is a factor. The direct effects of marine mining may include: (1) removal of the mined material; (2) introduction of new materials as discharges; (3) perturbation or mixing at the seafloor due to the dredging operation; and (4) subsequent replacement of dredged material discharges. Removal of substrate and consequent increase in the depth of the seafloor are the most apparent direct impacts to the geology of the seafloor. Potential indirect impacts include subsequent changes to the seabed topography and texture, local hydrodynamics and sediment mobility, and adjacent shoreface and shoreline change (Michel et al., 2001).

The MMS Marine Minerals Program commissioned numerical wave-modeling studies to determine the potential for shoreline erosion from dredging offshore sand borrow sites along the Atlantic and Gulf of Mexico coasts. The general conclusion of these site-specific studies is that no significant impacts to longshore sediment transport are likely from sand and gravel extraction from OCS sources. Where the OCS sand bodies were close to shore and/or shallow enough to influence the wave climate, there was high concern about the potential for increased shoreline erosion as a result of dredging. The orientation, depth, and shape of the sand body and borrow areas should be considered in evaluating the impact of dredging on wave climate (Michel, 2004).

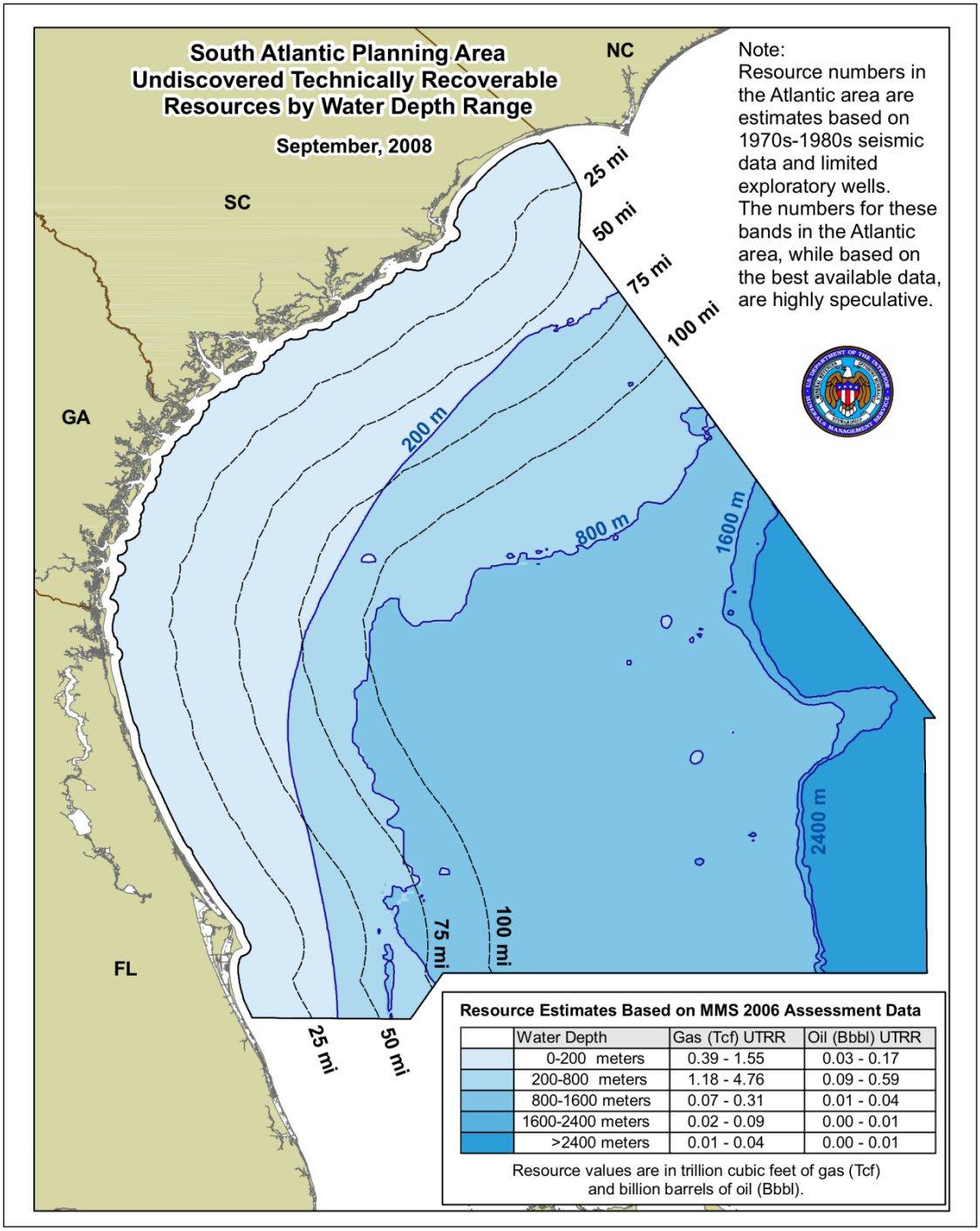

Figure 2.15 Resource estimates for natural gas and oil in the South Atlantic Planning Area (from MMS, 2006).

From a purely physical perspective, the most far-reaching potential impact of dredging is on far-field shoreline change due to unexpected hydrodynamic changes related to altering the depth in the borrow area. Changes in wave or current patterns can result in changes in shoreline equilibrium, erosion, or deposition (Continental Shelf Associates, 1993). Theoretically the shoreline change can occur in one of two ways: 1) through alterations to the wave regime,

changing the waves that reach the shore, in turn modifying nearshore circulation and sand transport, including erosion and accretion patterns; and 2) by interrupting or modifying a sand supply pathway to the shore (Nairn et al., 2004). A review of the currently identified OCS borrow deposits suggests that most of them are immune from the second impact because they are isolated from the sediment budget of the littoral system by great distances and the absence of a sand transport pathway (Michel et al., 2001). Careful consideration must be given on a site-specific basis to the possibility of interrupting a sediment supply pathway to the shoreline.

One of the main issues addressed by modeling efforts relates to sediment transport and infilling estimates at potential borrow sites and the impact of dredging operations on these estimates. Kelley et al. (2004) presented an analytical approach that incorporates analysis of nearshore wave transformation and wave-induced, longshore sediment transport, that applied to sites off North Carolina, Florida, and New Jersey, thus encompassing a range of physical settings bracketing what is found within the study area. Based on site-specific analyses, it is believed that greater impacts on nearshore sediment transport patterns result from larger sand extraction volume, closer proximity of the borrow site to the shoreline, and greater relative change in water depth due to the borrow (Kelley et al., 2004).

Removal of sediments from borrow sites can alter seabed topography, creating pits that may refill rapidly or cause detrimental impacts for extended periods of time. Up to a decade may be required for some offshore borrow sites to refill to pre-dredge profiles (Hitchcock et al., 2002; Van Dolah et al., 1998). Intentionally locating borrow sites in highly depositional areas, such as the leading edge of sand ridges, may dramatically reduce the time for recovery (Dibajnia and Nairn, 2011). In general, shallow dredging over large areas causes less harm than small but deep pits, with pits opening into a different substrate surface being particularly vulnerable to long-term change in surficial sediment type (Hartog et al., 2008; Nairn et al., 2004; Dibajnia and Nairn, 2001). If borrow pits are deep, current velocity and bottom boundary layer turbulence may be reduced sufficiently to lead to deposition of fine particulate matter (Benedet and List, 2008; Hartog et al., 2008).

In a representative study of the potential impacts, Zarillo et al. (2009) examined five shoals located off the northeast coast of Florida to identify the potential environmental impacts from dredging to the borrow sites themselves and to the nearshore beaches. Topographic changes through two-year simulations occurred over the shoreface from the shoreline to approximately 5 m depth where predicted sand transport rates were greatest. The overall pattern of change across the shoreface includes erosion of the upper shoreface at depths of less than 3 m and deposition on the lower shoreface at depths of 3–5 m, which marks the depth of closure (Zarillo et al., 2009). The impact of offshore borrow cuts is relatively small since the estimated difference in transport among all sites under study is well below the temporal variability in sand transport predicted for any location on the shoreface (Zarillo et al., 2009).

Studies evaluating borrow areas off South Carolina show infilling at variable rates, which highlights the need for site-specific consideration of factors including the depth, orientation relative to currents, and style of dredging. McCoy et al. (2010) documented changes over 2007–2010 at three borrow sites off Myrtle Beach, South Carolina associated with beach nourishment programs. Pre, post, and one-year post dredging bathymetric and side scan sonar surveys were

conducted at the Little River, Cane South, and Surfside borrow sites, along with additional side-scan sonar surveys across the inner shelf of the Grand Strand region. Relatively stable hard-bottom areas are separated by less stable shore-perpendicular sediment ridges, and mixed areas of hardbottom with patchy sediment cover show the highest sediment mobility across the inner shelf during the observation period (McCoy et al., 2010). Dredging in the borrow sites removed sediment to depths of >1 ft over 21% of Little River, 88% of Cane South, and 41% at Surfside borrow sites (McCoy et al., 2010). After one year post-dredging, Little River replaced 65%, Cane South replaced 7%, Surfside replaced 54% of the volume of the sediment lost by dredging (McCoy et al., 2010). Van Dolah et al. (1998) studied six dredged sites in state waters of South Carolina (two off Hilton Head Island, one off Hunting Island, and one in the Folly River behind Folly Island) and found that, at three of the sites, the borrow area had filled with muddy sediments, forming a cap over clean sand. Infilling with muddy sediments will change the benthic communities, and makes the site less useful as a future borrow area. Four of the six sites considered were refilling at rates that would require between 5.5–11.8 years to completely refill to pre-dredge profiles at these nearshore and backbarrier borrow sites.

2.9.3 Renewable Energy Development

Impacts on the geology of the seabed from development of renewable energy resources are expected to come from two sources: 1) direct disturbance and alteration of the seafloor from construction and the on-going physical presence of the foundations and supporting infrastructure of structures for extracting energy and 2) the nature of the surficial seafloor sediments, which determine sensitivity to any changes to flow conditions that affect sediment transport. In general, fewer studies have been completed on the geological impacts of renewable energy than traditional resources, and no site-specific completed studies within the South Atlantic Planning Area were found. Reviewed herein is the state of knowledge regarding geological impacts due to the available designs for renewable energy development in the study area.

Construction effects for renewable energy structures are related to the design of the structure, footprint on the seafloor, and requirements for supporting infrastructure such as electrical transmission cables. All operating offshore wind facilities are in shallow waters between 5–25 m (Michel et al., 2007; Musial et al., 2006). This depth places them in the inner shelf where the most common surface is a thin, mobile sand sheet within the study area. However, developers are currently looking to 40 m for bottom-founded structures and deeper for floating platforms. Wind projects use either concrete gravity bases or steel monopile foundations (Michel et al., 2007). Monopiles have a small footprint on the seafloor and are constructed by drilling or driving a piling tens of meters into the seafloor. Disturbances to the seafloor should be minimal and local to the immediate vicinity of the monopile. Gravity bases have a larger footprint, composed of concrete that typically rests above the pre-existing seafloor, thus replacing the seafloor with a hard-bottom substrate. Gravity bases require a level and compacted substrate, and may require significant changes to the seafloor during construction. Existing designs for wave and current energy converters either use the monopiles or gravity bases, or are floating structures that may be anchored using smaller anchors (Langhamer et al., 2010). Laying electrical transmission cables from offshore to onshore power stations would involve a very shallow trenching into the surface sands that cover the nearshore seafloor. This would likely constitute a minimal disturbance, as the sand drifts in this area are of sufficient volume to refill a narrow, shallow trench.

The potential impacts to sediment transport and erosion resulting from modified wave and current regimes are complex, and are likely to have more far-reaching effects than the construction and presence of the structures. The preferred locations for offshore energy facilities may be the ridges and shoals of the OCS, because this would take advantage of the shallow depth to minimize foundation costs. Ridges and shoals are typically areas where sediment transport is a significant process. While there is a relationship between the modification to the waves and currents and the effects on sediment transport, potentially the sediment transport regime could be modified significantly by a proportionally smaller change in the wave regime. For example, a structure or group of structures may cause a small amount of wave refraction that changes the net longshore sediment transport direction.

Changes to waves and currents may drive changes to sediment transport in the near-field, directly surrounding the structures, or in the far-field, on a regional scale. Two near-field impacts can result from a modified sediment transport regime: local scour and global scour. A submerged structure can increase turbulence and, in some cases, produce flow vortices. These changes near a structure often lead to increased bed shear stress, potentially causing local erosion known as local scour. Local scour is significant to structures because it often removes the supporting sediments. Floating structures may also experience local scour around anchors, chains, and beneath the floating structure if installed in shallow water where the bottom of the floating structure is relatively close to the seafloor. Scour may also be an issue around cables and cable trenches, particularly in the transition between hard and soft bottoms. This may be an issue of particular concern in the South Atlantic Planning Area due to the overall patchiness of the sandy substrate. Erosion of bottom sediments in areas between multiple structures is known as global scour. Global scour differs from local scour because it involves a multi-structure group influence and modified bed shear stress. It is unknown how global scour will affect the substrate; however, this issue would be an important part of site-specific designs and environmental impact studies.

With wave energies, on average, being reduced in the lee of offshore energy structures, there will be a tendency for sediments to accumulate there, leading to shoaling and possibly a shift to finer-grained sediment. The accumulation may be particularly problematic in the South Atlantic Planning Area where it could lead to a change from a hard-bottom to a sandy seafloor in the case of patch reefs or patchy low-relief hard bottom. Those changes will have a feedback effect on the processes, for example, altering the patterns of wave refraction if sediment accumulation significantly changes the water depths. Such a modification of the wave refraction will alter angles of waves breaking on the beaches, affecting the longshore currents and sand transport, and thus be carried into the far-field impacts.

Beach and nearshore sediment transport could be affected directly by the installation of offshore energy structures, as most shallow-water processes are driven by the heights and direction of waves. A reduction in wave heights on the beaches could significantly reduce the surf-zone width from its natural state, and, consequently reduce long-shore currents and sand-transport rates, although modeling suggests this effect on wave height is likely to be negligible (Alari and Raudsepp, 2010). Changes in nearshore currents and sand transport could produce shifts in the shoreline and changes in the erosion and accumulation zones along beaches.

Far-field impacts include a modified wave climate that could affect recreational potential and sediment transport along adjacent shorelines. These far-field impacts may include sediment erosion and deposition in areas that affects coastal structures, beaches and other recreational areas, navigation channels, and shoreline vegetation. Far-field impacts have not been reported at any existing installations. Establishing the degree of impacts on neighboring shorelines should be undertaken as a combination of numerical modeling to estimate how sediment transport rates may change and monitoring shoreline morphology rates.

Specific examples from other areas where renewable energy facilities have been installed illustrate how the study area may be affected by similar installations. The Scroby Sands coastal processes monitoring report (CEFAS, 2006) documented some evidence of global scour. In general, the findings show that global scour that occurred after the foundations were installed was not significant to the total volume of change on the bank. A year post-construction at the Kentish Flats project no seabed change was observed some distance away from the turbine foundations (Emu Ltd., 2005) or in the vicinity of the cabling (Emu Ltd., 2006). The expected local scour (Emu Ltd., 2002) was observed at both Scroby Sands and Kentish Flats. As anticipated at Kentish Flats, observations at three of four inspected foundations showed local scour pits 1.8–2.3 m deep and extending 5–10 m from the foundation (Emu Ltd., 2005). Observation in 2005 showed that scour pits created during installation by vessel jack-up legs varying between 0.5 and 2.0 m deep had started backfilling by as much as 1.8 m (Emu Ltd., 2005); however, six months later, the backfilling process had slowed or stopped; an average of 0.2 m had been deposited (Emu Ltd., 2006). On the basis of an assumption that driving forces in the far-field are minor, it also has been assumed that the effect sediment transport has on adjacent shorelines is negligible (as was the case at Horns Rev).

2.10 SUMMARY AND DATA GAPS IN THE STATE OF GEOLOGICAL OCEANOGRAPHY KNOWLEDGE WITH REGARD TO OCS DEVELOPMENT

The physiography of the South Atlantic Planning Area is a very wide continental shelf with a two-tiered structure consisting of the shallow, more typical Florida-Hatteras Shelf from the shoreline to ~80 m water depth, and the much deeper Blake Plateau, a relict continental shelf structure at ~800 m water depth, all backed by a low-relief coastal plain that slopes upward to the Appalachian Range. The coastal zone is made up of various types of barrier island complexes and capes. The stratigraphy consists of a thick sequence of terrigenous clastic and marine carbonate deposits. Sedimentation on the shelf consists mostly of fine-grained, subarkosic sand, with a higher carbonate fraction to the south within the study area. The Gulf Stream current scours the Blake Plateau and continental slope, producing an overall erosive environment there.

The geology of the South Atlantic Planning Area is well characterized on a regional scale, but detailed studies have been slow and much remains to be done. Data gaps in geological oceanography include:

- Studies linking onshore-offshore groundwater flow and submarine groundwater discharge fluxes, and temporal changes in offshore groundwater
- Studies linking basement structure to modern sediment deposition

- Detailed bathymetry and acoustic seafloor mapping of the Georgia and southern South Carolina upper continental shelf to identify and quantify the hard-bottom distribution, sediment thickness, and *Lophelia* lithoherm distribution
- Quantification of the rates and effects of sedimentary bedform migration on the inner shelf

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CHAPTER 3: PHYSICAL OCEANOGRAPHY AND AIR-SEA INTERACTIONS

3.1 INTRODUCTION

The early history of the oceanographic research in the South Atlantic Planning Area is described in Atkinson and Menzel (1985) where it is stated that first observations on the Gulf Stream were made in 1786 by Benjamin Franklin. A significant amount of research has been carried out subsequently (e.g., Bumpus, 1955; 1973), but the most comprehensive study of the circulation on the southeast US continental shelf was the result of an interdisciplinary study of the region supported by DOE and then MMS. A major experiment, the Georgia Bight Experiment (GABEX), was conducted 1980–1981; it included in-situ moorings of current meters and hydrographic surveys on board oceanographic ships. A winter experiment (GABEX I) focused on studying Gulf Stream water interactions when shelf waters were vertically mixed, and another experiment (GABEX II) was designed to address circulation issues under summer stratified conditions. The majority of the work and findings from these experiments is presented in Atkinson et al. (1985).

From 1984 to 1985 the Spring Removal Experiments (SPREX) focused on cross-shelf exchange processes. These extended on the shelf from Savannah, GA to Cape Romain, SC. The focus was the effect of circulation on biological and chemical exchanges during the spring season, when southern winds prevail and the coastal ocean in the region transitions from horizontally to vertically stratified. Processes occurring during fall season were the subject of additional work carried out from 1986–1987 (Fall Removal Experiments, Pre-FLEX and FLEX I) that focused on alongshore and cross-shore exchanges over the Georgia and Florida shelves during the fall, when the prevailing winds are from the north. Additional experiments (see Table 1.1 in Menzel, 1993) focused on outer shelf exchange processes off Charleston (Winter 1990 experiment), and on salt exchanges and frontal interactions in the nearshore frontal zone (1979 and 1981). A synthesis of the results of those experiments and the linkage between physical processes and bio-geochemical processes can be found in Menzel (1993) for the inner, middle, and outer shelf regions, respectively.

Since then, a number of additional, processes-specific studies of academic or applied research interest have been carried out. The results of these studies have mainly increased the resolution of the observations collected earlier but have not made any major changes in our understanding of the region. These new results (e.g., Blanton et al., 2003) built on the previous observations and are incorporated in this review, when relevant. It is important to mention that, during the last decade, the development and expansion of coastal observing systems (e.g., Marine Technology Society, 2008 and papers within) have provided a number of new in-situ observations in the region. Currently, these activities are being better organized through the establishment of the Integrated Ocean Observing System (IOOS®), a federal, regional, and private-sector partnership established to enhance our ability to collect, deliver, and use ocean information. IOOS coordinates a number of regional associations; its objective is the delivery of data and information needed to increase understanding of our oceans and coasts. IOOS is a resource of additional data for any future developments. Consequently a significant amount of recent data regarding ocean circulation and hydrography can be obtained from the IOOS data catalog on the

Internet. This catalog provides data from the regional associations, which for the study area is called South East Coastal Ocean Observing Regional Association (SECOORA). SECOORA coordinates data collection activities over the region extending from North Carolina to Florida. Direct access to southeast US is the Carolinas RCOOS that covers data collection in North Carolina and South Carolina. Data from these stations can be accessed either through the SECOORA home page or directly from the website for Carolinas RCOOS. At this juncture it should be noted that the user might find a significant overlap between the different database as the data displayed on these data portals are also fed to federal databases like the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) and National Ocean Service (NOS). Also, these regional organizations assemble and disseminate data collected by other federal, academic, and/or private organizations which might also appear elsewhere.

The morphology of the continental shelf, as described in Chapter 2 Geological Oceanography, together with atmospheric forcing (wind climate and temperature variations), tidal processes (including the influence of numerous inlets and estuaries), buoyancy fluxes introduced by the rivers discharging in the region, and large-scale oceanic processes as the Western Boundary Currents (i.e., Gulf Stream), define the circulation and hydrography over the region. The width of the shelf is highly variable; it starts as a very narrow shelf (5 km) at West Palm Beach, Florida and widens toward the north to 50 km wide near Cape Canaveral, Florida. The shelf takes its maximum width (~130 km) off the coast of Georgia. Further north the shelf starts narrowing again at a gradual rate to approximately 30 km at Cape Hatteras, North Carolina.

In addition to shelf width, water depths and proximity to the western boundary current constitute major factors affecting circulation processes. Therefore, and in consistent matter with previous studies (e.g., Menzel, 1993; Atkinson and Menzel, 1985), the description of the circulation is divided to three distinct but overlapping regions: the inner (coastline to 20 m depth), middle (20-40 m depths), and outer shelf (extending from 40 m to the shelf break which occurs at a water depth of approximately 80 m).

The number of physical oceanographic processes and the time-scales at which they operate vary significantly. Overall meteorology and the Gulf Stream are the two most important forcing factors that control the processes in the South Atlantic Planning Area. In this chapter, meteorological conditions are described in Section 3.2, where the episodic events–tropical storms and hurricanes–are discussed, followed by the monthly wind climatology as it has been revealed from the reanalysis of existing data. The synoptic weather patterns that operate at scales of 2 to 3 days are also discussed. The next section (3.3) discusses sea level across the domain as it relates to seasonal and long-term sea level trends that define the relative sea level rise. Tides and tidal currents are described in Section 3.4; the wave activity is presented in Section 3.5. Section 3.6 is a description of the hydrography (temperature and salinity) of the region and its spatial gradients. These are approached from a climatological view point and constitute the forcing that defines the baroclinic circulation in the South Atlantic Planning Area, which is subsequently presented in Section 3.7, together with the wind circulation as forced by the monthly climatology. Section 3.8 describes the Gulf Stream, its meandering and eddy generation that control mainly the variability of circulation in the outer and middle shelves with occasional influence all the way to the inner shelf. Finally, in Section 3.9, the subtidal circulation in

response to the synoptic weather systems and fronts that operate in time scales of 2 to 3 and 12 days are presented. This is significant in the inner shelf as it dominates the circulation in that region.

3.2 METEOROLOGICAL FORCING

3.2.1 Tropical Storms and Hurricanes

The southeast US in general is subject to the influence of tropical storms and hurricanes. Tropical cyclone climatology for the Atlantic region is maintained and continuously updated by the National Weather Service (NWS) National Hurricane Center in Miami, Florida. The results are continuously updated, and extensive climatological analyses are carried out and posted on the World Wide Web. The methodologies used in such analyses are standard statistical analyses and detailed descriptions of both data and results can be found in a number of technical reports published by NWS at the National Hurricane Center.

Overall, the Atlantic (including the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) hurricane season starts 1 June and extends to 30 November. A histogram of the average number of storms occurring during this period is shown in Figure 3.1. Clearly, the peak season is middle September.

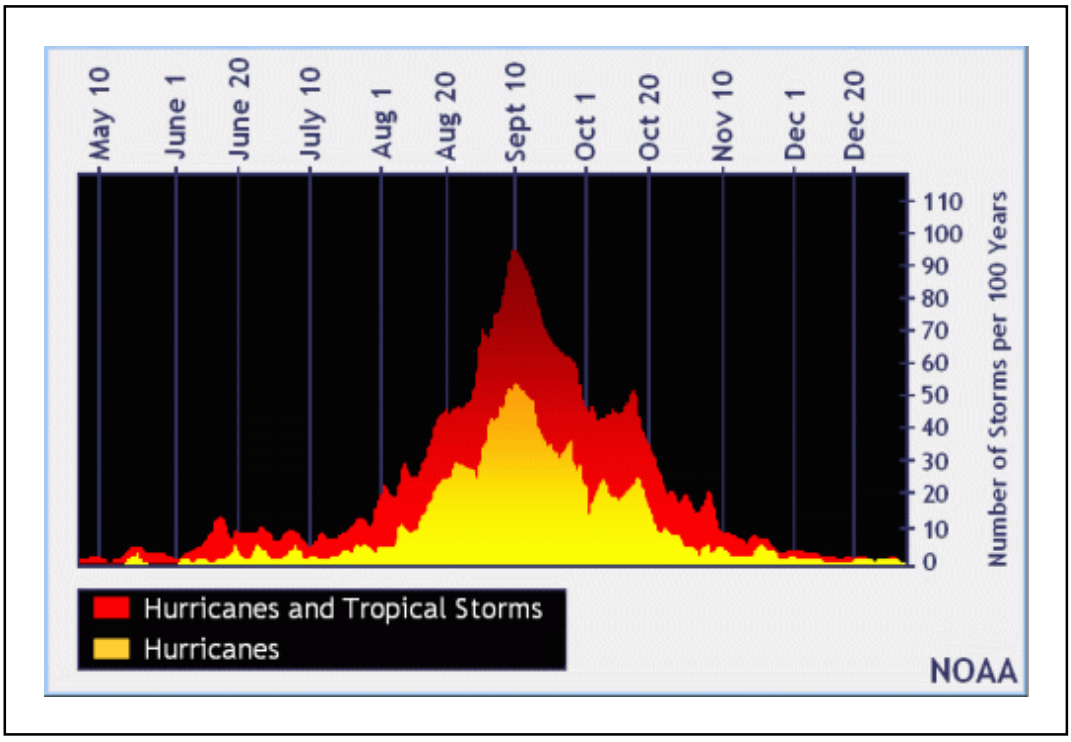

Figure 3.1 Average number of hurricane and tropical storm occurrence occurring over the Atlantic hurricane season over a period of 100 years. Source: National Hurricane Center, NOAA.

Analysis of Atlantic tropical storm tracking by year has been carried out by the Tropical Prediction Center Best Track Reanalysis. The raw data for re-analysis can be found in the form of an ASCII (text) file containing the 6-hourly center locations (latitude and longitude in tenths of degrees) and intensities (maximum 1-minute surface wind speeds in knots and minimum central pressures in mbars) for all tropical storms and hurricanes since 1851. The relevant information is described in Jarvinen et al. (1984) and Landsea et al. (2004). The raw data are updated continuously as the data become available. The raw data can be found in a database maintained by the Tropical Prediction Center, Atlantic Oceanographic and Meteorological Laboratory, NOAA.

Based on these data, hurricane return periods (i.e., the frequency at which a certain intensity or category of hurricane can be expected within 75 nautical miles [139 km] of a given location) have been estimated by the National Hurricane Center Risk Analysis Program using historical data up to 1999. Figure 3.2 provides a single figure summary of the return period analysis per hurricane category for the study area.

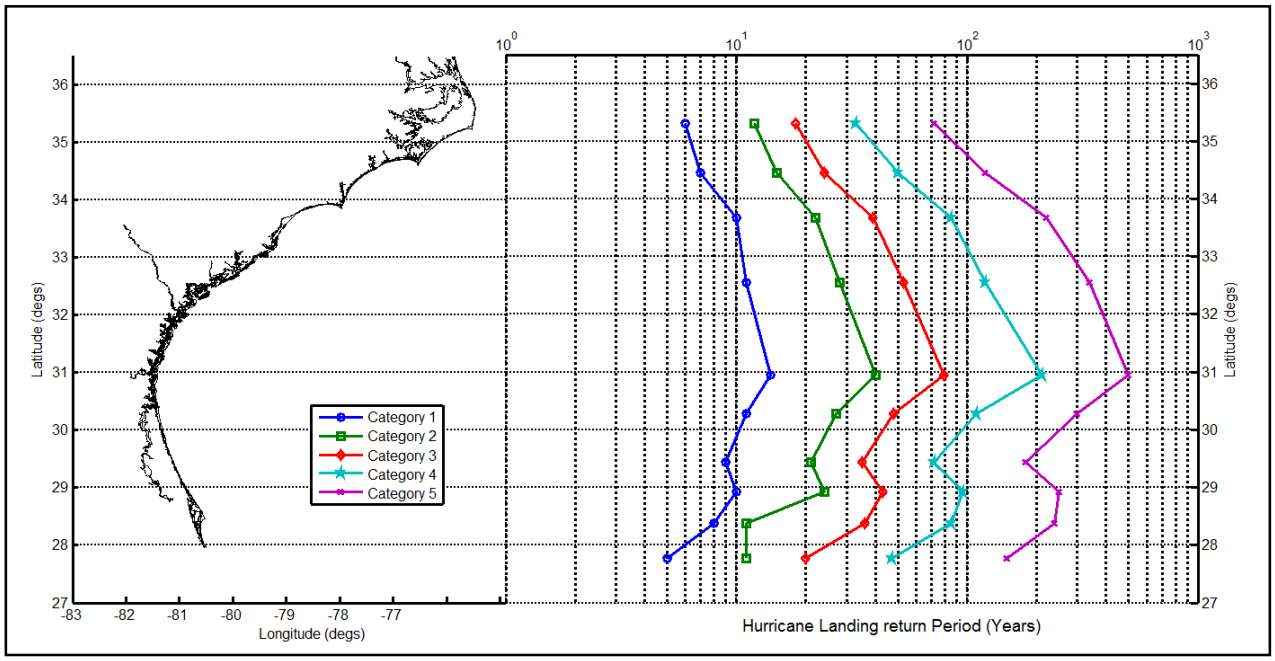

Figure 3.2 Return period of hurricanes per category (1 to 5) utilizing historical data up to 1999. (Data from NOAA, 2010a).

Based on the return analysis, it is easily concluded that any structure in the study area with an expected life of up to 30 years is guaranteed to be subject to at least two hurricanes of category 1 and one of category 2. Categories equal to or higher than 3 can be expected and any design should be made strong to withhold such forcing, but statistically those hurricanes may not occur.

In a re-analysis of the same data for the period 1871–2005, Mann and Emanuel (2006) suggested a positive correlation between sea surface temperatures and Atlantic basin tropical cyclones. Similarly, in their analysis, Holland and Webster (2007) found a doubling of the number of

tropical cyclones over the past 100 years. These studies suggest that these increases are due to human-driven greenhouse warming. However, Landsea (2007) has argued that such conclusions are due solely to bias in the data set imposed by the improved monitoring systems that have been in place in recent years. In particular, Landsea et al. (2010) noted that the increase of recorded short-lived storms (duration up to two days) has led to the previously stated conclusions about the increased frequency of tropical storms.

A superposition of all recorded tropical cyclones found in the NOAA database for the period 1851–2008 is shown in Figure 3.3 by storm category. It is obvious that tropical storms are a common occurrence in the study area. Tracks for hurricanes Category 1 to 3 are many. Category 4 hurricane tracks are limited to only five, while no track for hurricane Category 5 has been recorded over the ocean in the study site and for the period of data availability.

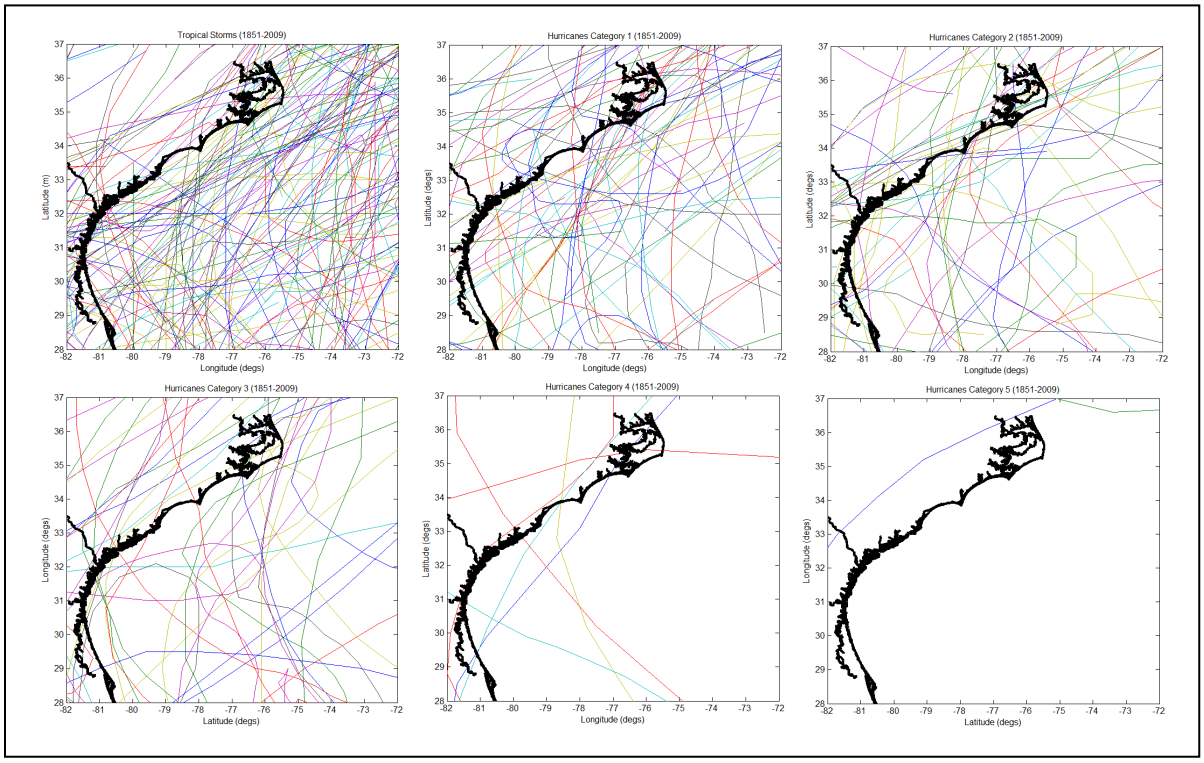

Figure 3.3 Track of tropical storms and hurricanes (Categories 1 to 5) that have occurred over the period 1851 to 2009 (data from NOAA, 2010b).

3.2.2 Monthly Wind Climatology

The surface of the coastal ocean reacts relatively quickly (within 3 to 6 hours) to wind stress forces applied on the sea surface, especially in the South Atlantic Planning Area, due to the relatively wide shelf and shallow waters (Blanton et al., 1985). It is characteristic that changes in water temperature are correlated with changes in air temperature on both seasonal (>1 month) and synoptic scales (2–3 days).

The climatology of wind stress on the South Atlantic Planning Area was systematically examined in the 1980s by Blanton et al. (1985). The seasonal wind patterns observed over the area are mainly due to relative changes of the location of the Azores-Bermuda High (which is also known as the "North Atlantic High/Anticyclone"or the "Bermuda High/Anticyclone") and the Icelandic Low. The former is a large subtropical center of high atmospheric pressure that is found near the Azores in the Atlantic Ocean. The Azores-Bermuda High, together with the Icelandic low, forms the North Atlantic oscillation. The latter is located between Iceland and southern Greenland and extends into the Barents Sea during the Northern Hemisphere winter.

The winds over the South Atlantic Planning Area originate from either the Azores High or a small-scale anticyclone center over the Ohio Valley. These winds cover the southern portion of the US and result in a long-term (mean) eastward wind. Overall the streamlines indicate a southward-directed dry air mass from the Ohio Valley that is separated by the northward-directed streamlines of warm and humid air originated from the Azores High. The relative separation of those two streamlines and their relative position define the monthly climatology of the region.

During spring (March–May) the Azores High influences the wind patterns with the development of a northward-directed flow of warm humid air mass which originates from the southern flank of the Azores High; it travels westward and turns toward the north over the Gulf of Mexico. This northward air flow intensifies during the summer (June–August) as the Azores High strengthens and shifts westward. During autumn (September–November) the air masses in the South Atlantic Planning Area are dominated by air originating from the Ohio Valley High and produce strong mean southwestward stresses. Details on the movement of these air masses can be found in Wendland and Bryson (1981) and Bryson and Hare (1974).

Initially, Weber and Blanton (1980) used wind observations from ships to produce monthly mean wind vectors over the South Atlantic Planning Area. This data set was later updated with ship observations from the Blake Plateau (Blanton et al., 1985), and a more extensive analysis including observations over the period 1945–1963 was produced. The general seasonal wind climatology was further examined in a study of the monthly circulation of the South Atlantic Bight (Blanton et al., 2004) that used a 3-D, shallow-water, finite-element model forced with monthly wind stress and hydrographic climatology.

The Comprehensive Ocean-Atmosphere Data Set (COADS, Woodruff et al., 1998) wind velocities from 1975-1999 were used to generate the monthly averaged surface wind stress that was applied on to the model (Figures 3.4 to 3.15). The COADS data set is comprised of an assemblage of in-situ observations of wind speed, atmospheric pressure, and water and air temperatures obtained from ships of opportunity. These data have been quality checked and

summarized statistically on a monthly basis on 1° squares. These monthly summary groups from the years 1975–1997 were taken for the northwest Atlantic region and monthly averages were produced. The data averaging was carried out in blocks of 1° × 1° grids (using data for which the sample size is greater than 20), smoothed with a nine-point Laplacian filter, and then linearly interpolated onto both the large-scale and climatology model grids for computations. At this juncture it should be mentioned that currently the database has been expanded significantly with the release of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS release 2.5 completed in May 2009 with data covering 1662–2007, plus preliminary data and products for 2008 to near-real-time).

The analysis of the COADS surface wind velocity and surface atmospheric pressure for the South Atlantic Bight in particular and the extended area of the southeast US of Blanton et al. (2004) showed that the earlier wind climatology described in Weber and Blanton (1980) and Blanton et al. (1985) is quite accurate. Overall five seasonal wind regimes are identified for the South Atlantic Planning Area:

November–February (winter season) when the winds exert a stronger southeastward (offshore) directed stress over the northern portion of the region, while the winds shift more toward the south in southern latitudes and are of reduced strength. A separation zone (high-pressure ridge) occurs over the Blake Plateau and winds are stronger on the shelf and weaker over the shelf break.

March–May (spring transition) is characterized by a gradual shift to eastward and northeastward (poleward) stress in the central portion of the region with more organized winds over the Blake Plateau. The strength of the high-pressure region decreases, and the ridge no longer extends westward into the South Atlantic Planning Area.

June–July (summer season) winds are westward and southwestward along the southern half of Florida, while the wind stress is more northward and northeastward in the northern half of the region and over the Blake Plateau. The winds are strongest in July over the northern area and the Blake Plateau with winds largely upwelling favorable, being along-shelf and poleward directed along the entire eastern US coast.

August is characterized as a transition regime by Weber and Blanton (1980). However, this was not the case for the analysis of Bryson and Hare (1974). Nevertheless, this is the period during which the Ohio Valley High is formed, generating air streams that oppose those coming from the Azores High. The relative dominance of those opposing systems appears to control the mean circulation during this period, and the net result can be variable from year to year. On the other hand the re-analysis of Blanton et al. (2004), using the COADS data, showed that in August weak winds begin to develop and shift counterclockwise from the along-shelf poleward upwelling-favorable summer regime toward the alongshore and south-directed downwelling-favorable direction.

Finally the September–October (autumn regime) is characterized by strong southwestward along-shelf wind stresses which do not extend all the way to the Blake Plateau, where the mean stress is smaller and mostly westward.

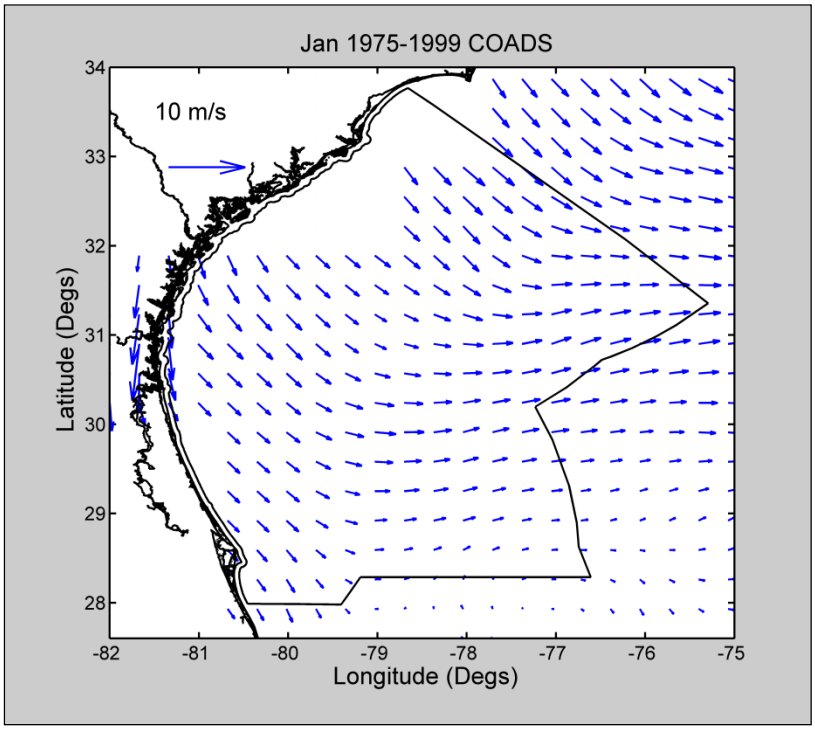

Figure 3.4 January wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data by Blanton et al., 2003).

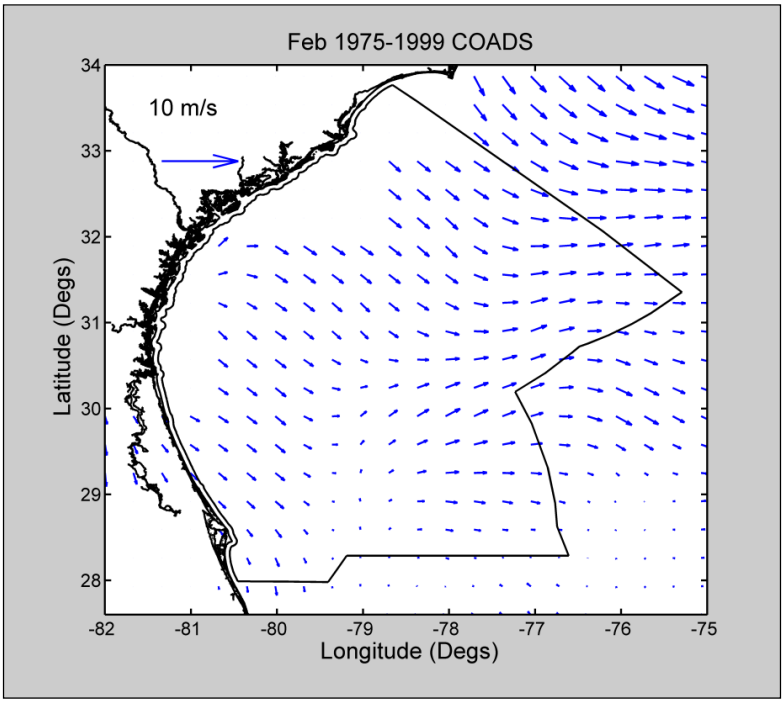

Figure 3.5 February wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of

COADS (data by Blanton et al., 2003).

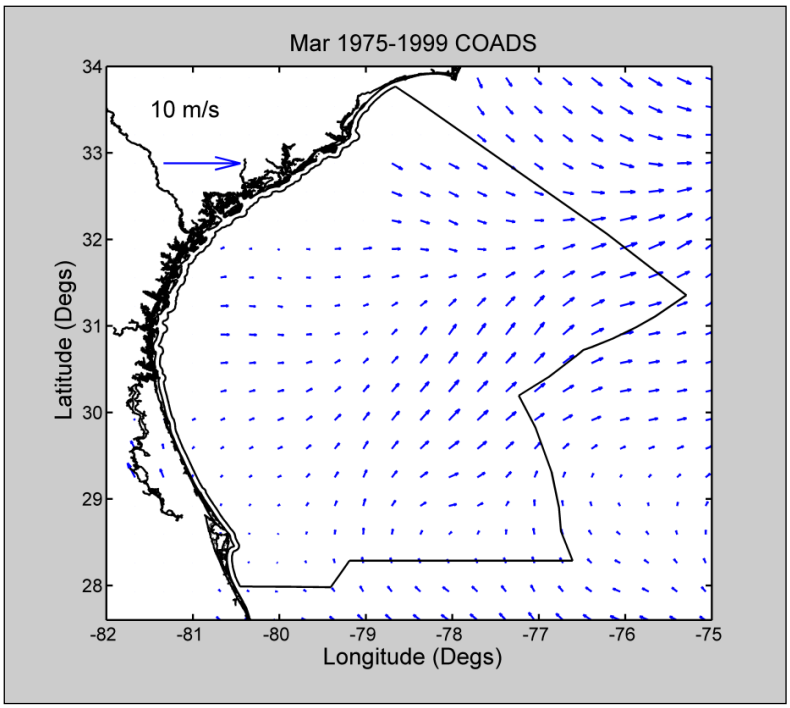

Figure 3.6 March wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

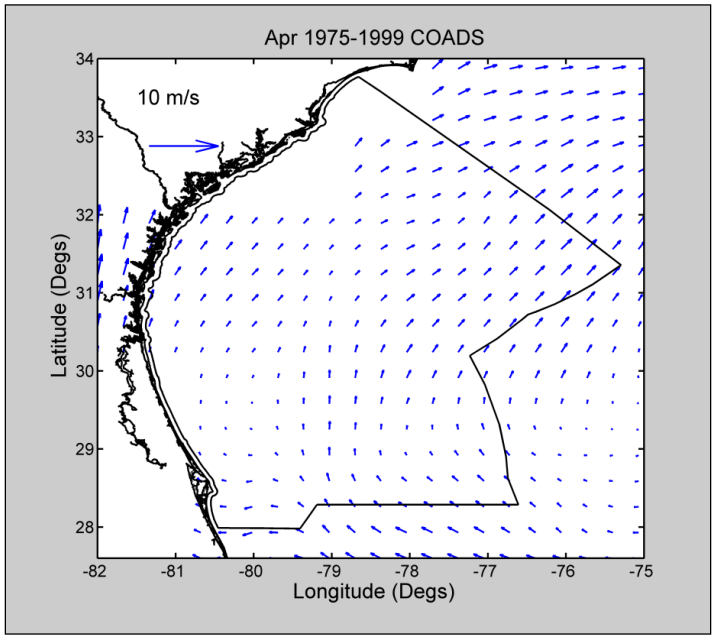

Figure 3.7 April wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

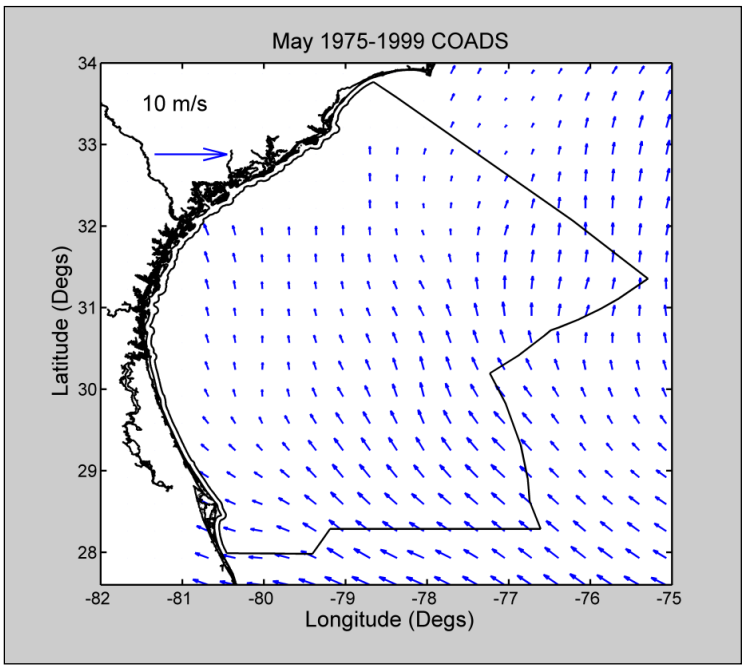

Figure 3.8 May wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

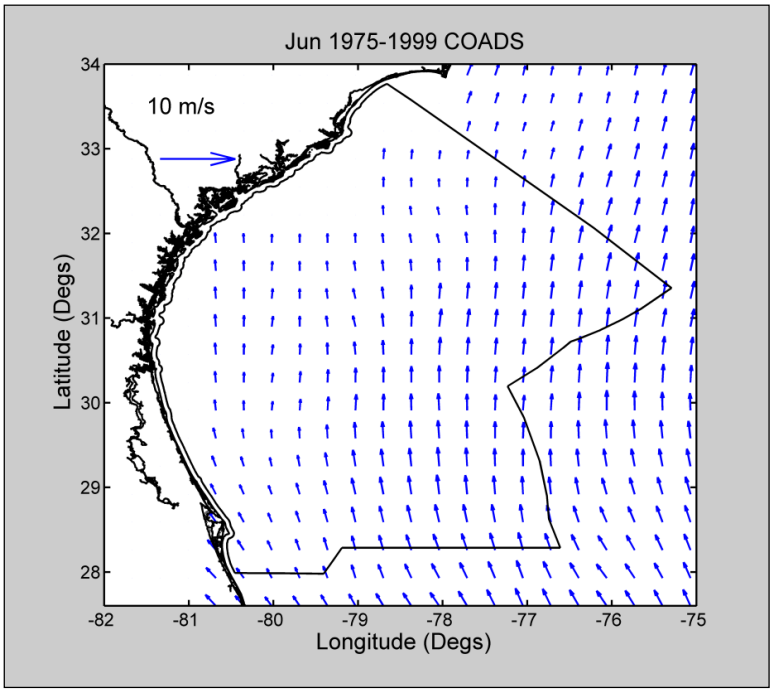

Figure 3.9 June wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

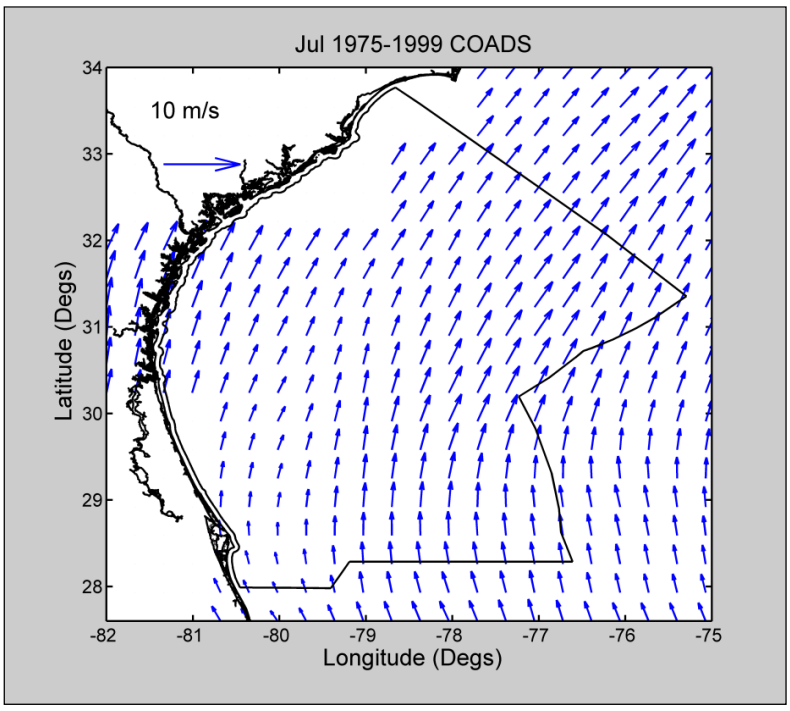

Figure 3.10 July wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

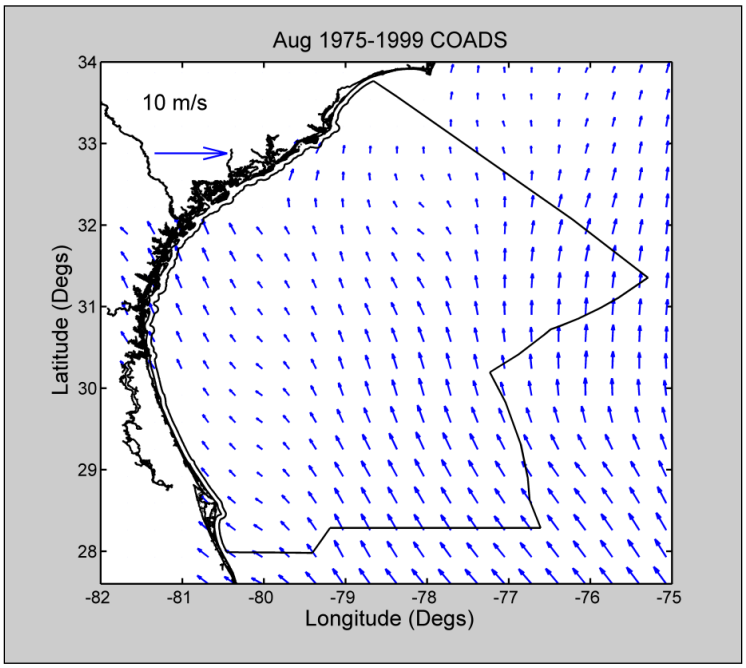

Figure 3.11 August wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

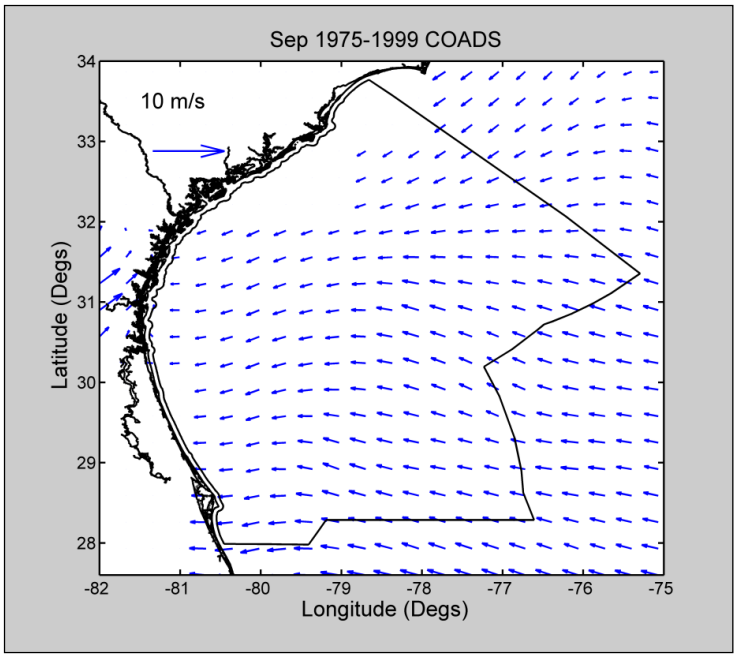

Figure 3.12 September wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

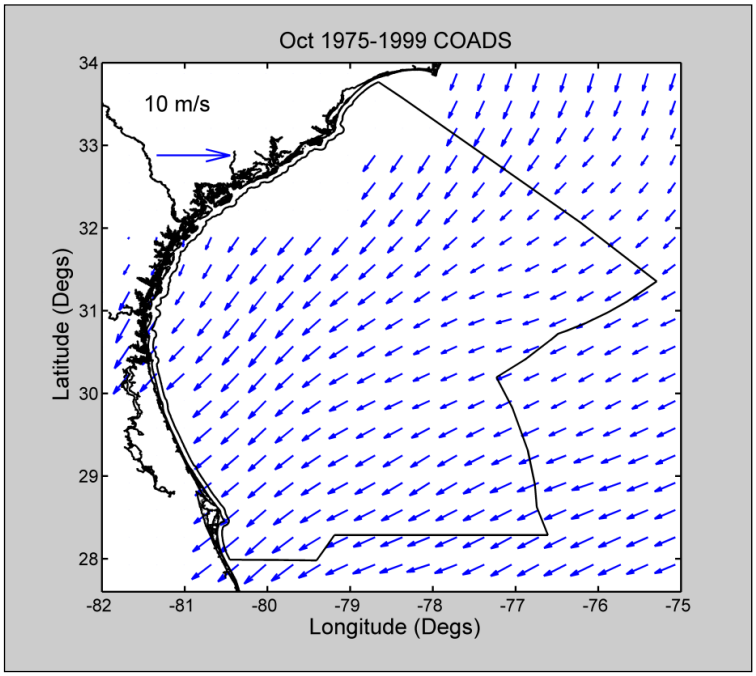

Figure 3.13 October wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

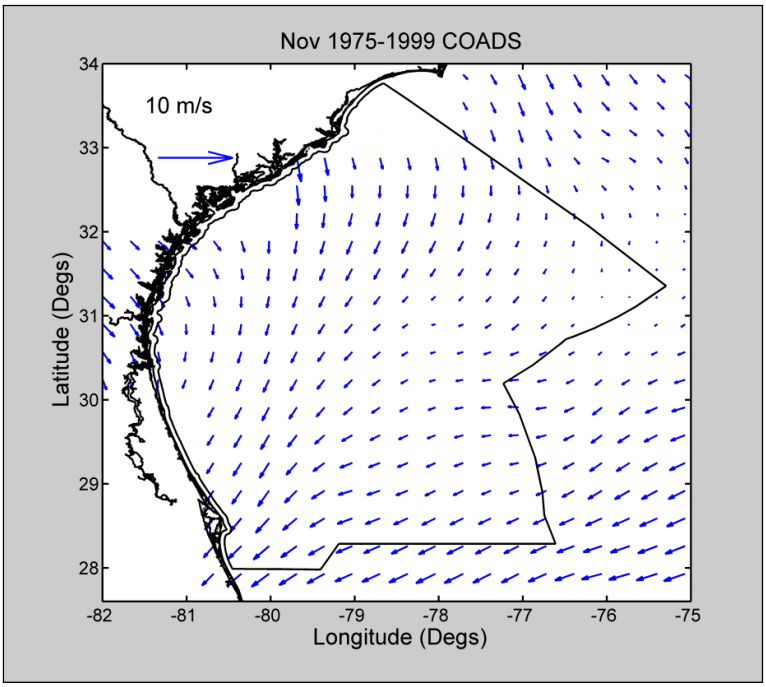

Figure 3.14 November wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data by Blanton et al., 2003).

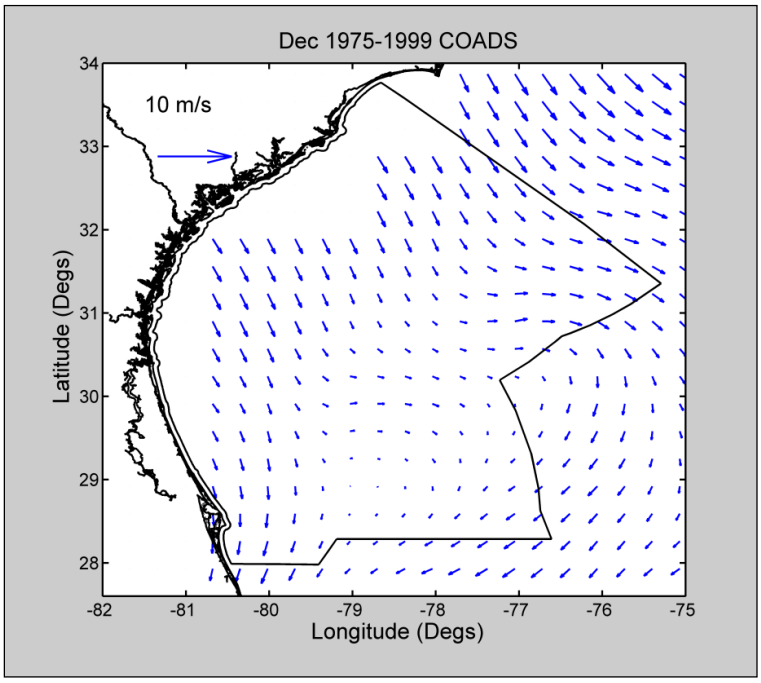

Figure 3.15 December wind circulation over the South Atlantic Planning Area, as derived by the re-analysis of COADS (data from Blanton et al., 2003).

3.2.3 Synoptic Wind Forcing

Passage of low-pressure atmospheric frontal systems over the southeast US introduces synoptic variations in meteorological parameters that exhibit a typical periodicity of 2–3 days. Energetic wave conditions and shelf flows at synoptic scales are attributed to three atmospheric front systems: 1) cold fronts, 2) warm fronts, and 3) tropical storms. Low-pressure systems associated with cold fronts move from west to east-northeast, and change the wind direction from northeast to southwest. Conversely, warm fronts are accompanied by an opposite change in wind direction. Tropical storms moving nearshore rotate the wind direction slowly from southwest to southeast. Long-term (2004–2007) nearshore wind, wave, and current data analyzed from a station located at 5 m water depth on the South Carolina coast (Springmaid Pier, Voulgaris et al., 2008) have been used to examine the relationship between meteorological forcing and nearshore hydrodynamic conditions. Analysis of atmospheric pressure, temperature, and wind velocity from the same station were used to identify 24 cold fronts, 18 warm fronts, and 14 tropical storms on average for each year from 2004–2007. These are typical for the region and can be found from North Carolina to Florida.

3.3 SEA LEVEL

Coastal sea surface elevation varies at a number of scales. The average seasonal cycles for coastal water levels are caused by a combination of the effects of the average seasonal cycles of air pressure, wind, water temperature, salinity, ocean currents, and river discharge. For many locations, the average seasonal cycle is driven mainly by the steric effect, which is the change in the volume of seawater caused by changes in water density due to temperature and salinity variations. As a consequence, water levels tend to be highest in late summer/early fall at the end of the heating season and lowest in the late winter/early spring at the end of the cooling season. In addition to this seasonal variation, there are long-term changes in the sea level due to eustatic effects.

For over 150 years, NOAA's Center for Operational Oceanographic Products and Services has operated the National Water Level Observation Network in the United States with tide stations on all US coasts. These gauges are used mainly for tidal analysis and predictions. Their data have also been analyzed in terms of changes in mean sea level (MSL). In the South Atlantic Planning Area there are currently six stations (Table 3.1) for which both monthly and long-term changes in MSL have been computed using a minimum span of 30 years of observations (NOAA, 2009). Monthly averages over the years are used to describe seasonal variations in sea level. This approach removes the effect of high-frequency phenomena, such as waves and tides. Time-series of monthly averages have been used to accurately compute a linear relative sea-level trend that can be used to assess relative vulnerability of the coastal areas within the region to sea level rise.

3.3.1 Monthly Variability of Sea Level

The stations from South Carolina to northern Florida have a double-peaked average seasonal cycle. The lowest sea level occurs during the winter (in January) increasing throughout the year to a local maximum in May–June. After that, mean sea level falls to a secondary low in July, before rising to the highest level that occurs September–October. This modification of the usual steric seasonal cycle has been attributed to the dynamic effect of seasonal variations in the speed of the Gulf Stream (Noble and Gelfenbaum, 1992; Blaha, 1984).

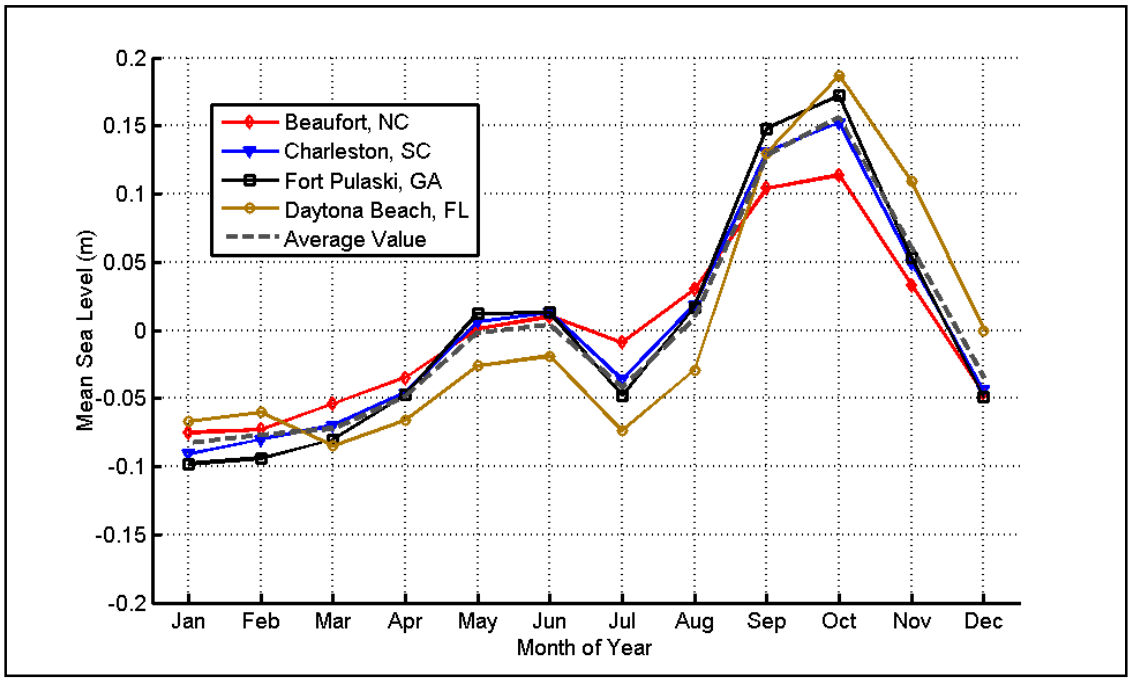

Figure 3.16 Monthly variability of sea level as recorded at four NOAA coastal tidal stations along the South Atlantic Bight (data from NOAA, 2009). Note two local maxima. One in May-June is attributed to the influence of the Gulf Stream, while the second largest one (September-October) is due to steric effects.

Table 3.1
NOAA/NOS (2010) published linear mean sea level (MSL) trends and 95% confidence intervals in millimeters per year (mm/yr) for stations within the South Atlantic Planning Area.

NOAA/NOS Tidal Station	First Year	No of Years	MSL trend (mm/yr)	95% CI (mm/yr)
Springmaid Pier, SC	1957	50	4.09	0.76
Charleston, SC	1921	86	3.15	0.25
Fort Pulaski, GA	1935	72	2.98	0.33
Fernandina Beach, FL	1897	110	2.02	0.20
Mayport, FL	1928	79	2.40	0.31
Daytona Beach Shores, FL	1925	59	2.32	0.63
AVERAGE			**2.83**	**0.41**

3.4 TIDAL FORCING IN THE SOUTH ATLANTIC PLANNING AREA

3.4.1 Introduction

Tidal information along the Atlantic Ocean can be obtained for the NOAA National Ocean Service stations that are available on the US east coast. These stations and their ID numbers are listed in Table 3.2. Real-time and historical data from these stations can be found on the NOAA Tides and Currents website.

There is also information in the form of analysis of in-situ measurements and results of numerical models that are available for inclusion in site-specific studies. The latest global ocean tide information available through numerical and data assimilation results is presented in Section 3.4.2. In Section 3.4.3, a data atlas derived using a 2-D depth integrated model forced by a global tidal atlas is presented. The latter has the advantage of incorporating the effects of tidal inlets and estuaries and provides much better tidal estimates for the study area that include non-linear effects due to bathymetric changes.

Table 3.2
NOAA National Ocean Services stations that are available on the southeast US coast.

NOAA NOS Station ID	Location	State
8651370	Duck	NC
8652587	Oregon Inlet Marina	NC
8654467	USCG Station Hatteras	NC
8656483	Beaufort	NC
8658120	Wilmington	NC
8658163	Wrightsville Beach	NC
8661070	Springmaid Pier	SC
8662245	Oyster Landing (N. Inlet Estuary)	SC
8665530	Charleston	SC
8667633	Clarendon Plantation	SC
8670870	Fort Pulaski	GA
8720030	Fernandina Beach	FL
8720059	Vaughns Landing	FL
8720145	Edwards Creek	FL
8720218	Mayport (Bar Pilots Dock)	FL
8721604	Trident Pier	FL

3.4.2 Global Ocean Tides

During the 1990s, many new tidal atlases were developed, primarily to provide accurate tidal corrections for satellite altimetry applications. Motivated by the development of the Topex/Poseidon mission, a large effort was undertaken to develop and/or improve new models for tidal prediction, aiming at attaining centimeter accuracy levels (Le Provost et al., 1995). Two main approaches were developed: 1) the empirical approach based on the direct analysis of the altimetry sea level time series (i.e., Cartwright and Ray, 1991), and 2) a modeling approach based on hydrodynamic and assimilation models. The latest global atlas for tides is the FES2004 (Lyard et al., 2006). Its performance is slightly improved in the deep ocean region while it provides significant improvement in the shelf and coastal areas with the exception of the K2 component, where the FES2002 atlas is recommended (Lyard et al., 2006).

The FES (2004) tidal atlas is based on numerical models that solve the tidal barotropic equations on a global finite element grid (~1 million nodes). Since the model is of global scale, it has no boundary conditions and so the solutions are independent of any boundary condition assumptions. The model has been run on a new original high-resolution bathymetry for ice on polar regions. Furthermore, the accuracy of these "free" solutions was improved by assimilating tide gauge and TOPEX/POSEIDON (T/P) and ERS-2 satellite altimetry data through a revised assimilation method. The atlas includes 15 tidal constituents that are distributed on 1/8 degree grids (amplitude and phase); 28 other constituents are taken into account by the means of a specific admittance method and a long-period wave computation. A new prediction algorithm is distributed within the FES2004 package to provide tidal heights at any location of the world ocean.

3.4.3 Tides in the South Atlantic Planning Area

Despite the improvement of the global tidal atlas, the coastal and shelf regions remain challenging areas, because strongly non-linear dynamics over the ocean shelves affect the tides significantly. This is particularly true for the South Atlantic Planning Area. The width of the continental shelf is 10–30 km at the northern and southern ends, and reaches up to 130 km wide off the Georgia coast. Although bathymetric contours are parallel to the coast, there are numerous estuaries and tidal inlets (referred to as the estuary/tidal inlet complex in Blanton et al. [2004]) that extend from the middle of South Carolina to northern Florida. Overall the tidal environment is a semidiurnal (primarily M_2) co-oscillation with the North Atlantic deep ocean tide (Redfield, 1958). Significant amplification occurs along the widest part of the continental shelf (off Georgia).

The tidal velocity ellipses are generally oriented in such a way as the major axes are aligned with the cross-shelf direction and they are twice larger than the minor axes (Redfield, 1958; Clarke and Battisti, 1981; Werner et al., 1993). The ellipses are re-orienting themselves parallel to the coastline close to the shore. This re-orientation starts some 2 km off the coastline (Gutierrez et al., 2006). As Werner et al. (2003) identified, the tidal Eulerian residual velocity is weak and directed toward the south at the shelf break and north on the shelf at about 1 cm/s.

The contribution of tides to the total water level and current variance is significant. According to Tebeau and Lee (1979) and Lee and Brooks (1979), the variance in the tidal frequency band accounted for 80–90% and 20–40% of the total cross-shelf and along-shelf current variance in

the middle shelf. Their work, when combined with that of Pietrafesa et al. (1985), shows that the cross-shelf variance can be explained by the semidiurnal tides which account for about 80% of inner- and middle-shelf kinetic energy, and some 30% of outer-shelf energy.

Redfield's (1958) work considered the M_2 elevation and velocity from shelf stations along the Middle Atlantic Bight and south to Savannah, GA. His analysis indicated that the M_2 surface tide is a standing wave on this region of the shelf. This suggests that the large-scale coastal water level at semidiurnal frequencies is in phase along the coast and that maximum shoreward tidal velocities lead the time of high water by about one-quarter period. Redfield found that this was also true for the semidiurnal tide on the shelf, at least as far south as Savannah.

Blanton et al. (2004) carried out the most recent comprehensive analysis of the characteristics of the principal barotropic diurnal and semidiurnal tides for the South Atlantic Planning Area. They used numerical and in-situ data to predict the tidal conditions. Numerical solutions in the western North Atlantic Ocean were computed using the hydrodynamic finite-element model ADCIRC-2DDI (Luettich et al., 1992). The model solves the vertically integrated, fully nonlinear shallow-water wave equations on linear triangular finite elements. The model domain extended westward from the only open boundary (60^oW) and includes the Gulf of Mexico, as well as a high-resolution representation of the estuary/tidal inlet complex along the coasts of Georgia, South Carolina, and North Carolina. The model grid contained 63,076 nodes and 111,748 elements, with horizontal resolution ranging from 100 km in deep water, 2–10 km on the shelf, to 50–100 m in the tidal inlets and estuaries. To assess the effect of the estuary/tidal inlet complex, the model was run with and without the inlets and estuaries and the results were inter-compared and checked against the in-situ available data.

The bathymetry used was a combination of ETOPO5 gridded elevation data in deep water and NOAA's Coastal Relief Model on the shelf and in the estuary/tidal inlet complex. Tidal amplitude and phase, as well as tidal potential, were specified along the open ocean boundary. The forcing spectrum is M_2, N_2, S_2, O_1, and K_1, extracted from the TOPEX-Poseidon altimeter-assimilated global atlas FES95.2 (Le Provost et al., 1998). The model was integrated for 180 days, and harmonic analysis was performed at each model node over the second 90-day period of the integration. The analysis combined a number of recent observations from pressure gauges and acoustic Doppler current profilers (ADCPs) on fixed platforms as well as numerous short-term deployments off the Georgia and South Carolina coasts together with NOS coastal tidal elevation harmonics which have been derived by a number of long-term tidal elevation measurements along coastal stations.

These data have shed light on the regional tidal propagation, particularly off the Georgia/South Carolina coast, which is affected by the dense estuary/tidal inlet complex. It was found that the presence of the estuaries and inlets make tidal propagation a highly dissipative process and affects the regional energy balance of the semidiurnal tides. The model showed that the nearshore, inner, and middle shelf semidiurnal frequencies are highly sensitive to the inclusion of the estuaries. The numerical solution that includes the estuary/tidal inlet complex showed a significantly improved agreement with the available observations when compared with model simulations that did not include the estuaries. For the M_2 constituent, which is the largest tidal frequency in the South Atlantic Planning Area, overall amplitude and phase errors are reduced

from 0.25 m to 0.03 m and 13.8° to 2.8° for coastal observation stations. Similar improvement was found for middle-shelf stations. It is characteristic that diurnal tides were found to be relatively unaffected by the inclusion of the estuaries and tidal inlets, with the greatest improvement occurring at the semidiurnal frequencies. A database of the results can be obtained from the authors. The database provides amplitudes and phases for both elevations and east and west components of depth-averaged velocities for the K_1, K_2, M_2, N_2, O_1, P_1, Q_1, and S_2 tidal constituents that are the most dominant ones in the region.

The semidiurnal tidal ranges over the domain have been estimated from the model-derived amplitudes of the M_2 and S_2 constituents are shown in Figure 3.17. The spring and neap ranges are estimated using $2\times(A_{M2}+A_{S2})$ and $2\times(A_{M2}-A_{S2})$, respectively, where A denotes amplitude and the subscript refers to the tidal constituent (Figures 3.18 to 3.20).

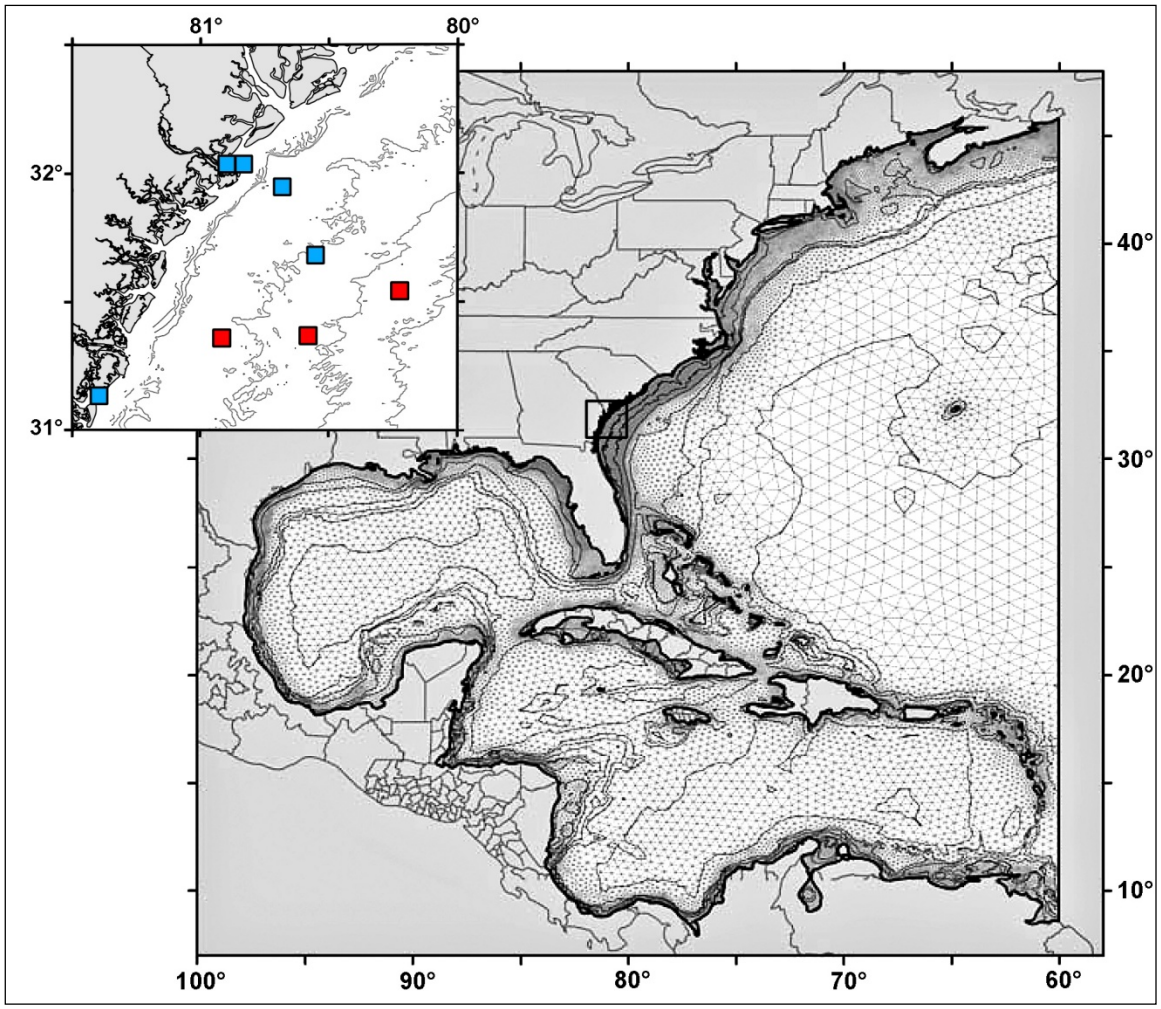

Figure 3.17 The domain of the ADCIRC model used to derive the tidal constituents in the South Atlantic Planning Area (modified from Blanton et al., 2004).

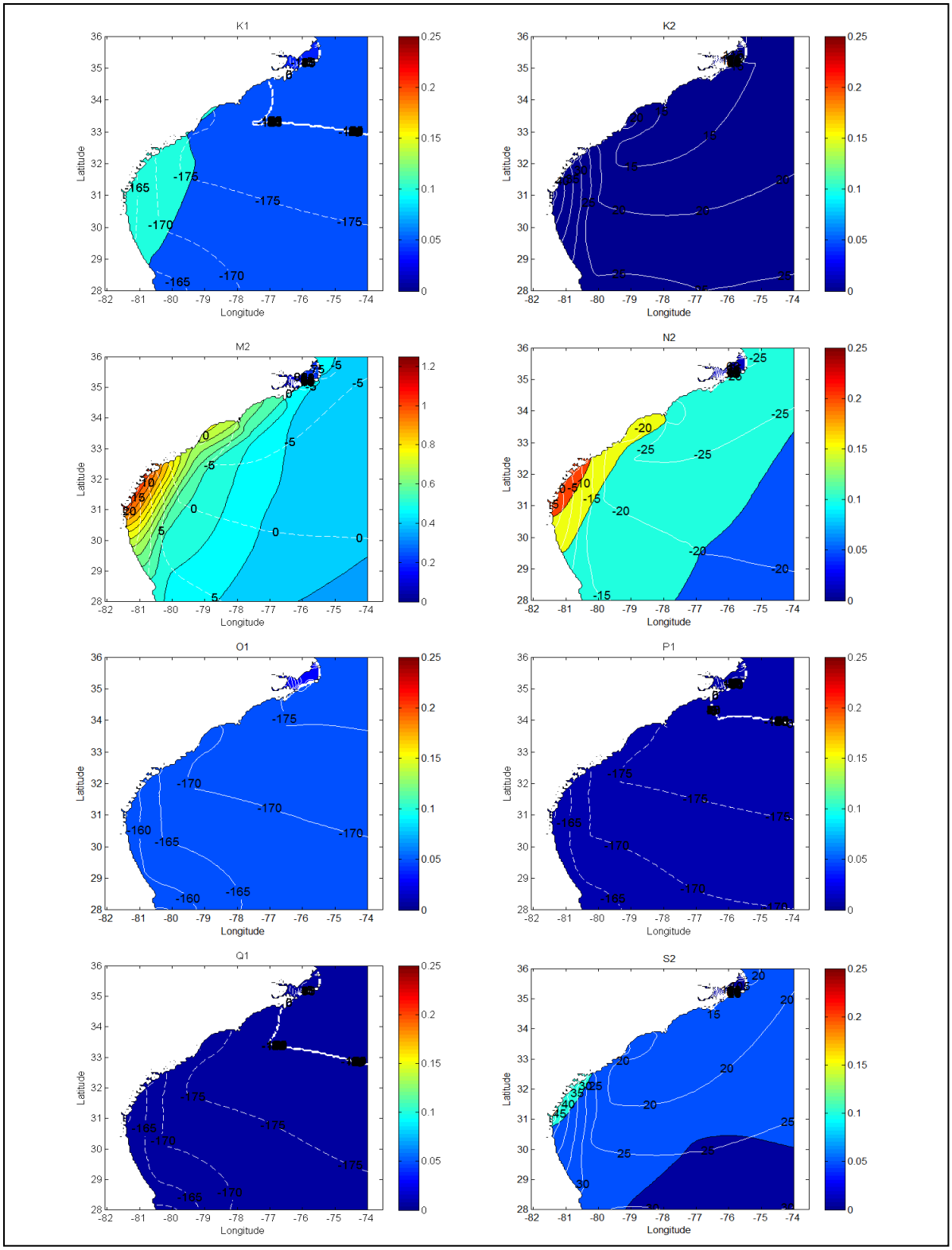

Figure 3.18 Spatial distribution of the eight major constituents of surface elevation (amplitude and phases) as derived by Blanton et al. (2004). Color-bar units are in m; phase contours are in degrees. Note different color scale for M_2.

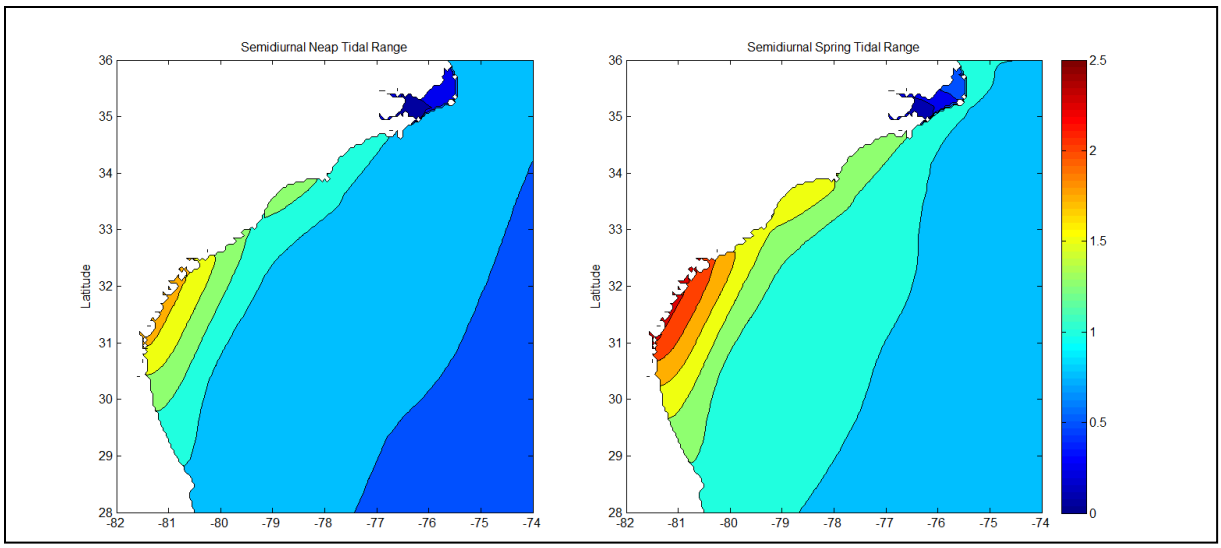

Figure 3.19 Spatial distribution of neap (left) and spring (right) semidiurnal tidal ranges from the Blanton et al. (2004) model for barotropic tides.

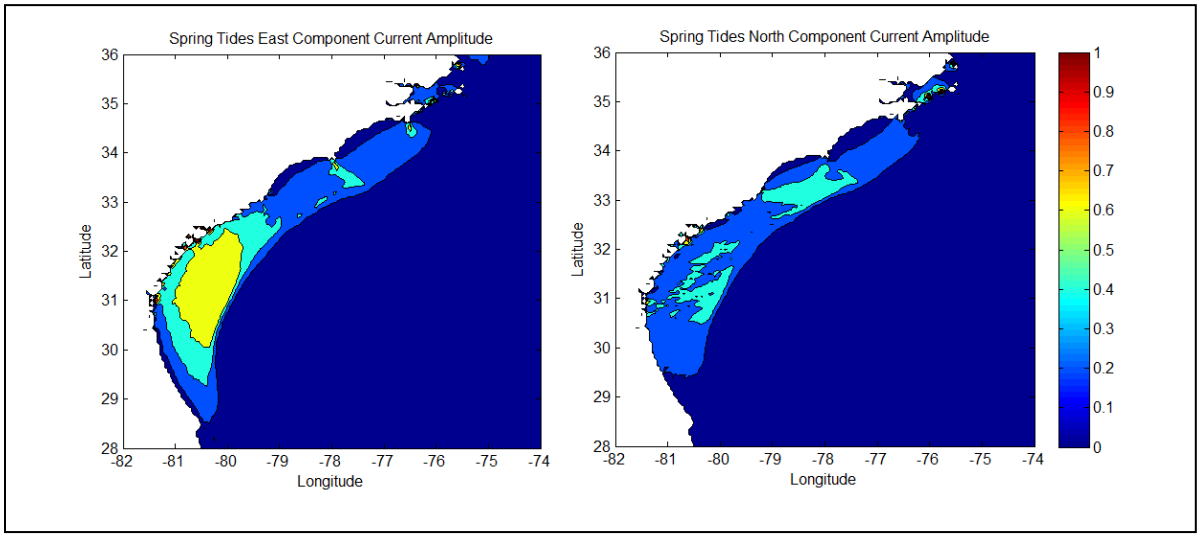

Figure 3.20 Spatial distribution of depth averaged tidal current amplitude (in m/s) for spring semidiurnal tidal range for the east and north components of the current. Values based on the Blanton et al. (2004) model for barotropic tides.

3.5 WAVES

Wave data are collected by NOAA/NDBC, and the real time-data and historical analyses and climatologies are routinely updated and published on the Internet for each station. The NDBC currently operational buoys in the study area are shown in Figure 3.21. These can be found in offshore deep ocean locations, on the outer shelf, and on the middle shelf. Also, more wave measurements are available in various nearshore stations as part of the IOOS efforts for coastal observing stations (e.g., Voulgaris et al., 2008). In an attempt to create a coherent picture for the study area, the meteorological and wave climatology data from four stations, which are located

from St. Augustine, Florida to Onslow Bay, North Carolina, are shown in Figures 3.22 and 3.23, where the monthly means and standard deviations of hourly records of air temperature, wind speed, and atmospheric pressure, as well as sea temperature, significant wave height, and mean period are shown. The important characteristic is that the monthly patterns are overall coherent throughout the region. Mean atmospheric pressure is mainly lower during the summer than the winter. Air temperatures are highest during the summer months without any significant gradient along the domain. Only during the winter can we see a small gradient with higher temperatures in the southern part decreasing in a northward direction. Monthly averaged wind speeds are of the order of 10–15 m/s, with slightly lower offshore winds in the summer than the winter. As in the case of air temperature, offshore wind speeds show a slight gradient with lower wind speeds in the southern part and slightly higher in the northern areas.

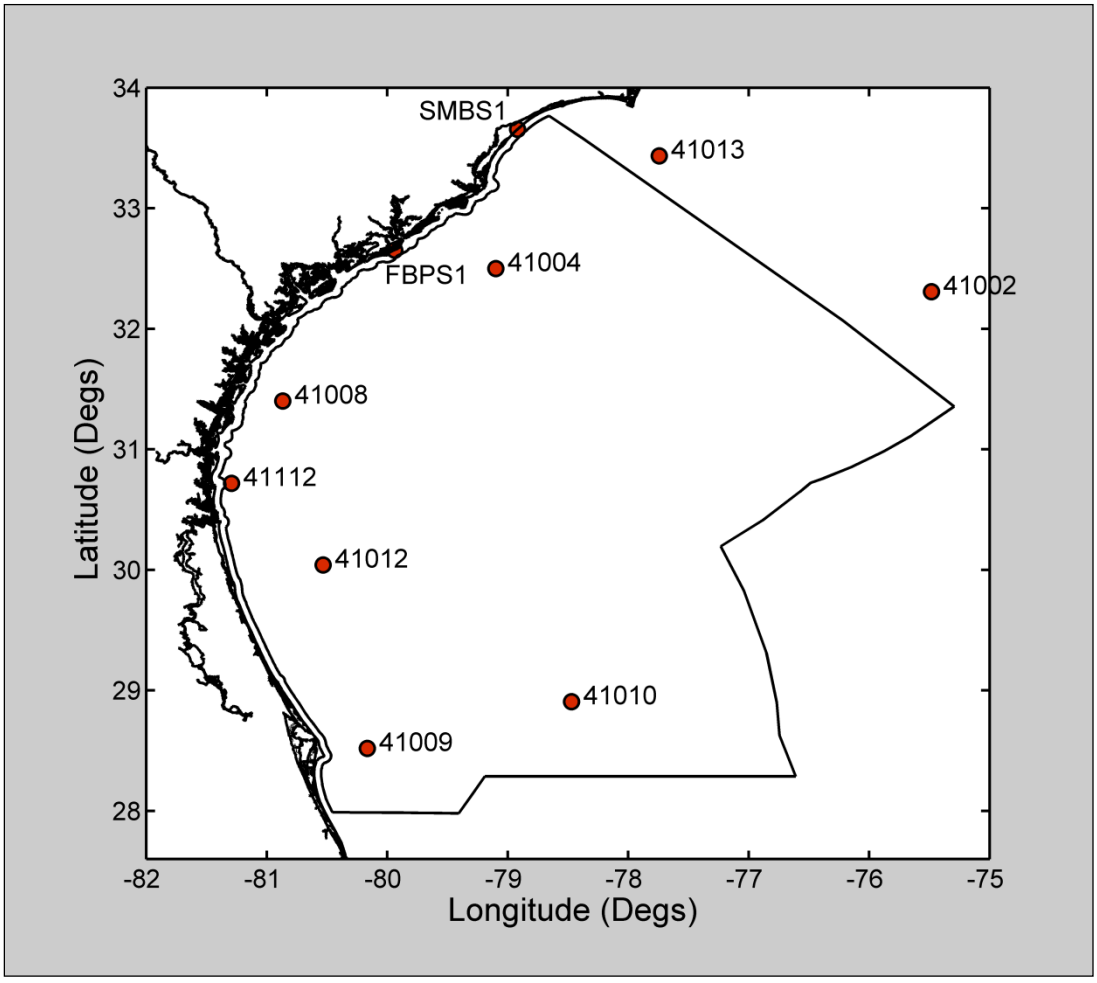

Figure 3.21 Locations of NOAA/NDBC buoys available with real time and historical data on wind and wave conditions over the South Atlantic Planning Area.

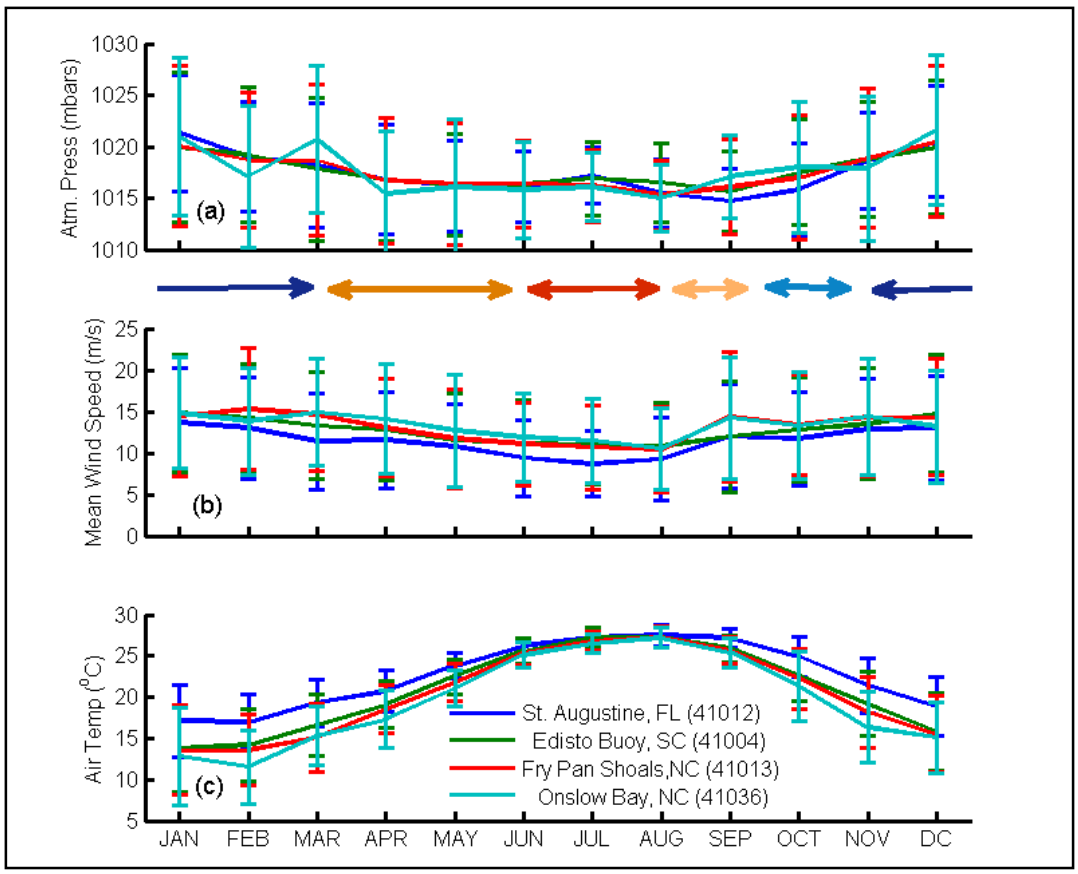

Figure 3.22 Monthly averaged meteorological data from the NOAA/NDBC buoys located on the outer shelf of the South Atlantic Planning area. (a) mean sea temperature; (b) mean significant wave height; and (c) mean wave period. The arrows denote the different periods winter, spring, summer, August transition and autumn as defined in Section 3.2.

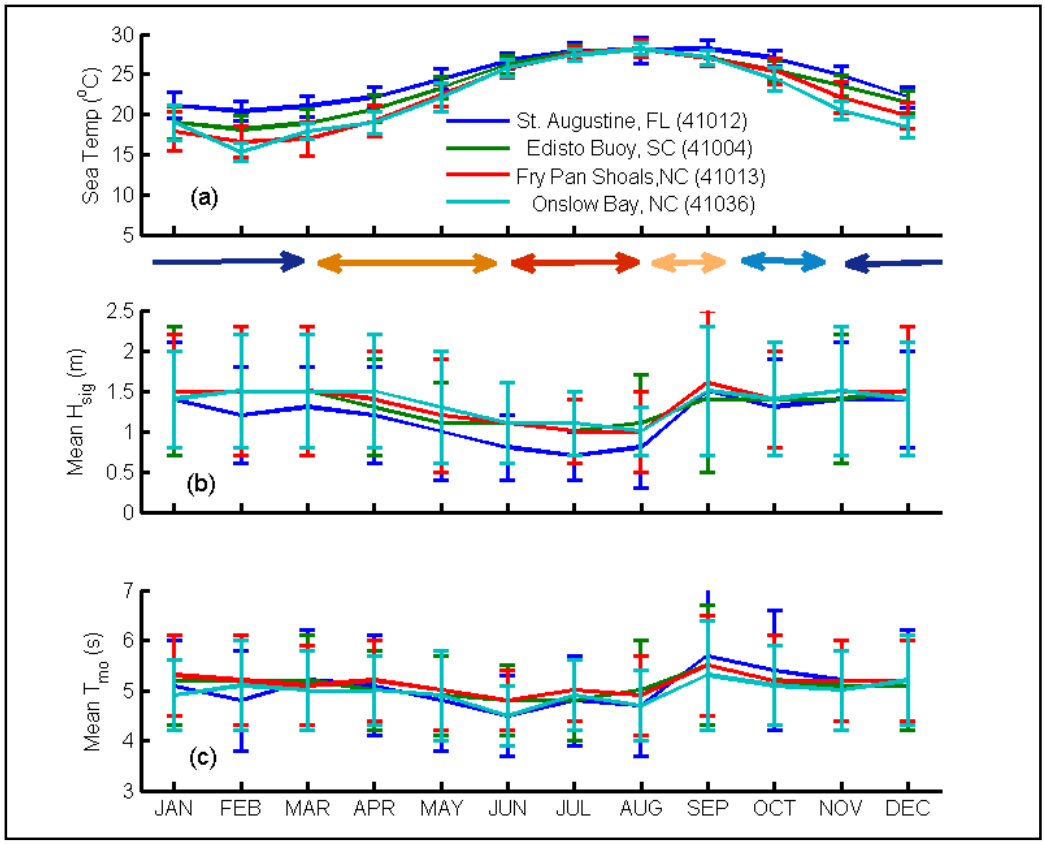

Figure 3.23 Monthly averaged meteorological data from the NOAA/NDBC buoys located on the outer shelf of the South Atlantic Planning area. (a) mean sea temperature; (b) mean significant wave height; and (c) mean wave period.

The monthly averaged offshore wave heights in the outer shelf are of the order of 1.5–2 m with mean wave periods 4–6 seconds. The wave climate is rather mild (except during the periods of hurricanes and tropical storms) and is characterized by the relative absence of frequent swell-period waves. The monthly variability of the wave height is highly correlated with that of the wind speeds showing that the wave climate in this region is driven by the local winds. Consequently wave energy is consistently lower in the southern part of the study area from January to September, while October to December the wave height is very similar in all offshore locations.

It should be noted, that, although there is significance coherence in the wave climate offshore, close to the coastline wave refraction and sheltering of the nearshore, especially in embayments such as Long Bay and Onslow Bay, modify the wave directional characteristics significantly.

There is not a comprehensive wave-climate analysis for the nearshore throughout the domain although the data are slowly become available for such studies. Voulgaris et al. (2008) presented some wave climate analysis results for the nearshore off Myrtle Beach, South Carolina (Long Bay) and Folly Beach, South Carolina. Also, Work (2008) has shown the availability of directional wave data off Tybee Island, Georgia.

At present, the only comprehensive wave-climate analysis available is based on modeled hindcast data provided through the Wave Information Studies (WIS) project that is managed by the US Army Corps of Engineers. This project produces an online database of hindcast, nearshore wave conditions covering all US coasts. The hindcast data provide a valuable source of decades-long wave data needed in coastal engineering design, at dense spatial resolution and a level of temporal continuity not available at present from in-situ measurements. Updated hindcasts are available to download for the Atlantic coasts covering the period 1980–1999. These Atlantic hindcast wave conditions were produced using the most recently updated version of the numerical ocean wave generation and propagation model, WISWAVE, along with wind fields produced by Oceanweather, Inc., as a value-added improvement to AES-40 wind fields. The hindcast data available are for a dense network of output stations (Figure 3.24) that follow 15–20 m depth contours along the coast. Data available include hourly wave parameters: significant wave height, peak period, mean period, mean wave direction, and wind speed and direction. Parameter information can be easily downloaded for use as input into nearshore coastal process models. Directional spectral information at 3-hour intervals is also available from the WIS staff through inquiry.

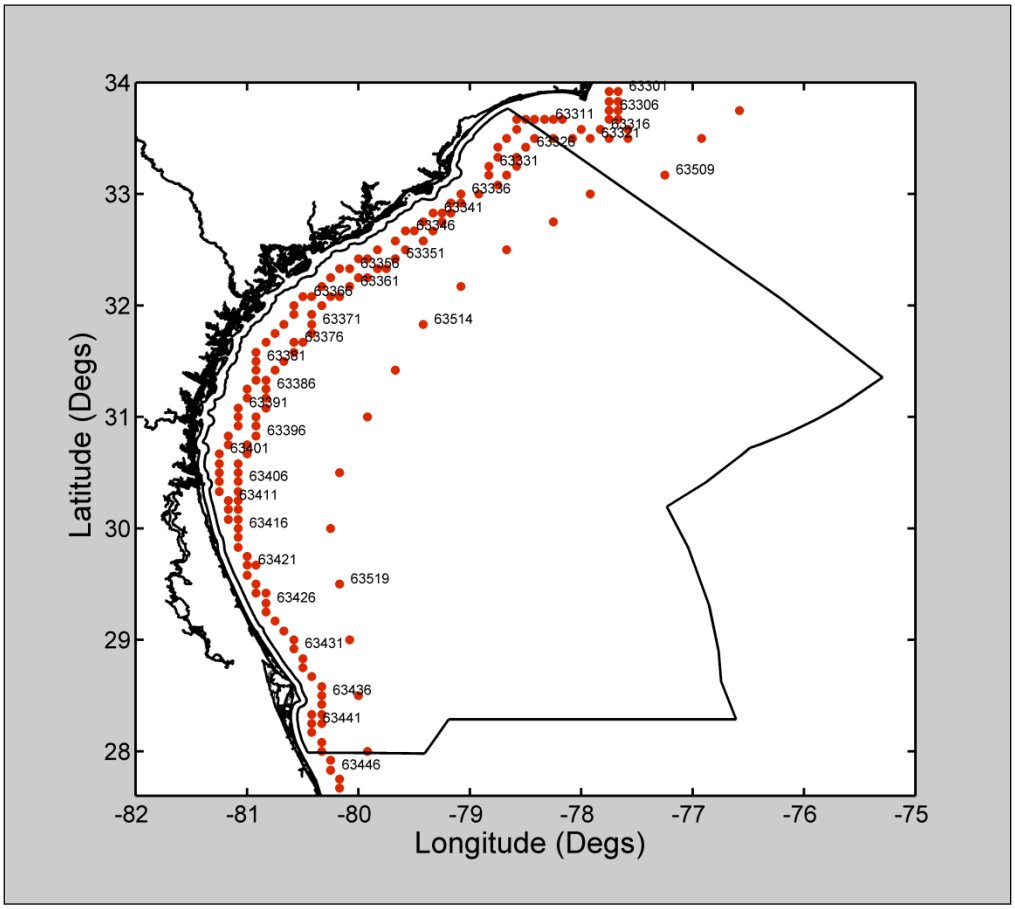

Figure 3.24 Map showing the spatial distribution of the available WIS stations for the South Atlantic Planning Area (USACE, 2010).

It should be noted that the WIS stations are located further inshore from the available NOAA/NDBC buoys and, as a consequence, data verification is not easy. However, a reanalysis project is presently underway. Its goal is to improve the quality of the Atlantic and Gulf of Mexico hindcasts using an advanced version of the wave hindcast model WISWAVE, more accurate and more highly resolved input winds, and better representation of shallow-water topographic effects and sheltering by land forms through use of more highly resolved model domains.

3.6 MONTHLY AND SEASONAL HYDROGRAPHY

3.6.1 Satellite Identified Thermal Fronts

Large-scale frontal patterns in the South Atlantic Planning Area have been identified using thermal satellite imagery (Belkin et al., 2009) and have been also used to define large marine ecosystems (LME). The South Atlantic Bight is within the Southeast US Continental Shelf LME#16. It has been found that these fronts are seasonally persistent because they are steered by the shelf break bathymetry. Overall, the Florida Current and the Gulf Stream are bordered by two fronts that correspond to their so called "cold" and "warm" sides. The cold-side front corresponds to the north wall of the Gulf Stream that extends over the upper continental shelf and shelf break; it is also called the "Inshore Gulf Stream Front" (IGSF) (Belkin, 2005). The IGSF is much better defined than the warm-side front due to increased sea-surface temperature differences. The latter, also called the "Offshore Gulf Stream Front" (OGSF), is approximately 100 km off and parallel to the IGSF. The sea-surface temperature difference across the cold front varies seasonally from 2ºC in August up to 10ºC in March (Belkin at al., 2009). On the other hand, the warm-side front, though less strong than the cold front, is systematically detected in satellite imagery, with the cross-frontal, sea-surface temperature range varying seasonally from 1.5ºC to 4.5ºC.

The Mid-Shelf Front is located west of the Gulf Stream and is found along the 35–40 m isobath. This front is a stable front and, as a consequence, it appears more prominently than the inner and outer Gulf Stream fronts in satellite imagery climatic analysis (Belkin et al., 2009). The separation between these fronts is maximal at two locations within the South Atlantic Planning Area: (i) near the apex (31°N) of the area, apparently because of the northward isobath divergence; and (2) and downstream of the Charleston Bump (east of 79°W), owing to the Gulf Stream and its fronts deviation toward east that also leads to the development of the Charleston gyre.

3.6.2 Analysis of In-Situ Observations

Atkinson et al. (1983) used data from 2,872 hydrographic stations to define the oceanographic climatology of the southeast US continental shelf waters. The data were sorted by each degree of latitude and by depth into three zones (0–20 m, 21–40 m, and 41–60 m), corresponding to inner, middle, and outer shelf, respectively. It was found that inner-shelf water temperatures were close to those of adjacent land air temperatures following a similar seasonal trend throughout the year. Outer-shelf temperatures, on the other hand, appeared to be moderated by the Gulf Stream. The

lowest and highest water temperatures appeared to occur in the inner-shelf waters of Georgia and South Carolina. Bottom temperatures were found to be coldest off Florida, and were attributed to shelf-break upwelling processes. Blanton et al. (2003) extended the work of Atkinson et al. (1983) by analyzing all temperature and salinity (T-S) profiles for the region found at the National Oceanographic Data Center. These data (Figure 3.25) consisted of approximately 45,000 T-S pairs from 5,000 profiles spanning the period 1950–1999. The data were separated by month of the year and they were subjected to a quality control procedure by which all profiles with a bottom depth less than 400 m were checked to ensure that their values of T-S fall within the range of values defined by the shelf climatology of Atkinson et al. (1983). T-S profiles from waters with a depth greater than 400 m were assemble-averaged on half-degree squares and T-S pairs that deviate by ±2 standard deviations from the computed T-S curves are eliminated.

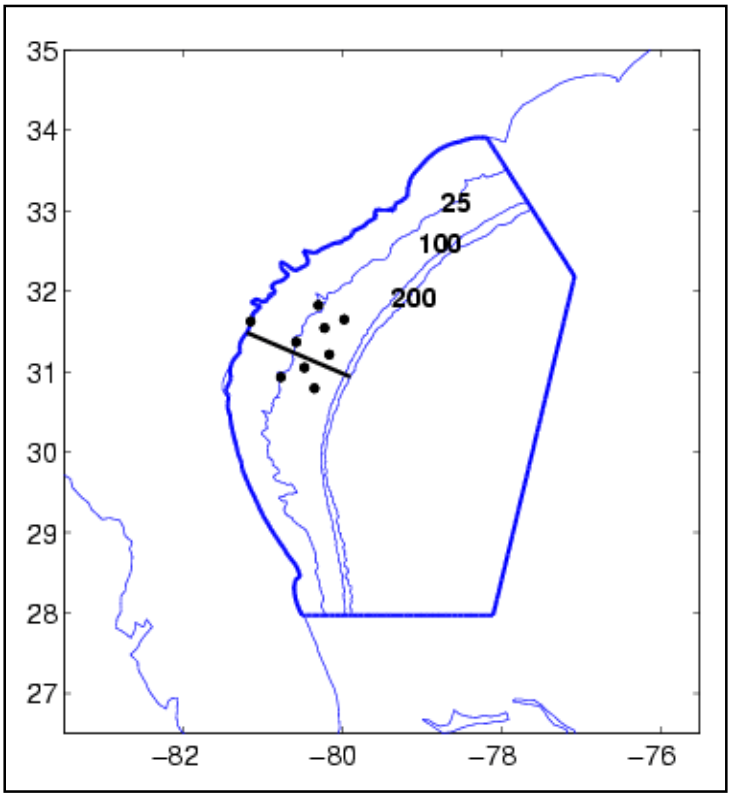

Figure 3.25 Model domain of Blanton et al. (2003). The transect line showing identifies the location of salinity and temperature transects shown in Figures 3.26 and 3.27 (dots indicate locations of Navy towers).

3.6.2.1 Seasonal Variability of Surface T-S

During the winter, shelf surface temperatures were found to be uniform along isobaths (Figure 3.26). The temperatures ranged from about 20°C at the shelf edge to 10°C along the upper coast (Georgia and South Carolina). The Florida coast experiences an along-shelf temperature gradient of about 6°C with increasing temperatures toward the south. Surface salinity ranges from 36.5 to 33 parts per thousand (ppt), with the isohalines following the bathymetric contours (Figure 3.27).

In the spring, shelf temperatures increase only slightly along the shelf break; along the coastline the increase is of the order of a few degrees (increased toward the south). This develops a cross-shelf temperature gradient which is significantly smaller than that found during the winter months. Salinity increases slightly along the shelf break and decreases by about 4 ppt along the coast. As Atkinson et al. (1983) indicate, freshwater discharge is larger from late March to early April and this is reflected in the salinity values of the surface waters, especially along the Georgia coast, where a minimum of surface salinity of 32 ppt occurs in the nearshore just south of the Savannah River entrance.

During the summer, the surface waters warm rapidly and reach an almost spatially uniform temperature of approximately 28°C in July. During this period, surface salinity exhibits spatial uniformity at 35–36 ppt, with slightly fresher water present near 32°N. The shelf waters start cooling rapidly after September. In October, the isotherms are oriented in the along-shelf direction with developing a cross-shelf difference of about 4°C.

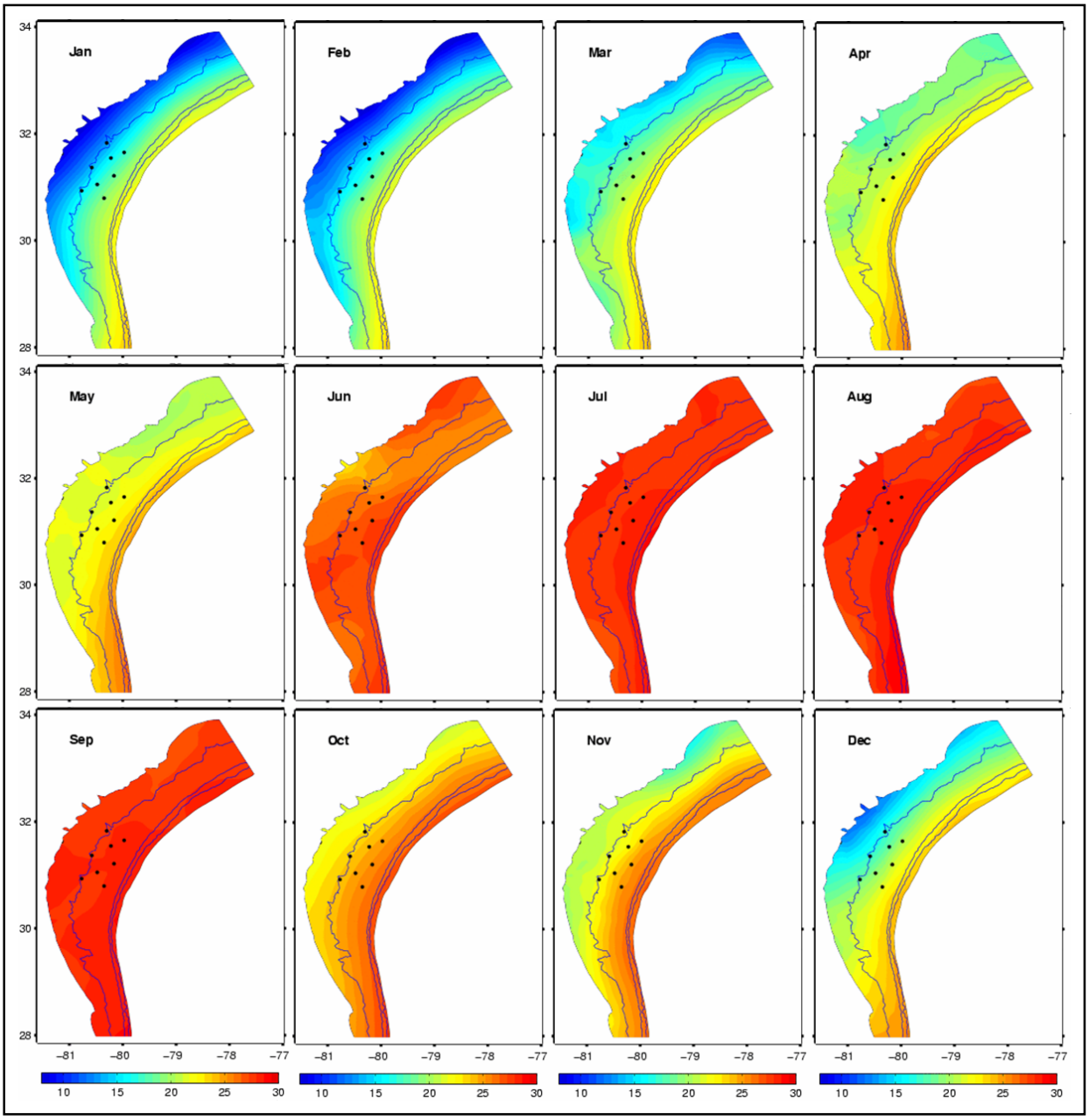

Figure 3.26 Monthly climatology of surface water temperature from Blanton et al. (2003).

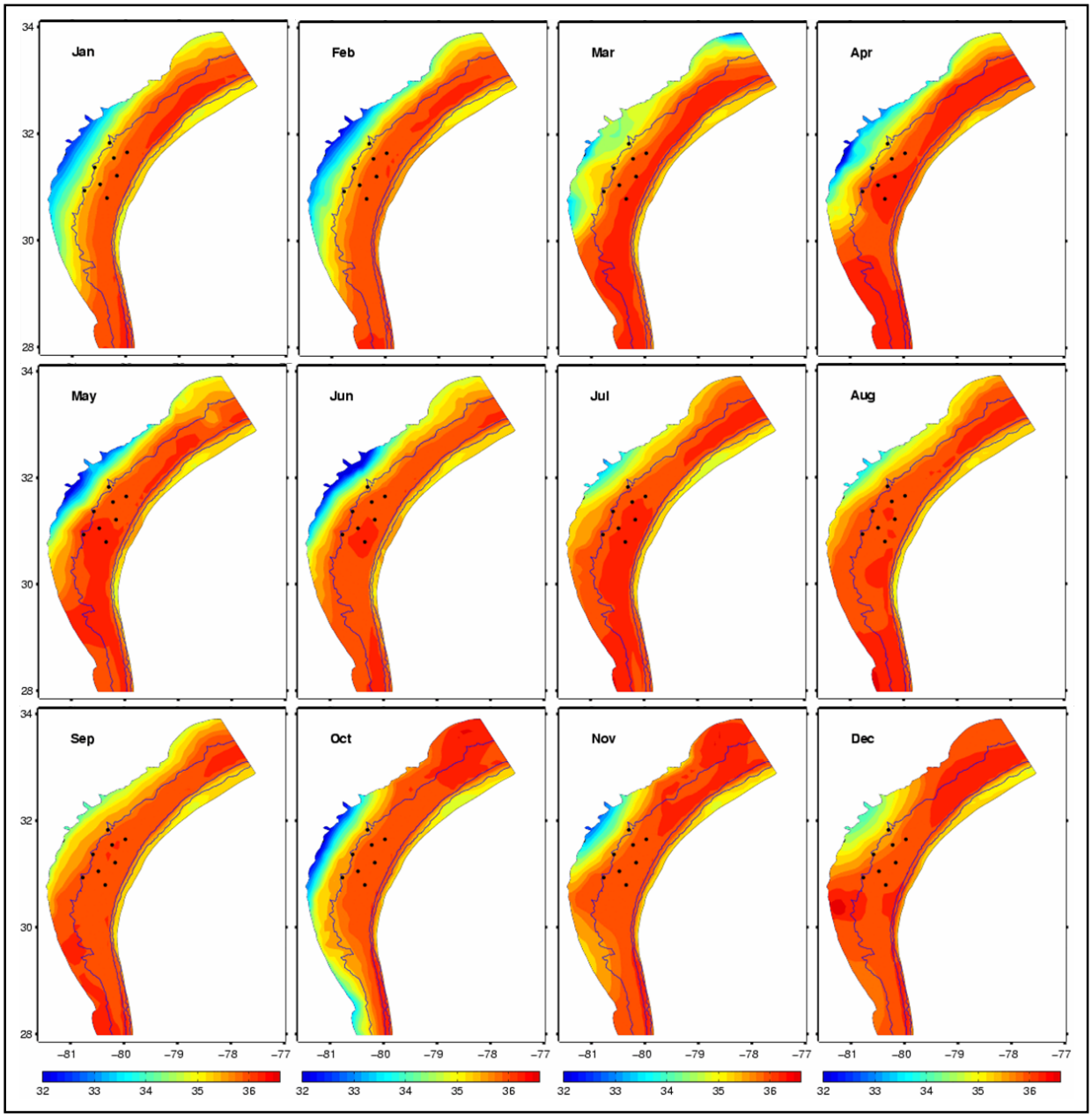

Figure 3.27 Monthly climatology of surface water salinity from Blanton et al. (2003).

3.6.2.2 Bottom T-S Distribution

In the winter (January), bottom water-temperature contours are oriented in the along-shelf direction and exhibit a strong cross-shore gradient with a difference approximately 11ºC. Cooler waters are present along the shelf break; the warmest bottom waters of approximately 20ºC found close to the 100 m isobath. By April, bottom waters warm by 6–8ºC, but in July they attain their maximum temperature close to the coastline. This is the period when upwelling of cooler water is observed along the shelf break, in response to the prevailing wind patterns. Unlike the surface temperatures in July, bottom water temperature exhibits a strong cross-shelf structure

while it is relatively constant along-shelf (Figure 3.28). In October bottom water temperatures range from about 21° to 25°C. Bottom water salinity is generally uniform in the along-shelf, with shelf break salinity constant at 36 ppt, and cross-shelf temperature differences ranging from 5°C in January to 2°C in July as shown in Figure 3.29. In all months, the cooler, more saline, shelf-break water is evident.

3.6.2.3 Stratification

To assess stratification, Blanton et al. (2003) used the National Oceanographic Data Center salinity and temperature profile data to make seasonal estimates of surface and bottom water density (Figures 3.30 and 3.31). The differences of those seasonal values indicate the degree of stratification of the shelf waters. Overall, the majority of the shelf is marginally stable during the winter. The shelf break is stratified throughout the year, even during the winter, because the presence of warmer Gulf Stream water in the upper ocean imposes a slight thermal stratification. By April, the buoyant fluxes from the Savannah and other rivers create a strongly stratified area limited to the area close to the 32°N. Stratification is weak initially at early summer but becomes stronger over time in response to solar heating, attaining a maximum in July. During this period, a strong stratification extends all over the shelf and it is strongest at the shelf break. The intensity of the stratification decreases by October and the inner shelf becomes weakly non-stratified.

Overall, over the South Atlantic Planning Area, heat-flux estimates indicate strong heating occurring from March through July with maximum heat-flux rates of 103 Watts per square meter of sea surface (W/m^2) (Atkinson et al., 1983). Cooling occurs during the period October to February; maximum rates are -90 W/m^2. Overall, in the spring, stratification increases in inner shelf areas because of decreasing winds and increasing heat flux and runoff. By summer the whole shelf is highly stratified in response to the contrasting high surface water temperatures and cooler bottom waters. Highest bulk stratification is found over the outer shelf. Stratification decreases with the approach of fall with the associated cooling and the development of higher winds.

3.6.3 Internal Waves

As reported in the atlas of internal waves (Jackson and Apel, 2004), there have been few scientific studies of internal waves along the southeast US The only observations of internal waves were made off the Florida coast near Cape Canaveral using SEASAT (L-Band, HH) SAR imagery (Fu and Holt, 1982). The waves identified were found to be very close to shore at approximately 100 m water depth and had wavelengths ranging from 300–500 m.

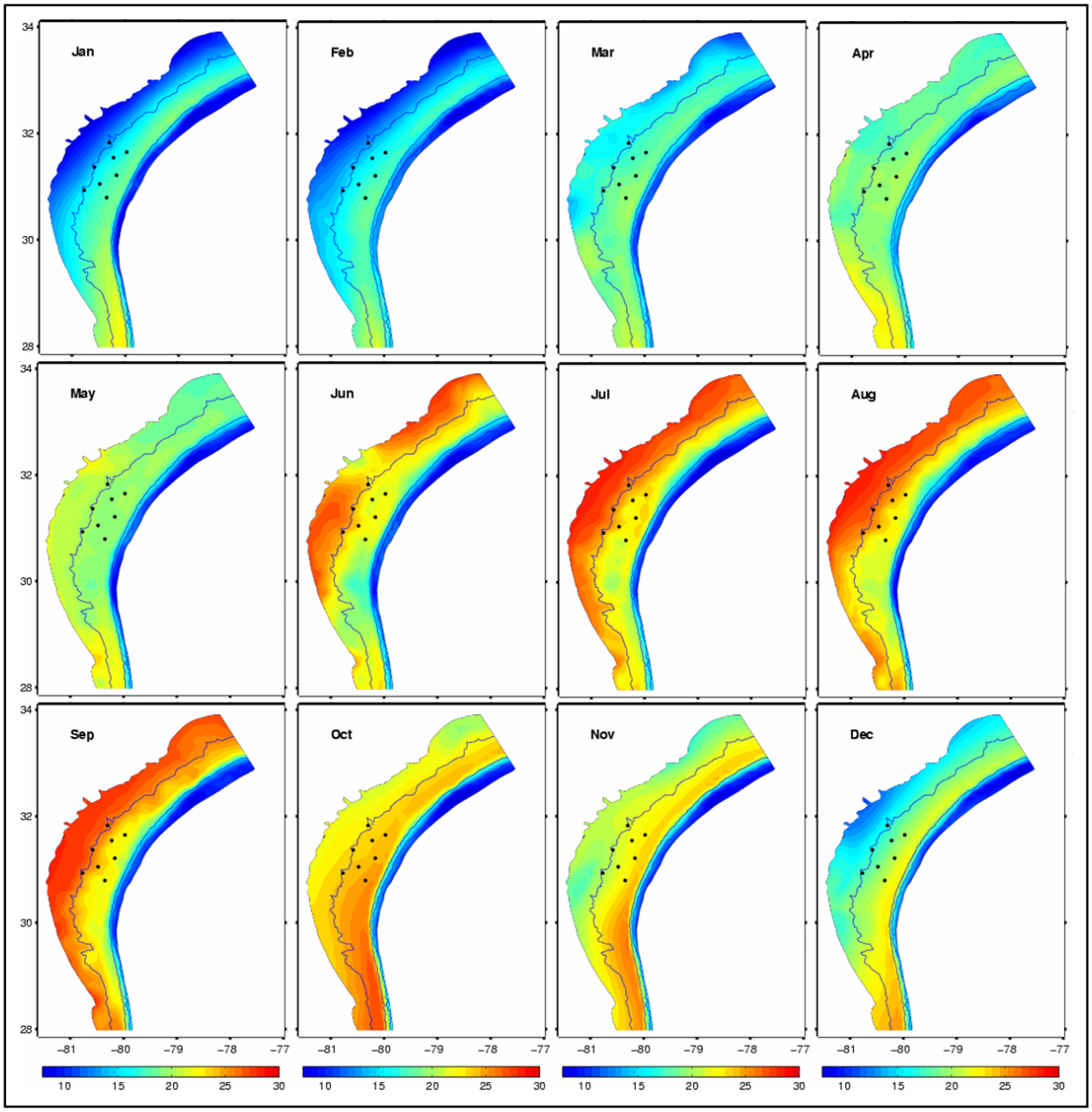

Figure 3.28 Monthly climatology of bottom water temperature from Blanton et al. (2003).

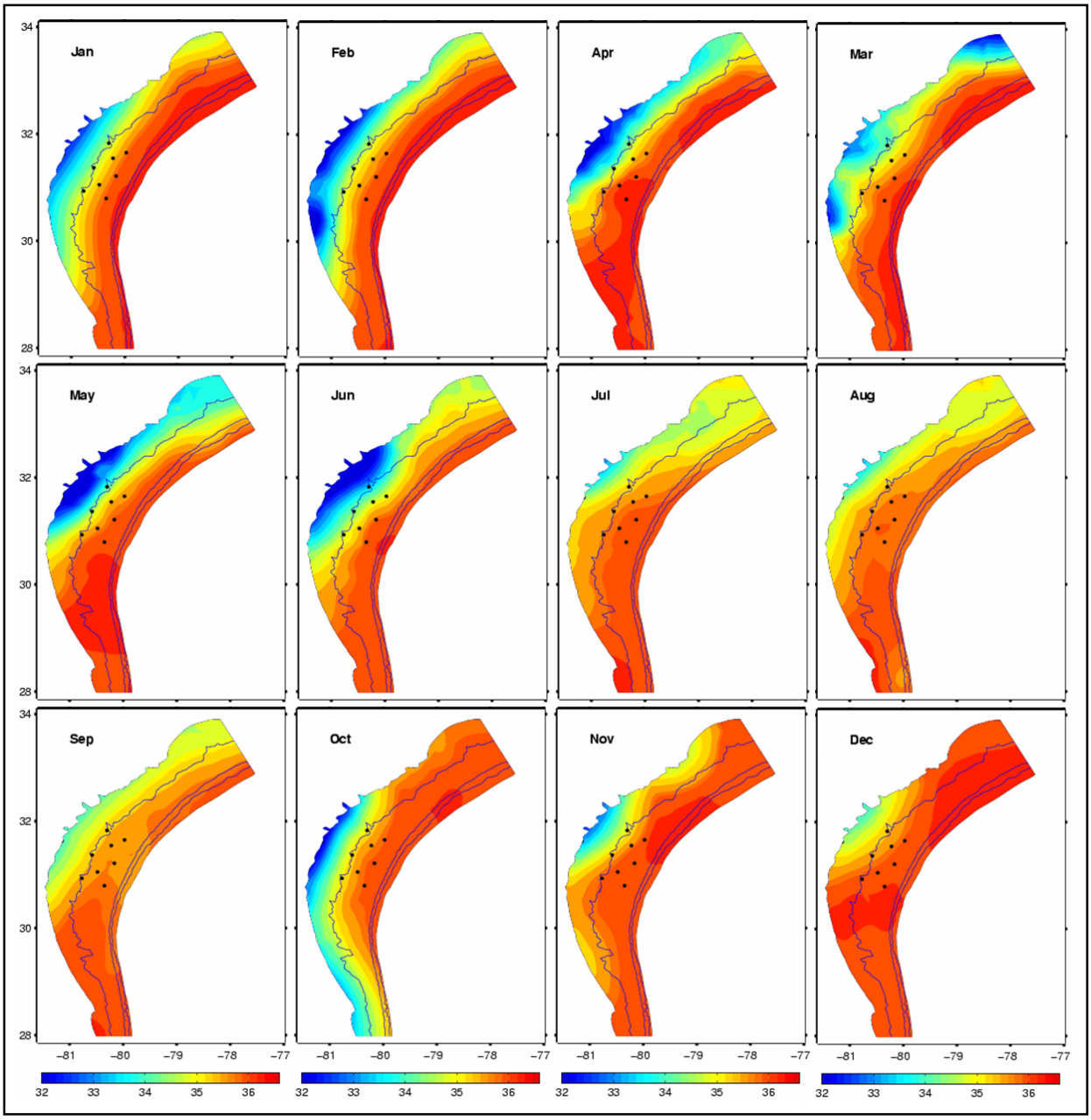

Figure 3.29 Monthly climatology of bottom water salinity from Blanton et al. (2003).

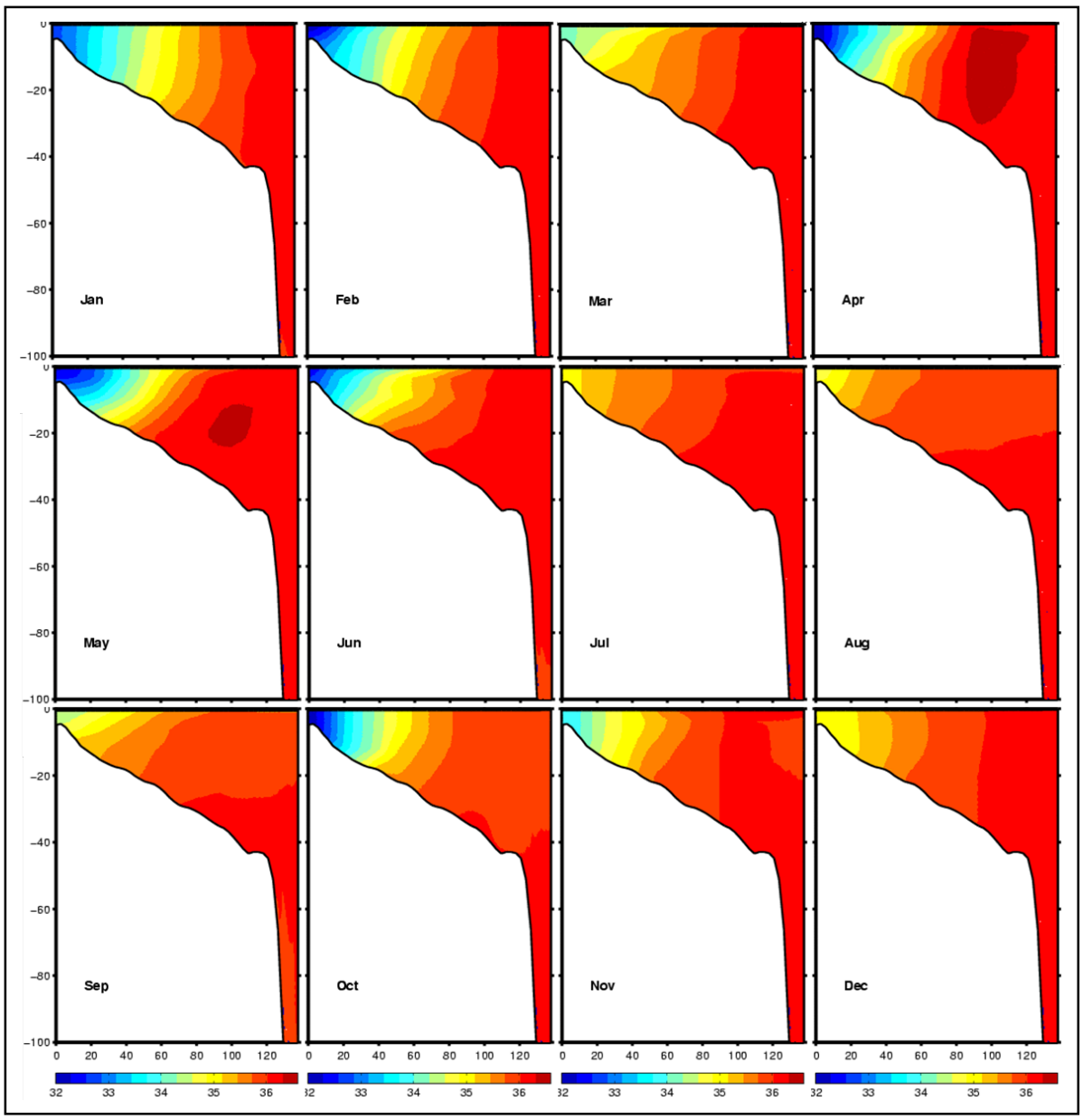

Figure 3.30 Numerical output of salinity structure along a transect off Georgia (for transect location see Figure 3.25). Data and figures from Blanton et al. (2003).

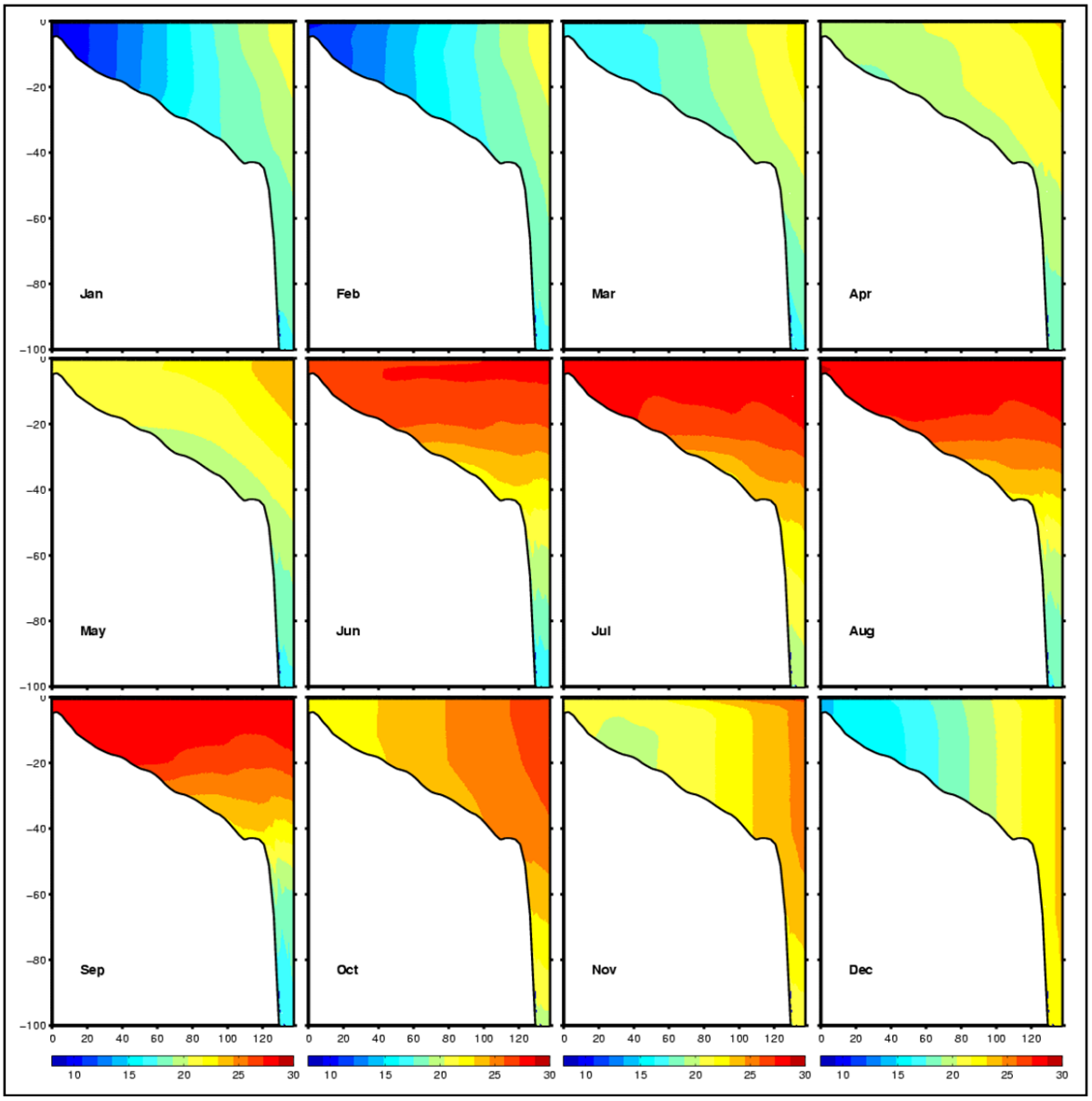

Figure 3.31 Numerical output of temperature structure along a transect off Georgia (for transect location see Figure 3-25). Data and figures from Blanton et al. (2003).

3.7 CIRCULATION DUE TO WIND AND DENSITY CLIMATOLOGY

3.7.1 Wind-Driven Flows

To assess the effects of wind forcing, Blanton et al. (2004) ran their 3-D model with the monthly wind stress fields alone. They found that the January downwelling winds have a large cross-shelf component in the northern regions of the South Atlantic Planning Area, turning more along-shelf toward the south. The along-shelf flow developed is equatorward (southward) and ranges from 0.05 m/s in the inner shelf to near zero on the widest part of the shelf. The Ekman-driven elevation setup is at a maximum along the Georgia coast (at about 31°N) reaching 0.025 m, and it drives a compensating offshore flow in the lower water column. This is a persistent feature along the length of the shelf; the cross-shore flow component decreases in intensity toward the north. In the vertical, the zero normal flow line is found to be at approximately mid-depth (35 m) along the entire shelf break.

April winds are significantly weaker and directed toward the north (poleward), resulting in a very weak wind-driven flow. Any flow developed is confined to the inner shelf where velocities are less than 0.02 m/s and there is effectively no response in sea-surface elevation.

In contrast, by July, the summer upwelling winds become stronger and a poleward along-shelf flow is developed, which is associated with a coastal set-down (i.e., reduction in surface elevation) which is maximum in the southern part of the South Atlantic Planning Area. The wintertime atmospheric pattern is re-established by October, during which the winds are along-shelf in the northern South Atlantic Planning Area and essentially onshore along the north Florida coast. The flow is equatorward at a speed of 0.025 m/s. Coastal elevations are highest in the southern area. In general, every time when there is a well-established along-shelf flow, the sea-surface elevation response generally follows the bathymetric contours. Furthermore, the highest gradient in elevation response is found along the north Florida coast, where the shelf is narrowest.

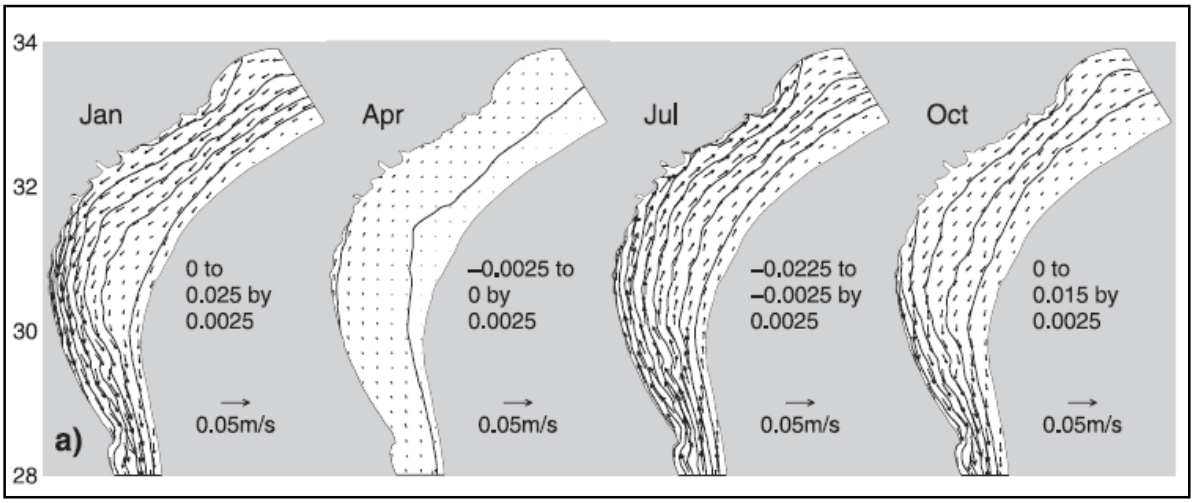

Figure 3.32 Surface elevation and depth-averaged velocity response of the South Atlantic Bight to the monthly wind fields from the model of Blanton et al. (2004). The elevation range and contour interval are given next to each month. Elevations nearest to zero are at the shelf break. (from Blanton et al., 2004).

3.7.2 Baroclinic Flows

In terms of baroclinically driven flow, the response of the model to the data-derived mass field obtained from the T-S seasonal patterns reveals the important effect of the Gulf Stream. The climatological signal of the jet fully dominates the circulation response in the southern portion of the shelf but it is significantly weaker than that of the wind forcing (Figure 3.33). In all seasons, the entire shelf flow is poleward, in inner- and middle-shelf speeds of 0.01-0.1 m/s. January flows are the strongest.

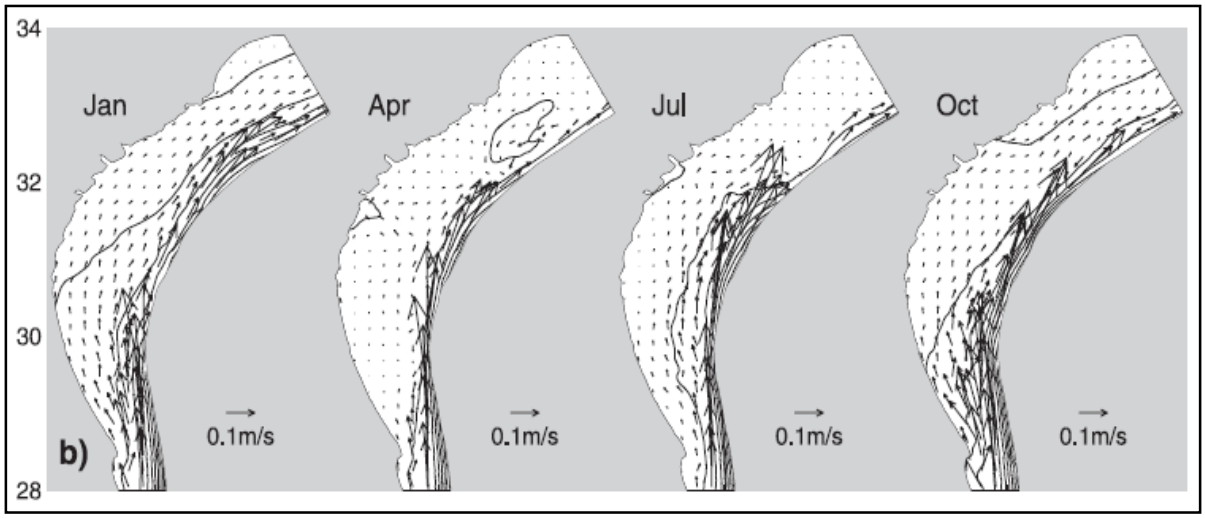

Figure 3.33 Surface elevation and depth-averaged velocity response of the South Atlantic Bight to the monthly salinity and temperature field (see Figures 3-28 to 3-31), as estimated by the model of Blanton et al. (2003). Elevation contours start at 0.025 m near the coast with a contour interval of 0.025 m. Largest elevations are at the shelf break, and the elevation at the northwest corner of the domain is set to 0 m for the density-driven solutions (from Blanton et al., 2003).

3.7.3 Combined Wind-Driven Baroclinic Flows

The combined (wind- plus density-driven flow) result indicates that during October and January there is net equatorward (southern) flow in the inner shelf, with limited if any net flow in the middle shelf (Figure 3.34). On the outer shelf, a net poleward (northward) flow is imposed by the Gulf Stream jet. During the summer, the northeastward-directed winds reinforce the mass driven flows resulting to a net shelf-wide poleward flow. By April, the net flow is very weak. In all cases, the effects of the Gulf Stream along the north Florida shelf appear to reach the middle shelf.

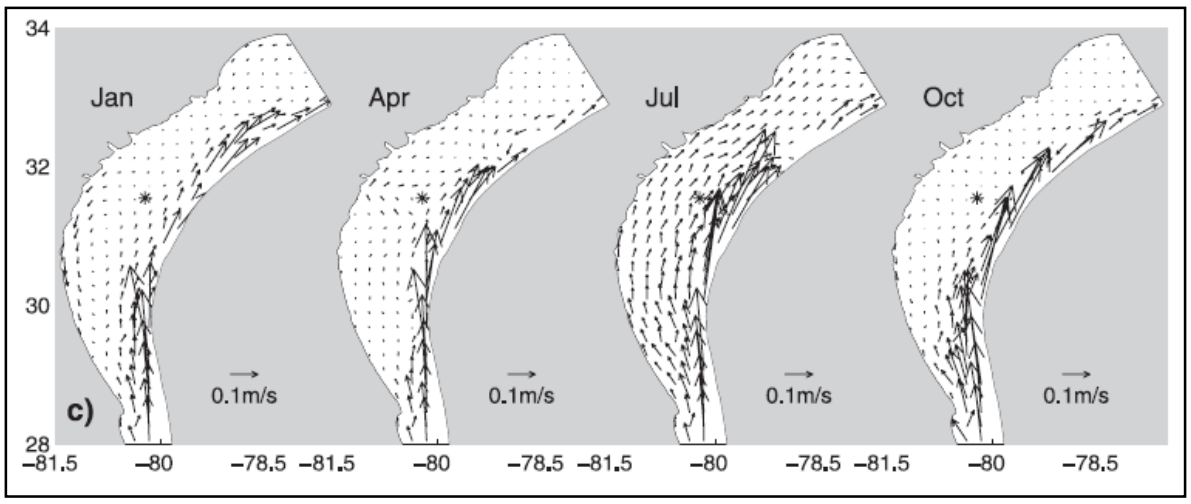

Figure 3.34 Depth-averaged velocity response of the South Atlantic Bight to the combined forcing of monthly and baroclinicity fields as estimated by the model of Blanton et al. (2003).

3.8 SYNOPTIC CIRCULATION

The general seasonal circulation patterns described in Section 3.6 represent long-term monthly averaged responses of the South Atlantic Planning Area shelf to climatic wind, temperature, and salinity forcing. These can be considered as the monthly averages; however, modulations on these averages are imposed at time scales of the order of hours (tidal forcing, Section 3.4) and days, in response to meandering and eddy production by the Gulf Stream and synoptic weather patterns. The former affect mainly the outer and middle shelf, while the latter dominate mainly the inner to middle shelf.

3.8.1 Gulf Stream Meandering and Cyclonic Eddies

As indicated by the in-situ observations and the numerical results of Blanton et al. (2004) shown in the previous section, the offshore oceanic environment of the South Atlantic Planning Area is highly influenced by the presence of the Gulf Stream. The stream is a highly energetic circulation feature that provides the connection between a variety of southeastern coastal oceanic environments extending from Louisiana to Florida in the Gulf of Mexico (where it exists as the Loop Current) and from Florida (called the Florida Current) to North Carolina along the east coast. This strong deep-ocean feature flows adjacent to the continental shelf of the southeast US, following the bathymetric contours along the continental slope; it strongly affects the wind-driven and baroclinic circulation discussed earlier. Processes associated with the Gulf Stream greatly modify the circulation patterns on the outer shelf both in the alongshore and cross-shore directions (Hamilton, 1987). The stream influence is also felt at the middle shelf; occasionally, this can be felt all the way to the inner shelf. This is more common in the southern part (off Florida) were the width of the shelf is very narrow (Santos et al., 1990), although lately there is some evidence that occasionally this might occur even in Long Bay, South Carolina (Voulgaris and Sanay, 2010; Sanger et al., 2010). The influences of the Gulf Stream are of particular importance because they provide an efficient avenue for the transport of nutrients, heat, and

marine organisms between the sub-regions of the coastal southeast US, but also contribute significantly to cross-shore fluxes of momentum, heat flux, and nutrients.

Given the high temperature of the Gulf Stream, thermal imagery obtained by satellites is the best way to identify processes related to the Gulf Stream on the South Atlantic Planning Area (Figure 3.35). These satellite images use the thermal signatures of the water mass as it flows out of the Gulf of Mexico through the Florida Straits. As the Gulf Stream moves northward, it closely follows the continental slope, except off South Carolina, where a ridge (Charleston Bump) deflects it offshore then it returns onshore again. Off Cape Hatteras, North Carolina the Gulf Stream leaves the coast and veers to the east across the Atlantic.

While the Gulf Stream in general follows the bathymetric contours along the shelf break, its surface manifestation is often characterized by the development of two distinct but interrelated features: meanders and frontal eddies. These have been the subject of numerous observations and studies over the last 30 years (e.g., Stumpf and Rao, 1975; Legeckis, 1975; 1979; Lee et al., 1981). These features have horizontal scales of 150–250 km in the alongshelf and 20–50 km in the cross-shelf directions. Meanders are wave-like movements of the Gulf Stream identified by troughs and crests. Troughs are defined the locations where the stream takes its most offshore location, usually further offshore the shelf break, while crests are the locations where the surface waters of the Gulf Stream move shoreward over the outer shelf.

Eddies usually spin off from the crest of the meander; a distinct spatial pattern is associated with these features so that the South Atlantic Planning Area is subdivided in two regions where eddy growth is common and two other areas where eddy dissipation is frequently observed. The eddy growth areas are located on the shelf break north of the Florida Straits (27^{o} to 30^{o} N latitude) and north of the Charleston Bump (32^{o} to 34^{o}N latitude). These meanders are generated due to a mixture of baroclining and barotropic instabilities (Miller and Lee, 1995a,b), and eddies associated with the trough of the meanders usually develop. These eddies propagate themselves downstream the direction of the Gulf Stream for a while and then dissipate, usually in the regions between 30^{o}N and 32^{o}N and 34^{o}N and 36^{o}N, respectively.

The southern eddy generation area is located just north of the Florida Straits. As soon as the Florida current exits the straits, the constraints posed by the morphology of the area cease and the shallow Bahama Bank falls off into the Blake Plateau. The tightly constrained Gulf Stream (Florida Current) relaxes and eddies start to grow rapidly reaching scales of the order of 100–-200 km in the downstream. It is important to note that these eddies are associated with offshore meanders of 30–50 km in size (Lee et al., 1981; Bane and Brooks, 1979; Lee and Atkinson, 1983).

In the second eddy generation area, just downstream of the Charleston Bump (Lee et al. 1991), eddies usually persist for 1 to 2 weeks, before dissipating or being overtaken by another meander. These types of events have been seen in thermal imagery, but have also been confirmed by in-situ measurements using inverted echo sounders near Savannah, GA (Li et al., 1985) and from an extensive current meter array extending over the area from Cape Canaveral,

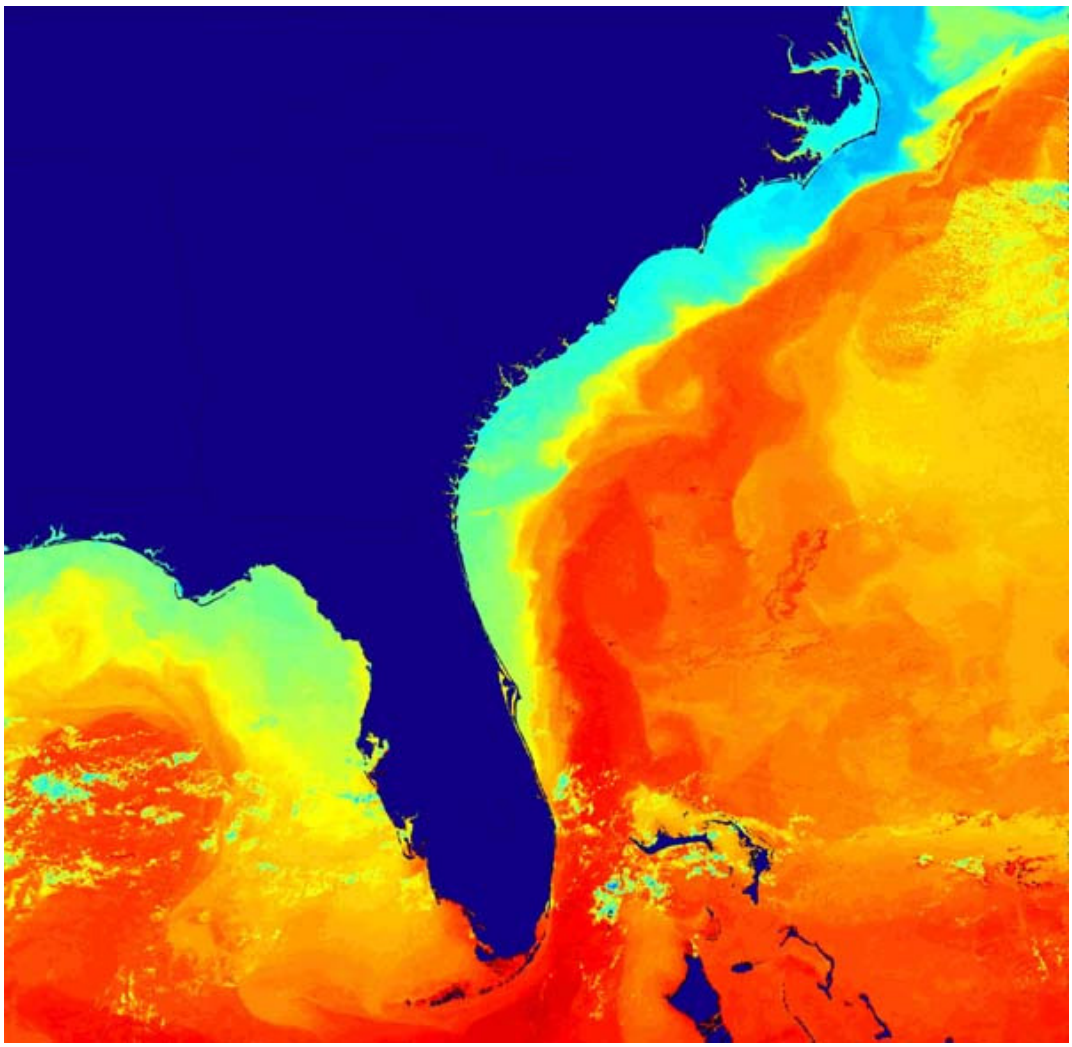

Figure 3.35 Synthetic satellite imagery of sea surface temperature showing the Gulf Stream from the Florida Straits in the south to Cape Hatteras in the north. A number of warm filaments on the shoreward side of the Gulf Stream can be seen as well a major deflection of the Gulf Stream to the east at the Charleston Bump (Sedberry, 2001).

Florida to Cape Romain, South Carolina (Lee and Atkinson, 1983). As Legeckis (1979) explained, the Charleston Bump deflects the Gulf Stream offshore to the east; further downstream the deflected stream turns onshore just off Long Bay, creating a semi-permanent feature known as the Charleston gyre, which is a cold, cyclonic eddy. Further downstream, a number of meanders occur with horizontal displacements of the order of 100 km and with a wave length of 100–200 km. These meanders exhibit themselves as northward-propagating waves with a mean speed of approximately 40 cm/s; they occur with a periodicity of the order of 2 days to 14 weeks (Legeckis, 1979; Bane and Brooks, 1979; Brooks and Bane, 1978; Bane et al., 1981; Olson et al., 1983). All the eddies and other perturbations and frontal instabilities, including

cyclonic cold-core eddies developed downstream of the Charleston Bump all the way to Cape Hatteras, North Carolina, are attributed to the Charleston Bump (Verity et al., 1993).

The three-dimensional hydrographic structure of a number of those cyclonic cold-core, frontal eddies has been reconstructed from observations off Onlsow Bay, North Carolina (Bane et al., 1981), and east of Jacksonville, Florida (Lee and Atkinson, 1983). These data describe a cyclonic geostrophic circulation around a cold core of water upwelled from beneath the primary current which is in agreement with satellite observations. In-situ measurements obtained with ADCPs confirm cyclonic circulation around the cold core of a loop current frontal eddy; similar results were reported from an analogous study in the South Atlantic Bight (Evans-Hamilton, 1987, cited in Miller and Lee, 1995a).

The available information about the density and velocity fields within an eddy is primarily from Chew et al. (1985), who used drogue trajectory data from the Florida Straits and hydrographic transects from Onslow Bay, North Carolina to make a composite of the internal structure of an eddy and its associated cold dome. Assuming quasi-geostrophic dynamics and making appropriate scaling arguments derived from the observations, Chew et al. (1985) showed that divergence of surface waters induces vertical motion within the cold dome, resulting in an upward-directed vertical velocity of the order of 0.10 cm/s at mid depth. Similar vertical velocities have been suggested by Osgood et al. (1987), who used moored velocity and temperature data from a site located just south of the Charleston Bump. They found that, at 350 m water depth and in the absence of meandering, mean vertical velocities were not present. However, during periods when meandering was occurring, the vertical velocities were greater than 0.25 cm/s. Following Chew et al. (1985), the eddy development starts at the meander crest, where a filament of warm water detaches and moves onshore. As the onshore flow in the lee of a meander crest overtakes the leading edge of the cold dome, upwelling is induced and the onshore flow decelerates. The opposite process occurs at the upstream end of the cold dome as the next meander crest approaches. Thus the meander and the cold dome move downstream in unison, and the water in the cold dome is continually replenished. This mechanism drives upwelling at the trough of the meander at the shelf edge and alters circulation patterns in the outer shelf.

Time series of moored current meter data (e.g., Brooks and Bane, 1981; Lee et al., 1981; Pietrafesa, 1983; Lee and Atkinson, 1983) also provide evidence of a cyclonic circulation around a cold core, although these data are of limited horizontal spatial resolution. However, the exact pattern of circulation within the warm filament is not fully resolved. The southern end of the warm filament is rarely observed to reconnect to the primary Gulf Stream front; therefore, a true ring-like eddy feature never develops. Instead, the warm filament remains to the west of the primary front at a distance comparable to the width of the surface expression of the upwelled cold core. Lee et al. (1981) have characterized the flow within the warm filament as being uniformly southward (Figure 3.36A) and presumably balanced by frictional dissipation, but Chew (1981) has suggested an anticyclonic circulation within the warm filament, which would return warm water to the north along the western side of the filament (Figure 3.36B). Lee and Atkinson (1983) reject Chew’s (1981) hypothesis based on the fact that they do not observe moving, warm, anticyclonic perturbations shoreward of the cold domes. On the other hand, Pietrafesa (1983), using a smaller set of data used by Lee and Atkinson (1983) and augmented by sea surface temperature data from a particular frontal eddy, supports Chew's (1981) description.

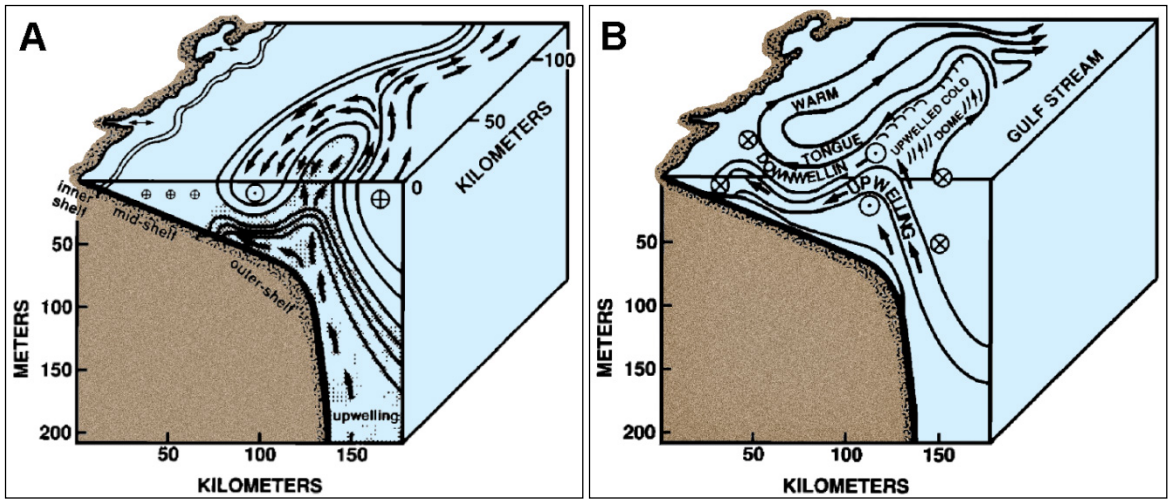

Figure 3.36 Conceptual models of Gulf Stream meander and eddy flow structure modified after (a) Lee et al. (1981) and (b) Chew (1981), respectively.

Numerical investigations on the subject by Miller and Lee (1995a, 1995b) were inconclusive on the exact structure and mechanisms. Both scenarios were found to be plausible because the meandering and eddy development is a complex instability process produced by a combination of barotropic and baroclinic instability processes.

The momentum fluxes computed from moored current meter data by Brooks and Bane (1981) for the part of the South Atlantic Bight north of the Charleston Bump indicate a transfer of kinetic energy from the meanders to the mean stream. Hood and Bane (1983) hypothesize the following scenario: small-amplitude meanders slowly extract energy from the mean flow as they propagate northward from the Florida Straits to the Charleston Bump through a weak baroclinic instability process; the decrease in bottom slope beneath the path of the Gulf Stream immediately downstream of the Bump creates a tendency for the stream to become strongly baroclinically unstable; the bottom slope again increases north of Cape Fear, and the baroclinic instability process is effectively shut down. Lee et al. (1991) generally support the Hood and Bane (1983) scenario, with the exception of the region immediately upstream of the Charleston Bump; they argue that the flow there appears to be baroclinically stable.

Lee and Atkinson (1983) noted the offshore energy fluxes for the region south of the Charleston Bump and concluded that the source of instability must lie south of their primary study area (i.e., south of about 29^{o}N latitude). They suggested that the meander/frontal eddy formation region may be upstream of Cape Canaveral, where the shelf and slope widen as the Gulf Stream emerges from the Florida Straits. However, later numerical results by Xie et al. (2007) have shown that the development of the Charleston meander that gives rise to the gyre is mainly the product of local generation by the Charleston Bump. Its stability is attributed to a combination of the high curvature of the general bathymetric contours along the shelf and the existence of the bump as a morphological disturbance.

3.8.2 Circulation Patterns on the Shelf Break/Outer Shelf

Along the shelf break, the development of cyclonic, cold-core Gulf Stream frontal eddies that occur on the shoreward end of the Gulf Stream is responsible for the majority of the low-frequency oscillations observed in circulation patterns. These oscillations are superimposed on the climatically-driven circulation described in Section 3.6. Lee and Atkinson (1983) obtained low-frequency current and temperature time series from the outer shelf between Cape Canaveral, Florida, and Cape Romain, South Carolina. These observations were combined with shipboard hydrographic data, satellite Advanced Very High Resolution Radiometer (AVHRR), coastal and buoy winds, and coastal sea level during a period of five months (February to June 1980). They found that these eddies travel northwards at speeds of 50 to 70 cm/s, that their occurrence has a periodicity of 5–9 days, and their length scale is of the order of 100 km. In the cold core, upwelling velocities of about 1–2 cm/s provide a major source of cold nitrate-rich waters into the euphotic zone that dominate new production of the continental shelf along the southeast US, supporting 4/3 x 10^{12} g C per year (Lee et al., 1991). This upwelled water can be transferred shoreward under upwelling wind conditions. The adjective scales of this shoreward, near-bed transfer of material depend on the precondition of the shelf through stratification either by freshwater (spring condition), heat flux (summer conditions), or a combination of both.

In addition to those poleward-propagating, cyclonic cold-core eddies, described earlier, the development of coastal observing systems and the collection of surface current data using high-frequency radar observations (Shay et al., 2008) has led to the identification of a new class of eddy circulation that appears to be tidally induced. Savidge et al. (2010) used ground based HF radar data to identify sequences of small, short-lived cyclonic eddies along the shoreward edge of the stream that spin up as the local tide turns along-shelf, anti-parallel to the Gulf Stream. In contrast to the cyclonic cold-core eddies, these features propagate toward the south along the shelf edge, sometimes progressing shoreward before dissipating 1–3 hours later. They are distinctly different from Gulf Stream meander eddies, which propagate northward and their swirl velocities can be as large as the local M_2 tidal velocities (40–50 cm/s). These eddies appear to occur due to high shear at the shoreward edge of the Gulf Stream. These short-lived cyclonic eddies contribute to shoreward momentum fluxes, in a similar way as the larger cyclonic eddies defining a link between Gulf Stream and outer shelf subtidal variability.

To date, these eddies have been observed off the Georgia coast, where the tidal currents attain their maximum value. This might be due to the fact that HF radar measurements capable to resolve these types of eddies was limited to the South Carolina/Georgia border, however , the fact the tidal amplitudes are smaller to the north and south suggests that this process might be limited in the central part of the region. More recently and since February 2012 a similar HF radar system has been installed on the northern part of South Carolina (Long Bay) by the University fo South Carolina data from which will enable assessment of the validity of such an assumption.

3.8.3 Middle Shelf Circulation

Subtidal flow variability at the 40-m isobath is influenced by both a response to Gulf Stream and wind forcing driven by the synoptic weather fronts described in Section 2.6. Barotropic along-shelf current oscillations are coherent with the local winds and sea level at periods of 3–4 and 10–12 days, respectively. This coherence extends over along-shelf scales of 400 km with small

phase lags, which suggests a nearly simultaneous frictional equilibrium response to coherent wind-induced sea level slopes. Time lags between wind and currents depend on water depth, but vary between 6 and 10 hours (Santos et al., 1990). The northern Florida middle shelf shows greater influence by the Gulf Stream (Hamilton, 1987) than that of off northern Georgia and at significant shorter periods of 4 days, compared to the 12-day periods reported for off Georgia.

A combination of synoptic weather and climatologically driven processes can contribute to the development of unusual flow patterns that can penetrate the middle shelf and impact the whole South Atlantic Planning Area. An example of this process is the unusually cold seawater temperatures that were observed along much of the US eastern seaboard during the summer of 2003 (Aretxabaleta et al., 2006; 2007). During that event, extremely high precipitation and river discharges during spring produced strong salinity stratification over the whole shelf. These conditions were combined with anomalously intense and persistent upwelling-favorable winds that were present from May until August. An analysis wind forcing data from both in-situ buoy measurements and North American Regional Reanalysis, by Hyun and He (2010), highlighted that the upwelling-favorable winds in 2003 were the strongest and most persistent over the period 2000-2008. These winds resulted in an intense upwelling and subsurface shoreward penetration of cold water with characteristics corresponding to that of the lower part of the Gulf Stream water column. The upwelled water entered the region in the outer shelf off St. Augustine, Florida and it contributed to the preservation of the stratified conditions throughout the summer of 2003 creating temperature gradients much higher (5–7^{o}C) than those expected by the climatological analysis of the region. This maintenance of stratification and the upwelling winds contributed to the expansion of the cold water over the region. Similar events were identified in the inner shelf Long Bay in 2004 (Sanger et al., 2010; Voulgaris and Sanay, 2010) and 2009 (Voulgaris and Sanay, 2010, Sanger et al, 2012), that led to the development of short-lived hypoxic conditions in the nearshore waters of Myrtle Beach, South Carolina at the center of Long Bay.

3.8.4 Circulation of the Inner Shelf

Although a significant amount of work has been carried out on subtidal circulation on the South Atlantic Planning Area, it has focused primarily on the large-scale shelf response to wind and buoyancy forcing as well as the influence of the Gulf Stream (Blanton and Atkinson, 1983; Lee and Atkinson, 1983; Lee et al., 1989; review by Atkinson and Menzel, 1985; Pietrafesa et al., 1985; Lee et al., 1985; Boicourt et al., 1998). All of these studies were based mainly on measurements acquired from middle- and outer-shelf locations and were limited to the Georgia Bight (Kundu et al., 1981) where freshwater discharge from coastal rivers and estuaries is important. This led to the general conclusion that the local wind forcing and buoyancy are the most influential factors controlling inner shelf dynamics in the South Atlantic Planning Area (e.g., Boicourt et al., 1998). It was these observations that showed the existence of a freshwater frontal zone that persists within 10–20 km of the coast for most of the year, which forms a dynamic barrier influencing the transport of low-salinity water from the inner shelf farther offshore (Blanton, 1981; Atkinson et al., 1983; Blanton and Atkinson, 1983). During southwesterly winds, the low-salinity zone is well formed along the coast, while under northward wind conditions, surface waters are transported across the shelf ejecting low-salinity water from nearshore regions and replacing it with higher salinity middle-shelf water from below.

Actual current observations used to characterize inner-shelf currents elsewhere than the Georgia Bight have been limited to one or two current stations (Schwing et al., 1983; Lee et al., 1989). For example, Schwing et al. (1983) examined summertime circulation offshore southern Long Bay near North Inlet, South Carolina, and suggested that the buoyancy dynamics identified along the Georgia Bight inner shelf are not as important for the inner shelf of the northern portion of South Carolina.

Gutierrez et al. (2006) provided some insights of circulation in the inner shelf through the analysis of data from current meters in water depths of 6–12 m. In the spring and under northeastward winds (upwelling favorable), a two-layered flow was observed at depths greater than 10 m; closer to the shore, the currents are aligned with the wind. The two-layered flow is attributed to the presence of stratification, which has been observed under similar conditions in the South Atlantic Bight. When the wind stress is southwestward (downwelling favorable) and exceeds 0.1 N/m^2, vertical mixing usually occurs and destroys any two-layered flow pattern; currents are then directed alongshore with the wind and throughout the water column. In the fall, near-bed flows close to the shore (water depth <7 m) were often reduced, compared with those measured farther offshore under southwestward winds. Using simple depth-averaged, alongshore momentum balance analysis, Gutierrez et al. (2006) showed that the alongshore pressure gradient can approach and even exceed the magnitude of the alongshore wind stress at the same time that nearshore alongshore current opposes the wind stress, while alongshore currents farther offshore follow the wind. It was suggested that wind stress reduction close to shore can allow for the alongshore pressure gradient alone to drive the flow against the wind.

On the other hand, Sanay et al. (2008) showed that similar flow reversals can be the result of detachment and subsequent downstream advection of mesoscale eddies/disturbances generated at the upstream Cape Fear during a downwelling event under inertial-dominated conditions that are more likely to occur during stratified conditions in the summer. During the summer, the inner shelf, at least in the northern part, is thermally stratified, and this can create upwelling flows all the way into the inner shelf. Using a numerical model, Voulgaris and Sanay (2010) showed that the response of a thermally stratified inner-shelf to constant upwelling favorable wind forcing was the formation of a coastal front and associated jet that moves offshore with time. Inshore of the front, the water column is homogeneous, while offshore of the front Ekman transport takes place, carrying middle shelf cold water toward the coast at the bottom layer. The numerical experiments showed that under typical summer conditions cross-shore transport of colder and nutrient rich water to the nearshore can occur as a combination of oscillatory upwelling wind conditions and thermal stratification by solar radiation. The cold-water intrusions help to keep the water column stratified, even under strong wind stress, a condition that enhances the Ekman transport and then vertical stratification which may lead to low-oxygen events.

Additional hydrodynamic data in the inner shelf of Long Bay were collected during the period October 2003 to April 2004 at eight sites in the vicinity of the shore-detached shoal offshore of Myrtle Beach. The deployment sites were at water depths of 7–10 m. This study involved the deployment of bottom-mounted instrumented tripods collecting data on waves, currents, bed morphology (ripples), and suspended-sediment concentrations. These data were augmented by wind measurements from nearby stations and were analyzed to assess sediment transport processes on the inner continental shelf (Warner et al., 2012). Details of the site locations,

equipment specifications, the data, and data processing techniques are presented in Sullivan et al. (2006); the analysis of the data is still in progress.

3.9 POTENTIAL IMPACTS OF OCS DEVELOPMENT ON PHYSICAL OCEANOGRAPHY

3.9.1 Oil and Gas Exploration and Development

Any potential impacts of oil and gas exploration and development activities on physical oceanography are expected to be mainly due to the erection of offshore infrastructure, including offshore rigs and pipelines. Such structures usually consist of individual elements (i.e., piles, structural elements, etc.) used to construct them. These elements interact with the flow, and a clear definition of flow pathways and dynamics around the elements is required. In general terms, as the moving particles of water interact with a structure, through frictional effects, the flow loses a small amount of energy. This energy loss is manifested through a local increase of turbulence and a reduction in mean flow strength. Theoretical developments of flow moving past a cylinder provide the basic understanding of flow and individual structure element interaction. The process can be found in any fluid dynamic textbook, and it is briefly described in the next paragraph.

As the water approaches the cylinder, fluid viscosity slows down its particles in the vicinity to the structure and forms a thin boundary layer. The flow velocity is zero at the surface to satisfy the no-slip boundary condition. Depending on the development of local pressure gradients, the boundary layer might be attached all the way around the structure and, in this case, no flow retardation is experienced. However, under certain conditions, pressure can increase in the direction of the flow, and the boundary layer can start separating from the structure surface. This flow separation leads to the creation of a highly turbulent region behind the cylinder called the "wake." The mean velocity in the wake region is reduced, and even reverses, behind the structure element. Sometimes the separated boundary layer forms a free shear layer which is highly unstable and starts oscillating; it generates vortices that can detach at some distance and propagate downstream with the mean flow. This process is called "vortex shedding," and it occurs at a discrete frequency (f) that is function of the Reynolds number. For high Reynolds numbers (>1,000) the frequency of the vortex shedding is estimated by $f = St \cdot V/D$, where St is the Strouhal number (=0.21), D is the diameter of the cylinder, and V the free stream current speed. This process can produce an oscillatory loading on the cylinder that can induce significant vibrations, especially if the frequency f matches the resonance of the structure.

The principles outlined above have been further investigated for flows around oil related infrastructures by Lighthill (1979; 1986) and Rainey (1989) amongst others. These and the majority of other studies focus on potential flow around cylinders that protrudes through the sea surface, as is the case with oil platforms, but the emphasis has been on force loading on the structure as it relates to stability and safety issues rather than as it relates to the effects of the structures on the physical environment.

McIver (2002) presented a review of theories developed on wave interaction with arrays of structures. The basic consideration has been that when there are numerous columns (piles) in the

water (e.g., legs of a platform), each pile scatters ocean waves in all directions. An array of piles presents the potential of constructive interference of the incoming and scattered waves and the development of higher waves in the region enclosed by the array of piles. More recently, and motivated by potential applications for offshore airports supported on vertical piles, Li and Mei (2007) examined the potential of wave diffraction by a periodic array of circular cylinders. These can be either elements of a large oil platform or piles of wind turbines in a wind farm. They studied the simple case of normal incidence on a rectangular array spaced at distances comparable to the incident wave wavelengths and with a diameter much smaller that the wavelength. They found that scattering at Bragg resonance can be very strong. Although this theory provides some insights on the spacing of cylinders in the marine environment, no direct field data exist to confirm this scattering of waves at Bragg frequencies.

There is a plethora of physical mechanisms by which waves can interact with structures; however, these interactions can alter the local wave field. Overall, these changes are rather local. They are limited to distances a few widths of the structure, thus are not be expected to cause any long-term impact on physical oceanographic conditions.

3.9.2 Sand and Gravel Extraction

Sand and gravel extraction could lead to changes in bed composition that, in turn, could adversely impact biota (e.g., Birklund and Wijsman, 2005; Le Bot et al., 2010; also see Chapter 6 Benthic Resources and Chapter 7 Fish and Fish Habitat). Changes in bed composition can cause changes in the physical roughness of the sea bed that might enhance or decrease the extent of the benthic boundary layer and the intensity of the turbulence levels encountered within. The impact on physical oceanographic processes can be adverse only if these activities cause changes in bathymetry. An extensive bibliographic reference index covering this issue, including international publications from 1993 to 2009, has been developed as part of a project titled "SAnD EXtraction in the Portuguese continental shelf: impacts and morphodynamic evolution. Van Rijn et al. (2005) reports on the results of SANDPIT, an EU-funded project. Overall, the ratio of bathymetric change (dh) over the mean water depth (h) is an important parameter that could help identify the importance of a bathymetric change. The larger this ratio, the larger is the anticipated potential impact. This impact is expected to be more severe in the nearshore due to changes in wave propagation, while no changes in circulation patterns are anticipated. Maa et al. (2004), in a case study in Delaware, concluded that the effect on storm surge and oceanic (including tidal) circulation was minimal. These conclusions were drawn using numerical modeling (SLOSH and POM, respectively) and for specific dimensions of a borrow pit. However, changes in circulation might occur if aggregate extraction activities take place over ebb tidal deltas very close to the shoreline or over shoals (e.g., Dibjania et al., 2010, 2011) where a veering in the mean current direction might occur. These offshore shoals are predominantly relict ebb tidal deltas or shore-treat massifs located offshore and present important sources of sand material in the South Atlantic Planning Area. The effects of such activities will depend on the depth of the extraction and the changes in the previously defined ratio dh/h.

To date, most of the concern has focused on changes in wave propagation (refraction/ diffraction) over pits generated by aggregate extraction. Demir et al. (2004) used numerical modeling of wave propagation over simple rectangular borrow pit geometries. They concluded that wave propagation alterations are mainly due to changes in wave-refraction patterns, while

wave diffraction did not appear to be as important. Similar results were obtained from the SANPIT project (Van Rijn et al., 2005). It is self-evident from wave-propagation theory that the effect of an aggregate extraction pit will be highly dependent on the water depth of the pit. If the water depth is greater than half the wavelength of the waves present in an area this effect will be insignificant. Given that in the South Atlantic Planning Area, most of the waves are wind-generated with swells being present only for short periods of time associated with the passage of tropical storms and hurricanes, then using waves with periods of 6, 7, and 8 s, we can estimate that any pit development in water depths greater than 56, 76, and 100 m, respectively, will have no effect in wave propagation through refraction and/or diffraction.

At shallower water depths, wave propagation is affected as wave speed is affected by water depth. This effect is exhibited mainly in the nearshore as the development of areas of wave divergence and convergence, which correspond to areas with decreased and increased wave heights, respectively. The latter areas are usually associated with higher mean sea surface elevations (i.e., wave setup) than are the former. This could potentially generate alongshore pressure gradients that can drive alongshore flows from the areas of wave convergence to areas of wave divergence. Demir et al. (2004) suggested that these effects are insignificant when the depth of the pit is small in relation to the water depth. A consequence of the wave divergence/convergence at the coastline, due to a change in wave refraction, is the development of erosion on the lee sides of the pit and accretion in a location between the two erosional locations.

Although such effects can be important, the methodology exists for studies to accurate predict the potential impact. Work et al. (2004) showed that for Folly Beach, South Carolina, a specific pit located some 5 km offshore the island and on the south end will have no significant effects on wave propagation and, consequently, on coastal erosion. Off Virginia, similar results were reported by Maa and Hobbs (1998) who assumed extraction from a shoal located at 12 m of water with its crest at 9 m of water depth. Maa et al. (2004) suggested the potential for adverse impacts to the nearshore for Maryland and Delaware if sand extraction from shoals results in a substantial reduction in their height. The effect was insignificant for low rates of extraction but was potentially severe when the cumulative extraction effect led to significant change of the shoal profiles.

Overall, the effect of sand gravel extraction may be severe only if such activity generates substantial changes on the ratio dh/h. Work et al. (2004) presented a methodology with which such effect can be predicted through the application of wave modeling coupled with a circulation model because the latter also affects wave propagation. However, their approach included only a one-way coupling (i.e., currents affecting wave propagation only). Dibjarna and Nairn, (2010) followed a similar modeling approach using a depth-integrated flow model. However, approaches using two-way coupling (waves-currents and currents-waves) and circulation models that resolve the flow close to the bottom boundary are better suited (e.g., Kumar et al., 2011) as these account for the effects of the waves on the currents and better simulate flows near the bed where the majority of the sediment transport takes place. These types of models are available in the public domain (Kumar et al., 2012), and studies using 3-D wave-current interaction models, such as that described in Kumar et al. (2012), with sediment transport capabilities are underway under BOEM funding (John Ramsey, Applied Coastal Research and Engineering, Inc., and

James Kirby University of Delaware, pers. comm.). These efforts will enhance our understanding of flow modification by sand extraction; they should be used as guidelines before permitting sand and gravel extraction. Furthermore, some projects with complicated morphology might merit their own 3-D numerical study before sand and gravel extraction is permitted.

3.9.3 Renewable Energy Development

Potential renewable energy harvesting solutions in the marine environment consist of the deployment of (1) wind turbines and the development of offshore wind farms, (2) wave energy converter (WEC) devices, and (3) tidal energy capturing devices. Currently, the deployment of wind turbines is the most readily available technology; there are successful applications throughout the world. WEC devices are currently experimental; tidal-energy projects are limited to very few locations with extremely high tidal ranges, although active research is being pursued to develop devices for operation in areas with relatively weaker tidal currents. Given the mild wave climate of the South Atlantic Planning Area and the limited tidal range, these two options are not deemed suitable at present for immediate deployment. The available technology favors the development of wind farms aiming at harvesting wind energy.

Overall, the deployment of WEC devices will lead to the extraction of wave energy (potential and kinetic) from the wave field. Because wave energy is proportional to the square of wave height, any energy extraction by WEC devices will lead to a reduction in wave height and create a wave shadow behind the WEC. However, depending on type of device, the number of devices deployed, and their relative distances (i.e., density of deployment), the amount of the energy captured and, subsequently, the wave reduction will be variable. All of the above characteristics can be parameterized as a transmission coefficient (Millar et al., 2007) with 1 indicating full transmission (small efficiency of WEC devices) and 0 indicating maximum harvesting of wave energy. This transmission coefficient depends on type and length of individual WEC and distance between multiple WECs within a WEC farm.

Millar et al. (2007) used a wave-propagation model to estimate changes in wave field for a hypothetical WEC farm development some 20 km off the coast of Cornwall, UK. Their study used wave incident conditions typical for the study site propagating toward the shoreline. Their results suggested that wave conditions behind the WEC farm would be altered and that the shoreline wave climate would be affected. However, they concluded that the magnitude of effects decreases linearly as wave energy transmitted increases. Their final results indicated that at probable wave energy transmission levels (based on available WEC technologies), the predicted changes in shoreline wave climate would be small.

Due to the width of the South Atlantic Planning Area continental shelf, waves are dissipating a large amount of their energy before reaching the shoreline. Thus any potential deployment of WEC devices is more likely to occur in the outer shelf where wave energy attains its highest level. At the same time, because the waves in this region are wind generated with no significant swell present, the directional characteristics of the waves are defined by the wind climate. The winds in the region are aligned with the coastline (see Section 3.2) and, as such, the offshore waves propagate mainly parallel to the coastline. This suggests that any wave shadowing due to WEC devices as predicted by the work of Millar et al. (2007) would occur in a direction parallel to the coastline and the effects would not be significant in the shoreline. However, a reduction of

wave energy in the lee side of WEC devices will potentially result in reduction of wave-induced mixing in the upper ocean surface contributing to the potential for increased thermal stratification in the lee of the WEC installation.

For the case of wind farms, the same basic theoretical considerations explained in Section 3.9.1 apply here. However, the installation of wind farms requires a spacing that it is much larger than the spacing for piles assumed in the case of oil platforms. On the other hand, the lateral extent (foot print) of a wind farm installation is larger than that of the structure elements of an oil platform.

The effect of the wind farms on circulation is expected to be local and characterized by a reduction of the mean flow immediately downstream the individual pile of the wind turbine (velocity defect region). In the same area, the development of vortices and vortex shedding would cause a local increase in turbulence and local water mixing. It should be noted that since the piles extend throughout the water column, the mixing would be more intense in the horizontal dimension while enhancement in vertical mixing would be minimal. The effect of flow reduction and vortex shading would extend no more than 10 to 20 times the diameter of the pile. However, in case of a wind farm array, the cumulative effect might lead to the development of a region of the ocean (within the vicinity of the farm) that has reduced mean flows and increased turbulence levels which would affect local stratification levels.

In terms of wave propagation, the theoretical concepts described earlier for oil platforms apply. Some additional insights have been provided by a study commissioned by the Center for Environment Fisheries and Aquaculture Science in the United Kingdom (CEFAS, 2005). That study investigated the effects of wind farm installation in coastal regions by assessing its effect on the wave field. The study used in-situ measurements and modeling techniques and considered an ideal array of wind farm monopoles, as well as the realistic conditions of the Scroby Sands wind farm field in East Anglia, UK. This wind farm is located over offshore sandy shoals with a water depth at high tide of ~3 m. The possibility of such a wind farm in the South Atlantic Planning Area is not realistic because such water depths are very close to the shoreline. However, as part of the same study (see Li, 2003), numerical experiments of wave propagation included wave refraction, diffraction and scattering effects. The experiment assumed a flat seabed bathymetry with three cases of mean depth of 2, 6, and 10 m and with no shore-perpendicular change in water depth. This assumption of constant water depth allowed clear identification of the effect of the wind farm in wave propagation, because the constant bathymetry eliminates processes of depth-induced wave shoaling and refraction. The coastline was set to a distance some 2.4 km from the ideal wind farm. The farm was simulated by an array of 10 x 6 individual monopoles with a diameter of 4.2 m. The long axis of the array was aligned parallel to the coastline, and the spacing between the monopoles was set at 250 m.

Three wave conditions corresponding to the 1, 10, and 50 year return wave height and period were used for a variety of directions. Inshore of the monopole array, wave diffraction was found to be the sole mechanism responsible for changes in wave patterns. Incident waves approaching perpendicular to the long dimension of the array experienced a reduction in height less than that experienced by waves approaching parallel to the long dimension of the array. These results suggest that the width of any wind farm array is proportional to the wave energy reduction

caused. Wave-interference and diffraction patterns were found to be most apparent for waves approaching the array diagonally. The wave height reduction (shadowing) zones were characterized by a wave height reduction of up to 5% and extending 5 to 6 turbine spacing lengths. It is worth noting that the effect of wave diffraction was more important for the deep-water (10 m) simulations although the wave reduction was only 3% in this case.

The above results indicate that changes in wave climate would be minimal and the impact on the coastal zone would be a slight reduction up to 5% of the wave height, depending on the array's distance from the coastline. Although a reduction in wave height intuitively suggests less wave forcing attacking the nearshore and potentially less wave-induced erosion, this might be misleading because the conditions over a larger region should be examined. This is important because wave energy reduction that is concentrated on a stretch of the coastline might be responsible for the generation of gradients in alongshore wave height in the nearshore. These might drive alongshore flows associated with pressure gradients induced by lateral differences in wave height. For example, smaller waves on the lee side of a wind farm installation can create lower wave set-up and subsequently a lower sea surface elevation than adjacent areas that are not affected by the wind farm. This can potentially create a pressure gradient that would drive alongshore flows toward the lee side of the wind farm with the reduced wave heights. This could have some implications on nearshore circulation and transport of material.

3.10 Summary and Data Gaps in the State of Physical Oceanography and Air-Sea Interactions Knowledge with Regard OCS Development

Overall, the physical oceanography knowledge is well developed in terms of climatology, especially in the outer and middle shelf. Some additional work might be required in the nearshore (inner shelf) where coastline irregularities disrupt large-scale oceanographic patterns through the development of additional pressure gradients. Also, the temporal variability of processes can be better developed through the coverage of the region with HF radars that can provide high temporal and spatial coverage and reveal mesoscale eddies like those identified by HF Radar and described in Savidge et al. (2010). These are smaller eddies that spin up at the M_2 tidal frequency; their identification has been limited offshore Georgia. It is not known if these exist all along the area; only HF Radar type coverage can reveal this.

The installation of wind farms will require the development of specific studies that can reveal if the slightest modification of the wave patterns in the lee side will have any significant effect in driving circulation patterns. Currently, this can be achieved only by using numerical models that include two-way wave and current interaction and that fully resolve the wave-inducing forcing. However, the development of methodologies for wave measurements with high spatial and temporal resolution using phased array HF radar systems (see Haus et al., 2010) is promising for examining the effects of wind farms on wave propagation.

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CHAPTER 4: CHEMICAL OCEANOGRAPHY

4.1 INTRODUCTION

Before the work conducted as a part of the South Atlantic Benchmark Program, OCS Environmental Studies (Texas Instruments, Inc., 1979), very few studies addressed the chemistry of the US South Atlantic coastal and shelf system in a way that allowed an overview of distributions, concentrations, and transport pathways of materials in this region. Even the results of this project were limited by the analytical state of the art for many substances (metal, nutrients, and organic compounds) and the lack of sufficient coverage in time and space. Since the Texas Instruments study, considerably more research has been conducted in the region. This new and ongoing research provides more spatial and temporal coverage and addresses processes, particularly inputs, and, in a few cases, provides data from which temporal trends can be assessed.

The foundation of much of the present knowledge about the chemistry of the South Atlantic Planning Area (North Carolina/South Carolina border at 34ºN to Palm Bay, Florida, at 28ºN) is in research sponsored by the US DOE between 1977 and 1991. This work has been complimented by a number of additional research projects, sponsored by the National Science Foundation, US Environmental Protection Agency (USEPA), NOAA, and others, which addressed specific processes or components of the system. However, the DOE-supported research was the major interdisciplinary, multi-institute project to be initiated to address shelf processes. An exhaustive review of every paper and report addressing the chemistry of the study area is not the intent of this section. The aim is rather to review important research that provides a summary of the state of knowledge from which a synthesis of the processes which control/influence the chemistry of the South Atlantic Planning Area is developed.

Coastal ocean margins are regions of rapid biogeochemical processing and transformation of materials at the interface between land and the oceans. As Martin and Windom (1991) point out, ocean margins are where the major portion of continental detritus is delivered and processed, whereby it is removed, transformed, and/or delivered to the ocean. For ocean margins dominated by continental shelves, the residence times of transporting media (i.e., water, particles) are longer and, therefore, they act as efficient filters of material transported from the continents to the ocean.

In this section, the chemistry of the South Atlantic Planning Area is reviewed with a focus on transport pathways. Emphasis is on reviewing existing knowledge of the processes that control concentrations and transformations in the various compartments (air, water, sediments, and biota) of the system and their interactions in time and space. Much of this will be controlled by physical and biological processes, covered in other chapters in more detail, which will be considered only as required to describe how they exert control on the chemistry of this area.

Menzel et al. (1993) divide the South Atlantic Planning Area into three compartments according to depth: inner shelf (0–20 meters [m]), middle shelf (20–40 m) and outer shelf (40–60 m). While this may be useful for discussing biological and physical processes, because the chemistry of the study area is more of a continuum, the more important focus should be at the interfaces. These include: the nearshore/inner shelf where transport from land, by rivers, is modified by

interactions within the estuarine system; the air/sea and the sediment/water interfaces; the outer continental shelf and slope; and the Gulf Stream interface. In the nearshore, interactions between the inner shelf and estuaries are dynamic, and this is where the chemistry is/will be most impacted by human activities and climate change. It is also the only area where materials accumulate in any significant amount. The outer shelf is where deep ocean waters mix with shelf waters and, as will be reviewed in the following sections, where the major nutrients input to shelf waters takes place.

Major factors governing the chemistry of the South Atlantic Planning Area are input and transport/exchange pathways of materials, associated transfer rates, and residence times in the various compartments of the shelf system. These will be emphasized in the following review in an attempt to provide a state of knowledge of the chemical oceanography of the study area. This will indicate the relative importance of processes and where additional information is needed. And, where possible with existing information, temporal and spatial trends will be identified as they relate to climate change and human intervention.

4.2 NUTRIENTS AND CARBON

Pomeroy et al. (2000) pointed out that ocean margins are distinguished by two overarching features: their modes of receiving organic matter and nutrients. In the case of the southeastern US continental shelf, the relative importance of these processes varies considerably in time and space and, while many shelves are net autotrophic (net producers of organic carbon; CO_2 sinks), as suggested by Tsunogai et al. (1999), that of the South Atlantic Planning Area is probably not, but this is still under debate (Cai et al., 2003). Nevertheless, nutrient and carbon cycles are intimately linked by processes active at boundaries and interfaces, including the marsh/estuary-nearshore, the air-sea, sediment-water, and the Gulf Stream/outer shelf. In the following section, transport across these boundaries and the processes occurring there which affect the fate of nutrients and carbon will be reviewed. But first, a general description of the compositional characteristics of shelf waters is provided.

Atkinson and Menzel (1985) summarized the history of research on he South Atlantic Planning Area shelf waters in the first half of the 20th century and the earliest work by Atkinson et al. (1978a, 1978b), which focused mostly on the mixing of freshwater across the shelf and, ultimately, on the importance of mixing of water masses at the shelf break where the dominate influence of the Gulf Stream on water column chemistry and biology was evident. Early studies by Haines (1974), Haines and Dunstan (1975), and Turner et al. (1979), as summarized by Yoder (1985), assumed that the middle- and outer-shelf region was homogeneous with regard to primary production and was similar to oligotrophic oceanic waters, recycling more than 90% of the nitrogen required. Dunstan and Atkinson (1976) were the first to suggest that upwelling was a major source of nutrients. These studies led to the initiation of a substantial amount of research on the shelf, shelf break, and Gulf Stream. The results of this research provide the present understanding of the major source of new nitrogen to the shelf—Gulf Stream intrusions—which is discussed below and in more detail in Chapter 3 Physical Oceanography and Air-Sea Interactions.

4.2.1 Water-Column Characteristics

4.2.1.1 Nitrogen, Phosphorous, and Silicon

With regard to water chemistry, the major characteristics of the South Atlantic Planning Area are that the water column is virtually always vertically mixed but horizontally stratified, with salinities approaching 30 ppt at the shoreline (lower near the mouths of rivers) and rapidly increasing 10–20 km offshore to ~34-35°N (Figure 4.1); salinity gradients off river mouths (e.g., Brunswick and Savannah Transects) are the steepest. During periods of extreme river runoff, salinities in the low 30s ppt have been observed out to the middle shelf (James Nelson, Skidaway Institute of Oceanography, pers. comm.).

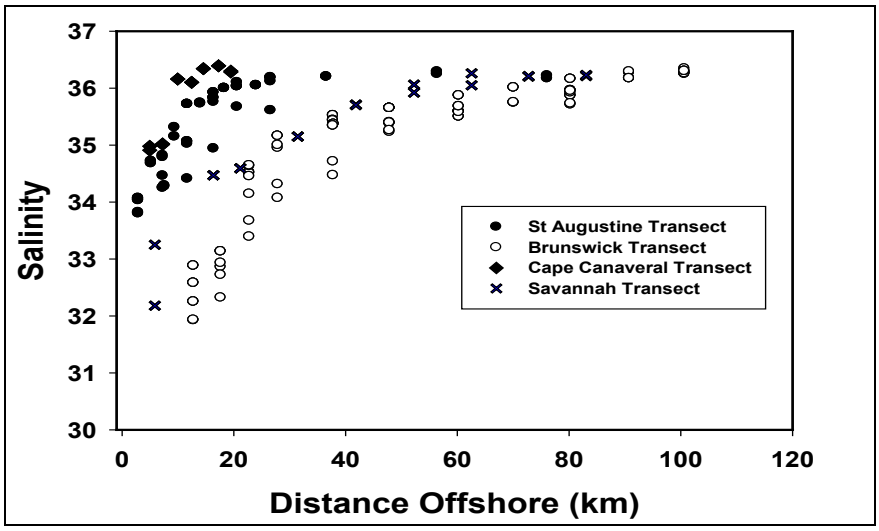

Figure 4.1 Salinity (in parts per thousand) compared with distance offshore along four transects of the South Atlantic Planning Area during the FLEX cruises, October and November 1987 (modified from Chandler et al., 1988).

The coastal salinity front produced by the band of freshwater input by the major rivers discharging along the coast provides an effective barrier to cross-shelf advection of materials (Blanton, 1986). Thus the nearshore, inner shelf is an area of significant sediment accumulation (and remobilization). The water column of the remaining shelf (mid, outer) is underlain by non-accumulating, relict sediments. In this region, much of the water-column chemistry is dominated by water-column mixing, primary production, and/or relative rapid turnover processes at the sediment/water boundary.

The first relatively comprehensive description of cross-shelf, water-column characteristics of the South Atlantic shelf and Gulf Stream was reported by Atkinson (1985) and provides a sufficient basis for understanding water-column nutrient concentrations. His results provide the first detailed description of the cross-shelf relationship between nitrate, dissolved oxygen (DO), and water-column physical characteristics for a typical southern cross-shelf transect off Florida and a northern transect off North Carolina for winter (Figure 4.2) and summer (Figure 4.3) conditions. These results indicate that DO is always near saturation in shelf waters, for both winter and

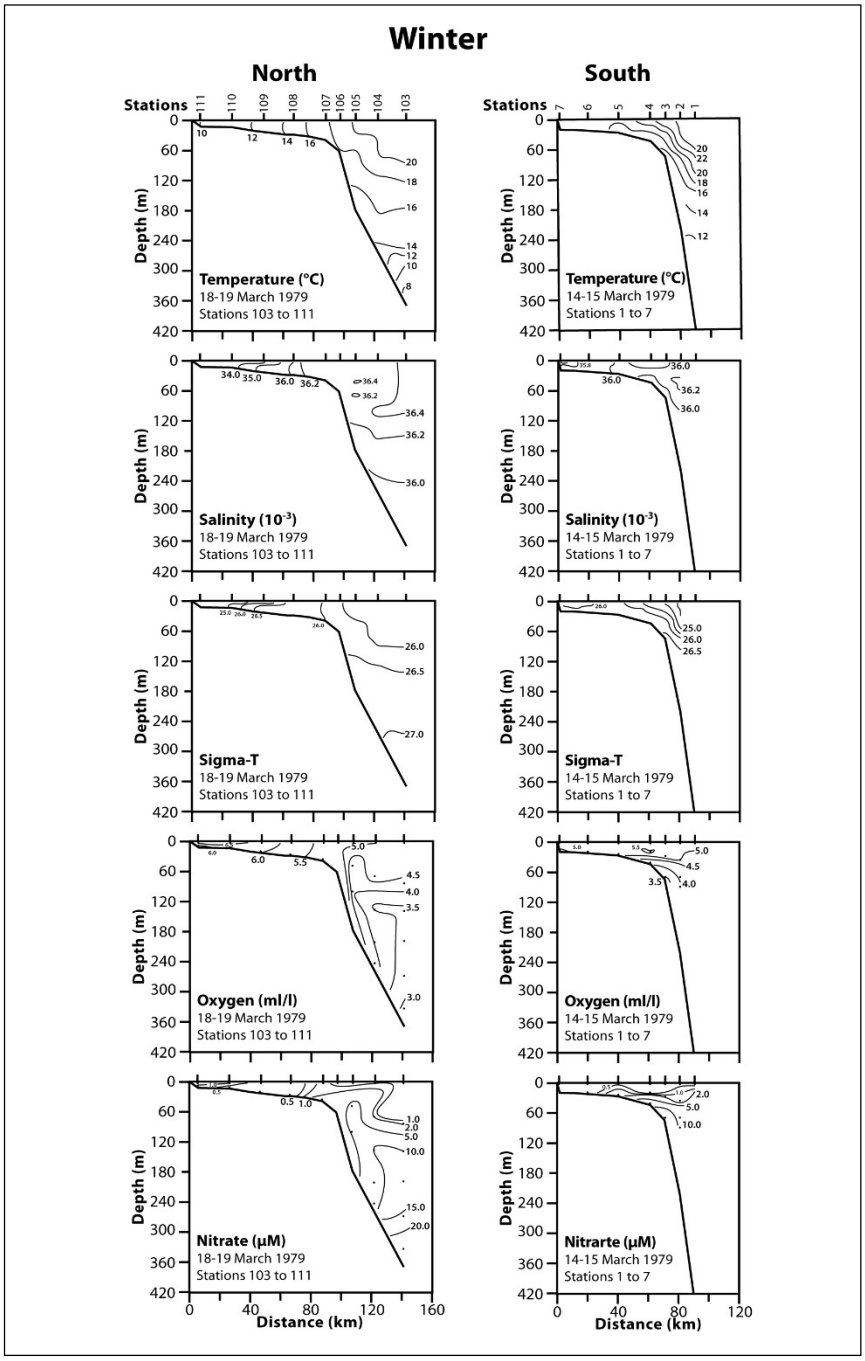

Figure 4.2 Cross-shelf sections of nitrate in relation to other water-column characteristics off north Florida (south) and North Carolina (north) during winter (modified from Atkinson, 1985). Reproduced/modified by permission of the American Geophysical Union.

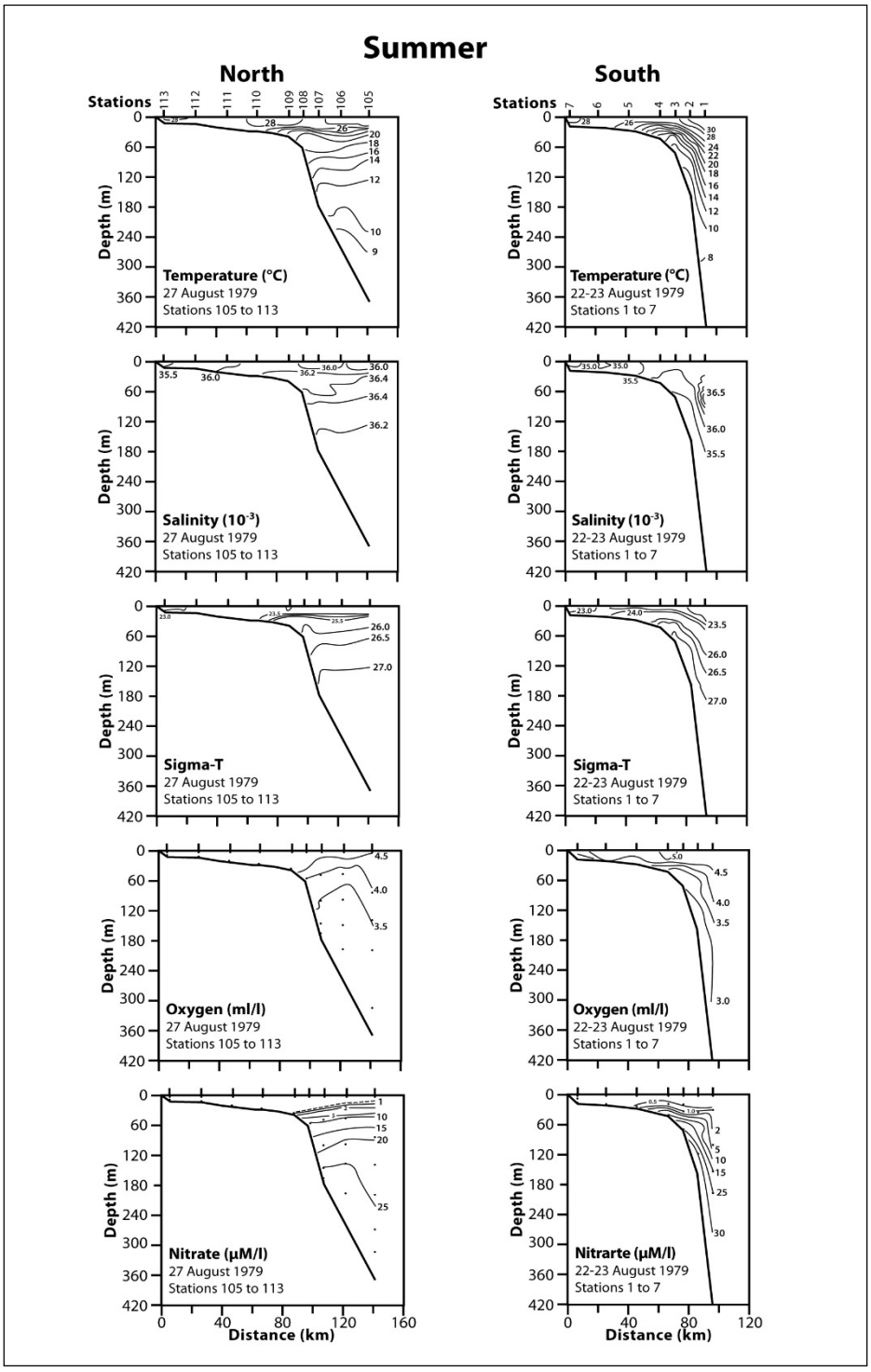

Figure 4.3 Cross-shelf sections of nitrate in relation to other water column characteristics off north Florida (south) and North Carolina (north) during summer (modified from Atkinson, 1985). Reproduced/modified with permission of the American Geophysical Union.

summer, and is observed to be under saturated only in deep, near bottom water at the continental slope. Nitrate is rarely above 0.5 micromolar (μM or μmol) in shelf waters; the only exceptions are areas of the inner shelf during higher river runoff, and the outer shelf associated with upwelling.

Nutrient concentrations along a transect across the outer shelf, Gulf Stream, and Blake Plateau and with depth were also described by Atkinson (1985), based on samples collected in September 1980. Nutrient regeneration with depth is clearly evident (Figure 4.4), and results in a considerable enrichment of nitrate, silicate, and phosphate with depth. Furthermore, as pointed out by Atkinson (1985), concentrations are closely related to temperature. An oxygen minimum is located at the base of the continental slope and coincides with the maximum in apparent oxygen utilization (AOU). The basic relationship between nutrients and temperature across the outer shelf, Gulf Stream, and Blake Plateau is shown graphically in Figure 4.5.

4.2.1.2 Carbon

Research by Cai and co-workers provides a good summary of dissolved inorganic carbon in shelf waters. Based on samples collected along a transect from the mouth of Wassaw Sound, Georgia out to the 200 m isobath, Cai et al. (2003) found that dissolved inorganic carbon (DIC) concentrations on the middle-outer shelf average 2,052±20 μmol/kilogram (kg) and many of the data lie along an extrapolated conservative river-ocean mixing curve with a river end-member concentration of 650 μmol/kg. But at lower salinities (i.e., 30–35 ppt), approaching land, the influence of discharge from marshes becomes more apparent and demonstrates this additional contribution to shelf DIC (this will be discussed further below).

Cai et al. (2003) measured the partial pressure of carbon dioxide (pCO_2) in surface water across the shelf of the South Atlantic Planning Area at different seasons (Figure 4.6). They found that CO_2 is under-saturated only during the winter (December 2000, 2002). During the rest of the year, CO_2 is over-saturated in surface waters throughout the shelf, with the exception of the outer shelf during April, which is likely related to CO_2 draw down by increased production associated with Gulf Stream upwelling. These results indicate that there is a net flux of CO_2 from the South Atlantic Planning Area.

Dissolved organic carbon (DOC) appears to be conservative across the shelf but with distinguishable differences depending on the Piedmont and Coastal Plain rivers' relative influence, which becomes more apparent nearer to shore. Piedmont rivers typically have lower DOC than do Coastal Plain rivers, resulting in two distinct conservative mixing curves of DOC versus salinity–one with a high DOC Coastal Plain, zero salinity end member and another with a lower DOC Piedmont, zero salinity end member (Windom and Smith, 1985). Fluorescence shows a similar trend (Atkinson, 1985) which indicates the refractory nature of the DOC. Offshore, DOC is generally <100 μmol/liter (L).

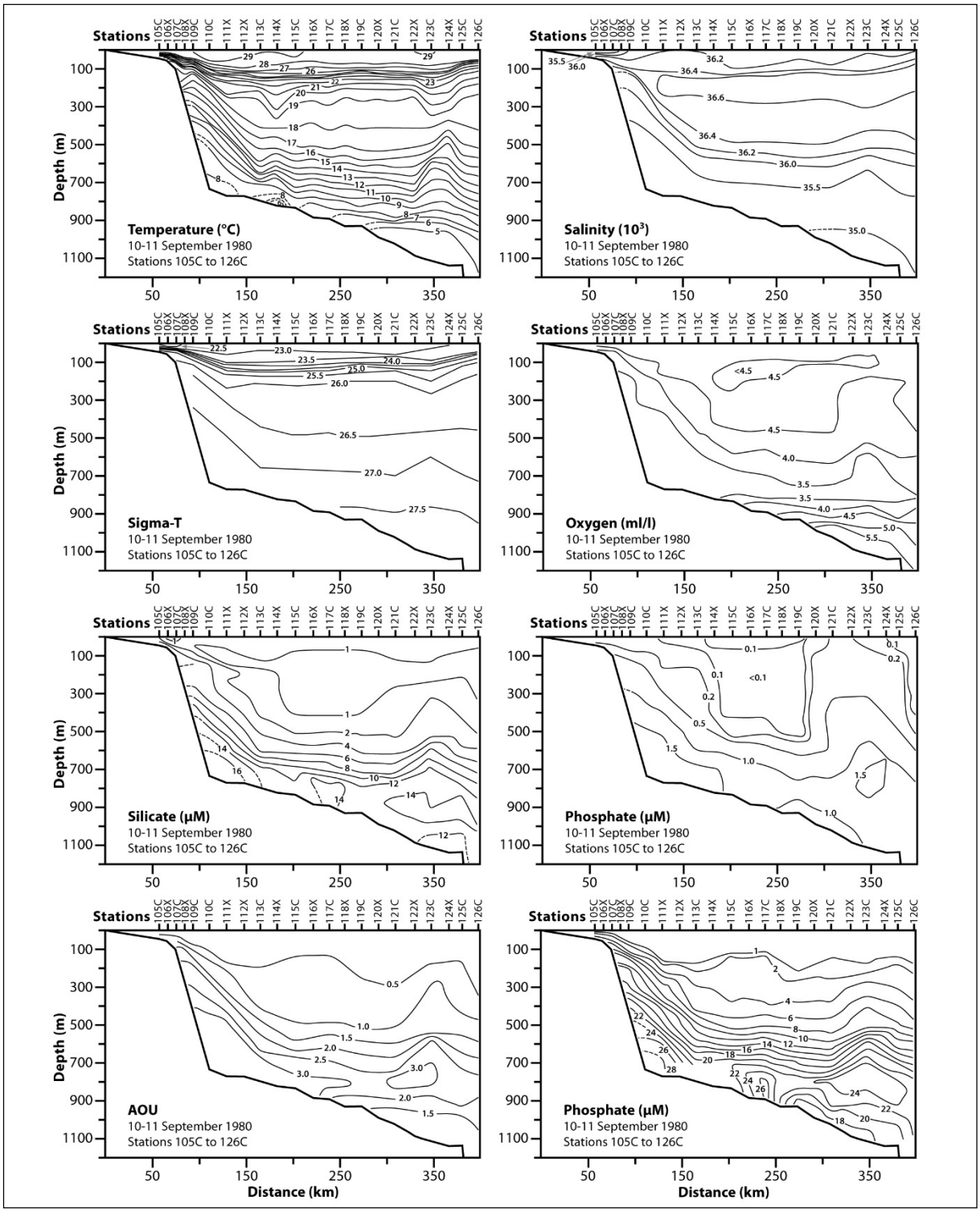

Figure 4.4 Water-column characteristics across a section of the outer shelf, Gulf Stream, and Blake Plateau at 29°N, September 1980 (modified from Atkinson, 1985). Reproduced/modified by permission of the American Geophysical Union.

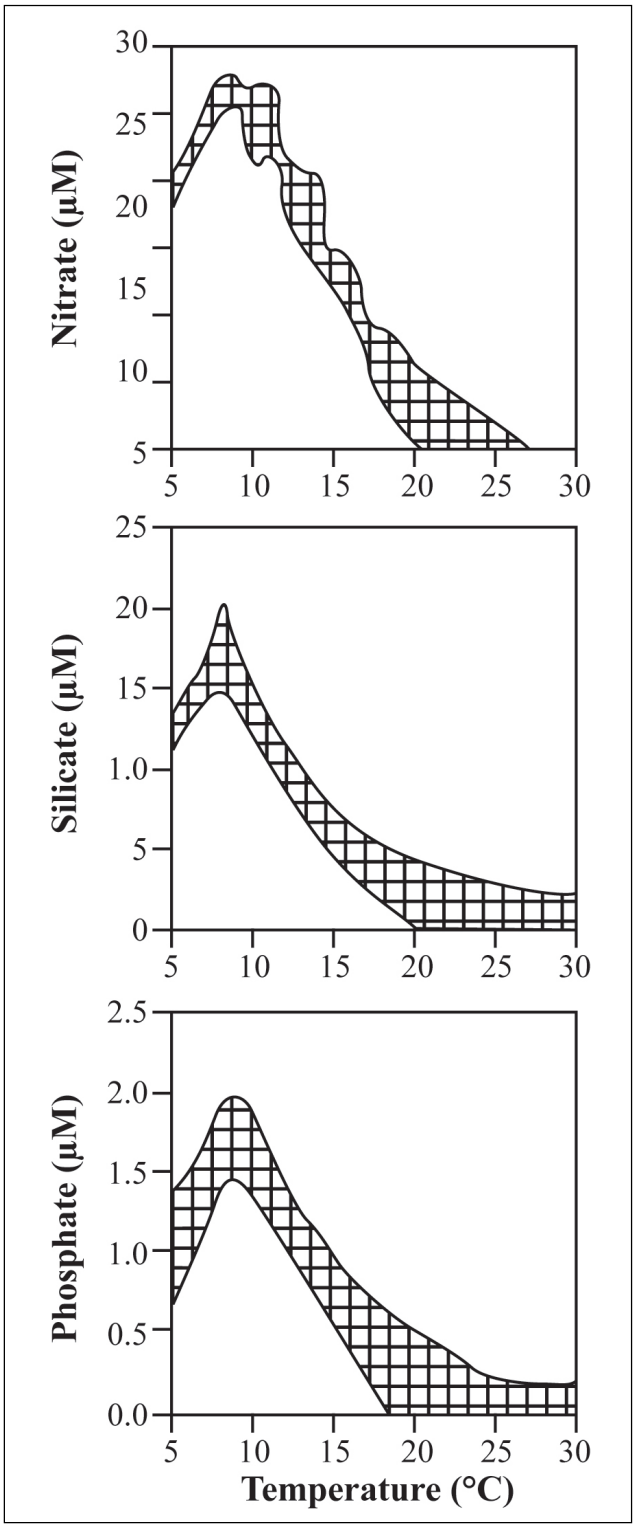

Figure 4.5 Schematic relationship between nutrients and temperature for waters of the outer shelf, Gulf Stream, and Blake Plateau (modified from Atkinson, 1985). Reproduced/modified by permission of the American Geophysical Union.

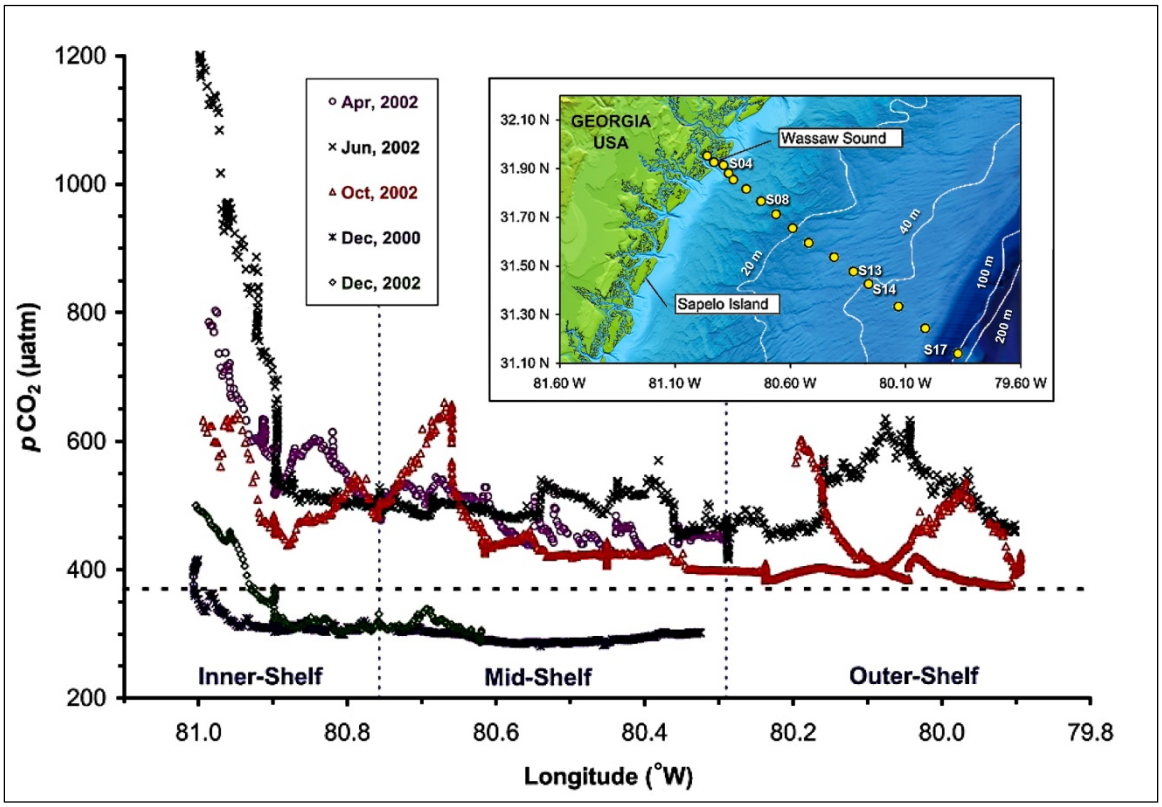

Figure 4.6 Sea surface pCO_2 along a cross-shelf transect off Georgia just south of the Savannah River (modified from Cai et al., 2003).

Particulate organic carbon (POC) decreases rapidly offshore, indicating the dominance of the salt marsh estuarine source (Figure 4.7). Particulate organic nitrogen (PON) shows a strong correlation to POC with a slope in the relationship of 0.1 or equivalent to an average C:N ratio of 10. This is higher than the ~6-7 Redfield C:N ratio for marine phytoplankton, showing again the dominating influence of the input of organic detritus from estuaries in the nearshore, high POC environment.

4.2.2 River/Estuary/Inner Shelf Interface

The major rivers discharging to the South Atlantic Planning Area are shown in Figure 4.8. The total annual freshwater flux from these rivers to the shelf is estimated to range from 66 to 84 km^3 (Atkinson and Menzel, 1985; Menzel et al., 1993). Particulate transport is about $5x10^9$ kg/year (yr) (Pomeroy, et al., 1993).

Materials transported in these rivers are "processed" in the extensive salt marsh estuaries of the southeastern Atlantic coast (estimated to cover $4x10^9$ m^3 by Reimold, 1977) and the inner continental shelf where most sediment accumulation occurs. As freshwater mixes with seawater, a number of biogeochemical processes may result in the exchange between particulate and soluble phases, thus modifying the form and rates of material transfer ultimately to the US South Atlantic shelf.

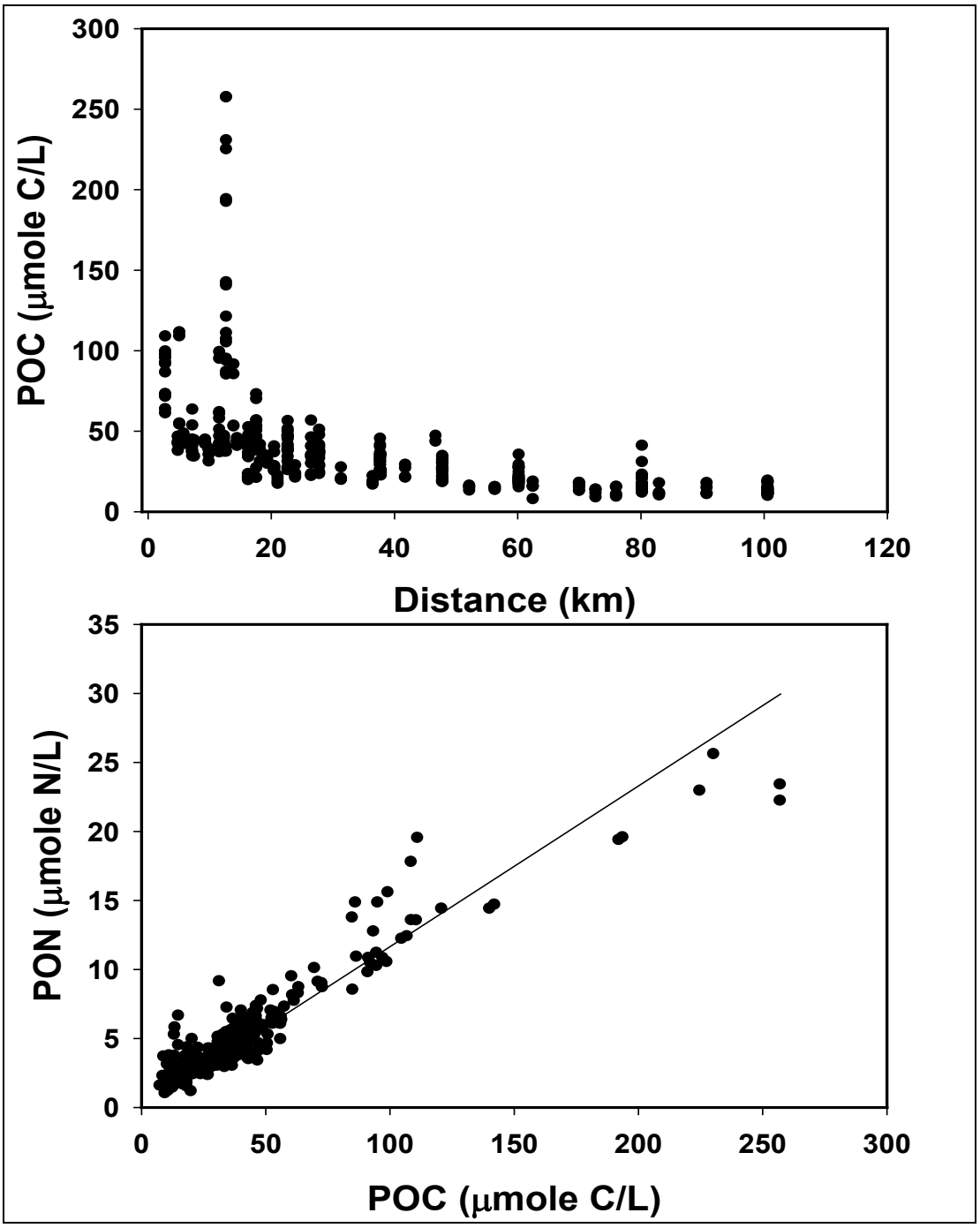

Figure 4.7 Relationship between particulate organic carbon, particulate organic nitrogen, and distance offshore along FLEX cross-shelf transect off Savannah, Brunswick, St. Augustine, and Cape Canaveral (October-November 1987). Regression line in the lower figure has a slope of about 0.1 (Windom, Unpublished data).

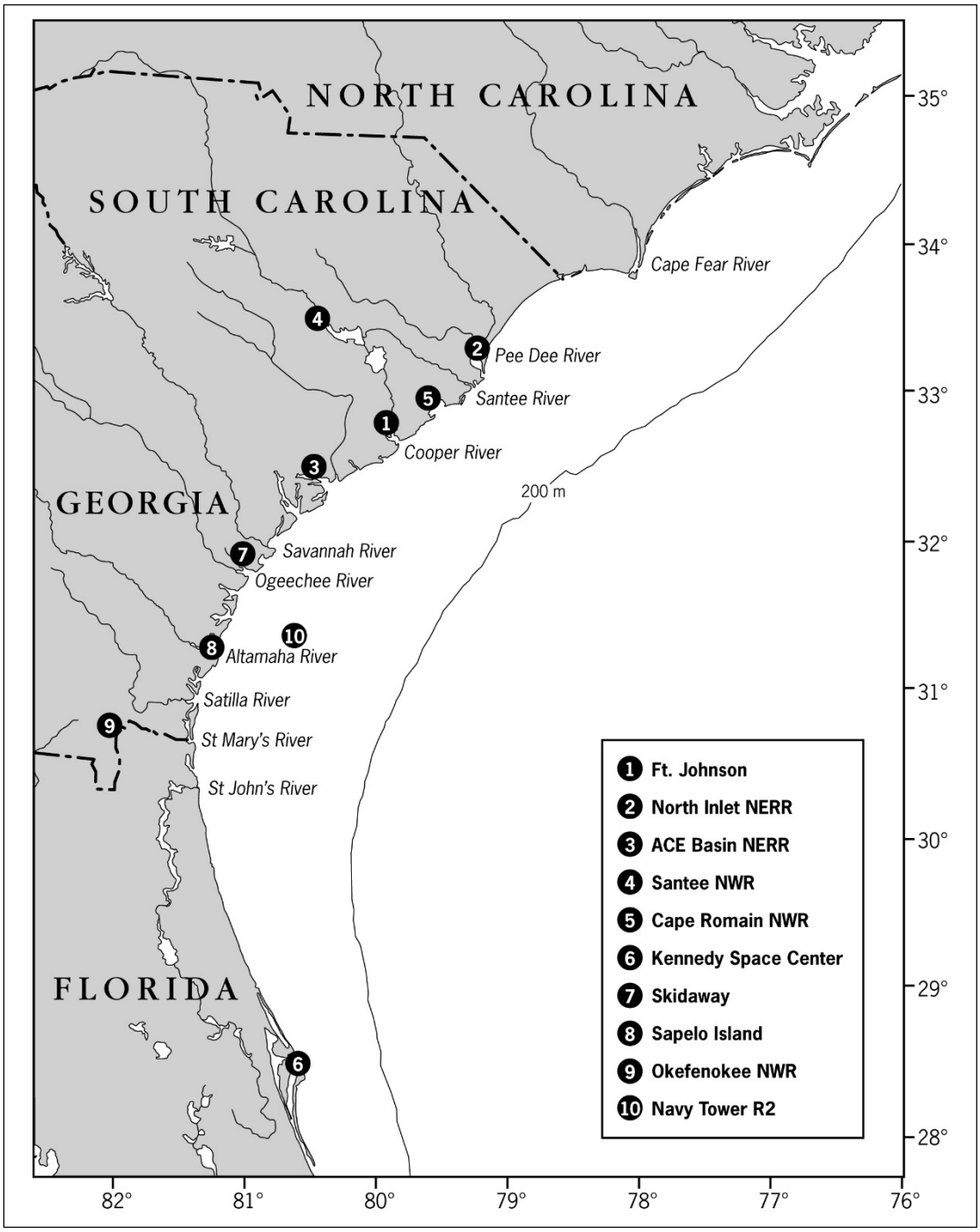

Figure 4.8 Major rivers discharging into the South Atlantic Planning Area and locations (1-9) of National Atmospheric Deposition Program sampling stations in the study area.

Most of the particulate matter in rivers is deposited in estuarine sediments. As pointed out earlier, the inner shelf also accumulates sediment at the rate of about 0.2×10^9 kg/yr (Pomeroy et al., 1993). But earlier work, reviewed in Pomeroy et al. (1993), indicates that the net sediment accumulation in the salt marsh estuaries is significantly greater than that supplied by rivers. Meade (1969; 1982) presented data that suggested shoreward movement of fine sediments,

winnowed out of shelf sediments during resuspension episodes, provides the required sediment. This process was confirmed by Schmitter and Freeman-Lynde (1988) based on heavy mineral distributions in coastal sediments.

It is clear that, at this dynamic interface, material will be cycled and recycled between sediments and the water column, and significant exchange between the inner shelf and salt marsh estuaries will occur. The following section, and subsequent sections related to material transfer and exchange at this interface, will summarize the important processes that affect material behavior as it relates to chemistry in the study area.

4.2.2.1 Nutrients

Windom et al. (1975) estimated the riverine supply of dissolved inorganic nitrogen (ammonia and nitrate) and phosphate to the southeastern salt marsh estuarine system and determined that this "new" nitrogen can only account for about 20% of the annual salt marsh production. The phosphate supply is sufficient to maintain the total production, so nitrogen is clearly the limiting nutrient. But dissolved organic nitrogen (DON) and particulate organic nitrogen (PON) are also transported by rivers and, along with atmospheric deposition, provide an additional supply of nitrogen to salt marshes, but still not enough to provide that necessary for annual production. This indicates that production requires significant nitrogen recycling at this interface to maintain both salt marsh and inner-shelf primary production.

Evidence of nitrogen cycling at the river/estuary/inner-shelf interface is provided in Figure 4.9, which shows the variation in nitrate in the Satilla, St. Marys (Coastal Plain), and Savannah (Piedmont) estuaries, going from freshwater out into the inner shelf. Relative to conservative mixing (river water mixing with seawater), nitrate concentrations in these estuaries are enriched toward the inner shelf. The differences in the concentrations for the Satilla and St. Marys, compared to the Savannah, may be due a seasonal effect related to salt marsh uptake of nitrogen (Valiela et al., 1978). The mobilization of ammonia in the Savannah estuary indicates nitrogen cycling from DON or PON.

Variations in phosphate concentrations in the freshwater-seawater mixing zone also show evidence of recycling toward the inner shelf (Figure 4.9). Silicate concentrations, however, exhibit mainly conservative mixing in the Satilla and St. Marys estuaries, suggesting no significant additional inputs or removals in the mixing zone–evidence that silica is not limiting production at this interface. Silicate concentrations in Piedmont rivers are considerably higher than those in Coastal Plain rivers as evidenced by results for the Savannah River estuary (Figure 4.9). Piedmont rivers drain more crystalline watersheds, with silicate-enriched weathering solutions, than do Coastal Plain rivers which drain highly leached sedimentary watersheds. The results for silica in the Savannah estuary also suggest addition in the mixing zone, likely due to continued "weathering" of suspended sediment in the estuary (Windom et al., 1991) and/or release from destabilized colloids. Based on the results of more recent research in the region (to be discussed in a later section), groundwater discharge might also explain some mid-mixing zone inputs.

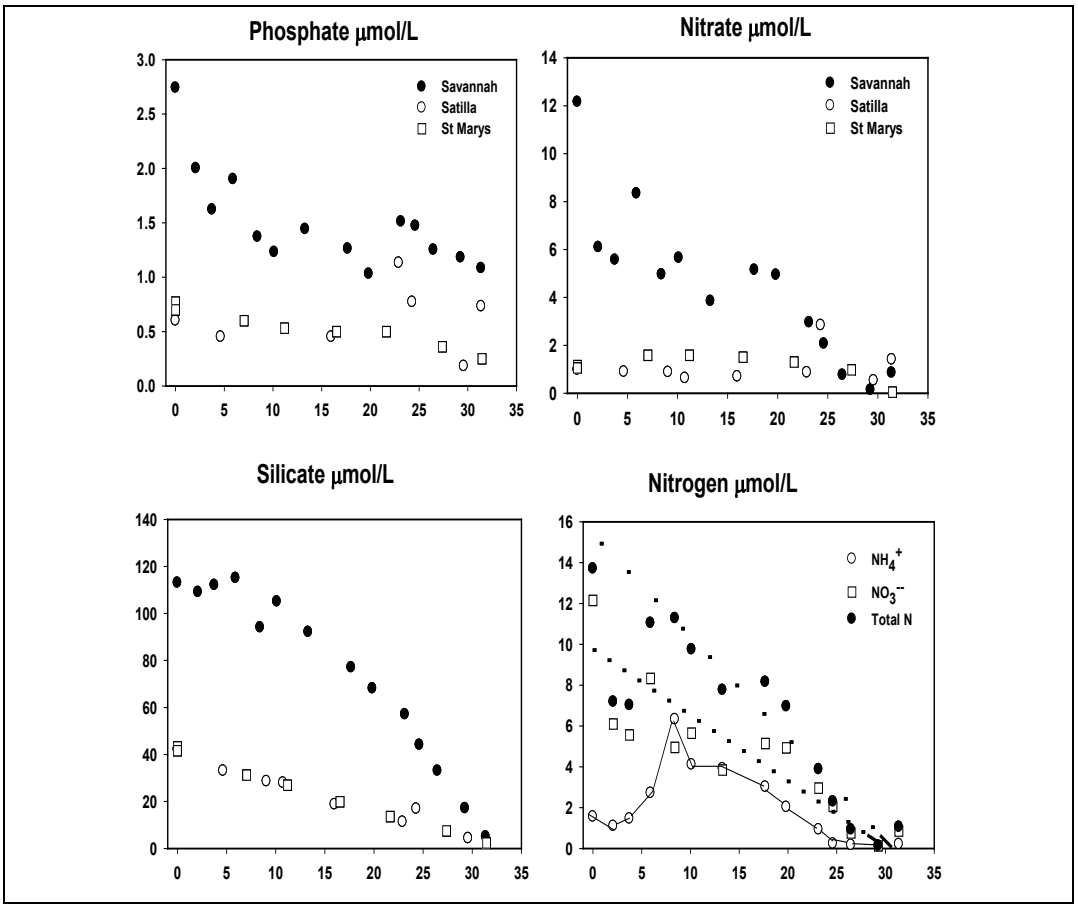

Figure 4.9 Dissolved nutrient concentrations versus salinity in ppt (horizontal axis) in representative Piedmont (Savannah) and Coastal Plain (St. Marys and Satilla) river estuaries (Windom et al., 1991 and Windom, Unpublished data). Long-dashed and short-dashed lines are regression curves for total nitrogen and nitrate against salinity, respectively.

With regard to inorganic nitrogen in the Savannah estuary, it is clear that the recycled nitrogen, represented by ammonia, results in an ~60% increase in total nitrogen delivery to the inner shelf (difference in the intercept of regression curves for nitrate and total N in Figure 4.9).

Although there is a significant amount of inorganic nitrogen flux to this interface, nitrogen input to the inner shelf is mostly regulated by export from salt marshes which is seasonally variable (Kjerfve and McKellor, 1980). Dame et al. (1991), in a study of a salt marsh basin in South Carolina, estimated that salt marshes appear to recycle most of the nitrogen (and phosphorus) with only DON being significantly exported. Bishop et al. (1984) and Dame et al. (1986) estimated that 90% of the nitrogen exported from marshes to the inner shelf is either PON or DON.

Weinstein et al. (1981) estimated that the total nitrogen export to the shelf from salt marshes in Georgia and South Carolina is 1.2×10^5 metric tons per year. Yoder (1985), using this nitrogen input flux and the primary production rate for the inner shelf (0–20 m isobath) estimated by Haines and Dunstan (1975), determined that only 17% of inner shelf primary production could

be sustained by this input, assuming all of the nitrogen was available. Hanson et al. (1990) argue that nitrogen sources, readily available to plankton in inner-shelf waters, likely account for less than 10% of the observed primary production. This requires relatively rapid microbial recycling to sustain observed production.

Water-column production, turbidity, and nutrient concentrations decrease sharply with distance from shore in the inner shelf (Figure 4.10). These distributions are controlled by the coastal salinity front, described by Blanton (1981), which acts as a barrier to cross-shelf exchange of water and suspended sediments. The distribution of POC along the freshwater-seawater mixing zone, with a trend toward higher concentrations in inner-shelf waters (Figure 4.7) is another manifestation of this process.

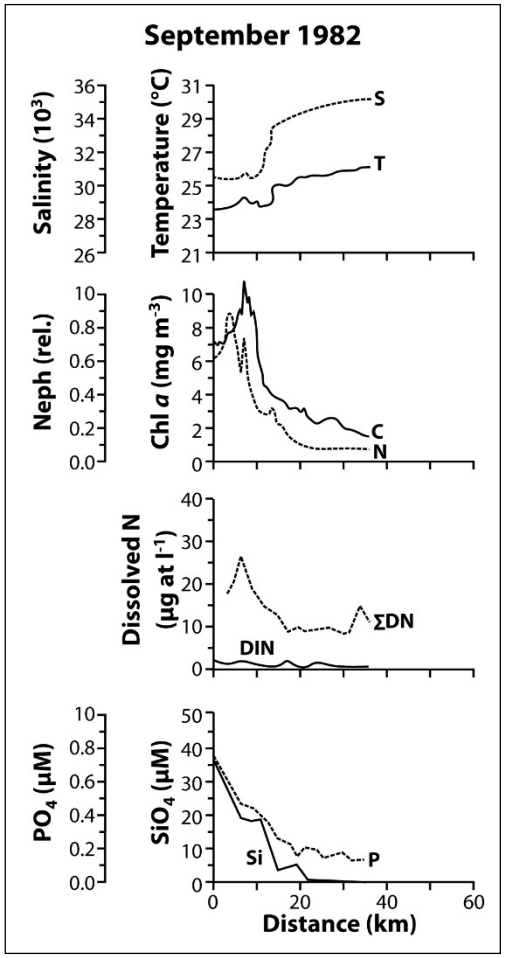

Figure 4.10 Water-column characteristics across the inner shelf to the 20 m isobath. Neph refers to relative turbidity as determined by nephelometry. DIN=NO_3+NO_2+NH_4, and DN=DIN+DON (Yoder, 1985). Reproduced/modified by permission of the American Geophysical Union.

The impediment to cross-shelf transport, due to the coastal salinity front, increases residence time in the nearshore and this, along with greater water-column mixing, leads to efficient recycling of materials. Hanson et al. (1990) have estimated that particulate nitrogen could recycle as often as 100 times during the summer.

4.2.2.2 Carbon

Data represented in Figures 4.7 and 4.10 demonstrate clearly the organic carbon-rich nature of the river/estuary/inner shelf interface. Salt marsh production is clearly the main contributor to this high carbon environment, but rivers also deliver dissolved organic (DOC) and inorganic (DIC) forms of carbon to the system. And, as eluded to above and discussed by Hopkinson (1985) and Griffith and Pomeroy (1995), total respiration rates in the coastal ecosystem which this interface comprises is typically greater than total primary production.

The concentrations of DOC in rivers discharging to the South Atlantic shelf (Figure 4.11) and their estuaries vary significantly between those draining Piedmont and Coastal Plain basins, with the latter being much more organic-rich than the former. As pointed out in Section 4.2.1.2, this DOC signature is traceable into shelf waters and clearly reflected in the inner shelf.

Coastal Plain rivers are rich in dissolved humic materials and, therefore, have a weak buffering capacity (Cai and Wang, 1998), and pH in their estuaries increases rapidly with increasing salinity. Piedmont rivers have relatively high carbonate alkalinity, reflecting their more carbonate-rich watersheds, resulting in a more gradual increase in pH with salinity. The carbonate alkalinity of Piedmont rivers is as much as nine times greater than that of Coastal Plain rivers (Cai and Wang, 1998), whereas the total alkalinity is around 4-5 times greater.

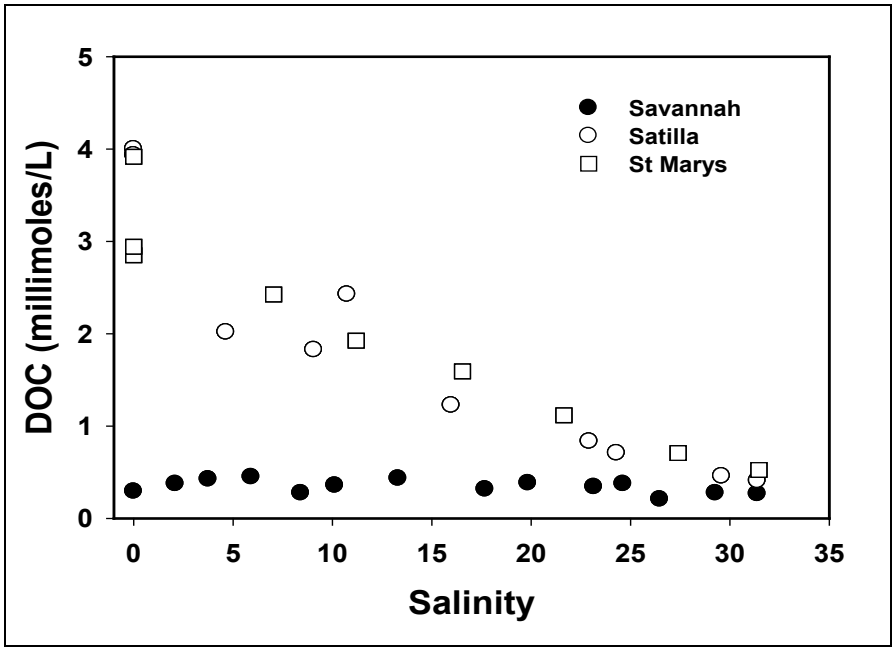

Figure 4.11 Dissolved organic carbon versus salinity in estuarine and inner shelf waters adjacent to representative southeastern river mouths (Windom, Unpublished data).

Along the freshwater-seawater mixing pathway of the river/estuary/inner-shelf interface, both alkalinity and DIC concentration-salinity curves show a slight curvature reflecting input within the mixing zone. Cai and Wang (1998), using a standard advection-diffusion model for estuarine mixing reported in the literature, estimated the total, net DIC input to the shelf waters of the SAB from rivers to be 52.5×10^9 mol/y.

Based on pH and DIC measurements, Cai and Wang (1998) calculated pCO_2 across the river-inner shelf mixing zone. They observed that CO_2 is above saturation virtually all the time. This reflects clearly the importance of respiration over photosynthesis resulting in a CO_2 flux to the atmosphere of from 20 to >250 mol/m^2/yr. This is 10-100 times greater than the CO_2 flux to the atmosphere from the open ocean estimated by Smethie et al. (1985).

4.2.3 Air-Sea Interface

4.2.3.1 Nutrients

The atmosphere has been recognized as an important input pathway for nitrogen enrichment of coastal waters by researchers over the past several decades. One of the first to recognize the potential importance of atmospheric nitrogen input to coastal waters of the South Atlantic Planning Area was Haines (1976) who estimated an annual input in rain of 0.3 g N/m^2 (2.1×10^{-2} mol/m^2). For the past three decades the National Atmospheric Deposition Program (NADP) has been reporting total inorganic nitrogen deposition in rain and for the coastal stations shown in Figure 4.7. The average annual rate over the period of record is amazingly similar (0.31 g N/m^2) as reported in Haines (1976).

More recently (2004–2008), total nitrogen deposition samples were collected monthly near the Skidaway Institute of Oceanography by Jahnke (2008), including both dry and wet (i.e., in rain) deposition. The average total deposition reported by Jahnke (2008) is 5.5×10^{-2} mol/m^2. Jahnke (2008) argues that his higher reported rate, compared to that reported by the NADP, is because the latter does not include organic nitrogen species. He also points out that his average atmospheric nitrogen deposition rate is comparable to those reported for other coastal areas ($0.21\text{-}0.71 \times 10^{-2}$ mol/m^2) reported by Pearl (1997).

Although rates were not calculated in Jahnke (2008) for atmospheric deposition, for samples collected at an offshore station on the South Atlantic shelf (R2 tower, Figure 4.7 above), total nitrogen concentrations were similar, suggesting the coastal deposition rates reported by him may be used to estimate atmospheric nitrogen input to the entire South Atlantic Planning Area. Using this rate (5.5×10^{-2} mol/m^2) and applying it to the entire 90,600 km^2 shelf surface area (Menzel et al., 1993) yields a total annual atmospheric nitrogen flux to the South Atlantic Planning Area of 5×10^9 mol/yr, or about 7×10^{10} g N/yr.

4.2.3.2 Carbon

The net annual CO_2 flux to the atmosphere from the South Atlantic Planning Area estimated by Cai et al. (2003) already cited above is 2.5 mol/m^2. Acid deposition is the only other atmospheric exchange which may affect carbon cycling in the SAB and for which there are data. The NADP has collected samples for acid deposition in rain at the coastal stations indicated in Figure 4.7. For the past three decades the average annual H^+ deposition for all stations is 0.024 mol/m^2.

Given that shelf waters are saturated with CO_2, addition of protons would, in principle, enhance the CO_2 flux, but the estimated acid deposition would obviously have an insignificant effect.

4.2.4 Sediment-Water Interface

Sediments of the South Atlantic Planning Area can be divided into three depositional environments: nearshore/inner shelf, middle shelf, and outer shelf. The first is differentiated from the other two in that fine-grained sediments actively accumulate there, whereas middle- and outer-shelf sediments are relict, relatively coarse-grained sands, although some fine sediment does exist on the slope.

Fine-grained material accumulates in the nearshore, out to about 15 km offshore (Figure 4.12) because the coastal boundary front, described by Blanton (1981), retards offshore advection of water, creating an alongshore, southward drift, and nearshore deposition of fines. Deposition centers are located between the major coastal inlets channels.

Based on the distribution of fine-grained material in inner shelf sediments and their accumulation rate, Pomeroy et al. (1993) estimated that 20% of the riverine suspended sediment of southeastern US rivers (Figure 4.7) escapes the estuarine environment. This is contrary to the concept of southeastern estuaries being efficient sediment traps (Meade, 1982) and to the observations of sediment accumulation in southeastern salt marsh estuaries, which exceeds the present rate of sediment delivery by rivers (Pomeroy et al., 1993). Meade (1969) argued that much of the sediment accumulating in these estuaries is from offshore, and Pomeroy et al. (1993) suggest that the continued winnowing of fines from shelf sediments during a transgressing sea provides the mechanism. Their data, as well as those of Windom et al. (1993), also indicate that even inner-shelf sediments are continually winnowed of fines that are ultimately transported into the estuaries. Ripple patterns in the coarse sands of the inner-middle shelf indicate clearly a mean shoreward flow of bottom currents, facilitating landward transport of sediment.

While inner-shelf sediments typically contain 1 to >15% fines, middle-shelf sediments contain less than 1% (Windom and Betzer, 1977). Concentrations of fines, however, do increase substantially on the slope and may be resuspended during bottom-water intrusion originating in the Gulf Stream. Suspended sediment originating from this process apparently does not penetrate significantly onto the outer shelf.

It is clear that there is a continual exchange of sediment, and other particulate-associated material, between the estuarine and inner-shelf environments. Episodic events are probably the dominating influence. Storms may also lead to the transport of fine material from the inner to the middle and outer shelf on short time scales, but the results of Windom and Gross (1989) suggest that insignificant amounts of inorganic particles greater that about 10 microns in diameter escape to the middle-outer shelf. Therefore, the only significant input to middle-outer shelf sediments is biogenic and, perhaps, atmospherically transported particles.

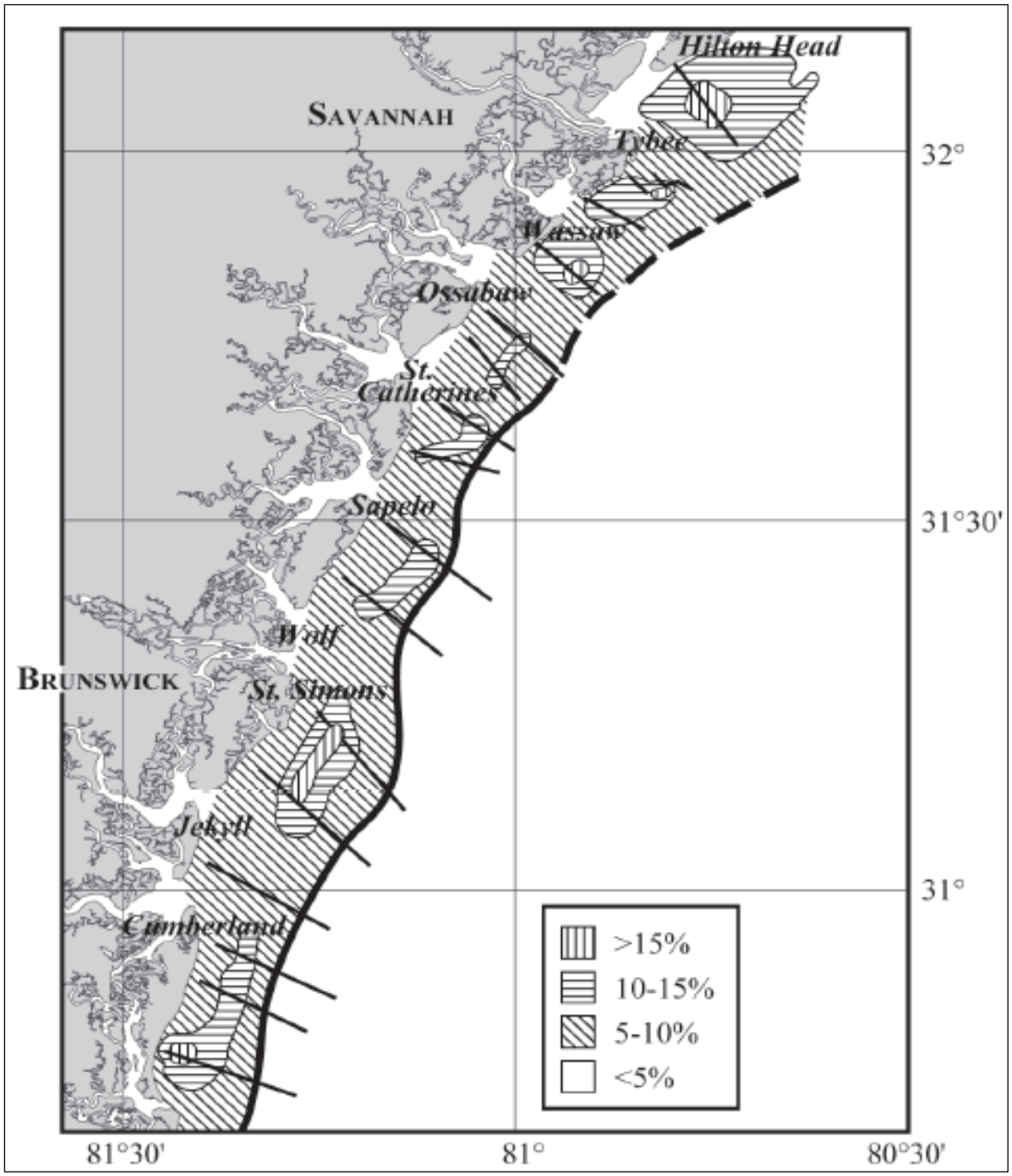

Figure 4.12 Distribution of fines (percent clays and silts) in inner shelf, bottom sediments (modified from Pomeroy et al., 1993).

4.2.4.1 Nutrients and Carbon

The role of sediments in nutrient and carbon transport and cycling in the inner shelf was, in principle, addressed in Section 4.2.2.1 on the river/estuary/inner-shelf interface. In general, these sediments accumulate fixed carbon and nitrogen (PON), along with silica and phosphorous associated with biogenic particles, originating in the salt marsh estuaries and/or produced in the water column of the inner shelf. Microbial metabolism in bottom sediments recycles the nutrients to the water column. Subsequent mixing brings the recycled nutrients into the relatively shallow euphotic zone to support water-column primary production.

Surface inner-shelf sediments contain typically ~0.1% organic carbon which increases with depth (to 0.5 m) to not much over 0.5%, (Verity et al., 1993). An average organic carbon concentration for middle- and outer-shelf sediments is probably considerably less than 0.1%. This is due to the biogenic origin of the input and its rapid remineralization.

As already mentioned, the coarse-grained, relict sediments of the middle and outer shelf receive very little allochthonous material input. Particulate organic matter, formed in the water column due to primary production and driven by intrusions of nutrient-rich Gulf Stream deep water (see next section), provides the source. Within the water column, elevated concentrations of POC are virtually always correlated with chlorophyll (i.e., primary production) (Atkinson et al., 1977), and chlorophyll increases are a response to the elevated nutrient (nitrate) input from Gulf Stream intrusions (Verity et al., 1993; Yoder, 1985).

In the coarse-grained sediments of the shelf, nutrient dynamics appear to be dominantly controlled by benthic primary production of a distinct, predominantly diatom, microflora (Nelson et al., 1999) and advection rather than diffusive transport processes (Jahnke et al., 2000). At water depths ranging from ~14–45 m (20–45 m off the Georgia coast), bottom sediments are within the euphotic zone (Marinelli et al., 1998; Nelson et al., 1999). This represents about 84% of the South Atlantic Planning Area continental shelf and Jahnke et al. (2000) estimate that benthic primary production is about 400 mg C/m^2/day, or about 60% of the water-column rate.

Marinelli et al. (1998) demonstrate that the permeable, non-accumulating sediments of the South Atlantic Planning Area act as a source of organic matter and a sink for nutrients. They found that pore-water nutrient profiles in sediments vary considerably in time and spatial scales of meters. Temporal variations, such as those shown in Figure 4.13, demonstrate that the relative rapid reaction rates, driven by pore advection in response to seasonal changes in benthic primary production, produce a cycle of remineralization and nutrient consumption. Even though respiration rates are high in shelf sediments (Jahnke et al., 2005), nitrate in pore water is above detection in only the oxic zone where concentration maxima are generally <1 μmole/L.

This low nitrate level led Marinelli et al. (1998) to speculate that nitrification and denitrification rates are low in shelf sediments. However, Rao et al. (2007; 2008), using experimental chambers, demonstrated that 78–100% of remineralized nitrogen could be released from sediments as N_2. They estimated a denitrification rate for the shelf of about $1\text{-}6 \times 10^{-6}$ mmol/cm^2/hr.

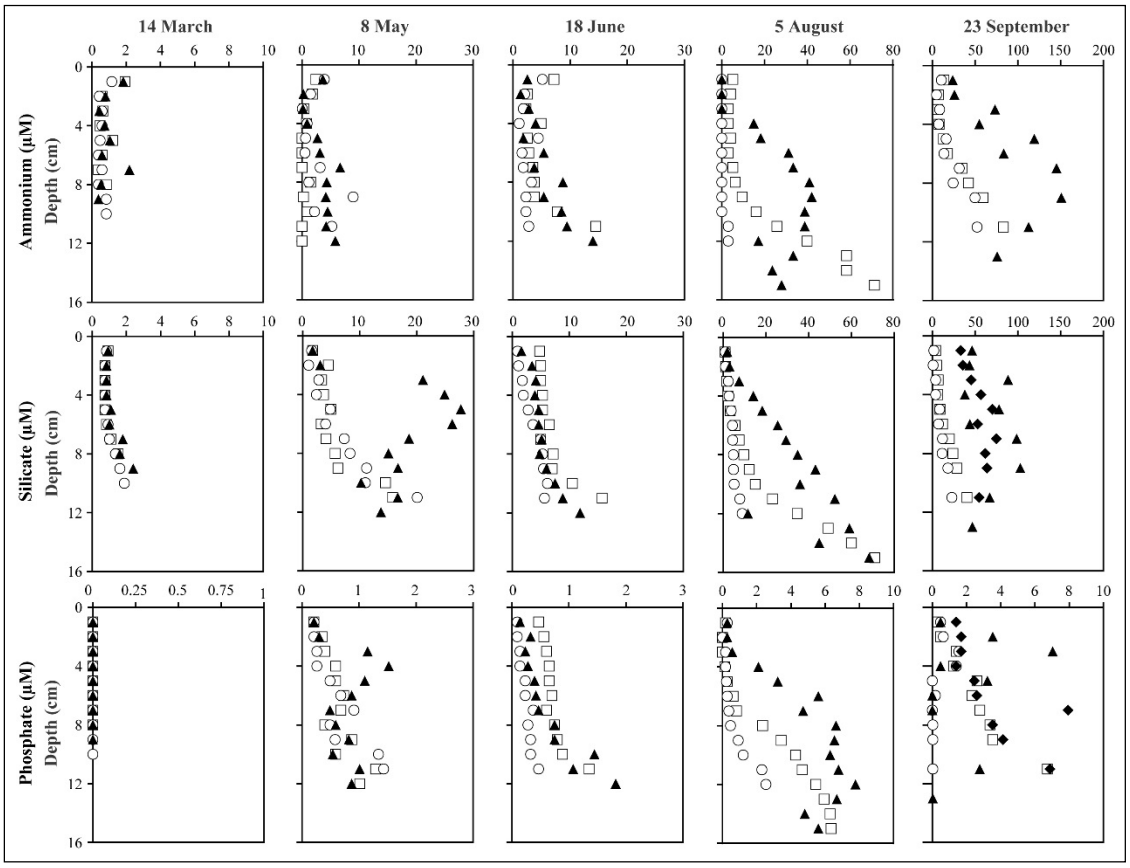

Figure 4.13 Seasonal nutrient variations with depth from three cores collected at a location off Wassaw Sound, Georgia in 27 m of water. Results demonstrate high seasonal and spatial variability (modified from Marinelli et al., 1998).

4.2.5 Ocean Inputs of Nutrients to the Continental Shelf

Deep Gulf Stream waters are rich in recycled nutrients, as discussed earlier, and provide the largest source of "new nitrogen" and phosphate and silicate (relative to nitrogen in approximately the Redfield ratio) to support primary production on the shelf. Upwelling of this water onto the shelf was postulated as a likely important process for supplying nutrients to the shelf by Dunstan and Atkinson (1976) and subsequently confirmed by later studies.

The mechanism that advects nutrient-rich waters onto the shelf has been described as due to meanders of the Gulf Stream and to spin-off eddies and is graphically depicted in Figure 4.14. An estimated nitrogen (nitrate) flux of 170 tons, due to a single eddy, was made by Atkinson et al. (1982). Atkinson et al. (1988) estimated that the summertime advection of nitrogen onto the shelf of the SAB which extends from Cape Fear, North Carolina to Cape Canaveral, Florida, is between 10,000 and 100,000 tons of nitrate. This flux represents the amount of nitrogen that reaches the shelf (i.e., crosses the 40 m isobath) rather than that which is merely transported across the shelf break isobath.

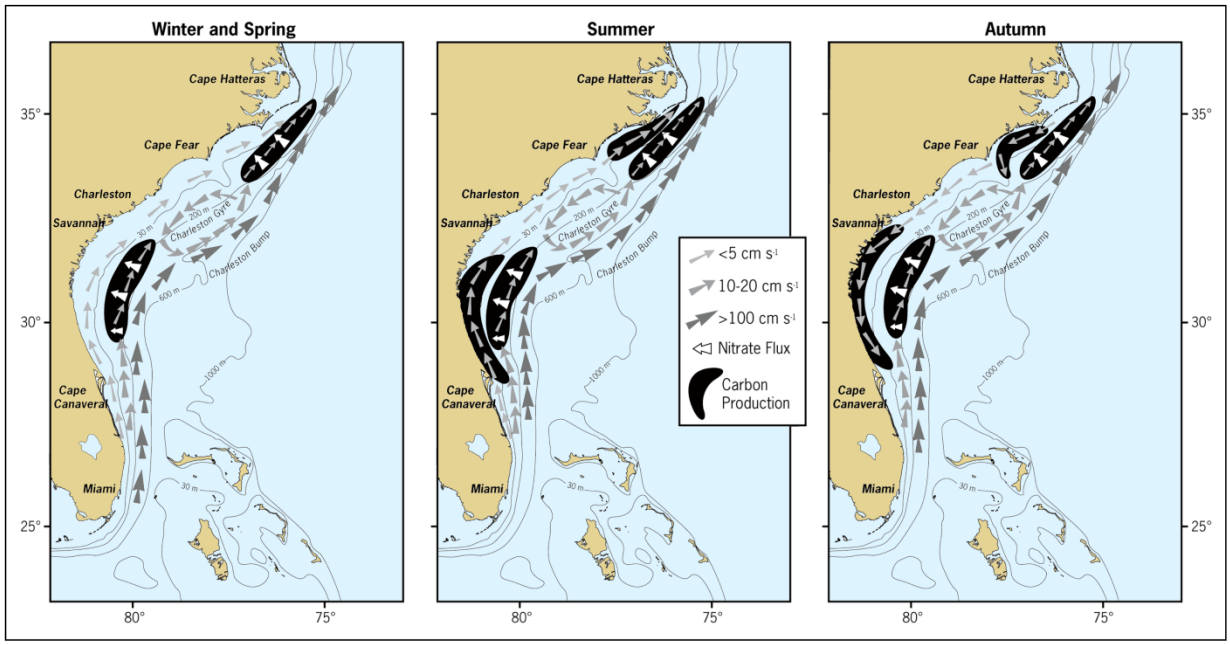

Figure 4.14 Nitrate flux and Gulf Stream induced organic carbon production in relation to mean circulation at the shelf edge during winter, spring, and summer (modified from Lee et al., 1991).

Lee et al. (1991) have estimated that the nitrogen flux from Gulf Stream frontal eddies which influences primary production on the SAB shelf is $6x10^{11}$ g N/yr (600,000 tons). This input of new nitrogen can be compared to that supplied by rivers. Windom et al. (1975) estimated that the major rivers discharging into the SAB delivered $9x10^{8}$ g N/y or about 0.1% of that from Gulf Stream intrusions. The atmospheric input, estimated in an earlier section ($7x10^{10}$ g N/y), could be as high as 10% of the total nitrogen input to the SAB shelf.

4.2.6 Trace Elements

In this section, existing information from published research on trace element biogeochemistry of the coastal zone, shelf, and slope of the South Atlantic Planning Area are reviewed. Some additional, unpublished data are also included. For this review, trace elements include metals and metalloids, most of which are of environmental importance, while some are of more scientific relevance as tracers of processes, etc. As with nutrients, the focus of this review is on inputs and processes that influence transport and fate within the South Atlantic Planning Area. Concentrations in sediments will be another focus, because these will provide a benchmark to compare with future observations.

The first systematic assessment of metal levels in various compartments of the South Atlantic Planning Area was carried out as a part of the South Atlantic Benchmark Program (Texas Instruments, Inc., 1979). However, because of inadequacies in sampling and analysis, especially analytical detection limits, the data from that program are of limited use in providing an overview of the dynamics of trace element transfer and cycling in the study area (Windom and Betzer, 1979). Because improving the quality assurance/quality control of sampling and analysis

has been a major focus in trace element research during the past three decades, the data in more recent papers are more reliable. The approach taken in the following sections is to include and emphasize those papers that meet these higher data-quality standards.

4.2.6.1 Water Column

The best approach to reviewing the water-column transport, cycling, and fate of trace elements is to consider the main input from rivers and the mixing continuum across the shelf. A concept that will be used in the assessment of processes involves the mixing of end members and conservative/non-conservative behavior during mixing, which indicates whether the element is removed or added to solution during mixing. In assessing the behavior of materials transported through systems where waters of two or more sources (i.e., end members), having significantly different salinities (e.g., seawater, river discharge, groundwater, hypersaline discharges), are mixed, salinity is often used as a conservative component of the system. Advection-diffusion models can then be used to determine if a material is removed or enriched as the end members are mixed. This has been the approached used in most of the past work, where advection-diffusion models are used to estimate fluxes.

4.2.6.2 River Input

Dissolved Load: The nine rivers shown in Figure 4.8 provide the major pathways for the transport of natural and anthropogenic mobilized materials from land-based sources to the South Atlantic Planning Area. Transport occurs in both particulate and soluble forms. Mean concentrations of a number of trace elements for which data exist in several published reports are provided in Table 4.1. As mentioned in the introduction to this section, the quality of trace element data has improved immensely over the past few decades, and this is reflected in the table (compare Windom, 1975 with Polmeroy et al., 1993). However, the data referenced to Polmeroy et al. (1993), which include recent data on additional metals and list the discharge-weighted mean concentrations, provide probably the best estimates of mean dissolved trace element concentrations in river discharges. There are, of course, a number of factors that influence concentrations among rivers and temporal variability within a single river, as briefly discussed below.

There are two basic types of watersheds which discharge into the South Atlantic Planning Area: Piedmont and Coastal Plain. The latter type is typically more enriched by dissolved organic matter; this can influence the solubility of some metals. For example, copper appears to be more enriched in Coastal Plain than in Piedmont rivers (Windom et al., 1983). The different weathering regimes in these watersheds, as reflected in the total dissolved solids concentrations (TDS), also appears to influence dissolved concentrations of metals, such as cadmium, lead, and zinc, which increase with TDS (Windom et al., 1991). River discharge can also influence the dissolved concentrations of some trace elements in rivers. For example, arsenic concentrations appear to increase with increasing discharge (Walenchuk, 1979). Copper also appears to increase with discharge, along with DOC (Windom et al., 1983). Also, the levels of DOC may influence trace element concentrations as discussed by Windom and Smith (1985).

With regard to dissolved metals, concentrations in southeastern US rivers are similar or significantly lower than concentrations observed in East Coast rivers discharging along the Atlantic seaboard north of Cape Romain (Windom, 1996). However, the soluble load rarely

reflects anthropogenic influences on transport in rivers. These influences are more likely manifested in the suspended load.

Table 4.1
Mean trace element concentrations in southeastern US rivers

Reference	As nM	Ba nM	Cd pM	Co nM	Cu nM	F µM	Fe µM	Hg pM	Mn µM	Ni nM	Pb pM	U nM	Zn nM
Windom (1971)						2.6–5							
Windom (1975)			6,700		6.9		3.6	200	0.3				
Windom and Taylor (1978)								100					
Waslenchuk (1979)	3												
Windom et al. (1983)					5–15								
Windom et al. (1991)			95		17						100		13
Polmeroy et al. (1993)	4	130**	69	0.5	8.8	4	0.6	100	0.3	5	270	0.17*	10

(nM = nanomoles; pM = picomoles)
* Averaged from Moore and Shaw (2008); Windom et al. (2000)
**From Shaw et al. (1998)

Particulate Load: Typically, the average suspended load of southeastern US rivers varies between about 10 and 70 mg/L (Windom et al., 1971; Windom, 1973). However, most of the sediment transported by rivers to the coast is trapped in estuaries and/or on the inner shelf, inside the coastal salinity front. And, as mentioned in an earlier section, fine sediments on the shelf are periodically resuspended and transported landward to be trapped inshore (Meade, 1969; 1982).

Horowitz and Stephens (2008) have shown that fluvial sediment trace-element chemistry shows relatively little response to human activity except for some slight enrichments which can be correlated to populations residing in the associated watershed. This demonstrates the fact that most metal levels in sediments are due to natural occurrences. Windom (1996), however, found that the impact of human activities in the watershed could be seen in particulates when the total suspended-sediment levels in the water column is low because the anthropogenic metal concentration in the sediment is not overwhelmed by the natural load. But, more typically, trace element concentrations in suspended sediments reflect their natural abundance.

For most trace elements, most of the load carried by rivers is in suspended sediments, the transport of which is related to river discharge, with the majority of the transport occurring during ~10% of the highest discharge period. But, in terms of impact on the trace-element chemistry of the continental shelf, the major control is exerted by particle-water exchange across

the freshwater-seawater mixing zone and the chemistry and transport of particle across the shelf. These subjects are considered in the next sections.

4.2.6.3 Concentrations in Shelf Waters

Windom and Betzer (1979), who reported on the trace metal results of the South Atlantic OCS Benchmark Program, the first comprehensive oceanographic study in the South Atlantic Planning Area, pointed out that "generally, analyses of water-column components, particularly water samples and suspended sediment samples, suffer from sampling and analytical problems that are typically state of the art." Fortunately, the state of the art has improved significantly over the past few decades, so there are now reliable data on dissolved and particulate (suspended sediment) concentrations of trace elements in South Atlantic Planning Area waters. The following sections summarize the state of knowledge regarding concentrations of dissolved and particulate trace elements in shelf waters and provide a historical context regarding quality assurance of data.

Dissolved: Since Windom and Betzer (1979), a few reports on dissolved trace element concentrations in shelf waters of the SAB have been published. These are listed in Table 4.2 and, because they represent a relatively small sampling in time and space, only average values from the papers cited are provided. A better sense of spatial variability and processes is provided in Section 4.3.1.3.

The results provided in Table 4.2 indicate that only lead and mercury concentrations are significantly higher than the range of those for the open ocean (Bruland, 1983). More work to validate these data is probably warranted, because of improvements in analytical and sampling techniques. Because both of these metals are also environmentally important and the data are over two decades old, the impact of regulatory efforts to minimize atmospheric emissions would also be expected to result in lower concentrations. The concentrations of other trace elements listed in Table 4.2 are well within the range of observed oceanic concentrations (Bruland, 1983) and similar to values reported for shelf waters of the northeastern US coast (Bruland and Franks, 1983).

Particulate: As a part of a Department of Energy program, conducted in the 1980s, a number of cruises across the continental shelf were conducted during which samples were collected for particulate trace element analysis. These included transects off Savannah and Brunswick, Georgia and St. Augustine and Cape Canaveral, Florida during the fall (October 1987), referred to as FLEX (Fall Experiment), and off Charleston and Kiawah Island, South Carolina and Savannah, Georgia during spring (April 1988), referred to as SPREX (Spring Experiment). These cruises traversed the shelf out to the 40 m isobath, to about 100 km offshore.

Of the samples collected from these cruises, the data for particulate aluminum from the SPREX cruises have been published (Windom and Gross, 1989) and were used to model cross-shelf particle flux (discussed in a later section). Tables 4.3 and 4.4 summarize data on the concentrations of trace metals in these samples (from Windom et al., 1989; Windom, 1988, Progress Report, DOE SAB Program, unpublished data)

Table 4.2
Average dissolved trace element concentrations in southeastern US shelf waters

Reference	As nM	Ba nM	Cd pM	Cu nM	Fe nM	Hg pM	Mn nM	Ni nM	Pb pM	U nM	Zn nM
Windom and Taylor (1978)						63					
Waslenchuk (1979)	15										
Windom et al. (1983)				1-6							
Windom and Smith (1985)			160	4.1	32		12	6			2
Windom et al. (1985)									120		
Shaw et al. (1998)		50									
Windom et al. (1999)										14	
(nM = nanomoles; pM = picomoles)											

Data from over 150 particulate samples collected from the FLEX cruises, along the four transects across the more southerly portion of the South Atlantic Planning Area, include POC, PON, aluminum, calcium, magnesium, iron, and 29 additional trace elements including transition metals, alkaline earth, and rare earth elements. These data are presented in Table 4.3 where they are separated into results from samples collected within 16 km of shore and those beyond. The influence of the coastal salinity front, which impedes cross-shelf transport, is evident in the significant difference in mean concentrations observed between the two regions. This is reflected to the greater extent in the trace metals associated more with inorganic particles. Because the fall experiences more intrusions of nutrient-rich waters onto the southern part of the shelf (Verity et al., 1993), often penetrating close to shore, PON and POC (as well as particulate calcium and magnesium) show less difference between concentrations in samples collected within and beyond 16 km offshore, indicating the influence of biogenic particle production on the shelf in this southern region.

Fewer data on particulate trace element chemistry are available from the SPREX cruises. Also, fewer elements were analyzed. Results from the approximately 90 sample collected along the three transects, summarized in Table 4.4, show that concentrations inshore and offshore of 16 km are significantly lower than those observed on the shelf south of Savannah, collected during the fall (i.e., FLEX cruises). This variation reflects the greater influence of river discharge going south along the coast and the dominant southward alongshore transport that occurs during the autumn (Verity et al., 1993).

Table 4.3
Concentrations of particulate organic carbon (POC) and nitrogen (PON) and trace elements in water along four cross-shelf transects off Savannah, Brunswick, St. Augustine, and Cape Canaveral, October 1987.

	POC µg/L	PON µg/L	Al µg/L	Ca µg/L	Fe µg/L	Mg µg/L	Ba ng/L	Be ng/L
<16 km								
Mean	880	128	769	321	441	135	1,146	38
SD	606	69	1,104	313	631	173	988	54
>16 km								
Mean	332	49	48	100	59	31	208	7
SD	179	21	112	116	235	37	306	10
	Cd ng/L	Ce ng/L	Co ng/L	Cu ng/L	Cr ng/L	Dy ng/L	Ga ng/L	Gd ng/L
<16 km								
Mean	393	697	131	236	927	90	298	51
SD	1,775	1,332	216	332	1,462	257	549	102
>16 km								
Mean	42	44	16	34	295	8	22	4
SD	206	83	35	90	744	30	46	6
	Hf ng/L	La ng/L	Li ng/L	Mn ng/L	Mo ng/L	Nd ng/L	Ni ng/L	Pb ng/L
<16 km								
Mean	47	315	783	7,903	37	293	450	219
SD	129	661	1217	15,327	33	601	910	386
>16 km								
Mean	4	20	72	704	23	19	126	19
SD	15	39	127	1,137	26	37	425	32
	Pr ng/L	Sc ng/L	Sm ng/L	Sn ng/L	Sr ng/L	Th ng/L	Tl ng/L	U ng/L
<16 km								
Mean	86	393	61	98	8,912	88	18,072	24
SD	162	945	114	363	9,369	192	18,350	35
>16 km								
Mean	6	62	4	9	3,493	5	2,571	4
SD	11	111	7	39	6,234	9	5,774	22
	V ng/L	Zn ng/L	Zr ng/L					
<16 km								
Mean	2,489	1,363	645					
SD	6,992	2,226	1,163					
>16 km								
Mean	185	385	91					
SD	661	551	238					

Unpub. data (Windom, 1987, DOE SAB Program, Progress Report).

Table 4.4
Concentrations of particulate organic carbon (POC) and nitrogen (PON) and trace elements collected along three cross-shelf transects off Savannah, Kiawah Island, and north of Charleston, April 1988 (Windom et al., 1989)

	POC ug/L	PON ug/L	Al ug/L	Fe ug/L	Cd ng/L	Co ng/L	Cu ng/L	Pb ng/L	Mn ng/L	Ni ng/L	Zn ng/L
< 16 km											
Mean	225	28	53.4	33	0.63	8.9	24	25	756	48	242
Median	223	29	54.0	35	0.59	9.6	16	21	855	41	160
SD	80	10	38.5	19	0.35	5.2	19	14	422	40	209
> 16Km											
Mean	93	14	3.9	3	0.46	0.9	10	4	60	17	36
Median	78	12	1.3	1	0.30	0.6	6	3	22	7	14
SD	52	7	10.2	8	0.45	1.4	11	4	116	28	76

4.2.6.4 Cross-Shelf Mixing

As freshwater and suspended sediments from land mix across the shelf, a number of processes affect the transfer between particulate and soluble phases and, therefore, influence transport and fate of trace elements in shelf waters. Trace elements can be removed from solution by precipitation and/or particle scavenging. Trace elements may also be enriched due to inputs along the mixing gradient/transport pathway. Inputs may include atmospheric fallout and/or release (dissolution, desorption) from particles. In the following sections, the cross-self distribution and transport of dissolved and particulate trace metals in the water column are considered separately.

Dissolved trace elements: The rapid increase in pH and ionic strength as freshwater mixes with seawater affects the solubility of many elements (e.g., iron, manganese, and cobalt). Increasing ionic strength also destabilizes colloids, which flocculate and can scavenge dissolved organic and inorganic species (Windom et al., 1971; Windom and Smith, 1985). Most of this removal occurs in the inshore portion of the freshwater-seawater mixing zone. Other elements, such as barium and radium, are desorbed from particles so that dissolved concentrations increase during mixing (Shaw et al., 1998). Still other elements undergo no chemical transformation, and concentrations in solution during mixing are simply a product of the proportion of the riverine (freshwater) and seawater end-member concentrations. These mixing behaviors are referred to as non-conservative and conservative, respectively. Concentrations of non-conservative elements will have a non-linear relation to salinity, whereas those of conservative elements will vary linearly with salinity.

An example of conservative mixing is the variation in dissolved arsenic concentrations in estuaries of southeastern US rivers (see Figure 4.15). Concentrations exhibit a linear relation to salinity with a freshwater end-member concentration around 0.2 μg/L (2.7 nM) and an ocean end

member of 1.5 µg/L (20 nM) at a salinity of 35 ppt (Waslenchuk, 1977), which is in the range of observed concentrations for open-ocean waters (Bruland, 1983). For elements behaving conservatively during estuarine mixing (i.e., simple mixtures of river and ocean end-members), the riverine flux to the continental shelf can be estimated from the discharge weighted concentrations of the rivers (C_O) multiplied by their discharge (Q), or:

$$\text{River Flux} = C_O \cdot Q_R \qquad (1)$$

The only other "conservative" element for which there are sufficient, reliable data for the South Atlantic Planning Area is fluorine or fluoride (Windom, 1971).

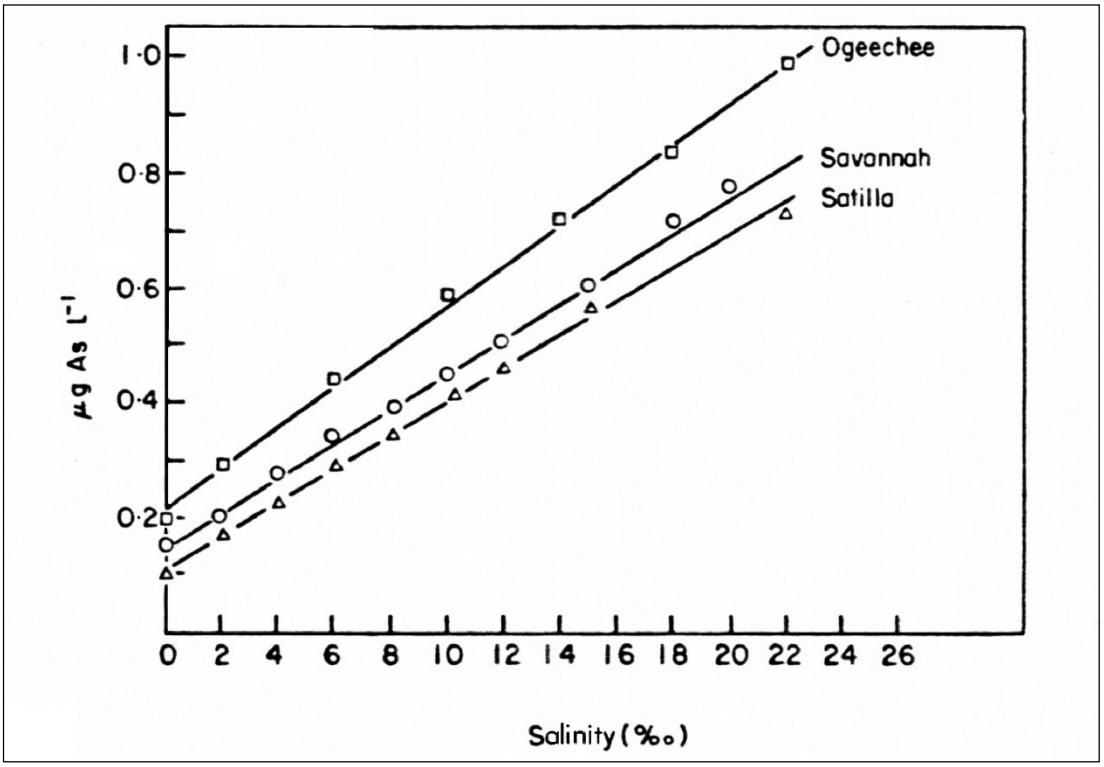

Figure 4.15 Variations in arsenic (As) concentrations with salinity (Waslenchuk and Windom, 1978); an example of conservative mixing.

Several authors have developed advection/diffusion, mass-balance models to assess the behavior of non-conservative elements during estuarine mixing (Boyle et al., 1974; Li and Chan, 1979; Officer, 1979). The aim of these models is to allow estimates to be made of rates of inputs to or removal from solution along the mixing gradient. They also allow for the estimation of net transport through the nearshore freshwater-seawater mixing zone to shelf waters. Parameters used in these models include the river discharge (Q_R), the observed river (i.e., freshwater) end-member concentration (C_O), and the apparent river end-member concentration (C_A), which is determined from an extrapolation of a linear regression of concentration on salinity at the higher end of the salinity gradient, as will be discussed with examples. Using these model parameters, the input (I) or removal (R) of a trace element during estuarine mixing is given by the equation:

$$I(\text{or } R) = Q_R(C_A - C_O) \quad (2)$$

And the soluble net trace element flux to the shelf is given by:

$$\text{Net Flux} = Q_R \cdot C_A \quad (3)$$

For the freshwater-seawater mixing zone of the South Atlantic Planning Area, both positive (input) and negative (removal) non-conservative behaviors have been observed. An example of the former is barium behavior in the Pee Dee River/Winyah Bay and the Savannah estuary mixing zones (Figure 4.16). As shown, barium concentrations reach a maximum at an intermediate salinity, then vary linearly at higher salinities. The Y (concentration) intercept of the regression curve provides the estimate of C_A, the apparent freshwater end member.

Other trace elements that exhibit of this type of behavior include cadmium, copper, and nickel (Figure 4.17). Results for these metals indicate that remobilization from particles or, as Windom and Smith (1985) suggest, atmospheric input probably explains the observed enrichments.

The distribution of zinc concentrations along the mixing gradient, shown in Figure 4.17, indicates estuarine removal. Iron and manganese are also removed during mixing, and their concentration compared with salinity can be modeled as follows:

$$\text{Ln } [C] = kS + a \quad (4)$$

where [C] is concentration and S is salinity. The constant, k, is the slope of the semi-log plot of iron or manganese concentrations against salinity as shown in Figure 4.18. From these data and equation (4), Windom and Smith (1985) estimated that about 90% of the iron and manganese transported from freshwater runoff is removed from solution during mixing. They applied the same approach to the zinc data and estimated that about 55% of this metal was likewise removed from solution. They suggest that most of this removal occurs in estuaries and in the nearshore, within 5 km of shore.

There is another type of non-conservative mixing behavior indicating removal of an element during freshwater-seawater mixing, but where the rate of removal exceeds the input in the freshwater runoff. An additional removal from an oceanic source must account for a portion of the removal. Uranium is an example of a trace element where this applies.

Maeda and Windom (1982) and Windom et al. (2000) have reported data on uranium behavior in estuarine and shelf water which indicates that there is removal of this element in salt marshes that act as a sink for seawater uranium, a process shown for other coastal systems along the East Coast (Church et al., 1996; Duncan and Shaw, 2003; Charette and Sholkovitz, 2006). This process is shown in the data presented in Figure 4.19, which is a plot of dissolved uranium relative to salinity.

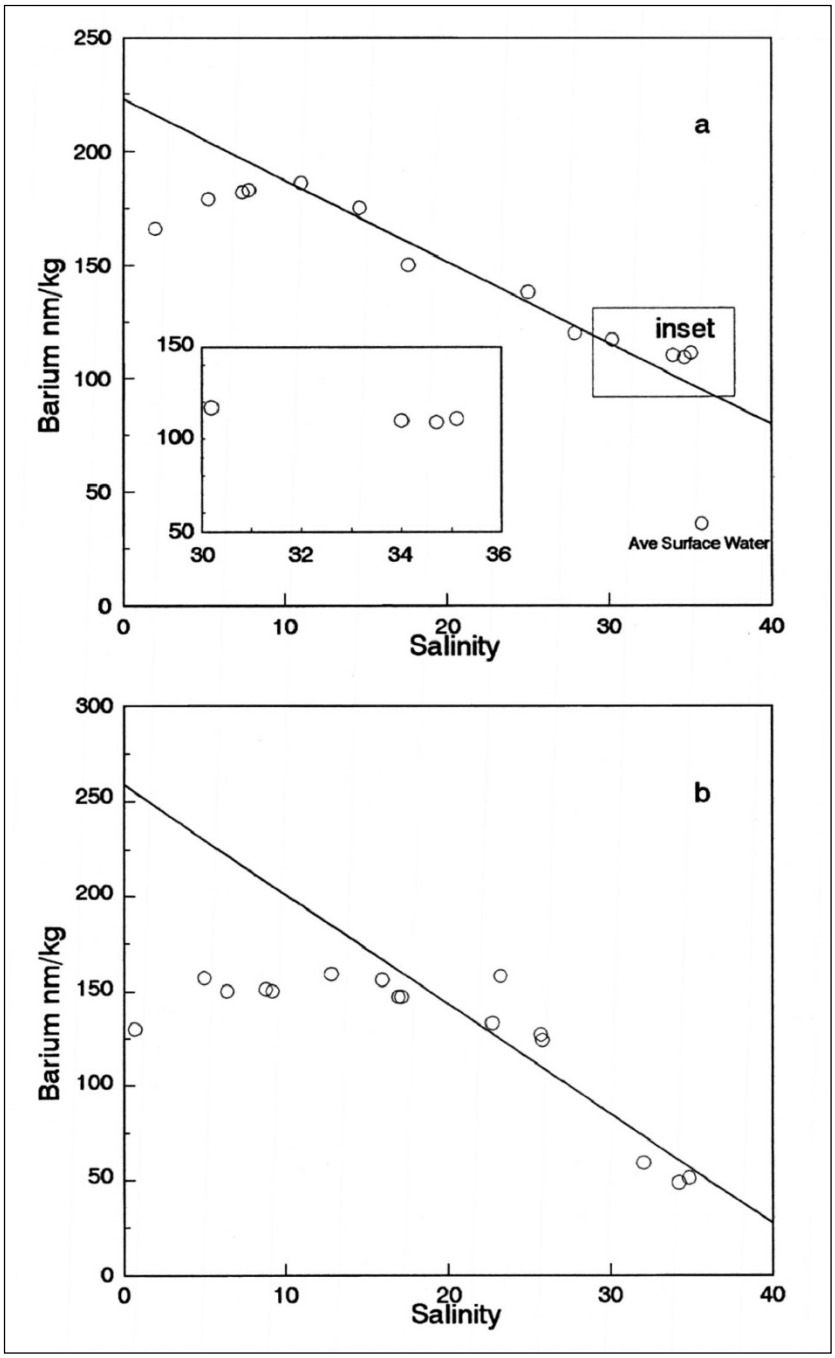

Figure 4.16 Dissolved barium versus salinity in the Pee Dee River at Winyah Bay (a, with inset for samples outside the mouth of the Bay) and the Savannah Estuary (b). Solid lines show the regression of the linear part of the mixing relationship (modified from Shaw et al.,1998).

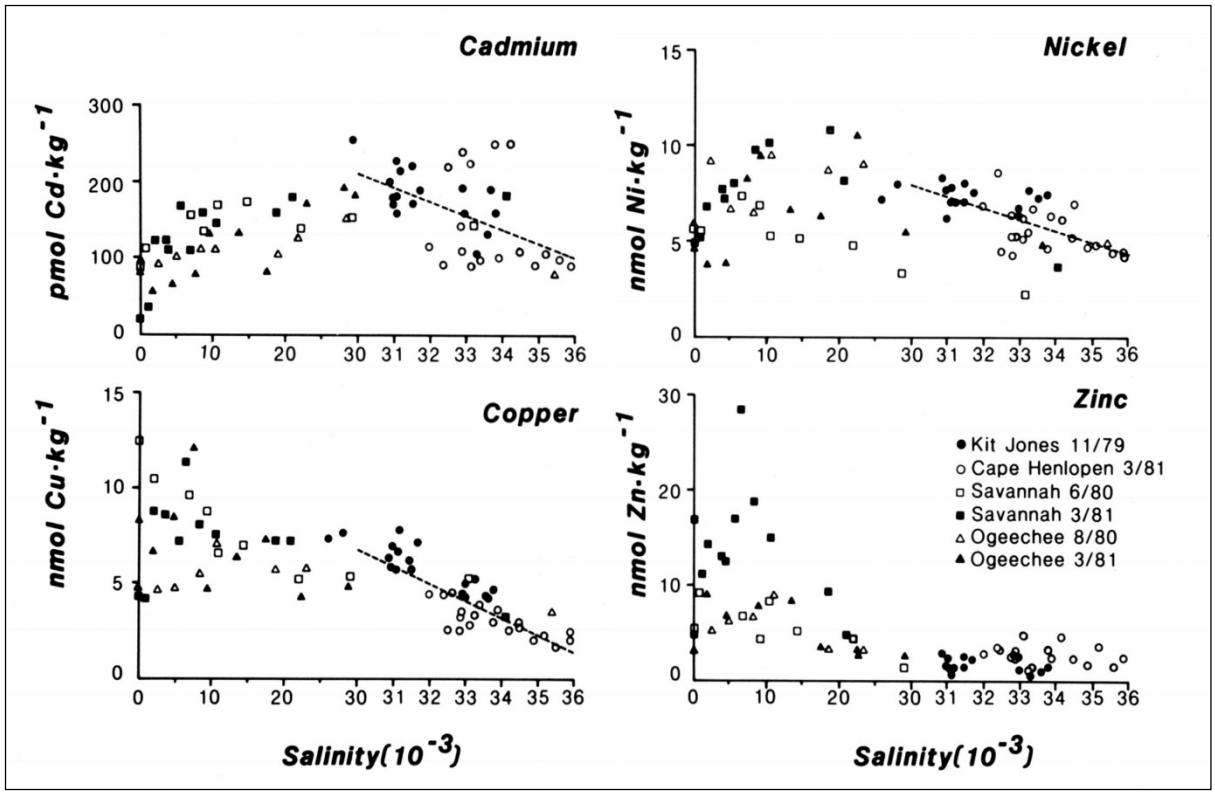

Figure 4.17 Dissolved cadmium (Cd), copper (Cu), nickel (Ni), and zinc (Zn) relative to salinity in southeastern US waters. Dashed lines are the regression curves for metal concentration on salinity for samples collected beyond the coast (salinity >30 ppt) (Windom and Smith, 1985).

In this plot it is clear that the uranium concentrations negatively deviate from conservative mixing. Using equation (3), the calculated Net Flux is negative, implying a net removal within the estuarine/coastal system. Also, from equation (2) the estuarine/coastal removal is greater than the River Flux (eq.1) which indicates that the excess uranium removed must be supplied by an oceanic source.

Windom et al. (2000) assumed that the uranium removal takes place in the anaerobic environment of coastal salt marshes and estimated a rate of removal of 70 μmoles U/m^2, which is comparable to the 15 μmoles/m^2 reported for salt marshes along the Delaware coast by Church et al. (1996). Although Windom et al. (2000) went on to extrapolate the removal estimate to the 80,000 hectares of salt marsh adjacent to the Savannah estuary to yield a net annual uranium removal of 5.8×10^4 moles, it is difficult to extrapolate this estimate to a wider area, given more recent reports. For example, Moore and Shaw (2008) have also observed evidence of uranium removal in other estuarine regions of the southeastern US Atlantic coast. Their results, however, indicate that under some conditions uranium might be added to the water column, perhaps due to submarine groundwater inputs or to redox cycles.

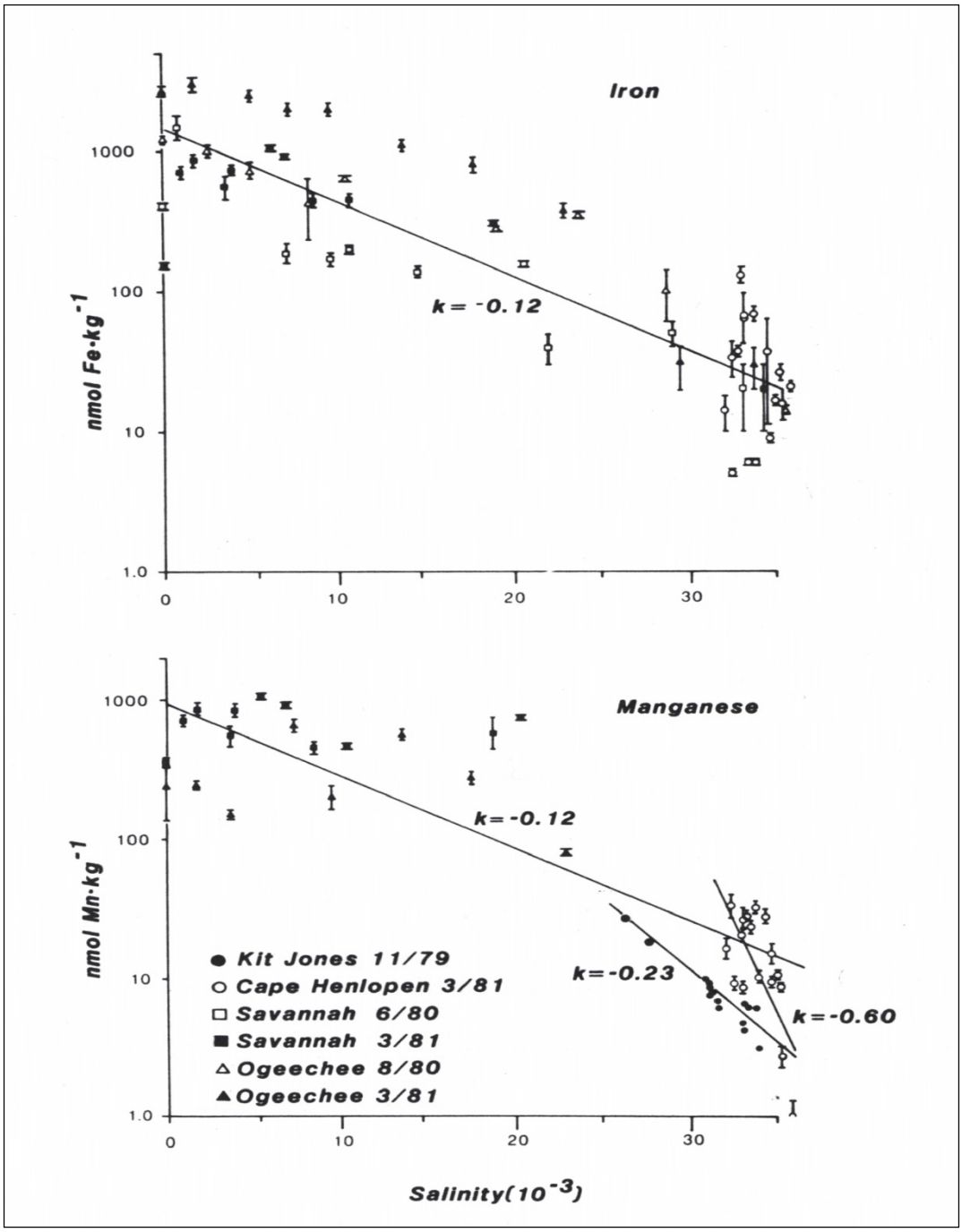

Figure 4.18 Iron and manganese versus salinity along transect out to the shelf break (Windom and Smith, 1985). The slopes of the regression curves (k) are shown and provide input to equation (3).

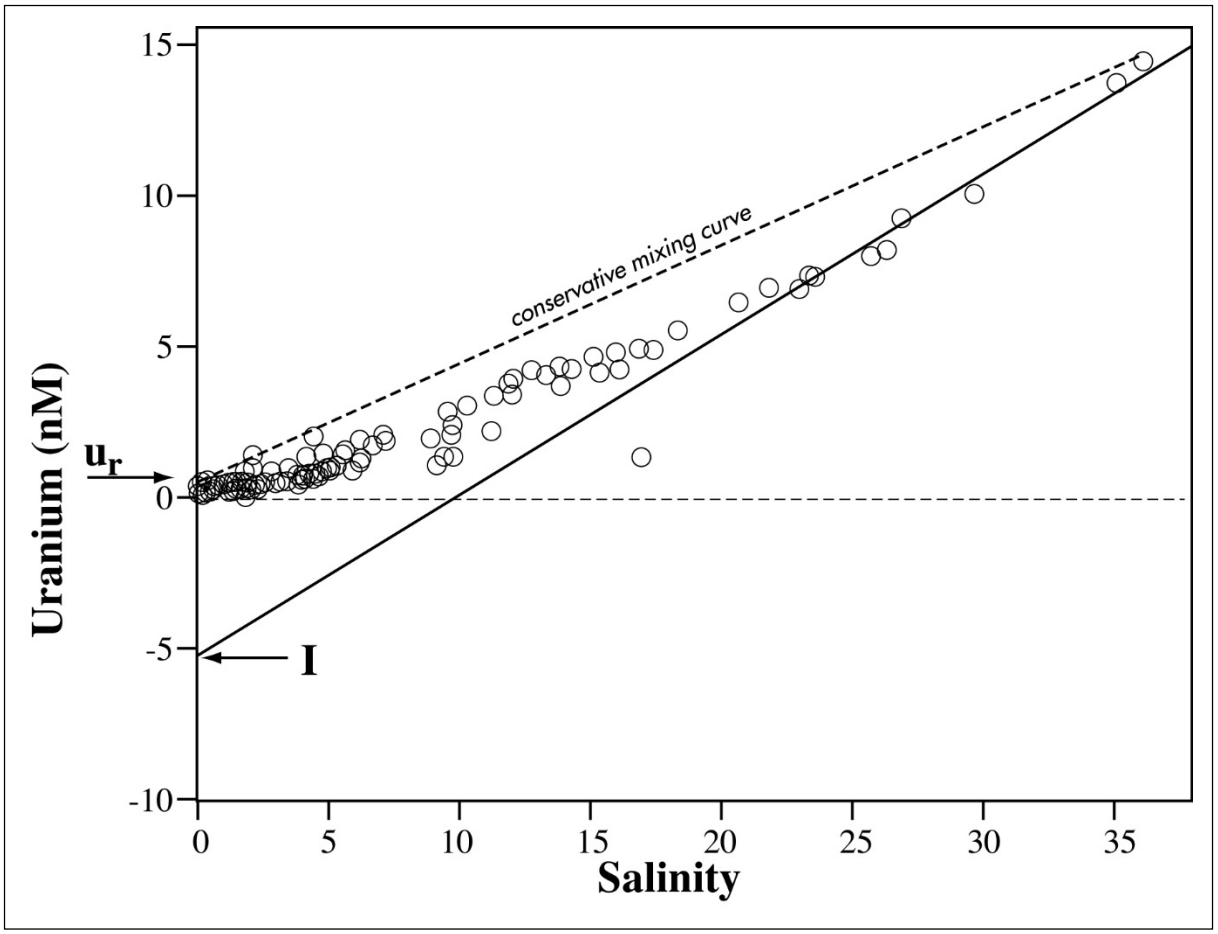

Figure 4.19 Dissolved uranium versus salinity (ppt) for samples collected along a salinity gradient through the Savannah estuary and adjacent shelf. The solid line is the regression curve of uranium on salinity for salinity >25 ppt. **I** is the apparent freshwater end-member concentration (Windom et al., 2000).

Particulates: A number of suspended particulate samples have been collected from the water column of the southeastern US continental shelf. Some of the earliest were collected by Bigham (1972) from the inner shelf for clay mineral analysis, but were also analyzed for percent organic matter. Observed suspended sediment concentrations were from <4 to >100 mg/L, and ranged from <10 to >90% organic matter, with higher values observed for the lowest suspended matter concentrations. There are considerably more, unpublished data similar to this (Clark Alexander, Skidaway Institute of Oceanography, pers. comm.), but the most useful for assessing cross-shelf particulate chemistry are those reported in Windom et al. (1989), Windom and Gross (1989), and unpublished data of Windom (1988, DOE SAB Program, Progress Report). The cross-shelf variation in concentrations of PON and POC was presented earlier (Figure 4.7) and shows the exponential decrease in particulate organic matter moving offshore. These data also indicate that the N:C ratio approximates the Redfield value across the shelf.

The data shown in Figure 4.7 characterize the organic fraction of suspended particles across the shelf. The inorganic fraction of suspended particles across the shelf can, likewise, be characterized with the results from Windom and Gross (1989), Windom et al. (1989), and

Windom (1988, DOE SAB Program, Progress Report). These data are summarized in Figures 4.20 and 4.21.

Figure 4.20 presents data for samples collected during the SPREX cruise along four northern transects (off Georgetown, Charleston, Kiawah Island, and Savannah) and during the FLEX cruises along four southern transect (off Savannah, Brunswick, St. Augustine, and Cape Canaveral). Results show that particulate aluminum concentrations decrease rapidly across the coastal boundary front similar to those for POC. The ratio of POC to aluminum, however, increases in offshore particulates, indicating the increasing importance of biogenic particles offshore as particles from coastal sources settle out of suspension (Windom and Gross, 1989).

The dominance of the inorganic fraction of the suspended sediment load on trace element concentrations is demonstrated by the strong covariance of their concentrations with particulate aluminum (Figure 4.21). But the biogenic fraction may also contribute to the trace element content.

Windom et al. (1989) argued that the trace metal content of suspended sediment on the continental shelf could be predicted from the particulate carbon to particulate aluminum ratio (C/Al) using the equation:

$$R_{obs} = R_i + R_o(C/Al) \qquad (5)$$

where the observed metal to aluminum ratio in particulate samples is represented by R_{obs}, where R_i is the ratio in nearshore bottom sediments, dominated by the inorganic fraction and relatively constant over a large range of aluminum values (Windom, 1989), and R_o, the metal to aluminum ratio in phytoplankton. For the trace elements they studied (cadmium, cobalt, copper, iron, manganese, nickel, lead, and zinc), particulate cadmium was influenced the most by the biogenic fraction and iron was influenced the least. This is demonstrated by comparing the results presented in Figure 4.22 with those in Figure 4.21. Clearly, cadmium shows a much larger variability over a range of aluminum concentrations.

4.3 BOTTOM SEDIMENTS

The only active area of sediment accumulation on the shelf is in the inner shelf as shown in Figure 4.12. The sediments further offshore are relict sands. The boundary between the accumulating and relict sediment region is approximately shown in Figure 4.12 and described more fully by Pilkey and Frankenberg (1964). This boundary coincides approximately with region of rapid decrease in particulate aluminum (Figure 4.20).

Polmeroy et al. (1993) report a mean annual accumulation rate for nearshore sediments in deposition centers (shown previously in Figure 4.12 as areas of fines) of 1.4 g/cm^2. They point out that this sediment accumulation is probably sustained by river input, but must also contain an input of fines winnowed from offshore, relict sediments.

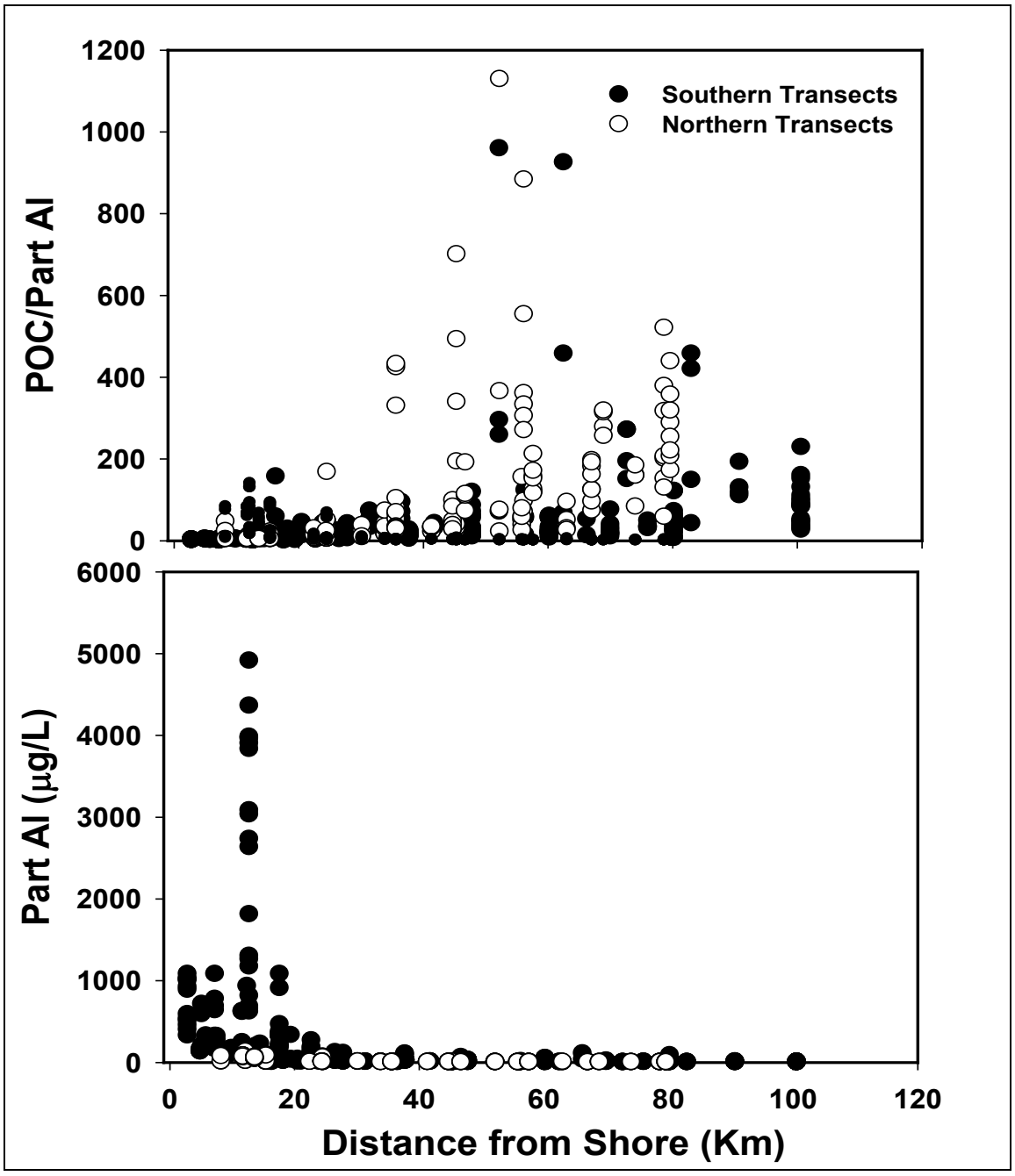

Figure 4.20 Cross-shelf variation in particulate aluminum and the ratio of POC to aluminum. Data from Windom et al. (1989) and Windom and Gross (1989).

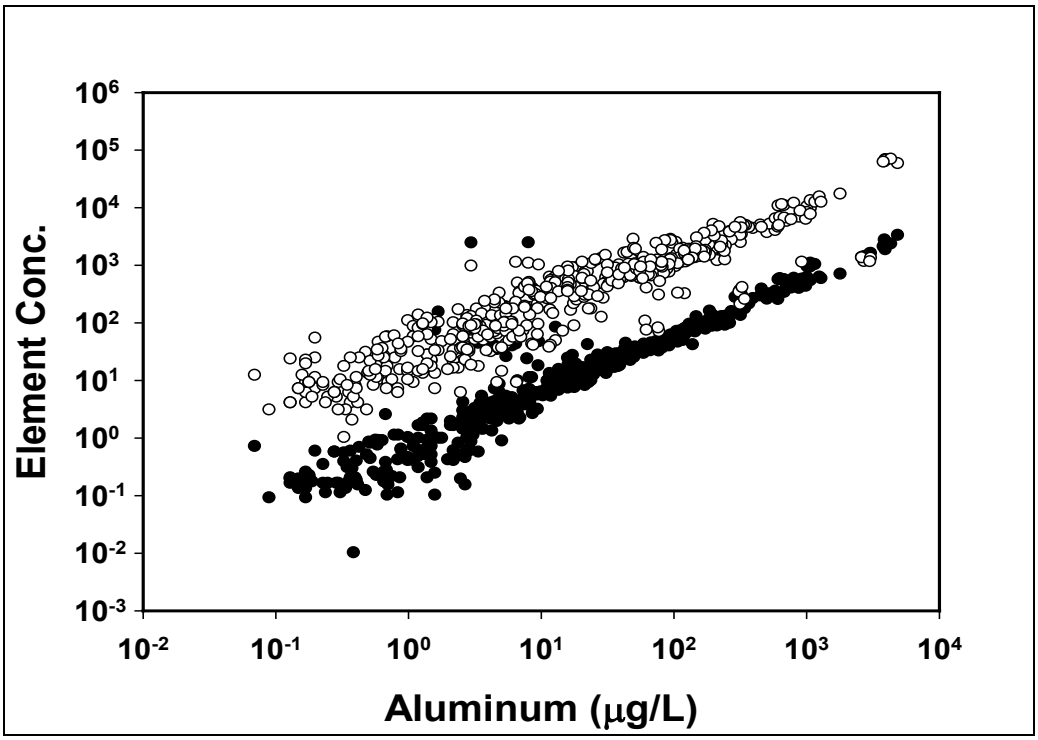

Figure 4.21 Cross-shelf inter-elemental relationships, particulate iron and manganese relative to particulate aluminum. Open dots represent manganese (ng/L) and closed dots represent iron (μg/L). Data are from Windom et al. (1989), Windom and Gross (1989), and Windom (1987, unpublished data, DOE SAB Program, Progress Report).

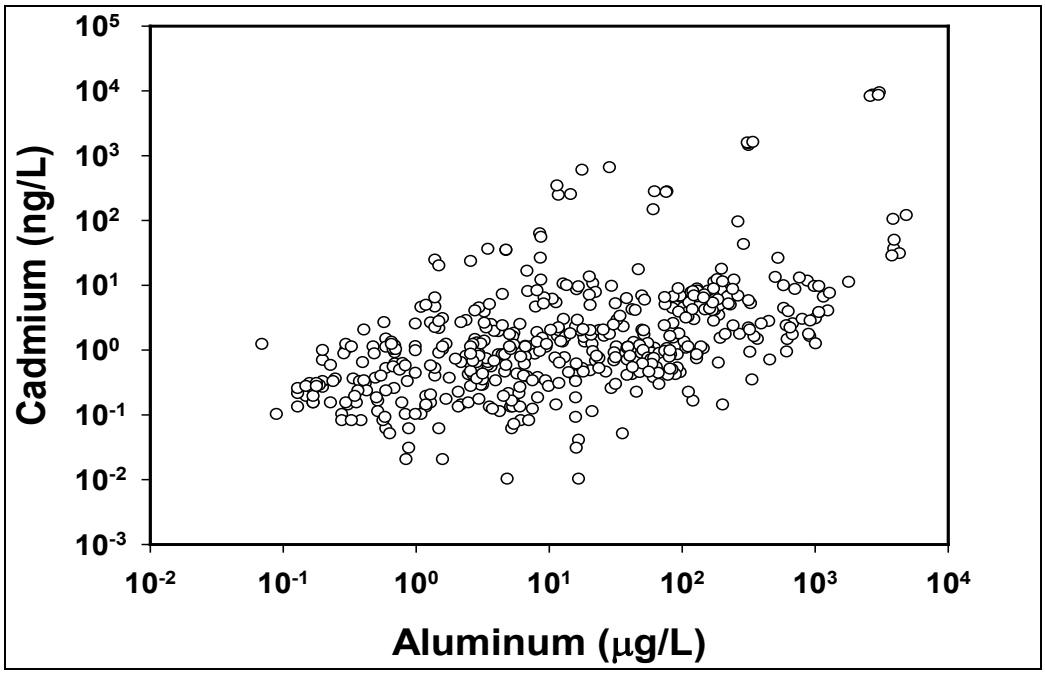

Figure 4.22 Particulate cadmium relative to particulate aluminum in cross-shelf samples. Data sources are the same as for Figure 4.21.

Windom et al. (1989) found that trace element concentrations in bottom sediments from the coastal region of the southeastern US, remote from any obvious contamination source, was significantly correlated to aluminum concentrations and the slope of regression curves were similar to the metal:aluminum ratio of natural in crustal material. Only concentrations of mercury and cadmium did not exhibit a significant relation to aluminum, and this was argued to be due to a significant, natural contribution of the organic fraction of bottom sediments. These authors demonstrated that aluminum concentrations, which are dependent on the clay fraction of sediment, can be used to "normalize" sediment metal data for grain-size effects. Thus, the metal-aluminum relationships, documented for natural estuarine and coastal sediment throughout the southeastern US, can be used to identify anthropogenic contributions to bottom sediment metal concentrations.

Polmeroy et al. (1993) reported data on down-core sediment analyses for several trace metals. Using aluminum as a normalizer, their results indicate that metal levels can be assumed to be natural, and inputs have been relatively constant over the time recorded by these core (>100 years before present).

Reports on trace element concentrations in outer-shelf and slope bottom sediments include Windom and Betzer (1979), from the BLM Southeastern Atlantic OCS Program, and another by Bothner et al. (1979). Results from Windom and Betzer (1979) were for surface samples while the report by Bothner et al. (1979) includes some results from cores.

Data presented in Table 4.5, from Windom and Betzer (1979), are for acid-soluble metal concentrations in bottom sediments collected at stations along four transects across the continental shelf and slope. The transect off Cape Fear is outside the South Atlantic Planning Area, but data for this transect and for those from the one off Cape Romain indicate that this shelf region is different, with higher concentrations of aluminum in samples on the shelf, than those from the southern two transects. It is difficult to compare acid-soluble results with those for total digestions, but the data suffice to suggest that the outer-shelf and slope sample are relatively metal poor (inner-shelf bottom sediments have aluminum concentrations two orders of magnitude higher).

Data reported by Bothner et al. (1979) are for a group of cores taken in an area on the outer shelf off Cape Romain and another group off Brunswick. These cores typically penetrated to depths of about 20–40 cm, but several vibracores penetrated >2–3 m. Off Georgia, the sediments were >99% sand and had carbonate concentrations on the order of 10%. A couple of cores from the northern group (near the boundary of the South Atlantic Planning Area) had a few percent of fines and carbonate concentrations >70%. Although the authors analyzed data for total concentrations of 32 trace elements, data are reported only for a subset of 30 samples from five cores. These samples ranged in aluminum concentrations from ~0.3 to 0.7%. Iron varied over an order of magnitude from ~0.1 to >1.0%. In general, all element concentrations were "low compared to those found in average sandstone and in average crustal rocks and are characteristic of an area having uncontaminated coarse-grained sediments" (Bothner et al., 1979).

Table 4.5
Mean acid-soluble trace metal concentrations in bottom sediments of the southeastern US shelf and slope (Windom and Betzer, 1979). Stations F, G, H, and I are on the slope

Transect	Sta	Al (mg/g)	Cd (ug/g)	Cr (ug/g)	Cu (ug/g)	Fe (mg/g)	Pb (ug/g)	Ni (ug/g)	V (ug/g)	Zn (ug/g)
Cape Fear	B	3.50	0.02	4.20	0.70	0.72	0.81	0.34	13.0	3.40
	C	2.20	0.02	3.50	0.41	0.85	0.71	0.20	12.0	2.10
	D	0.90	0.02	2.50	0.17	0.35	0.26	0.21	10.0	0.80
	E	2.50	0.03	5.30	0.41	0.60	0.85	0.38	14.0	1.80
	F	0.20	0.05	8.90	0.60	0.29	0.45	0.23	1.90	0.70
Cape Romain	B	0.30	0.03	1.10	0.16	1.00	0.81	0.81	1.40	1.70
	C	1.60	0.01	2.30	0.22	0.54	0.96	0.24	17.0	1.50
	D	3.60	0.01	3.50	0.23	0.91	1.68	0.84	29.0	2.40
	E	1.20	0.02	3.90	0.20	0.16	0.89	0.37	14.0	1.00
	F	1.10	0.02	6.10	0.14	0.37	0.83	0.27	14.0	1.70
	G	13.80	0.04	5.30	0.19	0.38	0.68	1.94	92.0	7.20
	H	0.80	0.07	13.10	0.09	0.51	0.35	3.10		4.60
Brunswick	B	0.08	0.03	0.50	0.20	0.26	0.56	0.56	0.90	1.30
	C	0.08	0.05	1.50	0.28	0.19	0.67	0.67	1.30	1.40
	D	0.10	0.04	3.70	0.15	0.98	0.85	0.86	1.80	1.90
	E	0.14	0.04	4.00	0.13	1.07	0.60	0.33	2.10	1.90
	F	0.10	0.02	3.70	0.07	0.34	0.58	0.25	1.50	1.30
	G	0.11	0.03	6.00	0.11	0.82	0.50	0.38	2.20	1.80
	H	0.18	0.02	11.20	0.33	0.93	0.92	0.34	3.00	2.90
	I	1.10	0.15	20.10	0.50	2.89	0.44	0.78	7.30	7.10
Daytona Beach	B	0.18	0.04	3.70	0.05	1.03	0.76	0.28	2.20	1.60
	C	0.10	0.02	3.30	0.01	0.54	0.10	0.11	2.00	1.40
	D	0.09	0.02	2.40	0.08	0.20	0.54	0.09	2.10	0.80
	E	0.04	0.02	1.60	0.16	0.13	0.20	0.05	0.20	0.90
	F	0.82	0.18	11.00	0.49	3.75	0.30	2.50	8.10	7.70

4.3.1 Atmospheric Inputs

The atmosphere is an efficient transport medium for the input of trace element to the continental shelf from both land-based and offshore sources. Offshore transport of air masses from land, in the dominantly westerly winds, supplies continual input to the shelf. Estimates of this input can be made based on average atmospheric concentrations and atmospheric-deposition model.

Several reports on the chemistry of the South Atlantic Planning Area have included data on trace element concentrations in air samples collected over the shelf. These are summarized in Table 4.6, where data from these various studies are provided for different offshore areas of collection. Data for most of the metals are from Mullin (1978) who collected 5–7 air samples each, for metal analysis, just off the coasts near Charleston, Savannah, Brunswick, and Jacksonville. With the exception of iron, nearshore air appears to have higher concentrations of metals.

Table 4.6
Trace metal concentrations in air samples collected over the southern US shelf (concentrations are ng/m^3 of air)

Area	Al	Fe	Mn	Cd	Cu	Ni	Zn	As	Hg	Pb*
Nearshore (Mullin, 1978)										
Charleston	100	74	4	1.8	10	2.9	23			31
Savannah	160	120	3.2	0.4	4.3	11	15			25
Brunswick	170	80	2.4	0.4	2.1	0.7	14			38
Jacksonville	180	80	4.1	0.2	3	2.2	7			28
Middle-outer Shelf										
Mullin (1978)	53.5	107	1.8	0.3	8.5	3.8	10			22
Waslenchuk (1977)		209					9.5	1.5		
Windom and Taylor (1979)									3.3	
Central Atlantic										
Duce et al. (1976)	140	94	1.2	0.2	0.9	0.1	3.2	0.07	>.49	3.5

* From Windom and Smith (1985)

Comparing all the data indicates that shelf air has consistently higher concentrations of trace element than open-ocean Atlantic air collected in Bermuda (Duce et al., 1976). This is not surprising, but only copper, nickel, arsenic, mercury, and lead were an order of magnitude or more concentrated in air over the southeastern US shelf.

Although most of the data that have been reported are for total metals collected on filters (i.e., particles), data for mercury include some information on the vapor phase contribution to air samples. Windom and Taylor (1979) reported that more than 75% of atmospheric mercury is in the vapor phase.

With the exception of mercury, all of the metal concentrations in air samples, when normalized to aluminum, appear to be of natural, crust origin (i.e., they have metal:aluminum ratios which

are similar to those in natural crustal rocks). It is clear that natural dust makes up the bulk of the atmospheric samples over the shelf. On some occasions, a single dust storm can transport tons of natural clay and silt material across the shelf at concentrations over 100 $\mu g/m^3$ (Windom and Chamberlain, 1978).

4.3.2 Fluxes and Budgets for the South Atlantic Planning Area

In this section, information presented in earlier sections is used along with dimensions, dynamic processes, and the hydrology of the South Atlantic Planning Area to assess fluxes and budgets of trace elements. This synthesis of the data allows estimates of rates of inputs and removal to the shelf system and to determine the relative importance of transport pathways and their sensitivity to change that may affect shelf chemistry.

4.3.2.1 Dissolved Trace Elements

Several authors have estimated dissolved trace elements fluxes across various boundaries of the shelf system in a variety of ways. For example, river inputs have been estimated by multiplying the total river runoff by the discharge-weighted, average dissolved trace element concentrations of the rivers discharging along the coast (Windom and Smith, 1979; Windom et al., 1985). Estimates of soluble trace element fluxes in rivers presented in Table 4.7, however, are based on the apparent river end member, discussed in Section 4.3.1.3, multiplied by total freshwater discharge to the South Atlantic Planning Area, 62 km^3 (total river discharge from Menzel et al., 1993, minus the Cape Fear River discharge). These types of data (i.e., apparent end-member concentration), when available, take into account removal or inputs in the estuarine/nearshore interface when assessing dissolved fluxes to the shelf.

For cadmium, copper, iron, manganese, nickel, and zinc, estimates of the apparent freshwater end-member concentrations, 69 pM, 8.8 nM, 100 nM, 10 nM, 4.5 nM and 9.8 nM, respectively, were based on data from Windom and Smith (1985), and arsenic, lead, and mercury were assumed to behave conservatively. An apparent freshwater end-member concentration for barium of 260 nM was based on the results of Shaw et al. (1998), and the net flux estimated for uranium by Moore and Shaw (2008) was used directly. Using the apparent end-member concentration, C_A, equation (3) can then be used to estimate a net flux to the shelf, through the estuarine/nearshore system.

Table 4.7 also presents estimates of atmospheric trace element fluxes to the South Atlantic Planning Area. These are based on atmospheric concentrations given in Table 4.6 and using dry deposition velocities for cadmium, copper, nickel, iron, manganese, and zinc of 0.4, 0.66, 2.5, 1.2, 1.04, and 2.1 cm/sec, respectively (Mullin, 1978; Windom and Smith, 1985; Duce et al., 1976) and 1 cm/sec for lead. The mercury flux is based on the average total deposition rate of 28 ng/m^2 reported by the National Atmospheric Deposition Program at the Cape Romain site for the time period of 2004 to present. These data allow estimates of fluxes at the air-sea interface, which are then integrated over the $5.9x10^4$ km^2 area of the continental shelf between Cape Romain, South Carolina and Cape Canaveral, Florida.

Table 4.7
Estimates of trace element fluxes (10^4 moles/year) to shelf waters of the South Atlantic Planning Area. Open ocean trace element concentrations from Bruland (1983) and Nozaki (1991) for uranium.

Trace Element	Freshwater Net Flux	Atmospheric Flux	Open Ocean Conc. (nM)	Gulf Stream Flux
Arsenic	23	36	23	9,200
Barium	1,600	-	100	40,000
Cadmium	4.2	1.9	0.7	280
Copper	54	155	4	1,600
Iron	620	6,200	1	400
Mercury	0.6	0.3	0.005	2
Manganese	61	63	0.5	200
Nickel	31	300	8	3,200
Lead	1.6	190	0.01	40
Uranium	1	-	14	6,000
Zinc	62	5,800	6	2,400

Although the estimated fluxes have large uncertainties, they still provide a basis for comparing the relative importance of different pathways. This comparison suggests that for most elements for which fluxes can be compared, the atmospheric input is of the same order as, or greater than the net input from freshwater runoff. Four elements have an atmospheric input of about an order of magnitude greater than that for freshwater runoff: iron, nickel, lead, and zinc.

The atmospheric lead flux is ten times the riverine flux. These data are from reports that are almost three decades old (Windom et al., 1985), and the quality of the data may be questionable. But atmospheric lead contamination from lead tetraethyl, used in gasoline, was certainly prevalent during the 1970s and 1980s. Also, Mullin (1978) reported that lead was the most enriched metal in dust samples he collected, relative to its natural crustal abundance, followed by copper, nickel, and zinc. His estimates of the atmospheric flux to the South Atlantic Planning Area, including nearshore data (shown in Table 4.6), are about a factor of 5–10 higher for the metals he studied (cadmium, copper, iron, manganese, lead, and zinc). He also found that a significant fraction (5–91%) of the copper, nickel, and zinc was soluble in seawater.

The higher atmospheric flux rates for iron probably reflect its natural abundance and enrichment in dusts. Large dust storms, originating from the arid regions of the southwestern US, have been reported to have transported tons of dust across the southeastern US shelf (Windom and Chamberlain, 1978) and are enriched in iron oxides as evidenced by the red color of the dust.

As is the case for nutrient inputs to the shelf, another input pathway for trace elements to the South Atlantic Planning Area shelf is through Gulf Stream intrusions and eddies. Atkinson et al.

(1983) estimated that shelf waters from the coastal front out to the shelf break (from about 10 to 80 m depth), between Cape Romain and Cape Canaveral, is turned over roughly every 2–6 months due to intrusions and eddies. Using their study area shelf volume (~1,000 km^3) and assuming that it is turned over every three months, an input volume of 4,000 km^3 of offshore ocean water would be transported on to the shelf annually. This water volume estimate, along with estimates of the trace element concentrations in the oceanic source water, can be used to estimate the significance of this source.

Also like nutrients, metal concentrations in the Gulf Stream and Western North Atlantic Water vary with depth depending upon their involvement in biogeochemical cycles, which often lead to surface depletion and bottom water enrichment. Although there have been several studies of various metals in the Sargasso Sea (Lewis and Landing, 1990) and near Bermuda (Jickells and Burton, 1988; Bruland and Franks, 1983), which demonstrate the biogeochemical behavior just described and metal variations with depth, the compilation by Bruland (1983) of average trace element concentrations in the oceans is the most comprehensive. His values for the average concentrations of trace elements, which are dominated by deeper ocean concentrations, are provided in Table 4.7 and used as the source water in estimating a "Gulf Stream" trace element flux to the shelf.

The estimates of Gulf Stream fluxes clearly dominate all other inputs with the exceptions of those for iron and lead. These two metals are extremely depleted in deep ocean waters. Iron is a major micro-nutrient necessary for primary production but is not regenerated with depth (or on the same time scales) as nitrogen, phosphorous, and silicon are. It is likely that the riverine and atmospheric inputs to the shelf are necessary to sustain the observed high primary production on the outer shelf, although this is not a subject that has received specific research focus.

Lead is particle-reactive, thus it is scavenged onto particles in the surface ocean and not regenerated at depth. As a result, lead is depleted in oceanic waters, and it is not surprising that other input pathways are more important on the shelf.

Another way to assess the significance of the trace element fluxes presented in Table 4.7 is to estimate residence time for each element based on a shelf budget using only the land-based fluxes (Table 4.8). Residence time is simply the total metal content of shelf water (volume=1,000 km^3) divided by the combined riverine and atmospheric fluxes. If these fluxes are significant, then the calculated residence times should be on the order of one year, or similar to the approximately 2–6 month turnover rate of the water as estimated by Atkinson et al. (1983). As the results show, land-based inputs are sufficient only to support shelf concentrations of copper, iron, lead, and zinc at shelf turnover rates of the order of a year or less. For the other elements, turnover rates would need to be much slower if concentrations are to be supported only by land-based inputs.

The conclusion drawn from these estimates (budgets, fluxes, and residence times) is that Gulf Stream intrusions and eddies dominate the input and concentrations of dissolved trace elements over the major part of the shelf. The influence of land-based sources is limited to inner shelf regions.

Table 4.8
Residence times for trace elements based on land-based inputs

Element	Combined Flux River+Atmos. (10^4 Mole/Y)	Total Metal Content of Shelf Water (10^6 Moles)	Residence Time (Years)
Arsenic	59	15	25
Barium	16*	50	3
Cadmium	6.1	0.16	4
Copper	209	4.1	0.2
Iron	6,820	32	0.5
Mercury	0.9	0.63	63
Manganese	124	12	10
Nickel	331	6	1.8
Lead	191.6	0.12	0.1
Uranium	1*	14	23
Zinc	5,862	2	0.3

4.3.2.2 Particulate Trace Elements

The transport/flux of trace elements across the southeastern US shelf on particles is inhibited by the strong coastal frontal zone (Blanton, 1981; 1986). Within this zone, particles are deposited and resuspended, and tend to be transported southward. But a fraction of the particles do escape the front. Windom and Gross (1989), using cross-shelf particulate aluminum concentrations as a proxy and particle size measurements, modeled the distribution using an advection-diffusion model with a Stokes settling velocity removal term. The model was fitted to observed cross-shelf particulate aluminum concentrations from which the cross-shelf advection velocity for particles could be estimated. The conclusions of this research were that only about 10% of the particulate load delivered to the coast by southeastern rivers escapes the estuary and inner shelf, and that an insignificant amount of inorganic particles greater than ~10 μm are transported to the shelf through the coastal front.

Windom et al. (1989) reported data on trace element chemistry in particles in samples collected across the shelf during the SPREX cruises (discussed above). Based on the metal:aluminum ratio of the particulate samples and using the results of Windom and Gross (1989), they estimated the particulate trace element flux crossing the 30 m isobath. This was then compared to cross-shelf soluble fluxes (Windom and Smith, 1985) to give a ratio of the soluble flux to that in particles (Table 4.9). Results demonstrate that, with the exception of iron, the cross-shelf particulate trace element flux is relatively insignificant when compared to the flux of dissolved trace elements. But these authors point out that these are very crude estimates and that most of the calculated trace element flux would be on biogenic particles, which are formed on the shelf.

Windom and Smith (1985) also assessed the potential importance of particulate trace element removal to bottom sediments. Although they developed a plot of potential trace element removal for various removal rates, the estimate given in Table 4.9 assumes that sediments are actively accumulating on the shelf in an area of 5.6×10^4 km^2, the accumulation rate is 1cm/1,000yrs, sediment specific gravity is 2.5 g/cm^3 and the metal concentrations in the sediment are similar to those reported by Windom and Betzer (1979) and Bothner et al. (1980) for the shelf.

Table 4.9
Particulate trace element fluxes on the South Atlantic Planning Area shelf. Removal is based on a sedimentation rate of 1 cm/1,000 yrs.

Trace Element	Dissolved:Particulate Flux Ratio	Particulate Flux mole/year	Shelf Sediment Trace Element Concentration μmoles/g	Removal Flux to Sediments 10^4 moles/year
Cadmium	370	114	0.0002	0.03
Copper	730	740	0.009	1.2
Iron	0.2	3,100*	19	2,700
Manganese	2.6	23*	0.8	110
Nickel	240	1,200	0.014	1.9
Zinc	20	3.1*	0.037	5.2
* Multiply by 1,000				

Clearly this sediment removal rate is very speculative, but it serves to point out that the removal of trace elements in bottom sediments is probably important, especially on the outer shelf where biogenic particles are formed and are either entrained in Gulf Stream eddies, remineralized in the water column, or deposited in sediments where they can be remineralized as well. The sediment accumulation rate may also accommodate for the large iron and manganese atmospheric fluxes.

Although trace element concentrations in bottom sediments may be extremely low, they represent a significant portion of the shelf trace element inventory at any given time. This is clear, using a few metals as examples, when the combined particulate and dissolved trace element content of a 50 m column of water (from Tables 4.1 and 4.4) is compared to the content of a 1 cm thick sediment layer (Table 4.10). Iron is particularly enriched in sediments, suggesting that shelf sediments may be a sink for iron. This may occur as a result uptake in phytoplankton blooms induced by Gulf Stream eddies and intrusion. Much of the organic matter produced then accumulates in sediments where it is remineralized leaving iron behind.

Table 4.10
Comparison of trace element content of a 50 m water column to a 1 cm thick shelf sediment layer

Trace Element	Water Column mg/m^2	Sediment Column mg/m^2
Cadmium	0.92	0.65
Copper	14	14
Iron	202	27,000
Manganese	38	1,200
Nickel	18	22
Zinc	8.3	60

The potential importance of sediment-water exchange on the shelf with regard to trace element cycling has received relatively little attention in the past. One of the few studies was by Byrd (1988), who observed a seasonal cycling of arsenic concentrations in shelf waters. Low concentrations observed in winter and spring, below that expected for conservative mixing, were attributed to biological uptake and/or adsorption on particles followed by removal to sediments. During the summer, concentrations were observed to exceed conservative mixing concentrations. This was attributed to sediment release of arsenic due to organic matter remineralization.

4.4 NATURAL AND SYNTHETIC ORGANIC COMPOUNDS

This section reviews past, pertinent research and data on natural or biogenic hydrocarbons, including those associated with petroleum and synthetic organic compounds, such as pesticides and polychlorinated biphenyls (PCBs). Because the southeastern US Atlantic coast is relatively pristine, there has been little concern about contamination of shelf areas from land-based sources of pesticides and petroleum hydrocarbon. Nevertheless, a few studies have been carried out and they are summarized below.

4.4.1 Biogenic Hydrocarbons

As was the case with trace elements and nutrients, the first, and apparently the only, systematic survey of hydrocarbon compounds on the South Atlantic continental shelf was conducted as a part of the South Atlantic (OCS) Environmental Studies reported by Lee (1979). Although this work suffered, as did the others, from analytical and sampling artifacts, the latter mostly associated with the sampling platform, it provides a reasonable view of conditions four decades ago. Before this study, the only data for the offshore region between Cape Canaveral and Cape Hatteras were those reported for water by Swinnerton and Lamontagne (1974) for low molecular weight hydrocarbons: methane, ethane, ethylene, propane, and propylene which averaged 45, 1, 4.7, 0.1, and 0.5 nl/L, respectively. Also, Brown and Huffman (1976) reported that hydrocarbon concentrations in surface and near surface waters in this region ranged from 1 to 17 µg/L; paraffinic hydrocarbons were the most abundant and aromatic compound (more typical of petroleum sources) were less than 20%.

The results reported by Lee (1979) included hydrocarbon concentrations in surface film, water, particulates, zooplankton, and bottom sediment samples. For the most part, the pattern of hydrocarbons observed in surface film samples was similar to that of the sampling vessel's oil, suggesting that these data are invalid. Samples collected during calmer weather contained some compounds, which suggested an origin in land plants.

Particulate samples taken from near surface and near bottom waters (Lee, 1979) had a similar range and pattern in seasonal average hydrocarbon concentrations of from 0.1 to 0.8 μg/L. Samples from which these data were obtained, however, also included some sampling contaminations from the sampling apparatus.

The results reported by Lee (1979) indicate that dissolved hydrocarbon concentrations were generally higher than particulate concentrations. Evidence of the local source of hydrocarbons in the water column and particulates is the close correlation between concentrations and chlorophyll and particulate and dissolved organic carbon. This clearly suggests that petroleum sources were not important.

As was the case with water and particulates, sediment hydrocarbon concentrations were also reported (Lee, 1979) to be low, ranging from 0.04 to 2.2 μg/g with a 0.6 μg/g average. They were mostly composed of saturated hydrocarbons such as C_{17} alkane and C_{18} pristane and phytane. The hydrocarbon signature of all sediments from the region was very similar except for the stations along a transect off north Florida where the highest concentrations of aromatic compounds were observed. This is an area of active sedimentation which may act as a deposition site of contamination from various petroleum sources (e.g., shipping).

4.4.2 Pelagic Tar (Tar Balls)

The best indicator of hydrocarbon from petroleum sources on the South Atlantic continental shelf is pelagic tar in the form of tar balls. Two studies included surveys of the concentration and distribution of tar balls in the waters within the South Atlantic Planning Area (Cordes et al., 1980; Van Dolah et al., 1980).

Results of Van Dolah et al. (1980), although published after those of Cordes et al. (1980), were based on samples collected using neuston net tows during a two-year period from 1973 to 1975. Out of the 282 neuston samples collected from all cruises, 153 contained tar at a level greater than 0.01 mg/m^2; of these, only 34 had concentrations greater than 1.0 mg/m^2, comparable to results observed for the MARMAP sampling programs off the northwestern Atlantic and Gulf coasts (Morris, 1971; Pequegnat, 1979). In general, the results of Van Dolah et al. (1980) indicated that the occurrence of tar increased offshore and their data showed little latitudinal variability (Figure 4.23). However, data from one cruise during the autumn of 1973 indicated that pelagic tar was about three times more prevalent in samples collected south of 32°N, either inshore or off.

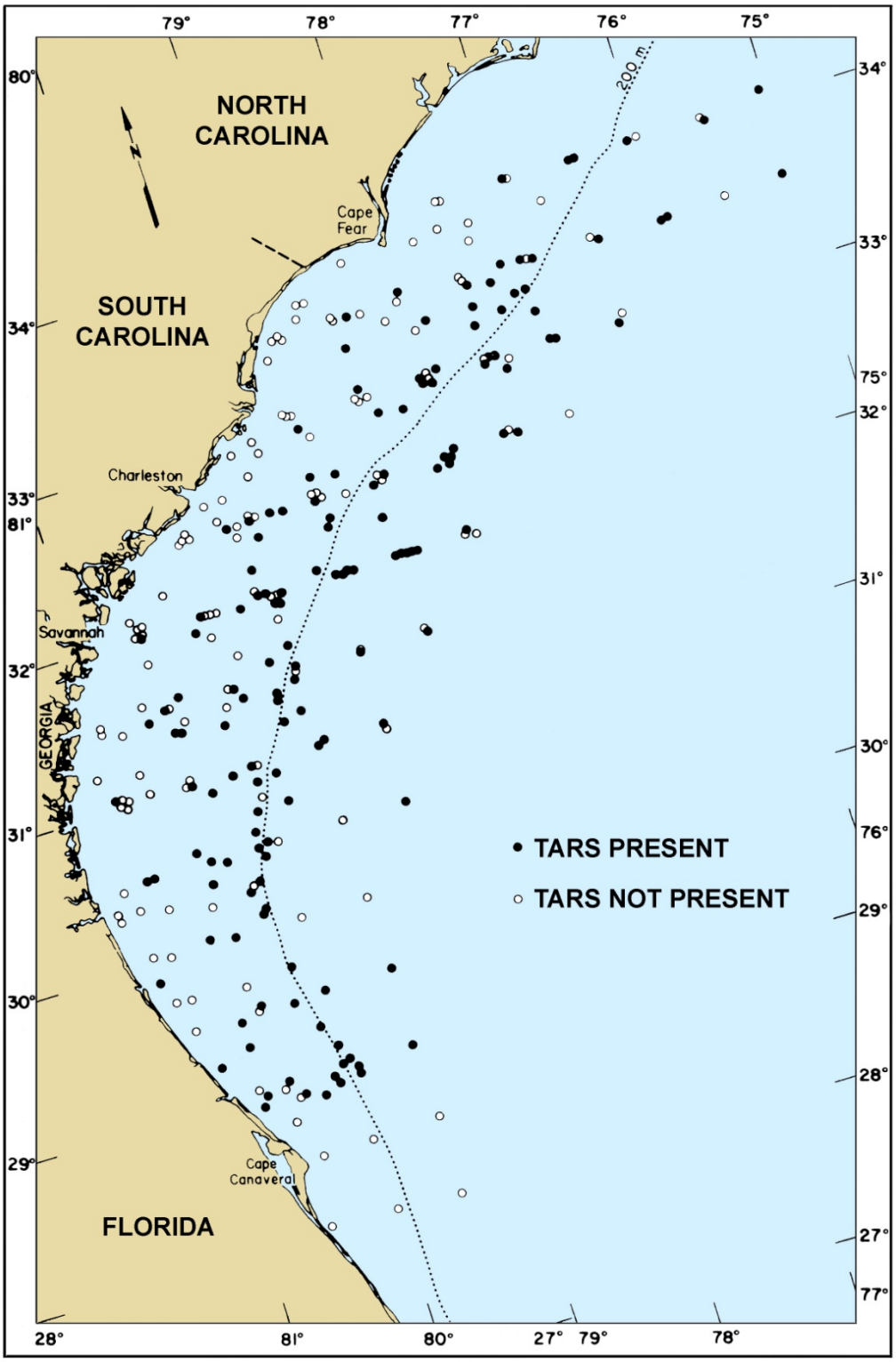

Figure 4.23 Stations at which pelagic tar was collected in neuston tows during six MARMAP cruises between 1973 and 1975 (modified from Van Dolah et al., 1980).

Van Dolah et al. (1980) also identified plastic beads in their neuston samples, and their distribution was similar to that of tar. They concluded that "the higher incidence of both tar and plastic in offshore waters combined with the lack of increased concentrations of these contaminants around South Atlantic industrial areas indicates that the primary source of pollution is through entrainment from other areas via currents and shipping traffic." This conclusion is supported by data reported by Windom et al. (1992a,b) that indicate concentrations below detection levels of polycylic aromatic hydrocarbons (PAHs) in inner shelf sediments off Brunswick and Savannah harbor entrance channels.

Cordes et al. (1980) collected tar balls using neuston nets along cross-shelf transects off Savannah, Georgia and New Smyrna Beach, Florida and at a middle-shelf, alongshore transect during October-December 1979, following the Ixtoc oil rig blowout in Campeche Bay, Mexico. Their purpose was to assess whether tar balls resulting from this spill could be detected along the Georgia-Florida coast due to transport in the Gulf Stream. They observed tar balls up to 2 cm in diameter. No tar was collected within 40 km of shore. The hydrocarbon in the tar that was collected was composed of about 30% PAHs. Of these perylene, because of its resistance to weathering, was the most abundant. Cordes et al. (1980) estimated that the mean concentration of pelagic tar offshore (i.e., >40 km) to be 0.82 mg/m^2, with a maximum concentration of 9.7 mg/m^2. These authors concluded that the observed pelagic tar concentrations along the Georgia-Florida coast, ten months after the Ixtoc blowout, were no higher than previously observed.

It appears, based on the above reports, that hydrocarbon compounds found on the south Atlantic continental shelf within the South Atlantic Planning Area are dominantly of natural origin and the occurrence of hydrocarbons associated with petroleum are limited to the outer shelf due to chronic inputs related to shipping activities.

4.4.3 Synthetic Organic Compounds

Lee and Maruya (2006) pointed out that several sources of synthetic organic compounds result in their release to rivers and subsequent transport to estuaries of the southeastern US Atlantic coast or are discharged directly to coastal areas. These compounds can accumulate in marine biota that may migrate offshore (Maruya and Lee, 1998). But, for the most part, synthetic organic contaminants that reach the coast accumulate in estuarine and salt marsh sediments and do not reach the continental shelf in significant amounts. A few exceptions may include newer, more-soluble pesticide compounds that have shorter environment half-lives but can be more easily mobilized in the water column.

The information base for pesticides and other synthetic organic compounds is relatively small for the South Atlantic Planning Area shelf. Most of these compounds have a low solubility and are therefore removed to particles, so the environmental focus on these compounds has been generally on the inshore, estuarine areas. Also, there is little industrial activity that would generate non-pesticide compounds, such as PCBs. Pesticides, however, have and are being used to support agriculture, the major economic driver in the region, and the dispersive nature of pesticide applications makes it clear that their transport to the shelf is likely.

Starting in the 1960s, pesticides such as DDT were phased out of use because of their environmental persistence. These chlorinated compounds were also hydrophobic and, therefore,

became stably bound to particles which determined their fate and thus limited their transport offshore from land applications. Today, pesticides and herbicides being used in southeastern agriculture are more environmentally degradable (Gianessi and Anderson, 1995a,b), but many are also more soluble and thus more likely to be transported by rivers and the atmosphere to shelf waters.

The earliest study of contamination of coastal waters of the South Atlantic Planning Area by this new class of pesticides was that reported by Kucklick and Bidleman (1994a). These authors collected microlayer samples and subsurface water samples from Winyah Bay and North Inlet, South Carolina every two months during 1990 to assess transport of the contaminants to the coast in rivers. They analyzed these samples for PAHs and the pesticides commonly used in regional agriculture. PAHs (fluoranthene and pyrene), because of their hydrophobicity, were enriched in the microlayer whereas the pesticides were not. Simazine, atrazine, alachlor, malathion α-, and γ- hexachlorocyclohexane were detected, but atrazine (a triazene herbicide) was the most abundant, ranging in concentrations up to 890 ng/L. Another study by these same authors (Kucklick and Bidleman, 1994b), conducted during the same time period, focused specifically on atrazine and found that its transport through the estuarine environment was relatively conservative and could be modeled so that its distribution could be predicted using salinity and fluorescence.

Because atmospheric transport is another likely pathway for pesticides to reach the continental shelf, Alegria and Shaw (1999) investigated the deposition of pesticides in rain to coastal waters. They conducted their study after a major rainfall event and were able to define coastal regions of low salinity off Georgia and South Carolina that, based on several tracers that helped to distinguish surface runoff from rain, reflected the input of rain. In these "pockets" of freshwater they found that atrazine, metolachlor, and trifluralin were 2-6 fold more concentrated than in surrounding surface coastal waters. They estimated that the 2-3 day rain event that produced the freshwater anomalies resulted in the input of 130-490 kg of atrazine, 95-130 kg of metolachlor, and 10-27 kg of trifluralin.

The significance of pesticide transport to the shelf was addressed by Alegria et al. (2000) who analyzed samples from the inner shelf (mainly off South Carolina) for the dominantly used pesticides on agricultural lands of the region. This work was carried out in July 1994 and August 1995, but only atrazine was found in samples from all stations occupied during both campaigns (5.6–12 ng/L in July and in 3.1–11 ng/L in August), and simazine, found in all samples from August, ranged in concentration from 0.8 to 4.6 ng/L, values similar to those reported for other coastal regions beyond the southeastern US The authors argued that the other commonly used pesticides were absent or barely detectable because of their lower solubilities and/or stronger absorption to particles, or their shorter environmental half-life.

Alegria et al. (2000) estimated the total amount of atrazine and simazine in inner shelf waters by multiplying their average concentration by the volume of the inner shelf of their study area (6.4 x 10^{10} m^3). The resulting atrazine content was estimated to be 325–550 kg and the simazine content was estimated to be 180 kg. Using a 30-day residence time for the inner shelf, estimated by Moore (1996), Alegria et al. (2000) estimated the atrazine and simazine fluxes to the shelf at 3,900-6,600 kg/yr and 2,150 kg/yr, respectively. These fluxes are of the same order or higher

than the riverine flux to the coast estimated by Kucklick and Bidleman (1994b). These results led Alegria and Shaw (1999) to suggest that a large fraction of the flux of these, and perhaps other, "newer" pesticides which reach the coast, may be transport to the shelf.

4.5 RADIONUCLIDES

This section addresses studies carried out in the South Atlantic Planning Area on naturally-occurring and human-made radionuclides. Few of the studies were actually conducted on the outer shelf but still have relevance to that region.

4.5.1 Naturally Occurring Radioisotopes

Most of the research involving naturally occurring radioisotopes involves their use as tracers of physical processes. The most commonly used radioisotopes are those in the uranium-238 (^{238}U) to lead-206 (^{206}Pb), ^{235}U to ^{207}Pb, and thorium-232 to ^{208}Pb natural decay series. Within these series there are a number of isotopes of varying chemical behavior and half-lives which make them useful as tracers of processes and in estimating rates. Of these isotopes, ^{210}Pb in the ^{238}U decay series and the quartet of radium isotopes (^{228}Ra, ^{226}Ra, ^{224}Ra, and ^{223}Ra) within the three decay series have been studied within the South Atlantic Planning Area.

Lead-210 is formed from the radioactive decay of radon-222 (^{222}Rn), through a number of short-lived intermediate isotopes. Because radon is a gas, the ^{210}Pb is formed in the atmosphere and, in principal, separated from its parent, ^{222}Rn. The atmosphere it is adsorbed onto particles and deposited (due to rainout) in sediments where it decays with a half life of ~23 yrs. Thus, the change in ^{210}Pb activity with depth allows for estimates of sediment accumulation rates to be made, with appropriate assumptions.

The geochemistry of ^{210}Pb in the estuarine region of the southeastern US has been discussed by Storti (1980) who studied how this isotope accumulates in estuarine sediments and applied it to sediment accumulation estimates. Goldberg et al. (1979) also applied this method to establish a chronology of sediment accumulation in the Savannah Estuary. More recently, Chen (1993) and Alexander et al. (1999) used ^{210}Pb down-core activity to estimate accumulation rates and to infer time horizons (i.e., year of accumulation) in the sediment column. The only application of ^{210}Pb measurements to shelf sediments was that reported by Pomeroy et al. (1993) who estimated sedimentation rates of inner shelf fine sediment deposition (Figure 4.12) sites to range from ~0.5 to 2.2 cm/yr, or 0.7-3.3 g/cm^2.

The application of radium isotopes to various studies of the South Atlantic Planning Area has been predominantly by W.S. Moore (University of South Carolina) and colleagues. The basic understanding of the geochemistry and fluxes of radium isotopes in southeastern rivers and estuaries has been summarized by Moore and Shaw (2008), but additional reports describe considerable work that has also been carried on the shelf. For example, Moore (2000) used models based on ^{223}Ra and ^{224}Ra to derive ages of continental shelf waters. The models compensate for tracer dilution by normalizing the short-lived tracers to each other or to longer-lived ^{228}Ra. Results suggest ages for waters 80-100 km from the inner shelf of from 20 to 30 days.

In addition to being used for identification of pools of rain water on the shelf, as discussed in the section on pesticides (Moore et al., 1998), radium isotopes have also been used to identify submarine groundwater inputs to shelf waters. Moore (1996), studying the radium budget of the US South Atlantic shelf, concluded that the ^{226}Ra budget could only be explained by invoking a significant submarine groundwater input via submarine groundwater discharge (SGD), which includes inputs of fresh groundwater or sea water advected through shelf sediments. More recently, Moore and Shaw (1998) and Shaw et al. (1998) have used radium isotopic tracers to assess the contribution of SGD on shelf water chemistry. While their results suggest that SGD may provide an important input of materials to the shelf, this pathway requires considerable more research.

Moore (2007) reported on the seasonal distribution patterns of radium isotopes measured throughout the water column of the southeastern US continental shelf from Onslow Bay, North Carolina, to Crescent Beach, Florida. Based on the distribution and seasonal inventories of ^{226}Ra and ^{228}Ra activities (highest off the coast of Georgia and decreased off the coast of South Carolina), Moore (2007) concluded that SGD is more important off Georgia than South Carolina, although there are likely to be local "hot spots" of SGD such as that observed by Viso et al. (2010). Based on the excess inventories and fluxes of ^{226}Ra and ^{228}Ra, an estimate was made of the residence time of water on the shelf. This ranged from 30–60 days with a mean of about 40 days compared to the 20–30 day estimate for the residence time of inner-shelf waters (Moore, 2000).

4.5.2 Human-made Radioisotopes

Other than data on cesium-137, the only studies that have involved determination of man-made radionuclides in the South Atlantic Planning Area have been related to releases from the Savannah River nuclear facility and the Chernobyl accident of 1986. Reports including information on ^{137}Cs concentrations in sediments have been previously cited (Chen, 1993; Alexander et al., 1999). In these studies the down-core activity of ^{137}Cs, which was produced by nuclear weapons testing starting in 1954 and reached a maximum in 1963, allows these two date horizons to be identified. These two radionuclide date horizons have been useful in estimating sedimentation rates and in establishing pollution histories based on data from sediment cores.

Although investigations focused on other human-made radioisotopes have been conducted in the estuarine/coastal environment, results are still pertinent to the shelf. For example, results from Goldberg et al. (1979) and Olson et al. (1989), which focused on the estuarine behavior of Pu, a radionuclide released between 1954 and 1974 from the Savannah River nuclear facility near Aiken, South Carolina, from which about 1.1×10^{10} becquerels, or 0.03 curries were released to surface waters within the Savannah River basin. As a part of a study of the pollution history of the Savannah estuary, Goldberg et al. (1979) studied the down-core chemistry, including plutonium activities and isotopic ratios, of sediment cores collected from the adjacent salt marshes. They found that only one of five cores contained detectable levels of plutonium. This core was collected from further upstream than the others and had a $^{238}Pu/^{239+240}Pu$ ratio similar to that of the plutonium released from the nuclear facility.

Olsen et al. (1989) reevaluated plutonium behavior in the Savannah estuary focusing on the suspended particle plutonium activity along the salinity gradient. Their results confirmed those

of Goldberg et al. (1979) in that the $^{238}Pu/^{239+240}Pu$ ratio of river particulates was similar to that of the plutonium released from the nuclear facility. But in the estuary, analysis of suspended particulates and surface sediments revealed the plutonium ratio to be typical of atmospheric fallout (i.e., of an oceanic source). They conclude that the estuary acts as a sink for oceanic plutonium. This conclusion is consistent with results described in other sections of this chapter that indicate that the estuarine environment is perhaps the major contaminant sink for the South Atlantic Planning Area.

Tritium is another radioisotope released from the Savannah River Site nuclear facility. Heavy water production was from 1953 until 1981. Releases of tritium subsequently entered tributaries and the associated groundwater system of the Savannah River and, ultimately, was transported to the coastal area. Bush (1988) reviewed the sources (which include atmospheric fallout from nuclear weapons testing, cosmic ray production in the upper atmosphere, and nuclear power plants, in addition to the Savannah River facility) and fate of tritium in the coastal and shelf environments. Her report clearly demonstrated that the tritium released from the nuclear facility was far more significant than that from other sources. While tritium is a relatively benign radioactive contaminant, its chemically conservative behavior made it an affective tracer of the Savannah River discharge in shelf waters as demonstrated by Bush (1988). While existing conditions have changed, this work demonstrates the usefulness of tritium as a tracer of transport from existing and future nuclear power generating facilities on shore and/or on the shelf.

The Chernobyl Nuclear Power plant accident occurred in April 1986. This resulted in the release to the atmosphere of a number of radionuclides, the most abundant of which was iodine-131 which has a half-life of ~8 days. Windom (1986) reported on the results of analyses of rain samples collected at the Skidaway Institute of Oceanography and analyzed by Curtis Olsen (Oak Ridge National Laboratory) between the time of release and the end of June 1986. Results indicate that the iodine was observed at its maximum within the month of release and decreased to non-detectable levels by June. Longer-lived isotopes (^{103}Ru, ^{134}Cs, and ^{137}Cs) reached maximum rainout during May of that year.

4.6 POTENTIAL IMPACTS OF OCS DEVELOPMENT ON CHEMICAL OCEANOGRAPHY

Impacts of OCS development on chemical oceanography will be related to chemical release from the various activities related to the development or to the interference and/or disruption of natural chemical processes. Because the impacts associated with oil and gas exploration, sand and gravel extraction, and the construction of facilities on continental shelves is understood relative well and is fairly generic, this section will address only impacts that may be specific and/or unique to the South Atlantic Planning Area.

4.6.1 Oil and Gas Exploration and Development

There is a considerable literature on the impact of oil and gas production on continental shelves and the types of materials and compounds released associated with these activities. The intent of this section is not to attempt to summarize this large body of knowledge but to focus on those generic impacts of oil and gas exploration and production that would potentially impact chemical processes in the South Atlantic Planning Area. These impacts are in addition to those related to

the release of specific pollutants that are governed by USEPA effluent limitation guidelines for oil and gas extraction.

The construction and operation of exploratory wells will have two types of potential impacts on the chemistry and chemical oceanography of the outer continental shelf South Atlantic Planning Area, due to material release and alteration of chemical processes. These are summarized in the following sections.

The operation of production wells will have chemical releases related to the oil or gas product and produced water. These releases may include a number of petroleum hydrocarbon compounds, metals, and gases. Speculation on which contaminants and volumes that might be released to the South Atlantic Planning Area if production activities were to commence will not be attempted.

4.6.1.1 Material Releases

By far, the largest amount of material releases related to oil and gas exploration is likely from the discharge of drilling wastes from drilling fluids. Neff et al. (2000) have reviewed the available USEPA data on wells in the Gulf of Mexico. In this region, the average exploratory well was estimated to discharge over board over 5,000 barrels of drilling fluids and over 1,000 barrels of cuttings.

Neff et al. (2000) provide some data on the chemical characteristics of drilling wastes that contain drilling muds, cuttings, and fluids. The major water-column contaminants from these are likely oil and grease and perhaps some metals such as iron, manganese, chromium, copper, and zinc. Formation brines may also be released as well. Other wastes will be associated with the drilling muds and cuttings. And still other, less significant discharges will be from deck runoff and associated with domestic wastes.

Water-based drilling muds (WBM), which would likely be used for drilling OCS oil and gas exploration wells, are typically composed an inert material such as natural clays (e.g., bentonite) or organic polymers, mixed with barite and seawater. During the drilling process, some of this material, mixed with the drill cuttings, is discharged to the surrounding waters. Neff (2005) estimates that about that the total mass of WBM and well cutting discharged per exploratory well is about 2,000 metric tons.

Depending on where the mixed WBM drill cutting wastes are discharged (i.e., near the seafloor or near the surface), the suspended particles and flocculants will settle downstream in the prevailing currents near the well. This will result in a “halo” of sediment around the drilling platform with considerably finer texture than the surrounding sands typical of the outer continental shelf. A number of metals will be considerably higher in concentrations than the surrounding ambient sediments, but they are not likely very labile.

Another plume of soluble and fine-grained suspended particle will create a second plume that will disperse in the prevailing currents, but Neff (2005) suggests that this material is diluted 100 fold within 10 m of the discharge. It is likely that a significant water column influence will be limited to the order of 100 m around the well.

Other potential releases will be associated with ship operations in support of the drilling platforms, antifouling paint ablation, etc., as will be the case for any structures placed on the OCS, as discussed under Section 4.6.3.

4.6.1.2 Alteration of Chemical Processes

Oil and grease discharged from several potential sources associated with the drilling operation will change the air-sea boundary layer in the vicinity of the rig, the dimensions of which will depend on prevailing currents. This layer would likely accumulate particulate and flocculent material and serve as a site for the potential concentration of contaminant organic compounds and metals and clearly impact air-sea exchange of gases.

As mentioned above, the discharge of drilling muds and well cutting during exploratory drilling will result in a deposit around the well that will be of finer texture than shelf sediments. The dimensions of this deposit can be easily determined from the analysis of barium concentrations in the sediments around the drilling platform. For example, a study by Continental Shelf Associates (2006) for exploratory wells in the Gulf of Mexico found that, based on barium concentrations, impacts of drilling mud discharges could be detected several hundreds of meters from the platform and at thicknesses reaching 45 cm. There are clearly contaminants associated with this deposit, especially near the platform, but perhaps more important is the potential impact that this fine sediment "cap" has on exchange at the sediment water interface.

The finer texture of the drilling mud cap will have a lower permeability and thus impede solute exchange across the sediment-water interface. This will affect oxygen penetration into the sediments, which, in turn, will alter redox processes (e.g., nutrient regeneration). This finer sediment would also be more easily resuspended. Overall, the change in the rate and timing of advection and diffusion across the sediment-water interface would be affected and would change how materials are cycled on the shelf, at least in the close vicinity of wells.

4.6.2 Sand and Gravel Extraction

Dredging for sand and gravel extraction may physically change the contour of the sea bottom and release sediment contaminants and/or fine particles during the process. As pointed out in discussions on sediment chemistry earlier in this chapter, the sands of the South Atlantic Planning Area have very low concentrations of any materials that might be released. So the major concern for impacts from this activity is any resulting change in bathymetry.

A common concern regarding the impact of sand and gravel extraction is any resulting depression that may become hypoxic (Byrnes et al., 2000). Also of concern is that depressions may also provide a localized sedimentary trap for finer particle. Both of these would result in an altered sediment-water interface and potentially affect boundary exchange and create a contaminant sink. But clearly the hydrodynamic of the site would control the extent of these impacts (Nairn et al., 2005).

4.6.3 Renewable Energy Development

Regardless of the type of alternate energy development on the OCS, multiple structures/platforms will be required and they will require periodic servicing by surface vessels.

In addition to the release of chemicals into the environment around the structure, impacts which can be anticipated, there may be additional unintended/unanticipated ones that may be belated to the siting of the structure. These are discussed separately in the following sections.

4.6.3.1 Anticipated Impacts

Releases of materials from structures constructed for the purpose of energy production are expected and strategies to minimize them can be put in place. Boehlert et al. (2008) reviewed potential chemical releases associated with offshore wave energy generation systems. Their findings are applicable to all offshore platforms/structures associated with energy production. These authors distinguished between unintentional leaks and spills and expected releases from sacrificial anodes and antifouling paints. Unintentional leaks would include fuels, oils, hydraulic fluids, etc. associated with support vessels. This material would initially concentrate on the surface where it may be subsequently either dispersed by winds and currents or accumulated on particles and deposited to the sediment column in the vicinity of the structure.

Sacrificial anodes and ablation type, metal-based (copper) antifouling paints are intended to release metals to the surrounding water column. These metals would be rapidly diluted but there would still likely be an increased concentration in adjacent sediments due to the particle-reactive nature of these metals.

The siting/construction of any structure on the continental shelf will likely involve disturbance of bottom sediments. For the most part, the sediments of the continental shelf are coarse-grained and contain insignificant amounts of contaminants or nutrients that could be mobilized during any sediment disturbing activity. Even nearshore, where sediments are more fine-grained in localized areas, the likelihood of contaminant mobilization is low, given that there is little or no evidence of sediment contamination.

Structures located in a shelf area that experiences nutrient inputs from Gulf Stream intrusions and/or eddies will act as nutrients traps as fouling organisms colonize it. This, in turn, attracts fish and ultimately creates a more particle-rich environment. Dissolved organic and inorganic matter (including nutrients) are more likely to be accumulated in particles and to be removed to adjacent bottom sediments or, perhaps, swept off the shelf and accumulated in slope sediments. The latter pathway, involving a longer water-column residence time, may allow for remobilization of the materials from particles and greater dispersion.

4.6.3.2 Unanticipated Impacts

The only potential unanticipated hazard, regarding impacts on the chemistry of the South Atlantic Planning Area, of sea bottom disruption is the breaching of coastal surficial aquifers in the nearshore or enhancing natural exchange along subterranean pathways which connect to the deeper Floridan Aquifer (Moore and Wilson, 2005). There is, however, a major gap in the state of knowledge about groundwater-surface water processes as they relate to these potential hazards.

4.7 SUMMARY AND DATA GAPS IN THE STATE OF CHEMICAL OCEANOGRAPHY KNOWLEDGE WITH REGARD TO OSC DEVELOPMENT

4.7.1 Summary

The chemical oceanography of the South Atlantic Planning Area is controlled primarily by ocean exchange at the Gulf Stream front and transport from the coast controlled by the coastal salinity front formed in response to freshwater runoff. These two physical features of the region influence, spatially and temporally, material inputs to and exchange on the OCS.

Gulf Stream intrusions and eddies deliver nutrient-rich waters from the slope to the OCS, and these same physical processes control the relatively short residence time (the order of month) of shelf water. Nutrients from land-based sources are trapped nearshore, where they are cycled within and between salt marsh estuaries and the inner shelf. Of the nutrients delivered to the coast, only a small portion is transported to the middle and/or outer shelf from the coast, and this is primarily on particles. As a consequence, the middle shelf is a nutrient-poor environment.

Because of their hydrophobic nature (petroleum hydrocarbons, organic compound), particle reactivity (metals, radionuclides), and/or biological accumulation (nutrients), the cross-shelf exchange of environmentally important materials is strongly influenced by the transport and fate of particles. This leads to the trapping of most contaminants from land-based sources in the nearshore due to the barrier to particle exchange caused by the coastal salinity front. Dissolved and particulate material from offshore sources, however, can be transported inshore to be trapped, as well.

High water-column production on the outer shelf, driven by nutrient inputs in Gulf Stream eddies and intrusions, periodically creates a particle-rich environment (phytoplankton detritus, fecal material, etc). Although a large portion of this material is swept off the shelf, some part is accumulated, perhaps only temporarily, in OCS sediments, along with materials that are scavenged on the particles.

Clearly, particle-water interactions and water-column dynamics will control the dispersion of materials released from a facility on the shelf and affect their fate. But particle dynamics in the water column and bottom sediment-water column interactions/exchange are not understood well in the fine-particle-poor environments of the middle and outer shelf. Increased understanding of these processes, in relation to material release from energy production development, will be important to decisions on siting such facilities.

4.7.2 Data Gaps

Although there is a considerable amount of information on the chemical oceanography for the South Atlantic Planning Area, much of this was acquired over two decades ago and, while it is useful for a fundamental understanding of important processes which govern the chemistry of the OCS, it is not very comprehensive in time and space or in the chemical species of potential concern. Improved sampling and analytical technologies that are now available would allow a better assessment, and new understanding is emerging about the importance of processes that have received little attention in the past.

The following sections address basic data/information gaps that should be addressed to develop a better understanding of the chemical oceanography of the South Atlantic Planning Area. This better general understanding of the region is, of course, an important scientific goal. The brief discussion provided in the following section, however, focuses more on data gaps regarding OCS development.

4.7.2.1 Water Column Chemistry

The understanding of the chemistry of the water column across the entire shelf and slope regions of the South Atlantic Planning Area is based on a relatively few cross-shelf sampling transects. The most data have been collected for dissolved nutrients, although most of these historic data have not been properly archived. However, there are still sufficient data to provide a reasonably good understanding of distributions and the dynamics at the Gulf Stream front. For metals, radionuclides, biogenic (i.e., natural), and synthetic organic compounds, the database is much smaller or non-existent.

Dissolved iron is an example of where the paucity of data limits the understanding of an important process in the South Atlantic Planning Area. Data on dissolved iron is limited to about three sampling campaigns off the Georgia coast, which were conducted with little relevance to transport processes on the OCS. It is now recognized that this element, which is not recycled in upwelled water along with the macro nutrients, is an important micronutrient for sustaining primary production. Off the Oregon coast, Chase et al. (2007) found that the iron input from winter and spring runoff is temporarily stored in shelf sediments to be later remobilized and swept off the shelf to support production in the upwelled nutrient-rich waters at the shelf break. Thus shelf sediments act as a capacitor of iron from land-based sources. A similar process may occur in the South Atlantic Planning Area, but there are insufficient data to address this. Alternatively, iron may be mobilized from slope sediments and carried onto the shelf in Gulf Stream intrusion and/or eddies.

Likewise, there is a paucity of dissolved data, similar to iron, for all trace elements and radionuclides and virtually no data on dissolved organic compounds; what does exist was certainly not collected on temporal or spatial scale to make the data useful in assessing shelf transport and cycling. Improved sampling and analytical technologies, superior to those available a couple of decades ago, would allow these data gaps to be filled.

For suspended particulates there is somewhat better spatial coverage of data on the shelf for trace elements and organic matter (i.e., PON and POC), but still insufficient to interpret regarding cross-shelf transport. What data that are available suggest that there is perhaps more efficient offshore transport off north Florida influenced by circulation associated with Cape Canaveral. The area around Cape Romain associated with Charleston Bump circulation may also be a more efficient transport route, but clearly data with more temporal and spatial resolution in the context of seasonal circulation patterns are needed.

An understanding of the spatial and temporal variability in the composition of suspended particles is another information gap that needs to be addressed. New applications of stable isotopes and organic biogeochemistry marker compounds in the suite of analytes would provide considerable insight into processes influencing particle source, cycling, and fate.

Of course, a better temporal and spatial assessment of tar balls and other floating anthropogenic debris is needed to assess the impact of all types of marine operations associated with OCS development. Collected in the context of coastal climatology, these data could provide important insights into the transport and fate of a number of potential contaminants.

4.7.2.2 Shelf Sediments

The coarse-grained, sandy sediments of the shelf region of the South Atlantic Planning Area have, in the past, been considered to be relatively chemically inert and a virtual "desert" biologically. Recent research (reviewed above in Section 4.4.1) by Marinelli et al. (1998), Nelson et al. (1999) and Jahnke et al. (2000, 2005), however, provide a different picture. These researchers have shown that the surface few centimeters of sandy shelf sediments are biologically and chemically quite reactive and that benthic primary production, over much of the shelf, rivals water-column production. There is a seasonal variability of these processes that is likely controlled by fine particle accumulation and resuspension at the sediment-water interface.

The database on the composition of shelf and slope sediments is very limited and primarily limited to bulk analyses of some trace elements and texture. Shelf sediments are generally reported to be composed of about 1% fine particles. But, as shown in Table 4.10, for a reasonable composition of the fines in the upper 1 cm of shelf sediment, resuspension of this material could significantly influence water-column chemistry.

Because of the demonstrated and potential importance of the shelf sediment and particle-water cycling at the sediment-water interface, the lack of understanding of the spatial and temporal variability their composition represents a clear data gap. The same can be stated for slope sediments in which the likely enrichment of organic matter and important sediment-bound nutrients (especially iron) may provide a source of both dissolved and particulate material to the OCS. Clearly, some regions of the shelf and slope of the South Atlantic Planning Area are depositional sites and should be studied. Data on both shelf and slope sediments would likely also provide a map of time-integrated, cross-shelf transport.

4.7.2.3 Groundwater-Surface Water Exchange

Advective flow within the porous shelf deposits of the South Atlantic Planning Area has been observed by several investigators (Brooks, 1961; Moore et al., 2002; Moore and Wilson, 2005; Moore, 2007; Viso et al., 2007). This flow can be driven by a combination of changing atmospheric pressure, tides, and groundwater discharge, or any one of these. The resulting SGD is typically a combination of freshwater and recirculated seawater and is considerably different in composition from the endmembers. The freshwater component originates from either coastal surficial aquifers or the deeper Floridan aquifer. It appears that SGD is more common nearshore (surficial aquifers) but may be more important in the more southern portions of the shelf (Floridan aquifer) of the South Atlantic Planning Area. For example, a submarine spring occurs about 4 km off Crescent City, Florida and connects directly with the Floridan aquifer.

The overall extent of SGD and the importance of material cycling and input associated with the groundwater-seawater exchange are still poorly understood. It is likely that SGD is more common around shelf areas underlain by karst and exchange may be enhanced by fractures in the limestones underlying the shelf. The location of a structure on the shelf in such areas may

facilitate communication between these fractures and the surface. For example, increased inputs of nutrients, commonly enriched in SGD, to an otherwise oligothrophic part of the shelf as a consequence of footings placed deep into the shelf bottom, could result in elevated primary production in the vicinity of the structure.

While consideration of SGD may not be a primary concern in OCS development, it is still of major scientific interest where there is a large knowledge gap.

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CHAPTER 5: PLANKTON COMMUNITIES

5.1 INTRODUCTION AND HISTORY OF PLANKTON STUDIES

The focus of this chapter is phytoplankton, microzooplankton, and zooplankton in the South Atlantic Planning Area (northern border of South Carolina at 34°N to Palm Bay, Florida, at 28°N). It includes a discussion of the features that affect the concentration and type of plankton of the inner (0–20 meter [m] depth), middle (20–40 m depth) and outer (40–60 m depth) shelves. These features include the wind, tidal currents, and rivers that bring freshwater and nutrients to the inner shelf, and the intrusions of deep Gulf Stream water that bring nutrients onto the shelf. The South Atlantic Planning Area is within the South Atlantic Bight (Cape Hatteras, North Carolina at 35°N to West Palm Beach, Florida at 27°N), which is sometimes referred to in this review since several studies have focused on this broader region. Table 5.1 lists plankton studies since 1953 in the US South Atlantic shelf, including large programs (GABEX I & II, US South Atlantic OCS Bench Mark Study, satellite studies) and a number of cruises to sample zooplankton on this shelf.

Before the late 1970s, most of the plankton work in the South Atlantic Planning Area consisted of seasonal studies emphasizing species identification. For example, the US Fish and Wildlife Service M/V *Theodore N. Gill* was used to collect zooplankton during winter, spring, summer, and fall in 1953–1954. The latitude of the collection stations ranged from 27°N (Jupiter Light, Florida) to 35°N (Cape Hatteras, North Carolina) and from inshore out to the Gulf Stream. The major zooplankton groups found at each station during each season were reported in Anderson et al. (1956a,b; 1957) and Anderson and Gehringer (1957; 1958a,b; 1959a,b). Bowman (1971) identified the various copepod species collected during the cruises; Pierce and Wass (1962) reported on chaetognath species. There was a grouping of species associated with coastal, shelf, and oceanic water. Twenty years later, a series of seasonal cruises was carried out over the same general area during the South Atlantic OCS Benchmark study; zooplankton results were summarized by Herman (1979). Offshore cruises to identify phytoplankton were taken by Hulbert (1967) in 1966 and by Marshall (1971) in 1964–1968. They concluded that major phytoplankton groups in this area were diatoms, coccolithophores, pyrrhophyceans, and cyanobacteria.

Earlier investigators had assumed that phytoplankton in the South Atlantic Planning Area followed the Sverdrup (1953) model (i.e., spring bloom) and, thus, there was a search for seasonal trends in primary production and an assumption of a high degree of spatial homogeneity (Haines, 1974; Haines and Dunstan, 1975; Turner, 1981; Turner et al., 1979). In fact, it turns out that an interesting feature of the South Atlantic Planning Area is the lack of the spring bloom that characterizes other areas of the US Atlantic coast. These earlier investigators had assumed that the only source of nutrients for phytoplankton growth on the outer shelf of the South Atlantic Planning Area were the coastal estuaries, since there was often a steep decrease in the concentration of nutrients and chlorophyll going from onshore to offshore (Figure 5.1). This assumption of close coupling of primary production to coastal estuaries led to the concept of "outwelling" (Turner et al., 1979).

Table 5.1
Plankton studies in the South Atlantic Planning Area

Area of Study & Shelf Area	Study Year(s)	Program/ Ship	Plankton Studied	References
29-34°N Inner-Outer	1953-1954	R/V *Gill*	Zooplankton	Anderson et al., 1956a,b; 1957; Bowman, 1971; Pierce and Wass, 1962
30-35°N Inner-Outer	1966	WHOI Cruise	Phytoplankton	Hulbert, 1967
30-35°N Inner-Outer	1964-1968	R/V *Eastward*	Phytoplankton	Marshall, 1971
29-34°N Inner-Outer	1974	S. Atlantic OCS Benchmark Study	Zooplankton	Herman, 1979
29-34°N Inner-Outer	1973-1974	R/V *Eastward*	Phytoplankton (PP, Chl)	Haines and Dunstan, 1975
32-33°N Inner-Outer	1973-1978	R/V *Blue Fin*	Phytoplankton (PP, Chl)	Oertel and Dunstan, 1981
29-32°N Inner-Outer	1980-1981 1983	GABEX I & II	Phytoplankton (PP, Chl) Zooplankton (Summer & Winter Intrusions)	Yoder et al., 1983; 1985; Pomeroy et al., 1987; Paffenhofer, 1983; 1985; Paffenhofer et al., 1984; 1987a,b
32°N Inner-Outer	1986-1988	R/V *Blue Fin*	Phytoplankton, Microzooplankton	Verity et al., 1993c
32°N Middle-Outer	1990	R/V *Cape Hatteras*	Zooplankton	Paffenhofer et al., 1995
32°N Inner-Outer	1781-1985 1993	R/V *Blue Fin*	Phytoplankton (PP, Chl)	Bishop et al., 1980; Yoder, 1985; Yoder et al., 1983; 1985; 1993
34°N Inner-Outer	1979-1981	R/V *John de Wolf*	Chaetognaths	Coston-Clements et al., 2009
29-34°N	1978-1980	Satellite	Chlorophyll	Ishizaka, 1990a; McClain et al., 1984,1990; Yoder et al., 1987
Chl = chlorophyll; PP=Primary Production.				

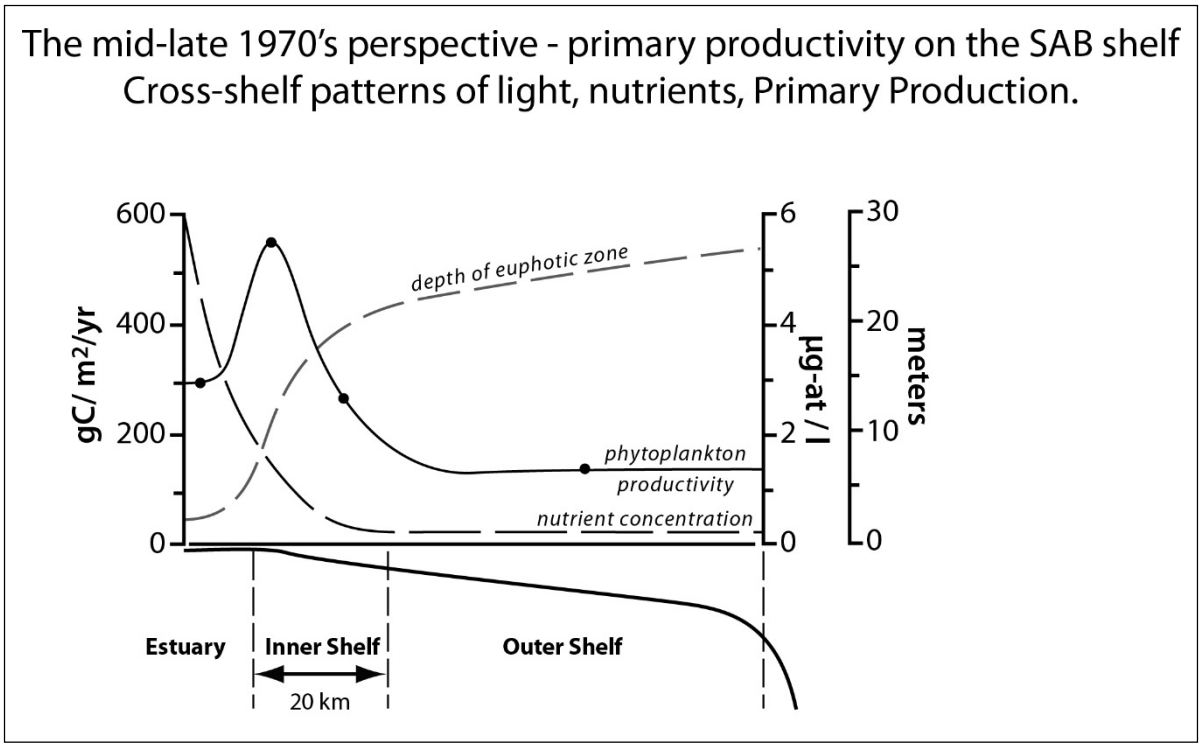


Figure 5.1 Relationship of phytoplankton production to depth of euphotic zone and nutrient concentration in Georgia coastal waters based on data collected in the 1970s (modified from Haines, 1979). Nutrient concentration is in units of µg-atoms/L, phytoplankton productivity is in $gC/m^2/yr$, and depth of euphotic zone is in meters.

However, Yoder et al. (1981a) criticized this outwelling concept and pointed out that, in fact, there was very little export of nutrients from the coastal zone to the middle and outer shelf. Stefansson et al. (1971) authored the first paper to suggest that periodic inputs of nutrients from upwelled Gulf Stream water affected primary production in the SAB, and Atkinson et al. (1978) suggested that the effects of the Gulf Stream on biological processes on the shelf was likely to be a significant factor on biological processes on the shelf.

Beginning in the 1980s, the study of such intrusions dominated offshore plankton studies, so rather than a seasonal sampling strategy, cruises followed intrusions (Figure 5.2). Cruises during Georgia Bight Experiment I (GABEX I, 1980) followed plankton changes after intrusions in mixed winter waters, and the next year GABEX II (1981) cruises followed plankton changes during stratified summer condition where there were subsurface intrusions (Yoder et al., 1983; 1985). The area of study for GABEX I and II was from Cape Canaveral, Florida to Savannah, Georgia. The use of satellites with color scanners that began at this time made available a much broader assessment of phytoplankton in the South Atlantic Planning Area. From 1978 to 1986 the Coastal Zone Color Scanner (CZCS) was used to assess changes in sea color obtained by satellite to estimate chlorophyll concentrations. High chlorophyll bands were found along the coasts of Georgia, South Carolina, and Florida (McClain et al., 1990; Ishizaka 1990a, b, c; Yoder et al., 1987). There were good correlations between the chlorophyll data collected on the GABEX cruises and the satellite color data from the CZCS (McClain et al., 1984). A second generation of satellites with color sensors followed the CZCS with the Sea-viewing Wide Field-

of-view Sensor (SeaWiFS) producing the highest quality ocean color data (McClain, 2009). Signorini and McClain (2007) noted a high correlation between the size of the North Atlantic Subtropical Gyre and chlorophyll a concentrations in the slope region north of the Charleston Bump. Hoge et al. (2001) examined reflectance data retrieved from SeaWiFS in October 1997 and found that highest phytoplankton abundance in the South Atlantic Planning Area was in waters surrounding capes.

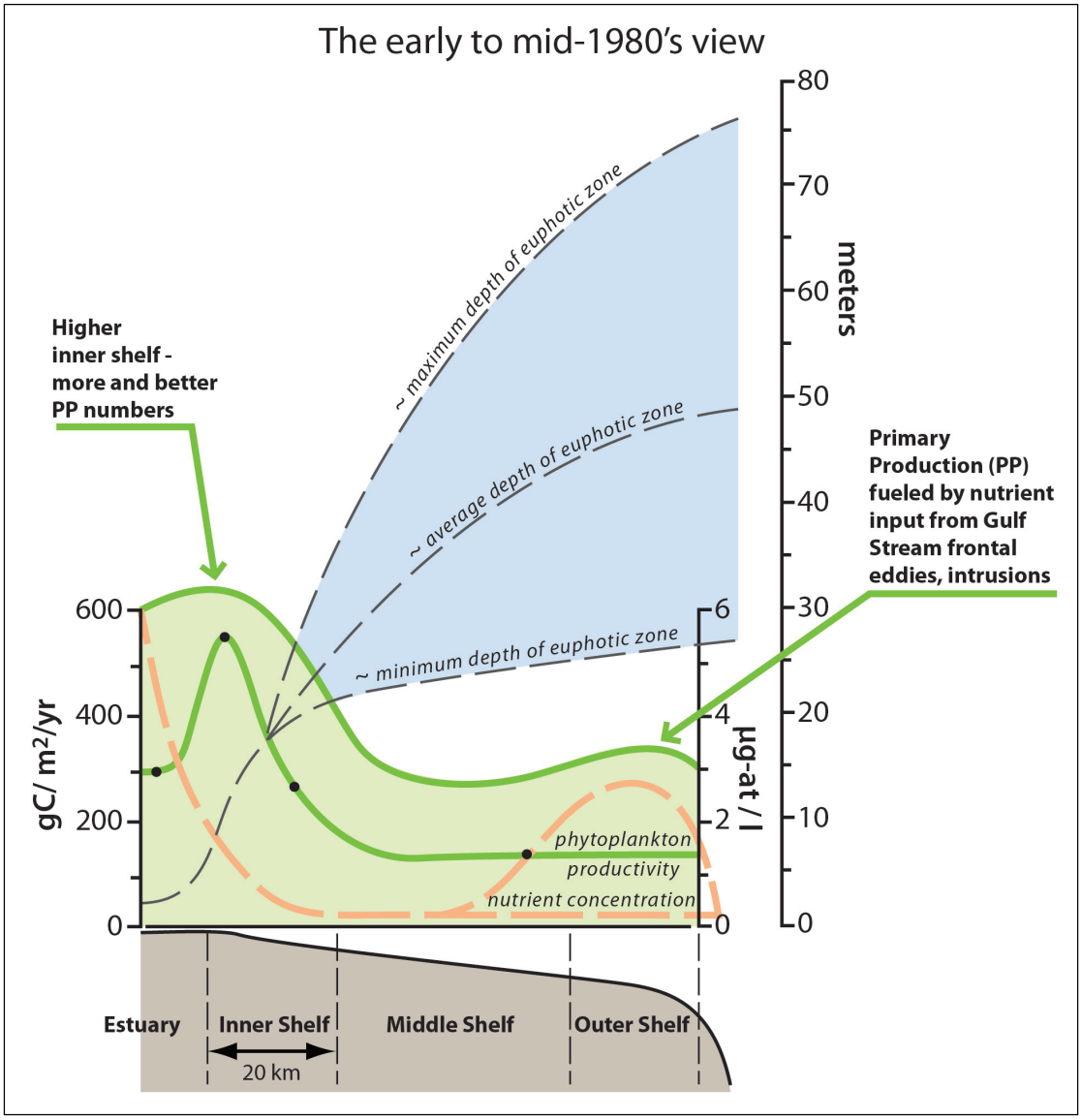


Figure 5.2 Relation of phytoplankton production to depths of euphotic zone and nutrient concentration in Georgia coastal waters (J. Nelson, unpublished). Nutrient concentration is in units of µg-atoms/L, phytoplankton productivity from the 1970s data (Haines, 1979) is in units of gC/m^2/yr and euphotic zones are in meters. The top line is the newer primary productivity numbers (g C/m^2/yr) based on data collected in the 1980's (Yoder et al., 1983, 1985).

5.2 METHODS USED IN PLANKTON STUDIES

A variety of methods has been used to measure primary production and to identify and quantify plankton in the shelf waters of this region. This section summarizes methods useful in understanding plankton dynamics in the US South Atlantic Planning Area. Observational platforms used to study plankton in the US South Atlantic Planning Area are shown in the photographs in Figure 5.3; these platforms include ship, glider, tower, buoy, and satellite. Shore-based, long-range HF-radar is used to measure surface currents across the shelf.

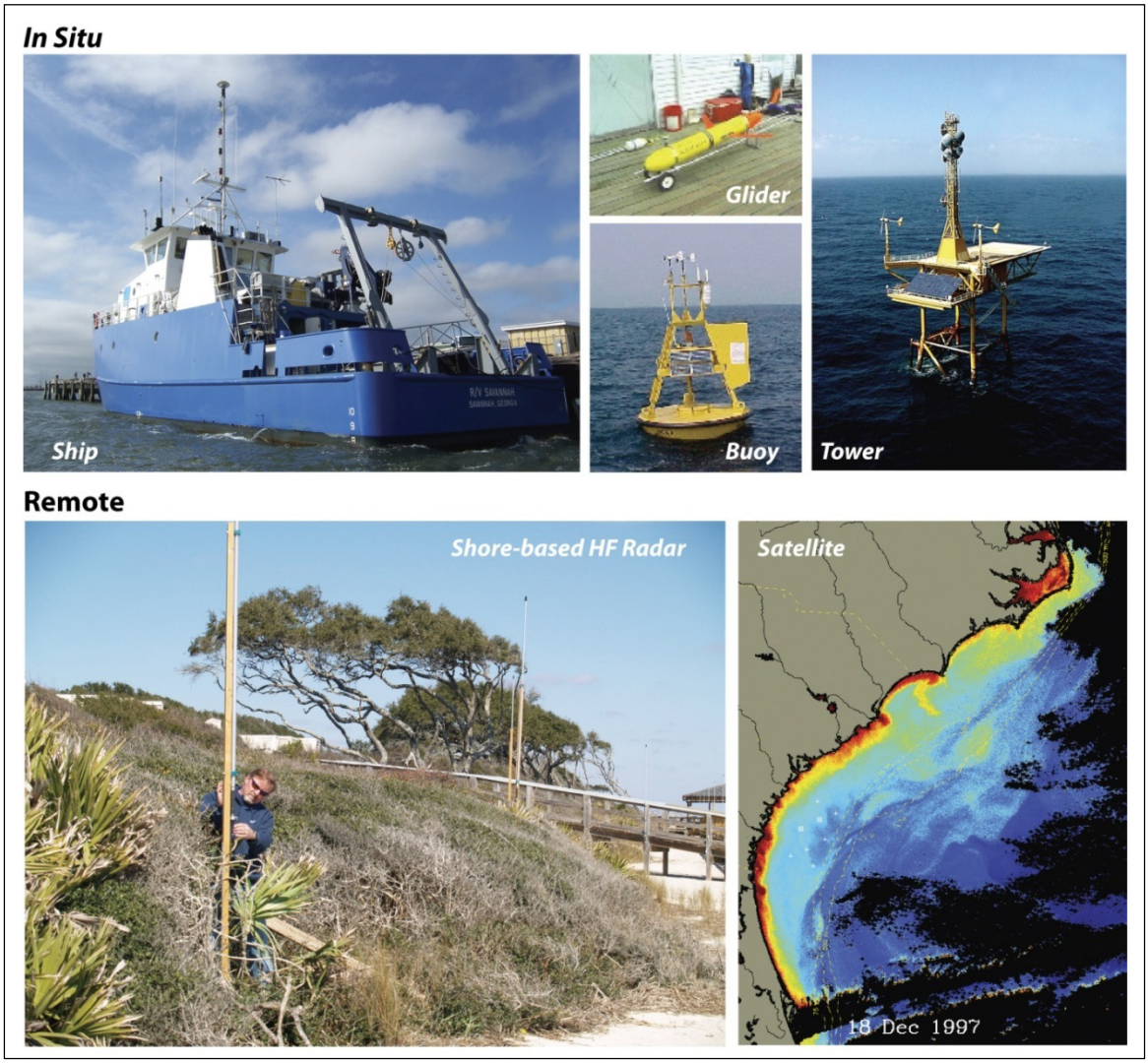


Figure 5.3 Vehicles and instruments used for plankton studies in the South Atlantic Planning Area. Images provided by permission from James Nelson, Skidaway Institute of Oceanography.

5.2.1 Microscope and Image Analysis

The procedures for the first plankton studies in the South Atlantic Planning Area were quite simple and included the addition of formaldehyde to seawater samples and, after fixed cells had settled, examining and counting plankton samples with a phase-contrast microscope. Scanning electron microscopy and electron microscopy were later used to help in the identification of phytoplankton. At present a variety of stains, such as fluorochromes, diaminopimelic acid (DAPA), or profavin, are added to seawater samples followed by fixation of cells in formaldehyde or glutaraldehyde, then examined by epifluorescent microscopy to facilitate the identification of unicellular plankton. A video plankton recorder can be used to help identify and quantify classes of phytoplankton and zooplankton (Gallagher et al., 1996). Verity et al. (1996) used a color-image analysis system to quantify taxonomic groups of plankton (photosynthetic groups–nanoplankton, diatoms, dinoflagellates, cyanobacteria, photosynthetic ciliates; nonphotosynthetic groups–nanozooplankton, heterotrophic nanoplankton, heterotrophic dinoflagellates, plastidic ciliates, aplastidic ciliates) in the South Atlantic Planning Area. Cell volumes were converted to cell carbon using published data for the different taxonomic groups.

5.2.2 Pigment Analysis

5.2.2.1 Chlorophyll Concentrations

Chlorophyll concentrations can be obtained by passing water through a glass-fiber filter, extraction of the particles on the filter, and determination of chlorophyll concentration in the extract based on chlorophyll fluorescence (Yentsch and Menzel, 1963). Data from continuous fluorescence measurements, where water is passed through a fluorometer on a ship, have been used to provide continuous chlorophyll a concentrations in shelf waters of the South Atlantic Planning Area (Atkinson et al., 1996; Verity et al., 1993a; 1998; Yoder et al., 1993). Solar-stimulated fluorescence by phytoplankton down to 40 m depth can be monitored from a ship (Toplis, 1985) or to a depth of 4 m using a Fluorescence Line Imager on a high altitude aircraft (Platt and Sathyendranath, 1988; Topliss, 1985; Yentsch and Yentsch, 1984).

5.2.2.2 High-Performance Liquid Chromatography (HPLC)

After pigments were extracted from water samples, high-performance liquid chromatography (HPLC) was used to determine the abundance of important phytoplankton classes (diatoms, dinoflagellates, prymnesiophytes, cryptophytes, chlorophytes, cyanbacteria, prochlorophytes, and prasinophyte) in coastal waters (Hassen et al., 2009; Lee et al., 2009; Mantoura and Lewellyn, 1983). Phytoplankton samples were collected on filters, chlorophylls, carotenoids were extracted from the filters, and analyzed with a reverse-phase HPLC equipped with UV-light and/or fluorescence detectors. The pigments detected by this method include chlorophyll a, chlorophyll b, chlorophyll c, and various carotenoids (diatoxanthin, diadinoxanthin, peridinin, zeaxanthin, fucoxanthin). One can analyze pigment data with CHEMTAX software (as described by Mackey et al., 1996), which uses the known pigment pattern of the various phytoplankton classes to provide data on the major phytoplankton groups in a study area. HPLC analysis of water samples from South Atlantic Planning Area showed a domination of diatoms (abundance of fucoxanthin) on the inner shelf; cyanobacteria (zeaxanthin) were more abundant in outer shelf sites (Verity et al., 1993c). Nelson et al. (1999) carried out an HPLC analysis of pigments off the Georgia shelf and noted a dominance of fucoxanthin (diatoms) inshore and then a mixture of fucoxanthin, 19'-hexanyloxyfucoxanthin (prymnesiophytes), and zeaxanthin (cyanobacteria) at

the 27–50 m isobaths. Thermally stratified stations offshore in late spring and summer showed a dominance of cyanobacteria since zeaxanthin was 40–50% of the total carotenoid by weight.

5.2.2.3 Electronic Cell Sorting Combined With Pigment Detection

Flow cytometry is a technique for rapidly counting small cells (0.5 to 200 microns [µm]) using the principles of light scattering, light excitation, and emission of fluorochrome molecules to generate data from the cells that are passing through a flow chamber. It can be used to determine the abundance of phytoplankton in various size classes (e.g., pico-, nano- and micro-phytoplankton) in oceanic waters (Veldhuis and Kraay, 2000). A more recent development is the combination of flow cytometry with immunology (antibodies to a phytoplankton species) to allow a determination the concentration of a particular phytoplankton species (Peperzak et al., 2000). A particularly useful application of flow cytometry is for the distinguishing cyanobacteria cells whose autofluorescence is due to phycoerythrin from cells whose fluorescence is due primarily to chlorophyll. The different pigments have very different fluorescence emission wavelength, with fluorescence at wavelengths longer than 650 nanometers (nm) generally ascribed to chlorophyll a, while fluorescence at wavelengths around 585 nm is ascribed to phycoerythrin (Li and Wood, 1988; Li, 1988). Mann and Gallant (2006) used flow cytometry to determine the abundance of different cyanobacteria in the inner-, middle-, and outer-shelf waters off the Georgia coast. Identification of the cyanobacteria was based on size and presence of phycoerythrobilin or phycocyanobilin. Phycocyanobilin containing picoplankton was confined to the inner shelf, while *Prochlorococcus* spp. was only in the outer shelf. The cyanobactereia *Synechococcus* spp. was found in waters of the inner, middle, and outer shelf.

5.2.2.4 Satellite Reflectance Data

Color sensors on satellites, such as SeaWiFS, are used to produce global representation of the ocean color (Figure 5.4). The optical signals are converted using algorithms to chlorophyll concentrations. The satellite reflectance data goes down to one light attenuation length, which is at about a depth of 20 m on the Georgia shelf (J. Nelson, pers. comm.). The chlorophyll data from SeaWiFS can be used to calculate primary production of a study area using a simple algorithm (Behrenfeld et al., 1998).

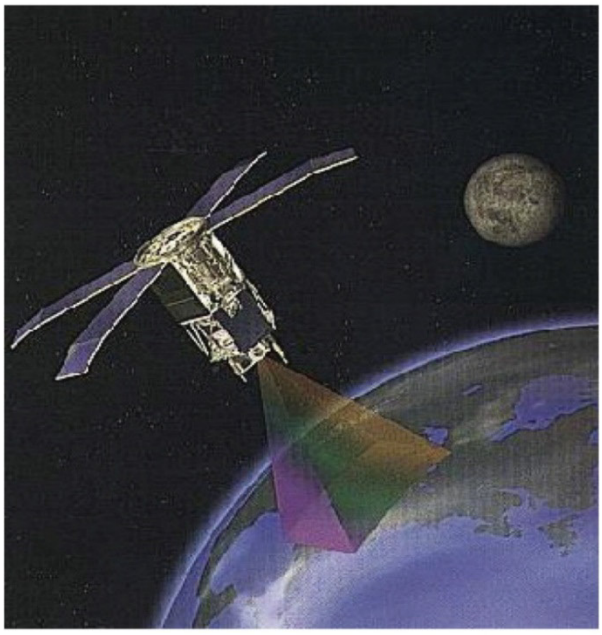
$$\mathrm{Log_{10}PP} = 0.559 \log_{10}\mathrm{C} + 2.793$$

Where C is the chlorophyll concentration, and PP is primary production. At a chlorophyll concentration of 0.56 milligrams per cubic meter (mg/m^3), the primary production is 0.6 g of carbon/m^2. It should be noted that there is a large amount of uncertainty in the calculation of chlorophyll from satellite data.

Using the differences in optical properties of different groups of phytoplankton, Alvain et al. (2005) used SeaWiFS nLw (water-leaving radiances) data between 412-555 nm to distinguish between four major phytoplankton groups–haptophytes, *Prochlorococcus, Synechococcus*-like cyanobacteria, and diatoms. In addition, the nitrogen-fixing cyanobacteria *Trichodesmium* and coccolithopohorids have distinct spectral signatures that allow them to be detectable from satellites (Brown and Yoder, 1994; Subramanian et al., 2002). Satellite reflectance data have been used to detect the extent of cyanobacteria blooms in a number of coastal waters, such as the Baltic Sea (Joint and Groom, 2000; Siegel et al., 1999). SeaWiFS color data combined with

depth profiles of HPLC-obtained profiles of chlorophyll data can be used to determine phytoplankton class-specific primary production (Uitz et al., 2009). The phytoplankton classes were pico- (0.1 μm), nano- (2 μm), and microphytoplankton (20 μm). An examination of SeaWiFS data from the South Atlantic Planning Area by Hoge et al. (2001) showed highest phytoplankton abundance in regions surrounding capes of the region. Potentially, SeaWiFS data can be analyzed to determine the abundance of the different groups of phytoplankton on the shelf including before, during, and after intrusions. One difficulty in the South Atlantic Planning Area is that summer intrusions are in deep waters and these deep phytoplankton blooms are not captured by the ocean color satellites (Signorini and McClain, 2007; Yoder et al., 1985).

SeaWiFS sensor



Operational from Fall 1997 to present

Instrument Bands	
Band	Wavelength (nm)
1	402-422
2	433-453
3	480-500
4	500-520
5	545-565
6	660-680
7	745-785
8	845-885
Mission Characteristics	
Orbit Type	Sun Synchronous at 705 km402-422
Equator crossing	Noon + 20 min, descending
Orbital period	99 minutes
Swath width	2,801 km LAC/HRPT (58.3 degrees)
Swath width	1,502 km GAC (45 degrees)
Spatial resolution	1.1 km LAC, 4.5 km GAC
Resl-Time data rate	665 kbps
Revisit time	1 day
Digitization	10 bits

Figure 5.4 Sea-viewing Wide Field-of-view Sensor (SeaWiFS) used to gather ocean color information.

5.2.3 Primary Production Methods (^{14}C and Chlorophyll)

The ^{14}C method described by Steeman Nielsen (1952) involves the addition of $NaH^{14}CO_3^-$ to a bottle containing collected water, followed by a short exposure (4–6 hours) to natural sunlight or to a solar simulated system. The carbon fixed is then quantified by determining the amount of radioactivity in the phytoplankton with a scintillation counter.

Primary production rate based on chlorophyll concentrations uses the formula of Platt et al. (1980):

$$P^B = P_S^B [1 - \exp(-\alpha^B E_0 / P_S^B) \exp(-ß^B E_o / P_S^B)]$$

Where P^B is the primary production rate normalized to chlorophyll concentrations. P_S^B is the saturated rate of chlorophyll specific photosynthesis, α^B is initial slope of photosynthesis-irradiance curve, $ß^B$ is the parameter to characterize photo-inhibition and E_o is the available quantum scalar irradiance.

The linear relationship between primary production and surface chlorophyll at different times of the year on the inner Georgia shelf (32^oN) is shown in Figure 5.5.

5.2.4 Molecular Methods

Newer methods available for the detection and quantification of plankton include PCR-based molecular assays for plankton species. Such methods have been used to detect a parasitic dinoflagellate and a larval clam species in coastal waters of the US South Atlantic (Frischer et al., 2006; Hitchcock et al., 2008). A DNA-hybridization-based analysis method employing bead-array technology has been used to detect phytoplankton species in the coastal waters off the west coast of the US (Ellison and Burton, 2005). While showing great promise, these molecular methods are not yet widely used for surveys of plankton species in oceanic waters.

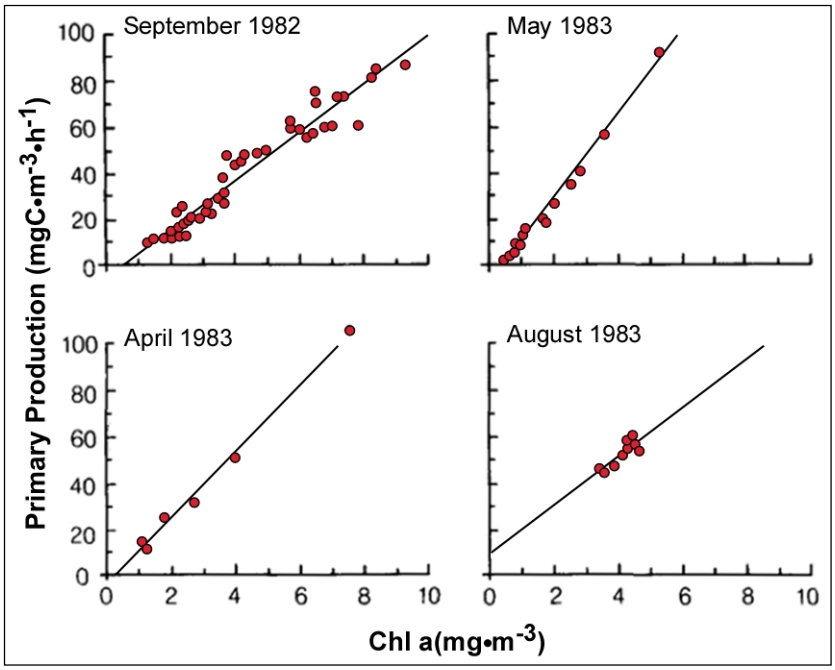


Figure 5.5 Primary production on the inner Georgia shelf (32°N) as a function of surface chlorophyll a (modified from Yoder et al., 1993).

5.3 INNER SHELF

5.3.1 Introduction

The inner shelf is roughly defined as that portion of the shelf inshore of the 20 m isobath, which is about one-third of the total area of the shelf. The inner shelf between Cape Romain, South Carolina and Brunswick, Georgia is wide and relatively isolated from the Gulf Stream. Cool, nutrient-rich water reaches the inner shelf off Cape Canaveral, Florida, but these intrusions do not reach the inner shelves of Georgia and South Carolina. Circulation along the inner shelf is controlled by winds, tides, and freshwater inputs. The large amplitude tides (2–3 m off the Georgia coast) cause release of nutrients from the sediments and, combined with wind, results in well-mixed inner shelf waters (Blanton and Atkinson, 1983; Yoder, 1985). The freshwater input produces a high-turbidity zone extending 5–10 km offshore, or roughly to the 5–10 m isobath (Oertel and Dunstan, 1981) (Figure 5.6). An aerial view of the turbidity front off the Georgia coast is shown in Figure 5.7. The turbidity zone is characterized by high concentrations of suspended particulates (9–200 milligrams per liter [mg/L]), low salinity, and low density. The fresh water mixing with salt water along the coast produces a low-density coastal front which extends beyond the turbidity zone on the inner shelf. The coastal front separates water with salinities less than 35 ppt from the offshore more saline waters and extend approximately 20 km offshore (Blanton, 1981). There is recycling of nutrients and organic material within the coastal front since the cross exchange of dissolved and suspended material is inhibited by the front, a so-called “dynamic barrier” (Blanton, 1981; Yoder et al., 1981a; 1993).

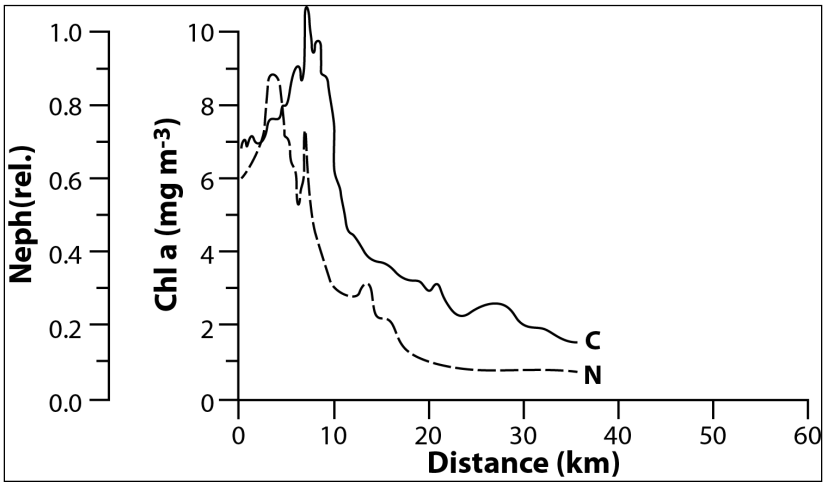


Figure 5.6 Turbidity and chlorophyll a concentrations along a transect on the inner shelf from Wassaw Sound, Georgia (32°N). Neph refers to relative turbidity as determined by nephelometry (modified from Yoder, 1985).

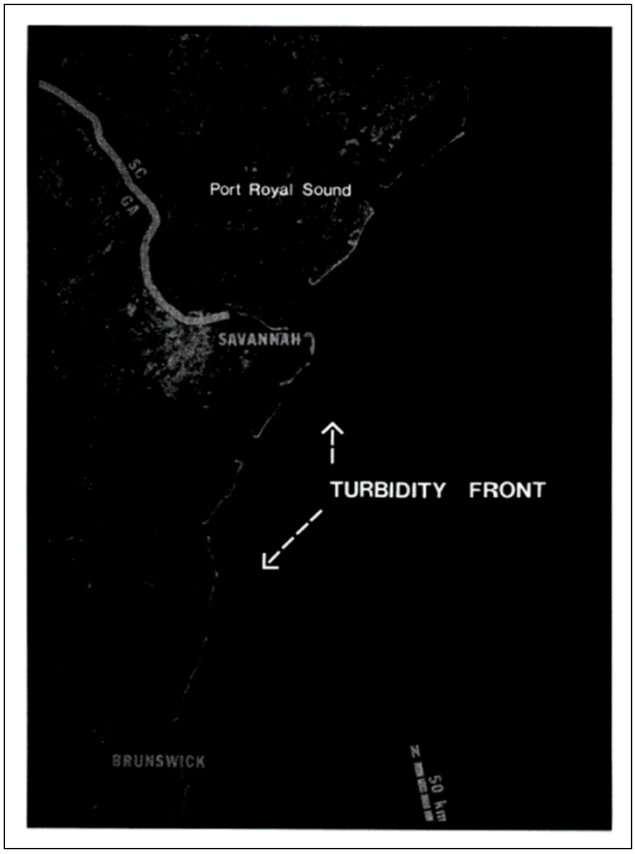


Figure 5.7 Infrared image of the Georgia coast taken with Thematic Mapper aboard Landsat D. Image taken at 0943 on 9 November 1982. Image by H. Kim, NASA Goddard Space Flight Center.

5.3.2 Nutrients

The sources of "new" nutrients for the inner shelf of South Carolina/Georgia are the estuaries and salt marshes along the coast. However, most of the nitrogen exported from marshes is in the form of DON or PON, rather than dissolved inorganic nitrogen (DIN) (Dunstan and Atkinson, 1976; Haines, 1979; Kjerfve and McKellor, 1980; Bishop et al., 1984). Castro et al. (2000) have reviewed the studies that suggest the input of atmospheric nitrogen, including anthropogenic nitrogen, into the coastal estuaries of the South Atlantic Study area. Other sources of nitrogen within the coastal zone front include the ammonia produced by zooplankton feeding on the phytoplankton, DIN released from the sediment during tidal mixing, and ground water. Since DIN is generally less than 1 micromole (μM) in this zone, a large proportion of exported nitrogen is not available to phytoplankton until mineralized by heterotrophs. Hopkinson (1987) and Hanson et al. (1990) concluded that recycled and regenerated forms of nitrogen limit primary production in the inner shelf waters off South Carolina and Georgia. The continuous, low concentrations of DIN indicate a balance between supply and consumption and high rates of nitrogen recycling. Export of nitrogen from the marshes to shelf waters was found to be highly seasonal with net export occurring from May to October (Kjerfve and McKellor, 1980). Turner (1981) estimated that nitrogen export from the Georgia and South Carolina marshes was 1.2 x 10^5 metric tons per year.

5.3.3 Chlorophyll and Primary Production

The high rates at which nitrogen is regenerated and recycled in the coastal frontal zone result in high chlorophyll and primary production. The inner and outer shores of the South Carolina and Georgia inner shelf are quite different with respect to chlorophyll concentrations and primary production numbers as shown in Table 5.2. The chlorophyll concentrations reach a peak in the turbid zone and then rapidly decrease going seaward (Figures 5.6 and 5.8; Table 5.2). Figure 5.9 shows chlorophyll a profiles across the coastal frontal zone off Georgia at different months and at low and high tides. The chlorophyll a concentration at 7.6 km offshore was 3-8 micrograms per liter (μg/L), while at the 26 km offshore station the concentrations was between 1 and 2 μg/L. The high turbidity in the turbidity zone should limit photosynthesis at depths below 1 m, the so-called compensation depth, and Jacobsen et al. (1983) argued that phytoplankton in the turbid zone are light limited. However, Oertel and Dunstan (1981) suggested that phytoplankton in this zone are not light limited because strong vertical tidal mixing allows the phytoplankton to constantly move in and out of the euphotic zone. Primary production numbers reported in the literature range from 12 to 3,000 mg C/m^2/day in the coastal frontal zone, with highest numbers off the Altamaha River, Georgia (31ºN) (Table 5.2). Thomas (1966) and Jacobsen et al. (1983) reported maximum primary production was just seaward of the turbid zone, while Oertel and Dunstan (1981) found highest primary production in the turbid zone. Jacobsen et al. (1983) reported a primary production number of 798 mg C/m^2/day on the seaward side of the turbid zone and 146 mg C/m^2/day inside the turbid zone (Table 5.2). Primary production is affected by nutrients, light, and mixing energy which are likely to be highly variable at the turbid zone boundary.

Coastal Zone Color Scanner imagery showed a high chlorophyll a band (2 to 25 mg/m^3) at about the 4 m isobath along the coasts of Georgia, South Carolina, and North Carolina (Yoder et al., 1987) (Figure 5.10). Figure 5.11 shows a satellite chlorophyll image (from the MODIS Aqua

satellite) from the South Atlantic Planning Area showing high chlorophyll concentrations near the coast and a transition to lower chlorophyll concentrations in the high salinity offshore waters.

Table 5.2
Chlorophyll concentrations and primary production on inner shelf of the U.S South Atlantic Planning Area

Location	Chlorophyll Conc. (mg/m^3)		Primary Production (mg $C/m^2/day$)		Reference
	Near shore	Outer Zone	Near shore	Outer Zone	
Altamaha River, GA (31°N)	3-6	1-3	1,000-3,000	-	Thomas, 1966
Savannah River, GA (31.5°N)	1-1.5	1-2	146	798	Jacobsen et al., 1983
Edisto, SC (32°N)	2-5	1-3	-	-	Verity et al., 1998
Wassaw Sound (31.5 °N)	4-10	2	12-160	2-18	Verity et al., 1993c
Savannah (31.5 °N)	2-8	-	-	-	Bishop et al., 1980
Charleston, SC (33 °N)	-	1-3	-	-	Atkinson et al., 1996
Wassaw Sound (31.5 °N)	6-10	1-6	40-100	10-40	Yoder et al., 1993

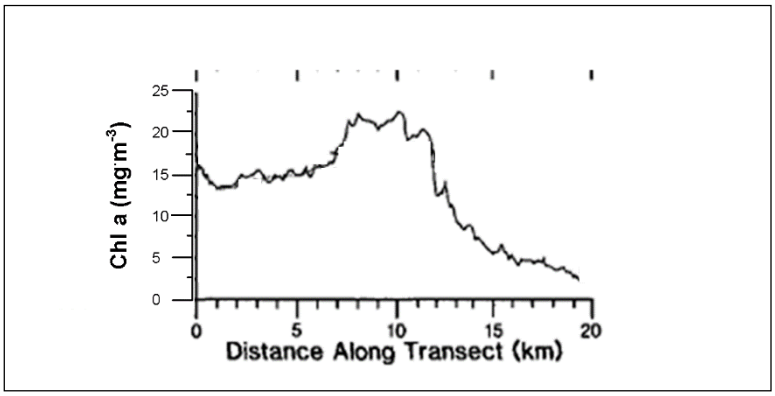


Figure 5.8 Chlorophyll a concentrations on the inner shelf at 32°N at in July 1986 (modified from Hanson et al., 1990).

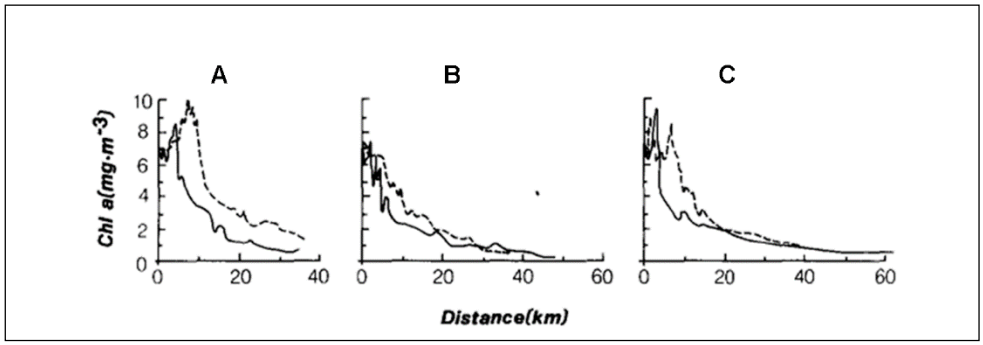


Figure 5.9 Chlorophyll a concentrations across the inner and middle shelf at 32°N at low (solid line) and high (dashed line) tide in (A) September 1982, (B) May 1983, and (C) August 1983 (modified from Yoder et al., 1993).

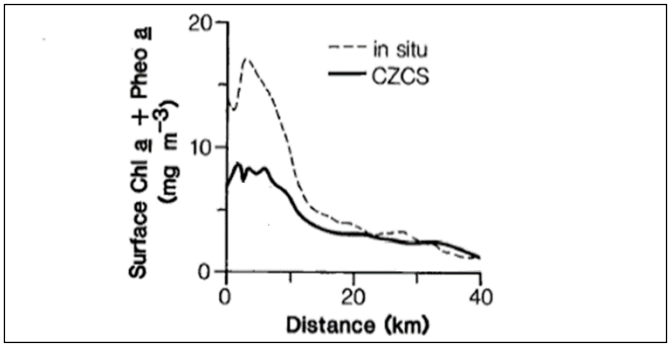


Figure 5.10 Near-surface chlorophyll a plus pheophytin a determined from a ship in 1981-1983 across the inner shelf at 32°N (*in situ* line) and chlorophyll concentrations obtained from Coastal Zone Color Scanner (CZCS) on the same shelf transect (modified from Yoder et al., 1987).

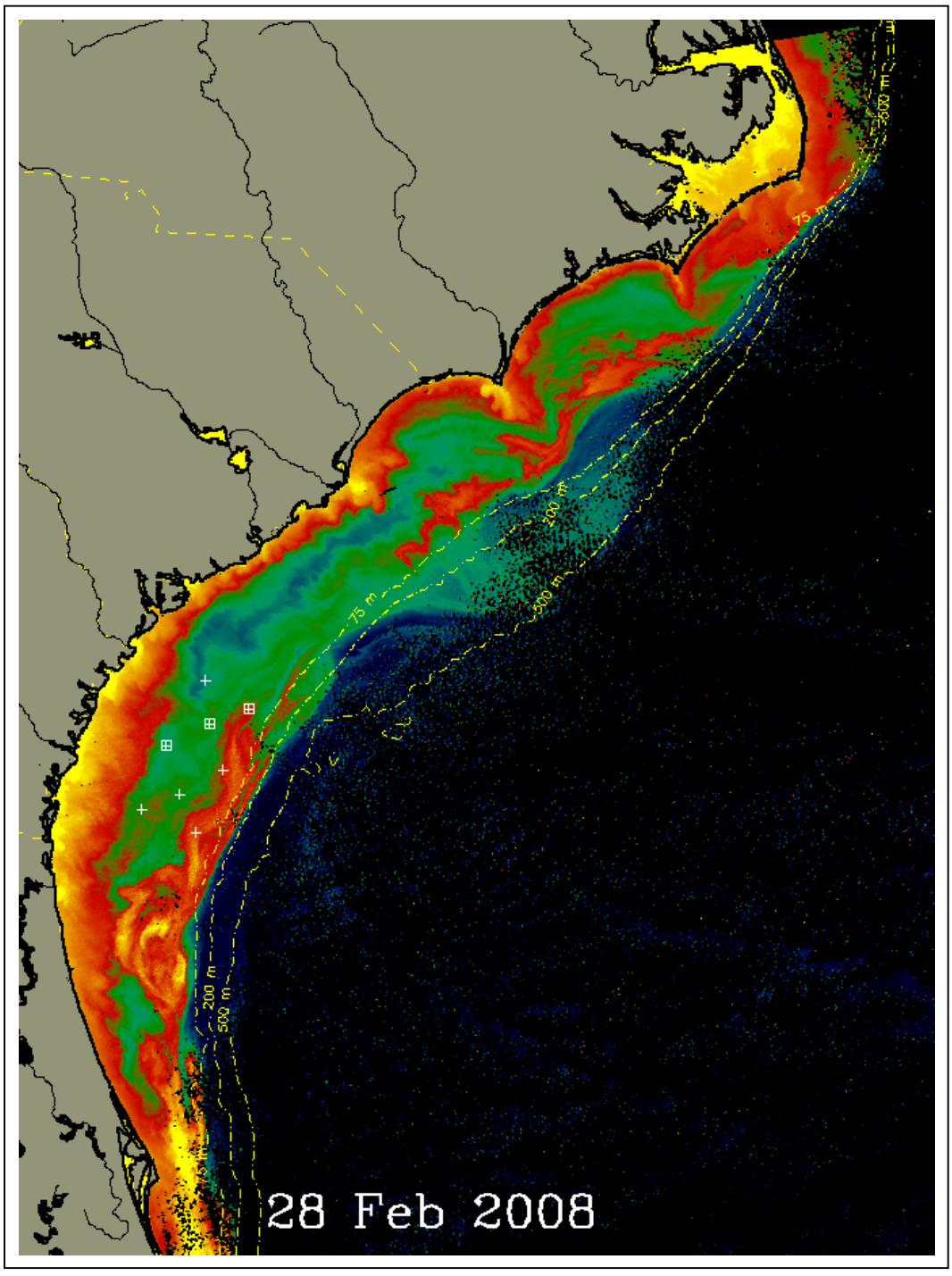


Figure 5.11 Satellite chlorophyll image (MODIS Aqua Satellite) of the US South Atlantic.

The coastal waters of the South Atlantic Planning Area are characterized by high concentrations of DOM, whose origins are the various rivers emptying into the coast. The optimal signal produced by this DOM overlaps with the chlorophyll spectra, and it is difficult to distinguish between reflectance produced by chlorophyll and DOM along the coast.

There are differences between winter and summer with summer chlorophyll concentrations of 8–16 mg/m^3 off Savannah (31°N) and winter concentrations of 4–8 mg/m^3 (Bishop et al., 1980). As a result, primary production was 310 and 3,800 mg C/m^2/day for average winter and summer days, respectively, at this site.

Average annual primary production was estimated to be 750 and 630 g C/m^2/year for inside and outside the coastal frontal zone, respectively, off the Georgia coast (Bishop et al., 1980). Thomas (1966) determined that annual primary production for a station off the Altamaha River, Georgia was 550 g C/m^2/year; Haines and Dunstan (1975) report a somewhat lower number (290 g C/m^2/year) for a Georgia inner shelf station. Primary production of 600–700 g C/m^2/year equals or exceeds the annual productivities for many of the world's coastal waters. Primary production over the inner shelf of the South Atlantic Bight was calculated to be 17.9 x 10^{12} g C/year (Menzel et al., 1993). The high temperatures and incident irradiances characteristic of subtropical climates, coupled with strong mixing and sufficient supplies of nutrients, likely accounts for the high productivity of the inner shelf of the South Atlantic Planning Area.

Except for the Florida coast south of Jacksonville to Cape Canaveral (region of 30°N), the rest of the inner shelf of the South Atlantic Planning Area is unaffected by upwelled nutrients (Yoder, 1985). The closeness of the shelf off northern Florida, as well as fewer salt marshes and rivers, allows cold and nutrient-rich water upwelled at the shelf break to move across the shelf as subsurface intrusions and reach the inner shelf along this coast. Such upwelling of nutrients results in high chlorophyll concentrations (>5 mg/m^3) during warmer months and is a major factor affecting phytoplankton production on the inner shelf off north Florida (Yoder et al., 1985). Figure 5.12 shows chlorophyll a distributions off the northeast Florida shelf (30°N), where intrusions have gone onto the inner shelf.

5.3.4 Phytoplankton

There is a rich assemblage of phytoplankton throughout the year in the coastal front of the inner shelf of the South Atlantic Planning Area; generally, centric diatoms (10^5 to 10^7 cells/L) are the dominant phytoplankton group (Bishop et al., 1980; Haines and Dunstan, 1975; Oertel and Dunstan, 1981; Turner et al., 1979). There is a good correlation between chlorophyll a concentrations and diatom concentrations (cells/mL) in shelf waters (Figure 5.13). While not as important in biomass as the diatoms, large numbers of nanophytoplankton are found in the summer (much lower numbers in the winter) in these coastal waters (Figure 5.14) (Paffenhofer et al., 1995, Verity et al., 1993c). In the summer months off Wassaw Sound, Georgia, the phytoplankton community is dominated by 2–4 μm monads and flagellates, though most biomass occurred as diatoms (Pomeroy et al., 1993). Common flagellates include *Pyraminonas, Cryptomonas, Katodinium, Gymnodinium, Procentrum*, and *Calycomonas.* Common centric diatoms include *Skeletonema tropicum, S. costatum, Leptocylindrus danicus, L. minimus, Cyclotella, Thalassiosira, Chaetoceros,* and *Rhizosolenia.* In winter there is a dominance of < 10 μm monads and flagellates, particularly *Katodinium rotundatum*. During January there are diatom blooms composed of *Skeletonema costatum, Asterionella japonica, Thalassiosira* spp., *Odontella sinensis, Chaetoceros, Rhizosolenia,* and *Eucampia.* Oertel and Dunstan (1981) noted a dominance of *Skeletonema costatum* in Georgia inshore coastal waters in the winter while in the summer approximately 50% of the population belonged to the diatoms *Rhizosolenia,*

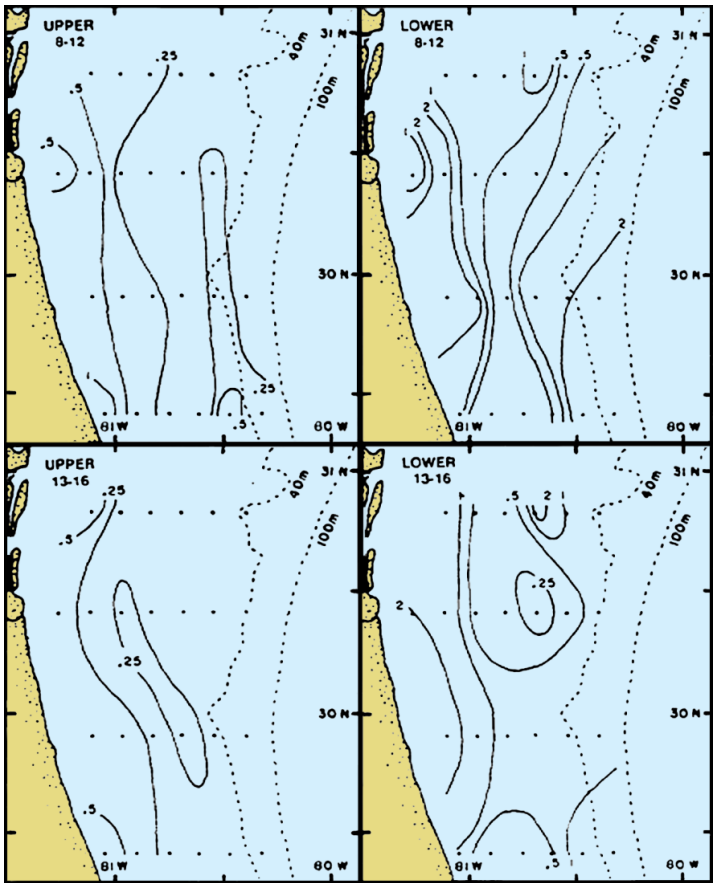


Figure 5.12 Evidence of subsurface intrusions on the inner shelf off St. Augustine, Florida (30°N) in summer 1981. Chlorophyll a concentrations are in mg/m^3 (modified from Pomeroy et al., 1987).

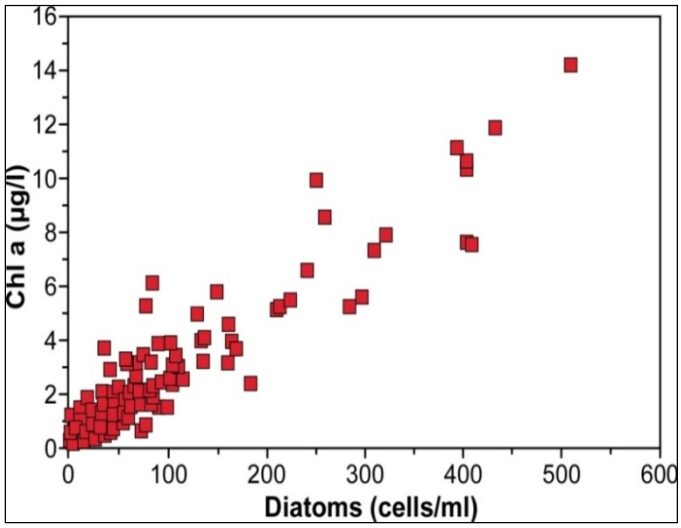


Figure 5.13 Chlorophyll a concentrations in µg/L versus diatom abundance on the shelf at 35°N (modified from Verity et al., 1996).

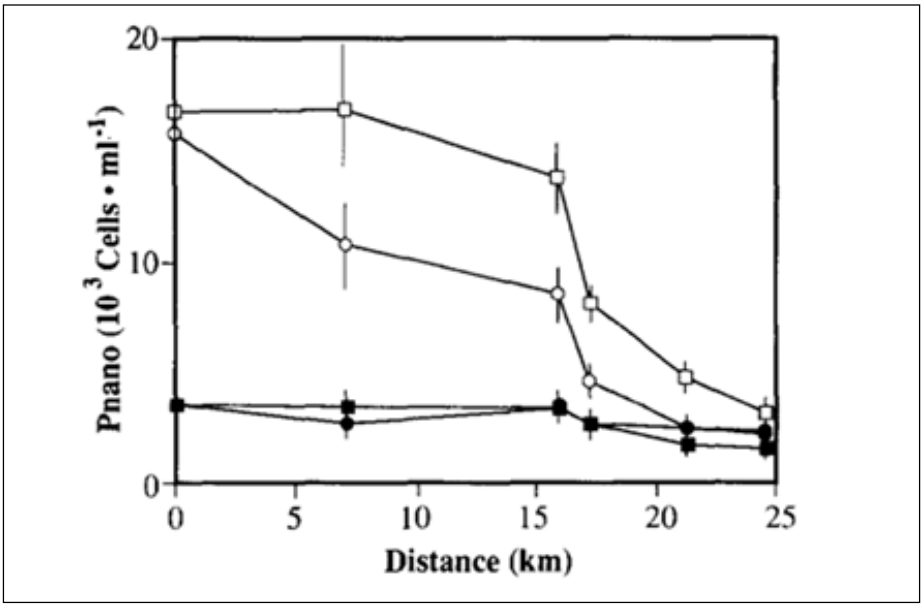


Figure 5.14 Mean (± standard deviation) seasonal abundance of photosynthetic nanoplankton (Pnano) on the inner shelf at 32°N. Open symbols represent summer 1986 (□) and 1987 (○). Filled symbols represent winter 1987 (■) and 1988 (●) (modified from Verity et al., 1993c).

Chaetoceros, and *Leptocylindrus danicus*. There are also reports of dinoflagellates (*Gymnodinium* spp.) blooms in inshore water off Georgia with concentrations reaching as a high as 18 x 10^6 cells/L (Ragotskie and Pomeroy, 1957). Pomeroy et al. (1993) collected *Gymnodinium splendens* and the photosynthetic ciliate *Mesodinium rubrum* year round in these

coastal waters. Dunstan and Hosford (1977) found large numbers of the cyanobacteria *Trichodesmium* on the inner, middle, and outer shelf waters off Georgia.

Phytoplankton assemblages in nearshore waters are quite different from those on the seaward side of the turbid zone. In the nearshore part of the coastal front there are reports of the dominance of large chain-forming diatoms, such as *Chaetoceros* spp. and *Asteronella* spp. (Jacobsen et al., 1983). On the seaward side of the front are smaller (5-10 µm diameter) single celled diatoms and cyanobacteria (1 µm diameter). Oertel and Dunstan (1981) found phytoplankton cell numbers to be 10 times higher in the turbid zone compared with water seaward of the turbid zone on the inner shelf off Georgia. Thus, the coastal frontal zone is characterized by an abundance of diatoms and very low numbers of cyanobacteria so that cyanobacteria biomass is twice as high on the outer shelf compared with the inner shelf (Verity et al., 1993b). The different phytoplankton assemblages on either side of the coastal frontal zone are further evidence that the phytoplankton is not transported across this boundary.

Another interesting feature of the South Atlantic Planning Area shelf is the importance of benthic primary production, due primarily to pennate diatoms (Nelson et al., 1999). Intense storms and tidal currents can resuspend these algae, so that up to 75% of the diatoms in the waters off North Edisto, South Carolina were epibenthic pennate diatoms, including *Asterionella, Bacillaria, Nitzchia, Thalassionema*, and several naviculoids (Verity et al., 1998). In addition, Verity et al. (1998) found centric diatoms on suspended detrital particles in these waters, including *Thalassiosira eccentrica*, which is known to bind to silt-sized particles.

5.3.5 Zooplankton and Microzooplankton

The diatoms found in abundance in the coastal waters are associated with large herbivores, and the nanoplankton which are more abundant in offshore waters support longer food chains with small grazers (e.g., heterotrophic nanoplankton). Heterotrophic carbon biomass on the inner shelf totaled 4.6 g C/m^2 and was dominated by juvenile and adult metazooplankton (Verity et al., 1993c). Genera of small copepods abundant on the inner shelf include the calanoids *Paracalanus, Centropages, Temora*, and the cyclopoid *Oithona* with *Paracalanus* a dominant form (Pomeroy et al., 1993). Their numbers decrease going offshore. The cladoceran *Penilia avirostris* and a larval fish *Anchoa* are primarily found on the inner shelf of the South Atlantic Planning Area (Paffenhofer et al., 1987a). Different species of *Oithona* are found in the estuary (*O. colcarva*), inner shelf (*O. brevicornis)*, and outer shelf (*O. plumifera, O.* robusta, and *O. setigera*) (Owre and Foyo, 1967). The estuarine copepods *Acartia tonsa* and *Labidocera aestiva* are abundant in the coastal front of the inner shelf but are almost absent from the middle shelf (Bowman, 1971). The dominant chaetognath species in the inner shelf are *Sagitta tenuis* and *S. hispida* while offshore the dominant species is *S. enflata* (Coston-Clements et al., 2009).

Planktonic ciliates were abundant throughout a transect taken from the estuary to offshore with highest numbers in estuarine waters (Verity et al., 1993c). Mean concentrations ranged from 10–40 cells/mL in summer to 4–12 cells/mL in winter. Dominant forms were "naked' oligotrich ciliates, which represented 80-90% of total cells. The most abundant genera included *Strobilidium, Strombidium, Laboea*, and *Tontonia*. The autotrophic ciliate *Mesodinium rubrum* was found throughout the year. A study was carried out off the coast of Georgia of the heterotrophic nanoplankton (2–10 µm in diameter), which feed on picoplankton (bacteria,

cyanobacteria, small eukaryotic phytoplankton) (Sherr et al., 1984; 1986). Concentrations ranged from 6.3 x 10^3 cells/mL in inner shelf waters to 0.3 x 10^3 cells/mL on the middle shelf with small, aloricate ciliates the dominant form. These studies suggest that protozoans are an important component of the zooplankton community in the South Atlantic Planning Area. High grazing rates and growth efficiencies are associated with zooplankton communities dominated by protozoans (Goldman et al., 1985; Verity, 1985).

Meroplankton (planktonic for only part of their lives, generally in the larval stage, with benthic adults) were found in a survey of zooplankton of the South Atlantic Planning Area (Herman, 1979). Collected in inner shelf waters were echinoderm larvae, bivalve larvae, cladocerans (*Penilia*), barnacle larvae, and polychaete larvae.

5.4 MIDDLE AND OUTER SHELF

5.4.1 Nutrients and Upwelling

The dynamics that control plankton production on the middle (20–40 m isobath) and the outer (40–60 m isobath) shelves of the South Atlantic Planning Area are principally controlled by upwelling-intrusion events associated with Gulf Stream frontal processes (Figure 5.15) (Atkinson, 1985; Lee et al., 1991). Except for these events, there is no source of nutrient-rich water, so the resident waters of the middle and outer shelves are nutrient poor, with nitrate concentrations less than 0.5 μM. However, when upwelling brings deep Gulf Stream waters onto the shelf, the nitrate concentrations can be as high as 15 μM (Atkinson, 1985; Atkinson et al., 1987; Bishop et al., 1980; Lee and Atkinson, 1983). The distance upwelled water penetrates across the shelf depends on wind velocity, local topography, and density of resident shelf waters (Atkinson, 1985; Lee et al., 1985; Pietrafesa et al., 1985). During warmer months (May-October), when the water on the shelf is thermally stratified, a combination of winds and frontal eddies brings cold, deep, and nutrient-rich water onto the outer and middle shelves. Figure 5.16 is an infrared photograph of the South Atlantic Bight showing cold core frontal eddies coming off the Gulf Stream. This cold, dense intrusion water (15–30 m depth) is below the warmer, lighter surface water (0–15 m depth). Under northward wind stress and summer stratification, subsurface intrusions can occupy almost the entire width of the shelf (Atkinson et al., 1987; Lee and Pietrafesa, 1987). The subsurface intrusions generally occur over 7 to 21 days but can persist for up to 50 days, and the subsurface blooms rapidly deplete the nitrate and other nutrients (Singer et al., 1983; Yoder et al., 1985). The fall-winter-spring (November through April) intrusions go over the colder, denser shelf waters, sometimes called overriding intrusions. These overriding intrusions are often due to frontal eddies, and the high density of the shelf water generally prevents them from intruding beyond the outer shelf.

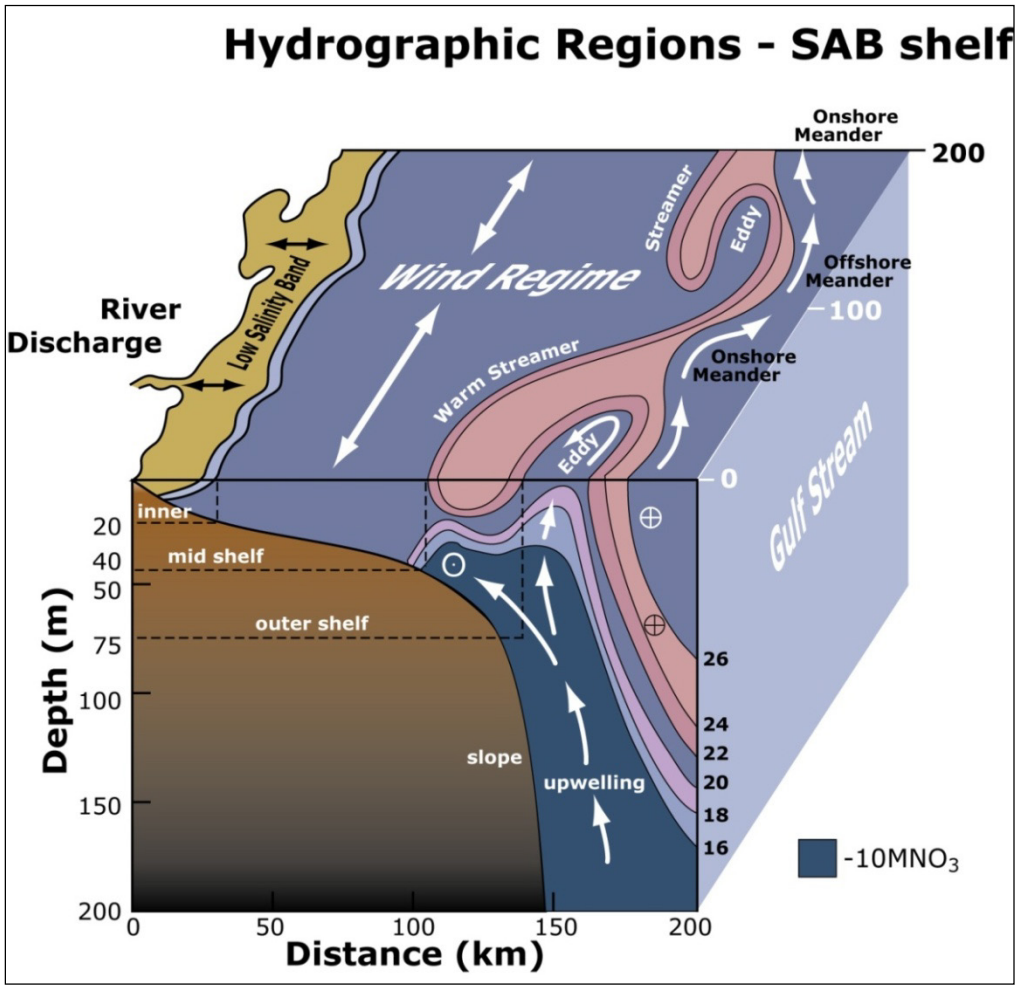


Figure 5.15 Gulf Stream meanders and frontal eddies. The upward arrows indicate upwelling driven by the meander/frontal eddy events, which supply nutrient-rich waters to the outer shelf modified from Lee et al., 1985).

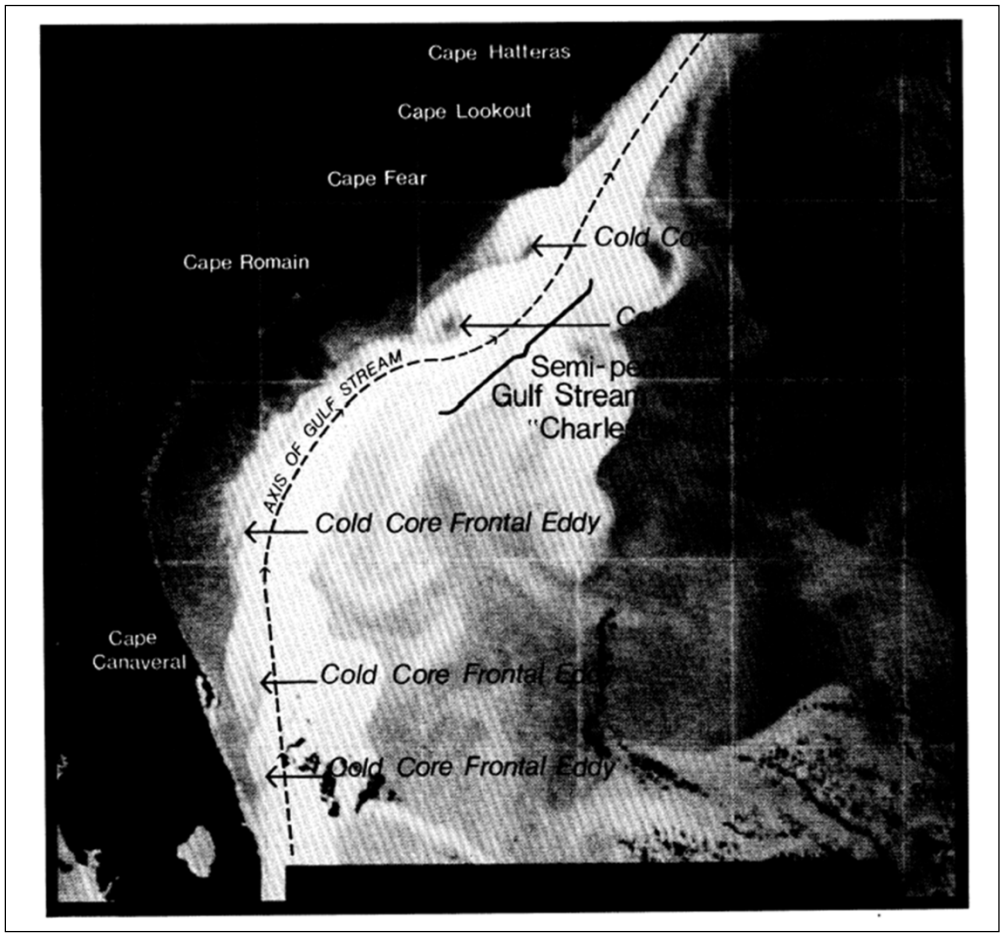


Figure 5.16 Infrared photograph of the South Atlantic Bight showing cold core frontal eddies coming off the Gulf Stream. Other prominent dynamic features are noted (from Atkinson and Menzel, 1985). Reproduced/ modified by permission of the American Geophysical Union.

An exception was noted by Deibel (1985) who reported on a large winter intrusion in 1978 that entered the middle shelf region of the Georgia shelf (32°N). Winter intrusions generally last from 2 to 14 days and thus are generally of shorter duration than summer intrusions. Intrusions are common throughout the year on the outer shelf with subsurface intrusions in the warmer months and overriding intrusions in the colder months, leading Yoder et al. (1983) to conclude that nutrient-rich waters are present half the time on the outer shelf of the South Atlantic Planning Area. This suggestion of a large number of intrusions throughout the year on the outer shelf is supported by the work of Lee et al. (1991) who concluded that upwelling occurred every 14 days at a station 130 km off from Brunswick, Georgia (31°N). In contrast, intrusions generally enter the middle shelf only in summer months, resulting in low nutrient concentrations for much of the year in this region of the shelf. See Chapter 3 Physical Oceanography for further description of the dynamics of the intrusions occurring in the South Atlantic Planning Area.

5.4.2 Primary Production, Chlorophyll, and Phytoplankton in Resident and Upwelling Waters

Primary production, chlorophyll concentrations, and phytoplankton cell numbers are all low in resident waters. The phytoplankton communities in oligotrophic resident waters on the shelf are composed of oceanic species of coccolithophores, dinoflagellates, and blue green algae (Hulbert, 1967; Smayda, 1958). Marshall (1971) recorded 19 species of coccolithophores in shelf waters. The most numerous were *Coccolithus huxleyi, Syracosphaeta mediterranea*, and *Syracosphaeta pulchra.* On the shelf, the most common pyrrhophycean species were *Amphidium* spp., *Ceratium furca, Ceratium tripos*, and *Ceratium fisus.* An oceanic blue green algae *Trichodesmium* spp. has been identified in shelf samples of the South Atlantic Planning Area.

Table 5.3 lists chlorophyll concentrations, primary production, and phytoplankton cell sizes in resident waters and after intrusions in the middle and outer shelf. In resident waters, chlorophyll a concentrations were 0.1–0.5 mg/m^3, primary production averaged 0.4 g C/m^2/day, and phytoplankton were dominated by cells <10 μm in size. Chlorophyll a concentrations in intrusion waters were 2–54 mg/m^3, primary production was 1.2–7 g C/m^2/day, and phytoplankton was dominated by cells >10 μm. A chlorophyll profile on the outer shelf showed large increases in chlorophyll a during August, as a result of intrusion events (Figure 5.17). Summer blooms on the outer and middle shelf are confined to the colder, nutrient-rich, intruded waters below the thermocline, with much lower chlorophyll and phytoplankton numbers in the surface mixed layer (Atkinson, 1977; Paffenhofer et al., 1987b; Yoder et al., 1985). Yoder et al. (1985) reported that primary production in a subsurface intrusion averaged 1.9 g C/m^2/day for 40 days, whereas in the surface mixed-layer it was 0.4 g C/m^2/day. In subsurface intrusions, the majority of the primary production occurs within the first ten days of the upwelling cycle (Yoder et al., 1983). Figure 5.18 shows that phytoplankton cell concentrations in surface waters were 1x10^4 cells/L but increased to 1x10^6 cells/L at 30 m as a result of a subsurface intrusion off Brunswick (Bishop et al., 1980). Total primary production over three months exceeded 150 g C/m^2 on the middle shelf, due to frequent subsurface intrusions (Yoder et al., 1985). Yoder et al. (1983) suggested that the duration of a bloom in an intrusion can be extended by nutrient recycling, since they found that primary production remained >1 g C/m^2/day for 19 days after nitrate depletion in an intrusion.

The frequency of intrusion events and the spatial extent of intruded waters on the middle and outer shelves influences the type and abundance of the phytoplankton. The phytoplankton community in subsurface intrusions in the study area is often dominated by diatoms, such as *Skeletonema costatum*, *Thalassiosira subtilis*, and *Asterionella japonica* (Table 5.4) (Bishop et al., 1980; Lee et al., 1991; Yoder et al., 1983). In a study of a summer intrusion off St. Augustine, Florida (30^{o}N) the dominant small phytoplankter was the diatom *Thalassiosira subtilis*; the dominant large phytoplankters were the large diatoms *Rhizosolenia stolterfothii*, *Rhizosolenia alta*, and *Guinardia flaccida* (Paffenhofer, 1983). As the subsurface intrusion ages there is a progressive change in the phytoplankton community, going from small to large diatom cells with the late stages of the bloom dominated by large diatoms such as *Rhizosolenia*, *Guinardia*, and *Stephanopyxis* (200–600 μm) (Paffenhofer and Lee, 1987; Paffenhofer et al., 1984; Yoder et al., 1983, 1985). It may be that the larger-celled diatoms are able to better survive in the nutrient-depleted waters of older bottom intrusions.

Table 5.3
Chlorophyll concentrations, primary production and phytoplankton size in resident and intrusion waters in the South Atlantic Planning Area

Area	Intrusion/ Resident	Season	Chl Conc. (mg/m^3)	Primary Production ($g\ C/m^2/day$)	Phyto Cell Size (µm)	Reference
Outer Shelf (31°N)	Intrusion	Winter Spring	2-6 in winter 2-3 in April	7	>10	Bishop et al., 1980
Outer Shelf (31°N)	Resident	All seasons	0.1	N/A	<10	Bishop et al., 1980
Outer Shelf (29 to 31°N)	Intrusion	Spring	7.5	1.2 to 2.4	>10	Yoder et al., 1981b
Outer Shelf (29 to 31°N)	Resident	Spring	<0.5	N/A	N/A	Yoder et al., 1981b
Middle Shelf (30°N)	Intrusion	Summer	30	1.9	>10	Yoder et al., 1985
Middle Shelf (30°N)	Resident	April	0.5	N/A	N/A	Yoder et al., 1993
Outer Shelf (30°N)	Intrusion	Summer	54	N/A	>10	Yoder et al., 1985
Middle Shelf (30°N)	Resident	Summer	<1	N/A	<10	Yoder et al., 1985
Outer Shelf (30°N)	Intrusion	Spring	15	Up to 6 (av. 2.7)	>10	Yoder et al., 1983
Outer Shelf (30°N)	Intrusion	Summer	4	1.9	>10	Yoder et al., 1983
Outer Shelf (30°N)	Resident	Summer	0.2 to 0.35	0.4	<10	Yoder et al., 1983
(N/A = Data not available).						

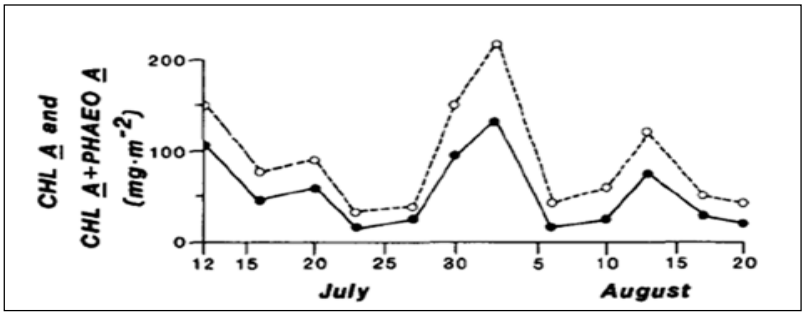


Figure 5.17 Chlorophyll concentrations on the outer shelf at 30°N during summer 1981 (from Yoder et al., 1985). Reproduced/modified by permission of the American Geophysical Union.

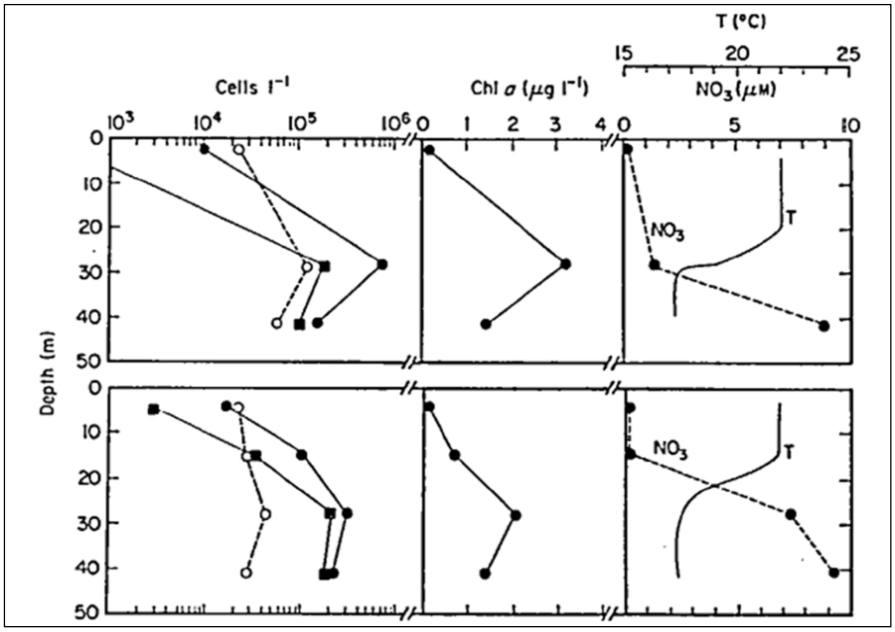


Figure 5.18 Vertical distribution of phytoplankton cells, chlorophyll a, nitrate, and temperature in April 1978 during upwelling on the outer shelf off Brunswick, Georgia (31°N). Sampling was at two stations (station 57-upper; station 60-lower) at the same shelf break location (130km offshore). Large cells (●); Small cells (○); Diatoms, *Skeletonema constatum* (■) (modified from Bishop et al., 1980).

This view is supported by the data of Turpin and Harrison (1980) who found that larger cells with greater nutrient storage capacity could survive in nutrient-depleted waters. Paffenhofer and Lee (1987) found reproducing large-celled diatoms in nutrient-depleted waters of an old intrusion. In addition to diatoms, other phytoplankton groups are reported in intrusions. For example, a bloom of the haptophyte *Phaeocystis puchetti* at a depth of 31 m was reported in a summer subsurface intrusion on the middle shelf off Savannah, Georgia (32ºN) (Long et al., 2007). Thus, during the summer on the middle and outer shelves there can be often a nutrient-

rich deep water with large chain-forming diatoms and above it an oligotrophic surface-mixed layer containing small dinoflagellates and coccolithophorides. After depletion of the nutrients in intrusions, there is a gradual return to the nanophytoplankton community found in the surface-mixed layer (Verity et al., 1993a; Lenz, 1992; Smetacek et al., 1990).

Table 5.4
Abundance of diatoms in intrusion waters at outer shelf (Spring 1979, Summer 1978; 31°N)

Diatom Species	Spring Abundance (10^5 cells/L)		Summer Abundance (10^3 cells/L)	
Depth	2 m	12 m	45 m	15-30 m
Chaetoceros spp.	23	18	n.d.	74
Leptocylindrus danicus	7	16	0.04	62
Nitschia spp.	27	72	0.18	--
Rhizosolenia fragilissima	20	45	0.14	64
Rhizosolenia stolterfothu	7	20	0.18	88
Skeletonema costatum	96	350	0.20	140
From Yoder et al. (1983). n.d. = not detected.				

Fall-Winter-Spring intrusion blooms are also characterized by an abundance of diatoms. The large diatoms *Guinardia flaccida* and *Rhizosolenia* spp. were dominant in an April bloom at 32°N (Deibel, 1985). However, Yoder (1985) reports the dominance of the small-celled *Skeletonema costatum* in an outer-shelf upwelling in April produced by a frontal eddy (Figure 5.19). Turpin and Harrison (1980**)** suggested that frequent nutrient input with rapid dilution, which is analogous to a frontal eddy upwelling, favors the growth of small-celled diatoms. *Asterionella* and *Stephanopyxis* are centric chain-forming diatoms found in both subsurface and overriding intrusions (Bishop et al., 1980; Yoder et al., 1981b; 1983; Paffenhofer and Lee, 1987; Yoder and Ishimaru, 1989). The short duration of upwelling in the colder months tends to produce short-lived phytoplankton blooms. Blooms produced during winter intrusions (February and March) on the outer shelf off Long Bay, South Carolina (33–34°N) and observed by satellite are shown in Figure 5.20.

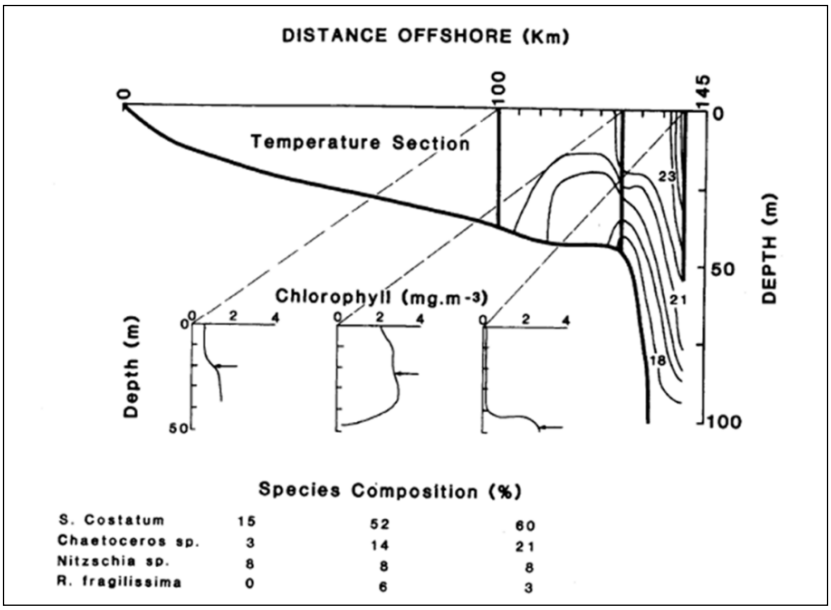


Figure 5.19 Outer shelf temperature sections (°C), vertical chlorophyll a distribution at three stations, and diatom species compositions at depths indicated by the arrows, following an upwelling event in April 1979 (from Yoder, 1985). Reproduced/modified by permission of the American Geophysical Union.

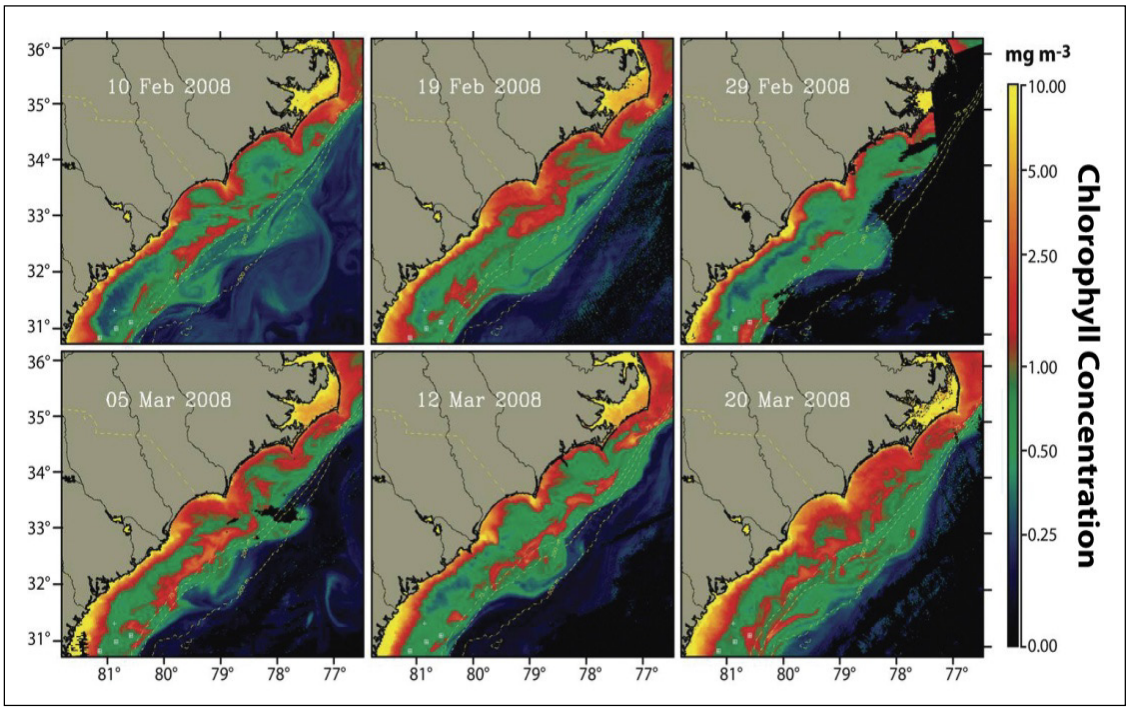


Figure 5.20 Satellite photos (from MODIS Aqua Satellite) on the outer shelf off Long Bay, South Carolina (33-34°N), showing phytoplankton blooms during winter intrusions of nutrient-rich water from the Gulf Stream.

5.4.3 Zooplankton and Microzooplankton

Phytoplankton are not abundant in resident waters on the middle and outer shelves and, as a consequence, these waters have low concentrations of ostracods, small calanoids and cyclopoid copepods, cladocerans, and cephalochordates (Hermann, 1979; Paffenhofer, 1980, 1983). Copepods always found on the shelf include *Paracalanus parvus, Centropages furcatus,* and *Eucalanus pileatus*. A thaliacean found in resident waters, such as in the low-nutrient, upper mixed layer above subsurface intrusions, is the salp, *Thalia democratica*, which does well at chlorophyll concentrations as low as 0.1 mg/m^3 (Paffenhofer and Lee, 1987). The tunicate *Oikopleura* spp. is another zooplankter which does well in low chlorophyll water. In the summer of 1978 at 30°N in the upper mixed layer and in a subsurface intrusion *Oikopleura* were 3,450 individuals/m^3 and 1,070 individuals/m^3, respectively (Paffenhofer, 1983). The lower abundance of *Oikopleura* in intrusions is likely due to its feeding better on small flagellates (<8 μm) than on the larger diatoms found in intrusions, and *Oikopleura* can feed on particles as small as 0.1 μm (Flood, 1978; Paffenhofer, 1976).

Phytoplankton increases as a result of upwelling-intrusion events in the middle and outer shelves lead to copepod patch formation that are composed of *Temora turbinata, Oithona,* and *Oncaea*. Other zooplankton whose numbers increase in intrusions are *Corycaeus, Paracalanus, Penilia avirostri* (cladoceran)*, Brachiostoma* (cephalochordate), and *Chaetognatha* (Table 5.5). In one intrusion, the total copepod concentration in the intrusion was >12,000 copepods/m^3 (Paffenhofer et al., 1987a). A summer subsurface intrusion on the middle shelf at 29–31°N produced a phytoplankton bloom which led in turn to a large increase in the population of reproducing *Temora turbinata* (>1,000 copepods/m^3) (Figure 5.21). This high numbers of adult *T. turbinata* led to the production of many nauplii (highest number in the upper mixed layer), followed by post-naupliar stages. Large *T. turbinata* and *Oithona* spp. patches were observed after a summer intrusion off St. Augustine, Florida (30°N) (Figure 5.21, Station A in Figure 5.22).

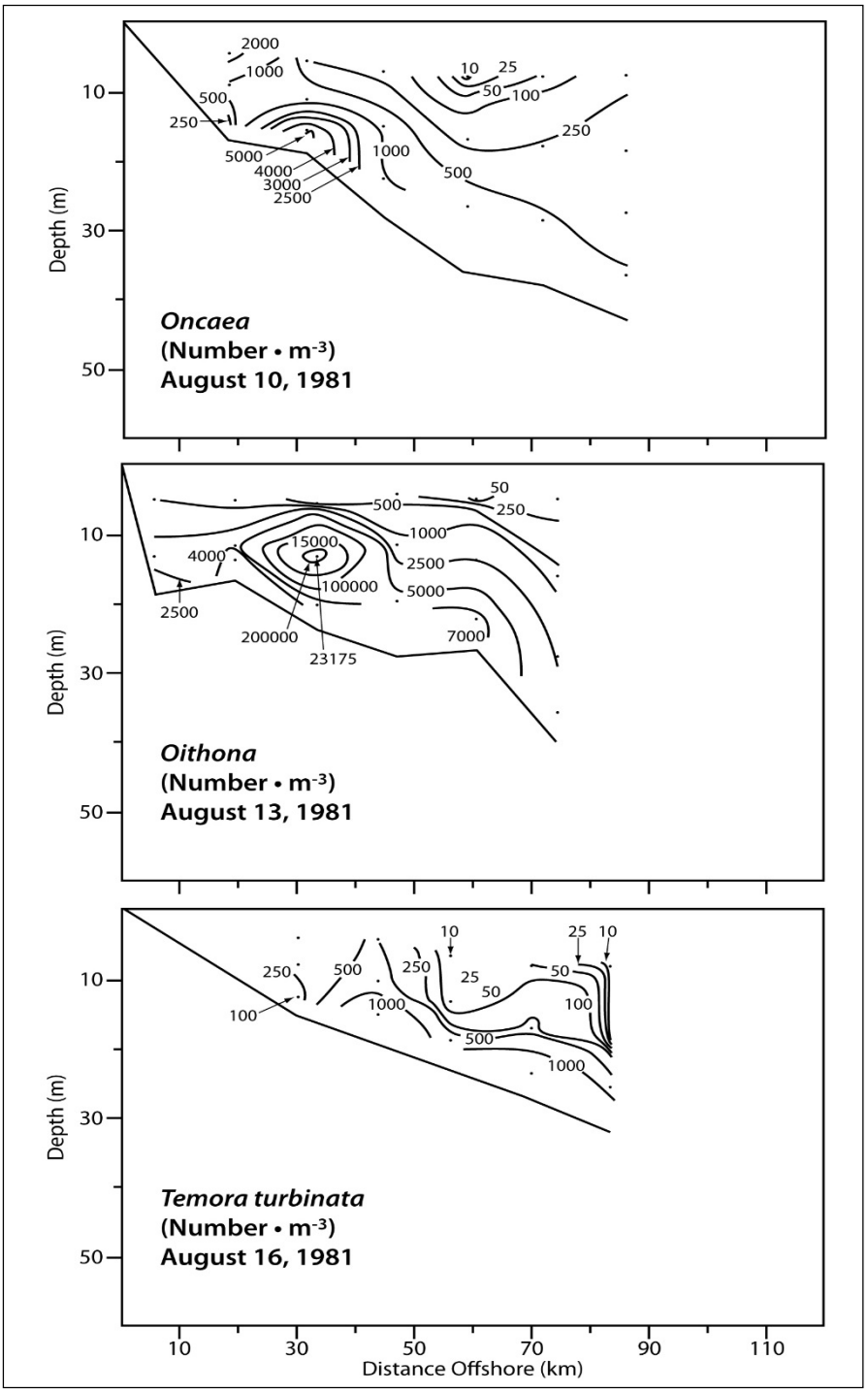


Figure 5.21 Vertical distribution of *Oncaea* spp,. *Oithona* spp., and *Temora turbinata* on the middle shelf at 30°N (modified from Paffenhofer et al., 1987a).

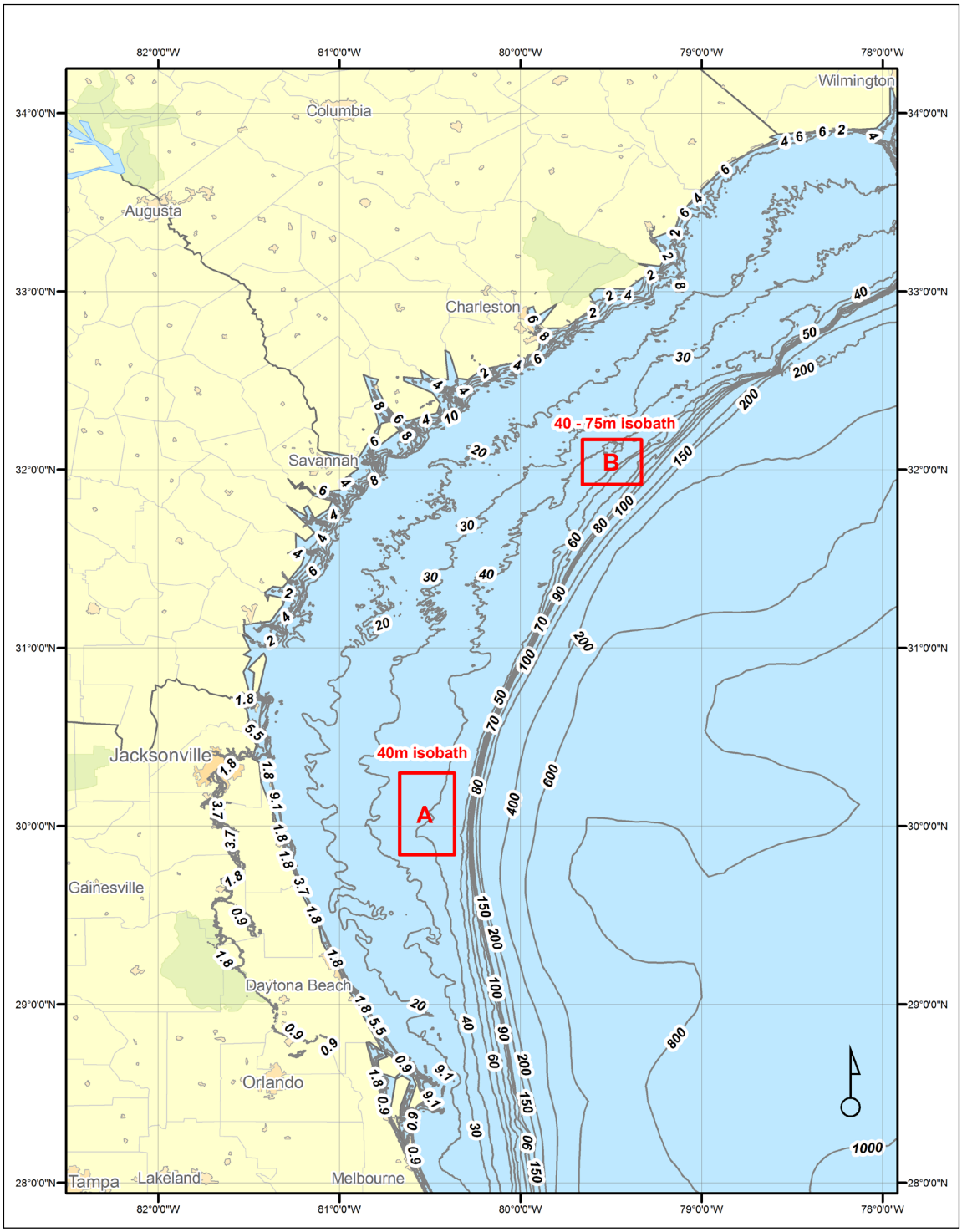


Figure 5.22 Sample stations for zooplankton on the middle and outer shelf from 30-33°N (data taken from Atkinson et al., 1989; Paffenhofer et al., 1987a).

Summer intrusions need to be at least fourteen days to allow one generation of *T. turbinata* to develop (Paffenhofer et al., 1987a). The seed population of the *T. turbinata* for the South Atlantic Planning Area may be from a population in the Gulf of Mexico (Fleminger, 1959) with advection through the Straits of Florida and into the Florida Current.

Another zooplankton taxa whose numbers rapidly increase after an intrusion onto the middle and outer shelves are the doliolid, *Dolioletta gegenbauri*. A comparative study of the worldwide distribution of thaliacean patches, including doliolids, indicated that they require a broad shallow continental shelf, a strong boundary current with eddies and meanders, and along-shelf, upwelling favorable winds (Deibel and Paffenhofer, 2009). These are conditions found in the South Atlantic Planning Area. *D. gegenbauri* appears to require relatively high phytoplankton concentrations to grow and reproduce, so they thrive in intrusions. Doliolids are efficient feeders, using their mucous feeding structure to capture cells smaller than 50 μm in size, including small-celled coccoid algae (2–3 μm) (Deibel, 1985). *Oithona* spp. numbers were inversely related to doliolid numbers, and it has been suggested that doliolids may also feed on the eggs and nauplii of this copepod (Paffenhofer et al., 1995). Several studies have followed changes in the doliolid population and distribution during intrusions. Doliolid blooms are most common in winter and spring and generally persist for 7–9 days, so they can rapidly colonize an intrusion (Deibel, 1985). Off St. Augustine, Florida (30ºN) changes in the population of *Dolioletta gegenbauri* were followed during a summer intrusion (Paffenhofer et al., 1987a). The initial concentration was 5 zoids/m^3, increasing to 1,000 zoids/m^3 after ten days and then sharply decreasing during the next four days (Figure 5.23; Station A in Figure 5.22). A survey on the middle shelf associated with Gulf Stream frontal eddies (32ºN) showed doliolid concentrations of up to 3,200 individuals/m^3 (Deibel, 1985). The near-bottom intrusion waters had much higher numbers of gonozooids (1,600 and 1,300 gonozooids/m^3) than the surface waters (700 and 200 gonozooids/m^3; stations C and D, respectively in Figure 5.24). Much lower doliolid concentrations were found at the outer shelf stations (15 and 10 gonozooids/m^3; station A in Figure 5.24)**.** Stages identified and quantified in the survey included gonozooids, oozoids, phorozooids, nurses, and trophozooids with gonozooids the most common stage found. One likely source of doliolids is the large population in the Gulf of Mexico and carried into the South Atlantic Study Area (Esnal and Simone, 1982; Paffenhofer et al., 1995).

Besides the larger zooplankton on the shelf, there are also significant numbers of phagotrophic protozoans (microflagellates, heterotrophic dinoflagellates, and oligotrich ciliates) which are major grazers of pico- and nanoplankton (Verity et al., 2002). The photoautotrophic ciliate *Mesodinium* spp. is abundant at intermediate depths in the middle shelf (Verity et al., 1996). Heterotrophic nanoplankton, thought to feed on bacterioplankton, were studied off the coast of Georgia by Sherr et al. (1984). Concentrations decreased from 6.3 x 10^3 cells/mL in the inner shelf to 0.3 x 10^3 cells/mL on the middle shelf. Nanoplankton are considered to support longer food chains with small grazers in contrast to diatoms which are associated with large herbivores and short food chains. When protozoans dominate a zooplankton community, grazing rates and growth efficiencies are high (Goldman et al., 1985; Verity, 1985).

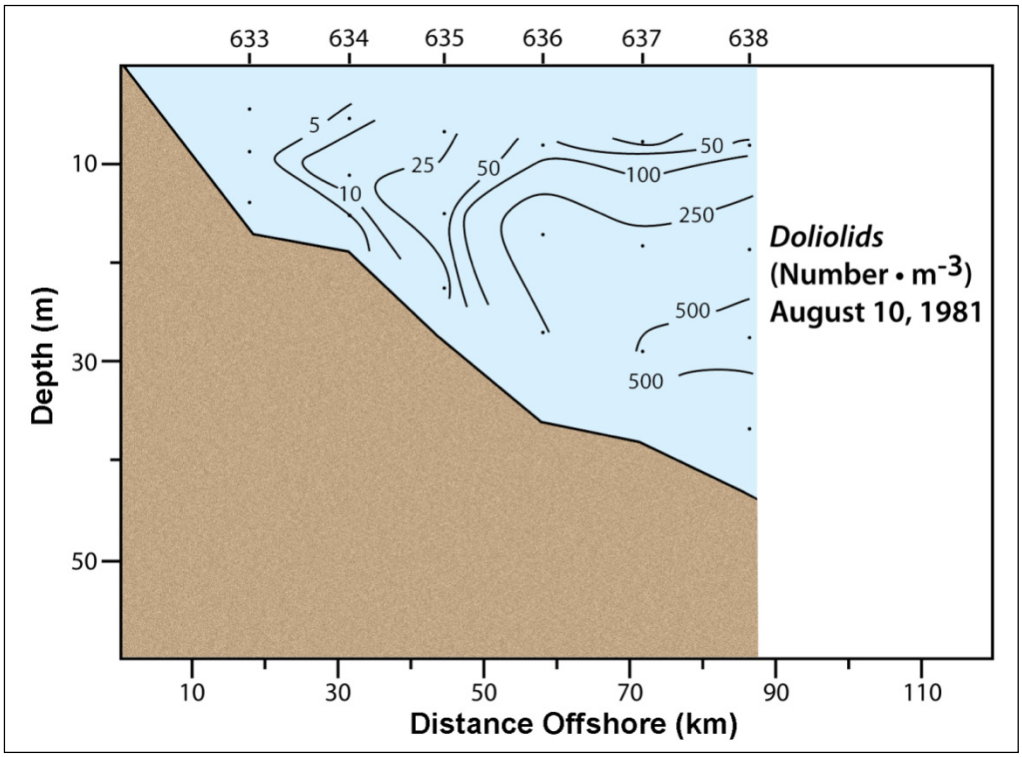
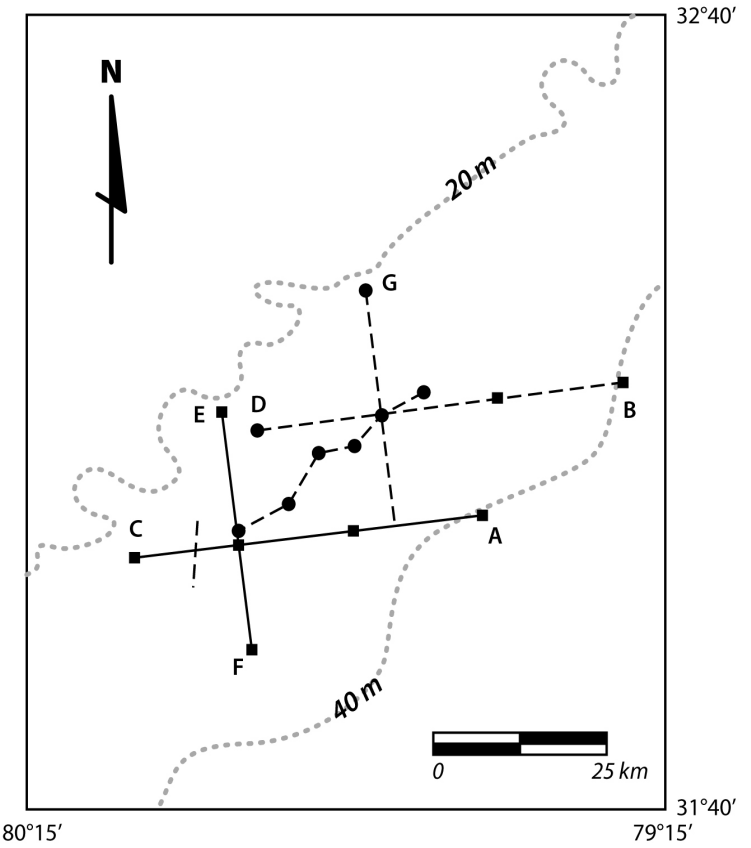


Figure 5.23 Vertical distribution of doliolids on the middle shelf near 30N. Station A in Figure 5.22 (modified from Paffenhofer et al., 1987a).

The diatom-dominated phytoplankton blooms produced by intrusions are associated with an abundance of three zooplankton species: *Dolioletta gegenbauri,* the cladoceran *Penilia avirostris*, and *Temora turbinata* (Paffenhofer, 1983; Paffenhofer et al., 1984). The sequence after an intrusion comes on to the shelf is first Doliolida followed by *T. turbinata*, Oithonidae, and Oncaeidae. The species of *Oithona* found on the shelves include *Oithona brevicornis* on the middle shelf and *O. plumifera, O. robusta*, and *O. setigera* on the outer shelf (Owre and Foyo, 1967). Concentrations of several copepod species (e.g., *Oithona* spp., *Oncaea* spp., *Temora turbinata*) were much lower in the upper mixed layer than in the phytoplankton-rich subsurface waters (Paffenhofer et al., 1987a) (Table 5.5). While doliolids are small particle feeders, *Oncaea* spp., *Oithona* spp., and *T. turbinata* are classified as omnivores. Doliolids and protozoans have an advantage in intrusions since they have short generation times and are thus able to rapidly colonize (7–9 days) a water mass by asexual reproduction within days of the appearance of a phytoplankton bloom (Deibel, 1985; Verity et al., 1993a). Copepods do not respond to frontal eddies, which last 5–7 days, but do respond to summer subsurface intrusions which have a longer duration (14–50 days). Paffenhofer (1980) suggested that approximately 21 days are required for copepods to respond to upwelling events.



Station	Surface Water	Near Bottom Water
	Gonozooids/m^3	
A	30	15
B	150	10
C	700	1632
D	200	1300
E	200	400
F	400	20
G	100	50

Figure 5.24 Concentrations of doliolids (gonozooid stage) at stations in the South Atlantic Study Area during an intrusion event (data from Deibel, 1985).

Table 5.5
Concentrations of zooplankton in upper mixed layer (UML) and subsurface intrusions in the US South Atlantic (from Paffenhofer, 1983)

Name	Off Onslow Bay, NC (34°N)		Off St. Augustine, FL (30°N)	
	UML	Intrusion	UML	Intrusion
	Concentration (individuals/m^3)			
Corycaeus	218	673	118	338
Oithona	1443	803	986	1414
Oncaea	1429	1985	576	5310
Paracalanus	1429	3033	265	350
Temora turbinata	115	166	737	1971
Eucalanus	51	32	42	170
Penilia avirostris	4	22	68	920
Brachiostoma	39	11	105	1553
Chaetognatha	190	420	37	129

5.4.4 Larval Fish

Atlantic menhaden, spot, Atlantic croaker, Gulf flounder, summer flounder, and southern flounder spawn on the outer shelf of the South Atlantic Planning Area, and the larvae are transported from the outer shelf to the estuary (Hare and Govoni, 2005). Govoni and Hare (2001) discuss the Charleston Gyre as larval nursery habitat for fish such as Atlantic menhaden *Brevoortia tyrannus*. There is an abundance of their zooplankton food that feeds on phytoplankton blooms associated with frontal eddies in the Charleston Gyre. It has been suggested that the larvae in the surface waters of the outer shelf are likely to be exported to the Gulf Stream while larvae in deeper waters are likely to be transported onshore to the estuary or some may remain on the shelf (Hare and Govoni, 2005; Werner et al., 1999). Atlantic menhaden (Nelson et al., 1977; Nicholson, 1978) and bluefish (*Pomatomus saltatrix*) (Kendall and Walford, 1979) migrate south of Cape Hatteras, North Carolina in the fall and the high concentrations of large chain-forming diatoms on the outer shelf during intrusions may be an important food for their larvae. Some data are available on the association of fish larvae with intrusions. A study of a subsurface intrusion off St. Augustine, Florida (30°N) found mean concentrations of 11 fish larvae/m^3 (range of 2 **to** 29) while concentrations in the upper mixed layer were 5 larvae/m^3 (range of 1–17) (Paffenhofer, 1985). Anchovy larvae were abundant in subsurface intrusions of the middle shelf at 29 to 31°N (Paffenhofer et al., 1987a). See Chapter 7 Fish Communities for further details of the spawning and larval distribution of fish in the South Atlantic Planning Area.

5.5 Plankton in the Gulf Stream and Adjacent Sargasso Sea

There are fewer studies describing the phytoplankton and zooplankton of the Gulf Stream and adjacent Sargasso Sea than there are studies focused on the plankton of the shelf. The resident waters of the middle and outer waters of the shelf have low phytoplankton concentrations, as

discussed above, and there is some similarity between the assemblages of phytoplankton found in the Gulf Stream and these shelf resident waters. The phytoplankton concentrations of the Sargasso Sea are lower than in the Gulf Stream; these, in turn, are lower than the phytoplankton concentrations on the shelf (Hulbert, 1967; Marshall, 1971). While diatoms are common on the shelf, this phytoplankton group is present only in small numbers in the Gulf Stream and adjacent Sargasso Sea. Marshall (1971) reported finding the following diatoms in the Gulf Stream: *Rizosolenia alata, R. calcar-avid, Chaetoceros decipiens,* and *Coscinodiscus lineatus*. An important group of phytoplankton in both the Gulf Stream and Sargasso Sea are the coccolithophores, which are generally a minor group on the shelf. Fourteen species of coccolithophores were found only in the Gulf Stream; the dominant species were *Coccolithus huxleyi, Gephyrocapsa oceanic, Syracosphaeta mediterranea*, and *S. pulchra* (Marshall, 1971). Pyrrhophyceans were more abundant than diatoms in the Gulf Stream; eleven species were found only in the Gulf Stream (Marshall, 1971). Silicoflagellates were identified in both the Sargasso Sea and Gulf Stream; *Dictyocha fibula* was the most common of four identified silicoflagellates. *Trichodesmium* spp. was identified in both the Sargasso Sea and Gulf Stream (Hulbert, 1967; Marshall, 1971).

Zooplankton concentrations are lower in the Gulf Stream and Sargasso Sea than the concentrations on the shelf in the South Atlantic Planning Area (Bowman, 1971; Herman, 1979). Calanoid copepods of the Gulf Stream and Sargasso Sea include *Undinula vulgaris, Euchaeta marina,* and *Clausocalanus furcatus* (Bowman, 1971). Cyclopoid copepods in the Gulf Stream include *Oithona plumifera, O. robusta*, and *O. setigera* which feed on the flagellates and are adapted to the low phytoplankton concentrations of this oceanic region (Owre and Foyo, 1967; Paffenhofer et al., 1987a).

5.6 USING MODELS TO UNDERSTAND PROCESSES AFFECTING PLANKTON

A number of biological models have been prepared which simulate effects of intrusions on plankton in the South Atlantic Planning Area (Hofmann, 1988; Hofmann and Ambler, 1988; Ishizaka and Hofmann, 1988; Pribble et al., 1994). These authors used the data collected in GABEX I and II to construct two mathematical models with an objective of understanding and quantifying biological responses to upwelling associated with frontal eddies and subsurface intrusions. GABEX I and II are described in the introduction of this chapter. Ishizaka and Hofmann (1988) considered circulation effects on the transport of plankton across the shelf of the South Atlantic Planning Area. Hofmann and Ambler (1988) developed a system of ten coupled differential equations (nitrate, ammonium, two phytoplankton size fraction [>10 μm and <10 μm], five copepod development stages, and detritus) to investigate the time-dependent biological interactions of phytoplankton and copepod developmental stages associated with frontal eddy and subsurface intrusions. The >10 μm cell size fraction included the large centric diatoms associated with intrusions and the <10 μm cell size included small flagellates associated with resident water on the shelf. In this modeling study, the initial value of phytoplankton was assumed as 0.2 mg chlorophyll a/m^3, the so-called threshold value, which was the chlorophyll concentration of resident water. Advective and diffusive processes associated with upwelling bring in nutrients, which produced a bloom dominated by large-celled diatoms. Large cells accounted for 63% of the total phytoplankton biomass produced during an upwelling cycle. The maximum chlorophyll concentration in the model was 6.6 mg chlorophyll/m^3. The large-celled

phytoplankton were grazed down by adult copepods and late copepodid stages while small cells were grazed by all copepod developmental stages. In the third paper (Hofmann, 1988), a ten-component biological model was prepared to investigate the effects of two types of upwelling (frontal eddies and subsurface intrusions) on the phytoplankton and zooplankton communities. The simulated distributions showed basic differences in the biological response to frontal eddy and subsurface intrusions. The subsurface intrusions had longer time scales than those associated with frontal eddies, allowing zooplankton to feed and reproduce on the phytoplankton bloom. Thus, subsurface intrusions had zooplankton biomass approximately twice that associated with frontal eddies. The subsurface intrusion simulations showed that approximately 20 days were required for the cycle going from nitrate input to the end of the copepod bloom with 40-day intervals between nitrate pulses. Simulations from the model suggested biological mechanisms that may account for the phytoplankton and zooplankton distributions observed in frontal eddies and bottom intrusions.

Pribble et al. (1994) combined a one-dimensional, time-dependent biological model with a three-dimensional physical model. They used the Coastal Zone Color Scanner images at 31.5ºN. They were successful with this model in simulating new primary production during upwelling. A time-dependent numerical model was developed by Haskell et al. (1999) to determine the interactions of doliolids, copepods, and phytoplankton during upwelling at the Charleston Gyre (32ºN) produced by the flow of water over the Charleston Bump. Simulations showed that copepod populations were significantly reduced when doliolids were present. The authors suggest that this copepod reduction was due to predation by doliolids on copepod eggs and juveniles. Also, the cooler, upwelled waters favored the growth of the rapidly growing doliolids.

5.7 SATELLITE STUDIES

Satellites with color scanners have been used over the past three decades to assess phytoplankton over the South Atlantic Planning Area (Figures 5.3, 5.4, 5.10, 5.11, and 5.20). These included the Coastal Zone Color Scanner (CZCS) on the Nimbus Satellite in 1976, SeaWiFS on the Orbview-1 spacecraft in 1997, and MODIS in 1999 on the Terra satellite. Chlorophyll concentrations by satellite sensors are determined by the reflectance from the ocean in the blue and green spectra regions. Water low in chlorophyll reflects more blue light than green, while water with high phytoplankton concentrations reflects more green light since there is selective absorption of blue light by the phytoplankton. Using algorithms, the optical signals are converted to chlorophyll concentrations, although there is a large degree of uncertainty in these chlorophyll numbers. Using the algorithm developed by Behrenfeld et al. (1998), the primary production can be calculated from the chlorophyll concentrations as follows:

$$\mathrm{Log_{10}PP} = 0.559 \log_{10}\mathrm{C} + 2.793.$$

where C is the chlorophyll concentration and PP is primary production. At a chlorophyll concentration of 0.56 mg/m^3 the primary production is 0.6 g C/m^2. More recently, a carbon-based production model (CbPM) has been developed where the particulate backscatter coefficient is used to estimate phytoplankton carbon with phytoplankton growth rates obtained from chlorophyll:carbon ratios (Behrenfeld et al., 2005; Westberry et al., 2008). The parameters needed to calculate net primary production by CbPM includes chlorophyll concentration,

particulate backscattering coefficient, photosynthetically active radiation, mixed-layer depth, and day length.

Besides phytoplankton chlorophyll, other water constituents, including suspended particles and dissolved organics, are optically active and contribute to the reflectance observed. The high concentrations of dissolved organics on the inner shelf of the South Atlantic Planning Area make it difficult to distinguish between chlorophyll and dissolved organics. Intrusions in the cooler months go over the colder, denser shelf waters, so-called overriding intrusions, and the satellites can obtain reflectance from this bloom in the upper photic zone. Primary production obtained by the ^{14}C method correlated well off the North Caroline coast with primary production calculated from chlorophyll concentrations obtained from satellite reflectance data (Brown et al., 1985). However, during the summer, when there are subsurface intrusions and consequent blooms, there is no optical signal coming from this deep chlorophyll which occurs at more than one light attenuation depth. Off the Georgia shelf one attenuation length is about 20 m, and the chlorophyll maximum during summer subsurface intrusions is often between 15–30 m depth on the middle and outer shelves (J. Nelson, pers. comm.). Using the different optical properties of different groups of phytoplankton, satellite reflectance data have been used to distinguish between haptophytes, coccolithophorids, nitrogen-fixing cyanobacteria, *Prochloroccoccus, Synechococcus*-like cyanobacteria, and diatoms (Alvain et al., 2005; Brown and Yoder, 1994; Joint and Groom, 2000; Siegel et al., 1999; Subramanian et al., 2002).

An examination of SeaWIFS data from the South Atlantic Planning Area by Hoge et al. (2001) showed highest phytoplankton abundance in areas surrounding capes of this region. Sea surface temperatures changes can be used as a proxy for surface nitrate concentrations and thus following temperatures by satellite can be used to follow frontal intrusions. Ishizaka (1990b) used chlorophyll concentrations obtained from the CZCS data over Gulf Stream frontal eddies off northeast Florida in a four-component ecosystem model with advection-derived current meters. Signorini and McClain (2007) studied a nine-year ocean color time series from SeaWiFS over the US South Atlantic. They noted that the blooms produced by summer subsurface intrusions were not captured by ocean color satellites, but by analysis of ocean color data, sea surface temperatures, sea surface heights, and climatological data sets, they presented evidence for a connection between Gulf Stream intrusions and variability of the size and strength of the North Atlantic Subtropical Gyre (NASG). They found a high correlation between the size of the NASG and chlorophyll a concentrations in the slope region north of the Charleston Bump. Thus their analysis of this complex data set from the satellite allowed them to provide indirect evidence of a subsurface bloom.

5.8 POTENTIAL IMPACTS OF OCS DEVELOPMENT ON PLANKTON COMMUNITIES

5.8.1 Oil and Gas Exploration and Development

Offshore oil production and development can result in oil spills that can affect the plankton. A number of studies have addressed oil uptake by zooplankton after oil spills. After a Bunker C oil spill in Chedabucto Bay, Nova Scotia, Canada, Conover (1971) found copepods (*Temora longicornis*) with oil particulates in the spill area. The oil particulates in this spill ranged in size from 10 to 100 µm in diameter, and Conover (1971) calculated that as much as 10% of the oil

particulates in the water column were associated with zooplankton and their feces. Wong et al. (1981) noted that the freshwater crustacean, *Daphnia pulex*, took up oil particles (1–100 µm in diameters with most in the 5–10 µm size range). While they are feeding, marine protozoans can take up oil droplets and presumably such uptake could occur in an oil spill area (Andrew and Floodgate, 1974; Lanier and Light, 1978). Lee (1975) showed that copepods, euphausiids, amphipods, crab zoea, ctenophores, and jellyfish could take up petroleum compounds from seawater. The crustacean zooplankton metabolized a portion of the hydrocarbons, but the ctenophores and jellyfish could not.

A unique aspect to the recent Gulf of Mexico oil spill was the wide spread application of dispersants, namely Corexit 9500 and 9527. These dispersants include diooctyl sulfosuccinic acid and sorbitan monoleate polyethoyxylate. Paffenhofer, Koster, and Lee at the Skidaway Institute of Oceanography exposed copepods (*Eucalanus pileatus*) and doliolids (*Dolioletta gegenbauri*) to dispersed oil droplets (Lee et al., 2011). These dispersed oil droplets, which varied in size from 10 to 50 µm, were formed by mixing Corexit 9500 with oil from the *Deepwater Horizon* spill. The oil droplet is stabilized by the surfactant properties of the dispersant so that the hydrophobic end of the dispersant is in the oil droplet while the hydrophilic part of the dispersant faces into the seawater (Figure 5.25). Thus, the addition of dispersant to an oil spill results in stabilized dispersed oil droplets in contrast to unstable oil droplets produced when dispersant is not used.

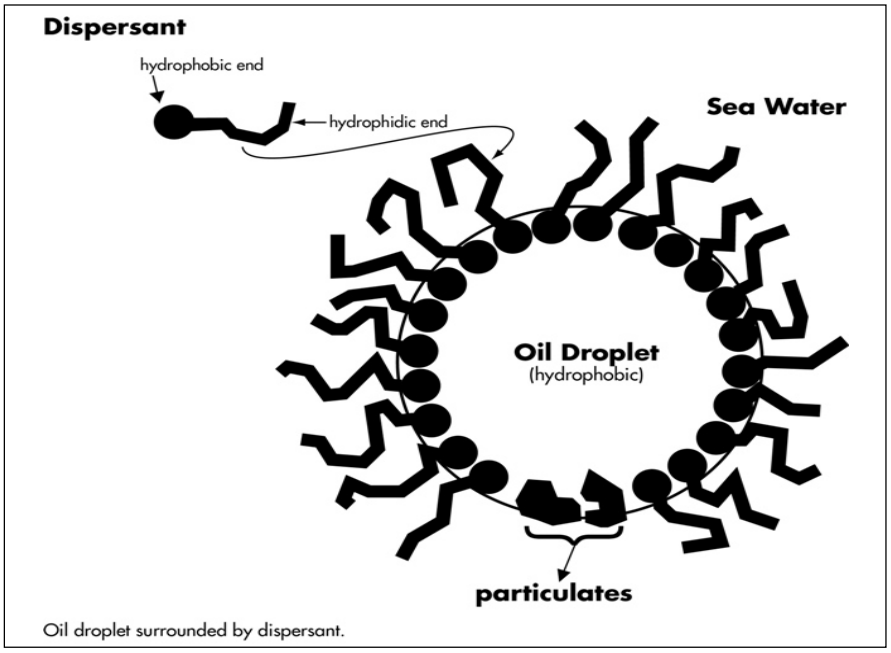


Figure 5.25 Oil droplet surrounded by dispersant.

A microscopic examination of *E. pileatus*, which were feeding on phytoplankton, found they had taken up these dispersed oil droplets. After taking up these droplets, it seems likely that there would be effects on the reproduction and growth of the zooplankton. In addition, as noted in earlier work, the zooplankton can be an important factor in determining the fate of the oil by metabolizing some of the oil and by passing oil droplets into their feces that can enter the

benthos. There seems to be few, if any studies, on the effects of an oil spill on zooplankton populations. The possibility of using hyperspectal sensors such as NASA's Hyperion (on-board EO-1 satellite) and AVIRIS (on-board ER-2 aircraft) may allow zooplankton researchers to carry out more intensive sampling of zooplankton with oil droplets associated with the path of both dispersed and untreated oil spills (Liang et al., 2011).

Relatively few studies have examined the effects of spilled oil on phytoplankton. One study that provides some insight into the possible effects on oil on phytoplankton after an oil spill involved the addition of water extracts of fuel oil (initial concentration of 20 μg/L) to large mesocosms (60,000 L) suspended in Saanich Inlet, British Columbia, Canada (Lee and Takahashi, 1977; Lee et al., 1977). In the oil-treated mesocosm, there was a significant decline in diatoms, followed by a bloom of the microflagellate, *Chrysochromulina kappa*, which replaced diatoms as the dominant phytoplankter. This, in turn, was followed by an increase in tintinnids and rotifers, presumably feeding on the microflagellates. The control enclosure continued to be dominated by a diatom, *Ceratualina bergonii*. Thus, in this study there were major changes in the ecosystem of the enclosure, in terms of the type of primary and secondary producers. This change in primary producers was thought to be temporary because hydrocarbon concentrations returned to near-baseline levels nine days after the addition of petroleum. The growth of a laboratory culture of *C. kappa*, isolated from the fuel oil-treated mesocosm, was stimulated by fuel oil (Parsons et al., 1976). Further work is needed to determine the effects of oil spills, both with and without dispersant, on both primary and secondary producers.

5.8.2 Sand and Gravel Extraction

Little information is available about possible effects of sand and gravel extraction on plankton of the South Atlantic Planning area. A possible effect would be any turbidity produced by sand and gravel extraction that could affect primary production on the shelf. However, this effect would be expected to be temporary since any suspended particles produced by such extraction activities would likely settle quickly to the bottom.

5.8.3 Renewable Energy Development

Energy from solar, marine wind, tides, currents, waves and thermal gradients are examples of renewable energy in the coastal environment of the South Atlantic Planning Area that could be used to produce electricity. Michel et al. (2007) summarized the information available on the environmental effects of renewable energy use on the outer continental shelf of the US, including the east coast shelf. While fish and benthos were identified as affected ecological components, there was no specific mention of effects on a plankton component. It was noted that using energy from currents could affected longshore sediment transport and even changes to major ocean currents, such as the Gulf Stream. Such current changes would be predicted to have effects on plankton (see earlier discussion in this review on the importance of offshore currents in producing upwelling and consequent plankton production). Increases in turbidity as a result of resuspension of sediment or sediment transport could potentially affect primary production by limiting light penetration in the nearshore. Mention is made of anti-fouling chemicals, some of which are quite toxic to plankton, being used in offshore installations of renewable energy systems. Boehlert and Gill (2010) reviewed the environmental and ecological effects of ocean renewable energy development. They discuss the effects of renewable energy in terms of stressors (features of the environment that may change with renewal energy) and receptors

(elements of the ecosystems with potential for some form of response to the stressor) with one environmental receptor being the pelagic habitat and its plankton component.

Mention should be made of the effects on plankton of ocean thermal energy conversion where large volumes of both cold deep and warm waters are moved to take advantage of the thermal difference between them. Any dramatic changes in temperature would likely have significant impacts on plankton (Harrison, 1987). Another response could be increased primary production as a result of bringing deep-water nutrients to low-nutrient surface water, similar to the upwelling that occurs on the outer shelf of the South Atlantic Planning Area. An additional response by plankton could be due to acidification as a result of bringing deep water the surface (Feely et al., 2008). Any renewable energy systems that have devices that use hydraulic fluids present a potential for spills with consequent effects on plankton. Boehlert and Gill (2010) concluded that the equipment associated with renewable energy devices is likely to have only a minimal impact on both phytoplankton and zooplankton.

5.9 SUMMARY AND DATA GAPS IN THE STATE OF KNOWLEDGE FOR PLANKTON COMMUNITIES WITH REGARD TO OCS DEVELOPMENT

One of the most dynamic zones of the South Atlantic Planning Area is the north Florida coast south of Jacksonville to Cape Canaveral (30ºN region). There is almost continuous upwelling along the inner, middle, and outer shelf of this zone, resulting in high primary production throughout the year. High zooplankton concentrations are associated with the high primary production and, in addition, an abundance of shellfish, such as clams, scallops, and crabs. An unusual assemblage of foraminfera has been found on the north Florida shelf with some of highest densities reported from the world's oceans (Sen Gupta et al., 1981). We suggest that a concerted effort is warranted in this productive zone to better understand the coupling between the high primary/secondary production in the water to the high production of the benthos. Because of the upwelling found in the shallow waters of the inner shelf of this zone it may be that there is also high primary production on the bottom. Any OCS development in this zone needs to consider the unique aspects of the plankton dynamics of this zone.

As noted earlier in the chapter, satellites with color scanners have been used to assess phytoplankton in the South Atlantic Planning Area. Using the different optical properties of different groups of phytoplankton, satellite reflectance data has been used to distinguish among these different phytoplankton groups. Future studies should focus on satellite data to determine the abundance of different phytoplankton groups on the shelf including before, during, and after intrusions. SeaWiFS is now down and hopefully a new satellite will be launched in the near future with improvements in ability to collect high-quality satellite reflectance data.

One problem with satellite reflectance data that needs to be addressed is to distinguish the optimal signal production by dissolved organic matter along the coast from the signal produced by chlorophyll. Another problem that needs to be addressed is the inability to detect subsurface intrusions and their associated bloom by satellite or other aerial sensors.

Further work along the South Atlantic Planning Area with some of the newer molecular techniques may prove useful for plankton studies in this area. For example, a DNA-

hybridization-based method of analysis employing bead-array technology has been used to detect phytoplankton species in the coastal waters off the US west coast (Ellison and Burton, 2005).

The importance of nutrients brought into the shelf by ground water is a topic of interest since this may be source of nutrients for phytoplankton in the oligotrophic resident waters of the inner shelf when there little or no upwelling. See Chapter 4 Chemical Oceanography, where groundwater and nutrients in the South Atlantic Planning Area are discussed. Another source of nitrogen that needs further evaluation is atmospheric nitrogen into the shelf of the South Atlantic Planning Area (Castro et al., 2000).

One of the postulated effects of global climate change is a slowdown of thermohaline circulation in the Atlantic as a result of glacial melting which could weaken the Gulf Stream with consequent effects on the plankton (Schiermeier, 2006; Vellinga and Wood, 2002).

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CHAPTER 6: BENTHIC COMMUNITIES

6.1 INTRODUCTION

This synthesis of the literature on benthic communities is divided into the topics of soft-bottom and hard-bottom communities, which was done for several reasons. First, the research experience and expertise of the authors were similarly divided. Second, the two substrata are dominated completely by different taxonomic communities with different population patterns, reproductive strategies, feeding mechanisms, and responses to environmental change. Third, quantitative sampling methods differ for the two habitats: remotely deployed, area-based, volumetric coring and grabbing devices in soft substrata and in situ observations and image analysis methodologies using scuba, remotely operated vehicles (ROV), or submersibles over hard/live substrata. Fourth, the literature cannot readily be split geographically, creating a high likelihood of repeated effort and inefficiency. Thus, dividing the writing tasks by habitat was an acceptable and effective manner in which to present the findings. This division, however, by no means diminishes the actual continuity and commonalities that exist between soft- and hard-bottom communities. They share many similar ecological processes with some exchange of fauna and flora in overlapping patchworks that maintain high biodiversity and support harvestable quantities of biomass. The soft- and hard-bottom communities discussed in this section are not physically or ecologically disjunct; both co-exist and function in a complex web of interactions characterized by spatial and temporal variability driven by both biotic and abiotic forces.

6.2 SOFT-BOTTOM BENTHIC COMMUNITIES

6.2.1 Summary Overview and Introduction

Most of the survey, transect-based assessments of soft-bottom benthos in the South Atlantic Planning Area were conducted in the 1970s. In the 1980s and 1990s, South Carolina Department of Natural Resources personnel conducted several studies in relation to beach renourishment/disposal activities; in the 2000s, NOAA personnel conducted more surveys. Since its establishment in 1981, the Gray's Reef National Marine Sanctuary has also been a focal point for studies of benthos and benthic processes.

Approximately 30% of the South Atlantic Planning Area is hard bottom or "live" bottom that harbors a species-rich community that differs greatly from its surrounding sandy bottom. Section 6.3 covers that community. The majority of the South Atlantic Planning Area consists of sandy sediment that shifts and moves with the tides in shallow portions of the shelf and with waves and currents, especially during storm events, all across and along the shelf. Compared with other areas of the US continental shelf/slope, the South Atlantic Planning Area soft-bottom benthos has low abundance, low biomass, and moderate biodiversity. The predominant infauna are polychaete worms and amphipod crustaceans, with bivalves, oligochaetes, gastropods, and echinoderms also prominent members of the community. The entire region suffers from undersampling to the extent that it has been difficult to establish with the extant data whether there are consistent seasonal changes or even consistent changes in longitude (across shelf) or latitude that can be found year-to-year. The inner-shelf benthos receives organic matter input (food) as outwellings from rivers and estuaries out to about 20 km from shore where a persistent

salinity front isolates these shallower waters from the deeper middle and outer shelf. The more seaward portions of the shelf receive periodic intrusions of nutrient-rich water from below the Gulf Stream that cause higher levels of primary production. Detrital rain that results from these intrusions fuels the benthos there.

Different studies have used different sampling gear, making inter-study comparisons tenuous. The region needs 1) additional monitoring with standardized sampling and processing protocols and 2) experimental determination of the relative importance of biotic and abiotic forcing functions before it can be possible to predict how the soft-bottom benthos will respond to future development activities. As additional samples are collected in the future, hundreds of undescribed new species will be found, so our taxonomic expertise needs upgrading as well.

Unconsolidated, soft-bottom sediments comprise the largest, by area, habitat on Earth, yet it is perhaps the least visible of all and one of the most difficult to study. Describing and understanding benthic communities require background knowledge of invertebrate biology, taxonomy, ecology, statistics, and of the types of problems inherent in sampling the benthos. Benthic communities are somewhat unique in the sea because the organisms comprising them do not move around very much and can be revisited and sampled repeatedly over time. Benthic organisms interact intensely with and are strongly affected by physical, geological, chemical, and biological factors. Therefore, an interdisciplinary approach is necessary to study or place the benthos into its proper ecological context in the grand scheme of things oceanic.

This section provides a summary of soft-bottom benthic communities, how they are sampled and processed, their diversity, and how they fit into the bigger marine ecological picture. Some web sites that can assist understanding include:

- The National Benthic Inventory web site (http://nbi.noaa.gov) contains pictures of benthos sampling methods and gear that would help the reader understand more about how quantitative collections are made.
- The Gray's Reef National Marine Sanctuary web site provides a non-technical introduction to "Benthic fauna: life below the sea floor." (http://www.seamonsters.noaa.gov/). Plates 6.1 and 6.2 show photographs of benthic organisms of the region from this site.
- The NOAA Photo Library Collection web site contains images of organisms. http://www.photolib.noaa.gov/nurp/index.html brings up a section called "Voyage to Inner Space–Exploring the Sea with NOAA" with images from their Ocean Exploration, National Undersea Research Program, and Oceanographic History collections.
- SEAMAP collects, manages, and disseminates fishery-independent data in the southeastern US. The SEAMAP-South Atlantic component contains data on shallow-water, bottom-trawl surveys, benthic characterization and bottom mapping projects.
- The Digital Library for Earth System Education web site contains resources for grades 9-12 that address National Science Education Standards. It is part of the Ocean Explorer offerings from NOAA. This lesson is for students to investigate the shape of the continental margin by studying bathymetry in the South Atlantic Bight. http://www.dlese.org/library/catalog_DLESE-000-000-007-708.htm.

Plate 6.1 Photographs of benthic organisms of the South Atlantic Planning Area. Top panel shows mollusks; bottom panel shows enchinoderms. Source: Grays Reef National Marine Sanctuary (2010).

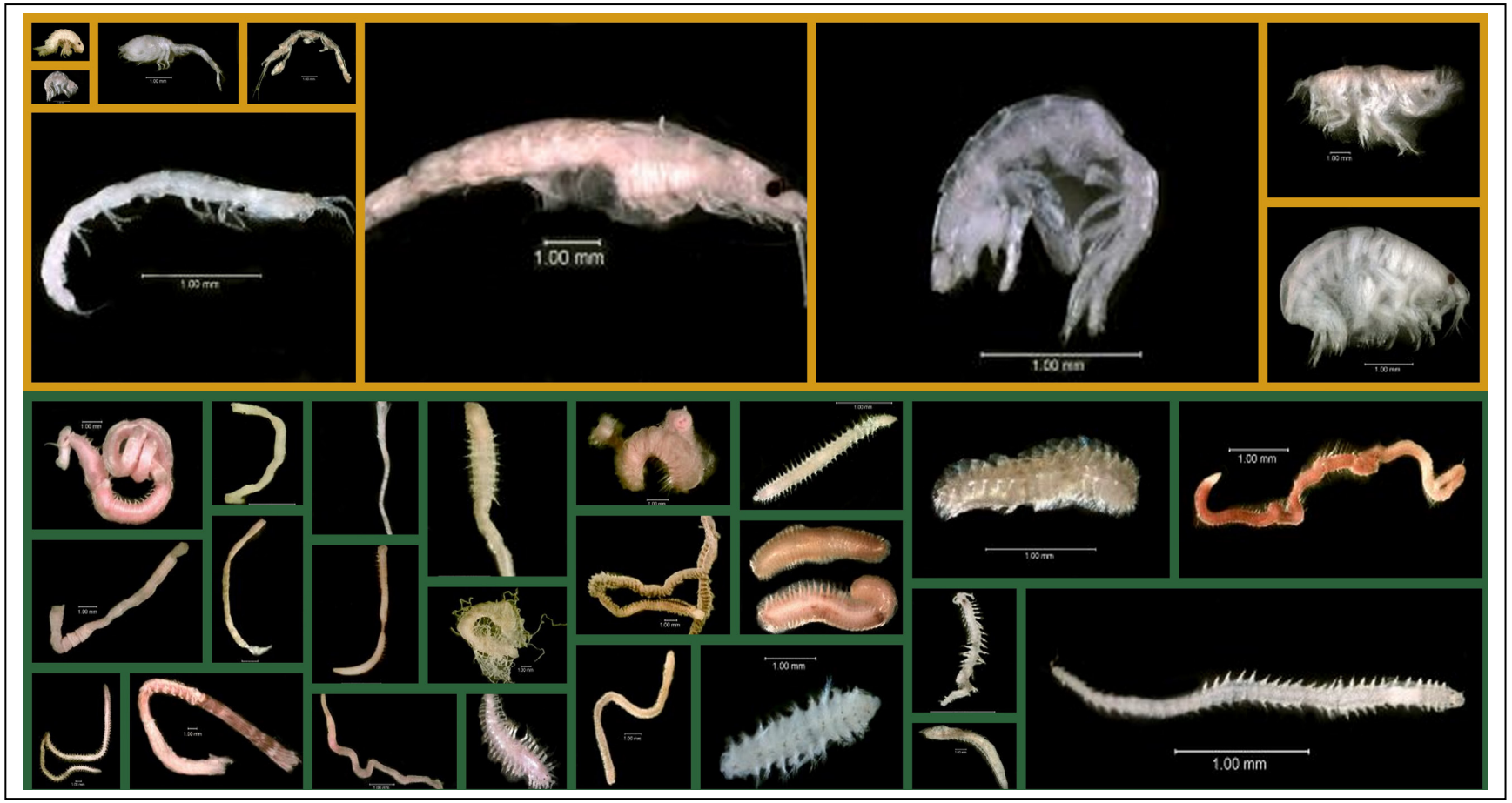

Plate 6.2 Photographs of benthic organisms of the South Atlantic Planning Area. Top panel shows crustacea; bottom panel shows polychaetes. Source Grays Reef National Marine Sanctuary (2010).

6.2.1.1 Classifications of Benthic Animals

Based on organism size, the largest benthos are called megabenthos (e.g., 30 m long kelp, deep-sea hydrothermal vent tubeworms over 3 m long, clams as long as 1 m, king crabs with leg spans of 2 m, and sea stars 1 m in diameter), hence best "sampled" using a camera or large trawls. The common benthos (mollusks, crustaceans, annelids, and echinoderms) are called macrobenthos (will not pass through a screen or mesh with 1.0 mm openings). The meiobenthos consists of metazoan organisms (nematode worms, copepods) that can pass through a 1.0 mm screen but will be retained on a 0.062 mm mesh. The bacteria and unicellular organisms (protozoans) belong to the smallest group of benthos called microbenthos. These are usually counted in very small-volume samples of un-sieved sediment.

Based on organisms' habitats and mode of living, some other terms used to describe benthic organisms are infauna (animals that live amongst the sediment particles or "in" the bottom), epibenthos (those that live on or slightly above the surface of the seabed, like some shrimp and crabs), and combinations of descriptors, such as macroinfauna, meiobenthic infauna, and attached macroepifauna, such as barnacles and limpets. Demersal zooplankton is a group of motile, semi-benthic organisms that emerge periodically from temporary residence on the bottom and swim in the overlying water before returning to the bottom.

Benthic organisms may also be classified according to the types of food they eat and how they obtain that food (e.g., carnivorous, omnivorous, herbivorous, detritivorous, scavengers, heterotrophs, autotrophs). Heterotrophs gain nutrition by eating other organisms, whereas autotrophs make their own food, usually using photosynthesis. According to their modes of feeding, benthos can also be classified as deposit feeders (eat sediment particles) or filter feeders (take particles out of suspension as it flows past them), or according to where they feed (e.g., surface deposit feeders, sub-surface deposit feeders). These latter two terms describe animals that ingest both organic and inorganic sediment particles, including any attached bacteria that are digested to provide nutrition. Most of the deep-sea soft-bottom benthos are deposit feeders, whereas most shallow-water benthos, with exceptions, exhibit a variety of feeding modalities.

Benthic organisms living in a unit area of the seafloor can be quantified as to their "standing stock" or biomass. Biomass can be expressed as weight, and organism weight may be measured after blotting excess water from the external parts of the body as wet (living) weight, after oven drying to remove internal water (= dry weight), or after removal of organic components by combustion of the dry organism (= ash-free dry weight, AFDW). Their elemental carbon weight can also be measured. To account for respiration, differences in the measured biomass of heterotrophic organisms as they grow and gain weight over time is called net secondary production, while changes in the biomass of autotrophs is called net primary production.

Carbon, C, is the basic elemental building block of all living organisms. One can measure the amount of carbon (or nitrogen or sulfur) in organisms as a surrogate measure of their biomass for comparative purposes. The C in a polychaete worm comes from C in the food it ingests, and although most of that organism's C is lost as CO_2 during respiration, some ingested C is incorporated into new muscle tissue and reproductive products (sperm and eggs) as the animal grows. This cyclical behavior of C from the air into organisms and back out again makes it a common currency for the construction of food webs in terms of C fluxes. All the C in food webs

ultimately came from atmospheric CO_2 that became incorporated into the living tissue of primary producers, like algae and some bacteria, through photosynthesis using energy from sunlight, the base of the food web. By following the dynamics and amounts of C as it cycles through ecosystems, we can better understand the flow of energy and materials (biomass) in marine (or terrestrial) food webs. Productivity can be expressed as, for instance, grams of carbon per square meter per unit time (hour, day, or year) to get an idea of how fast a population of organisms is increasing its carbon biomass. Therefore we measure the C content of nearly everything in the ocean. The Shelf Edge Exchange Programs and the Ocean Margins Program conducted in the northeastern US continental margin are representative of the types of research questions being asked about C-cycling on the continental shelf and slope (Bauer et al., 2002; Verity et al., 2002).

6.2.1.2 Sampling and Processing the Soft-bottom Benthos

Benthic fauna may be sampled qualitatively to quickly get an idea of what organisms are there and their relative abundance. Qualitative samples are not very useful for making anything other than descriptive comparisons of the fauna found from place to place. Quantitative samples of benthos are those for which the volume and/or area of sediment collected can be measured. However, if the volume of sediment collected from sample-to-sample is quite variable, or the area of sediment collected changes each time, it is not possible to quantify organism abundances per unit area or volume with either precision or accuracy.

Benthic ecologists use many different sampling devices–core tubes with different diameters, grab samplers that cover different sediment surface areas or that dig to different depths–all of which may be quantitative but which make it difficult to compare among samples collected with different devices. Often the same sampling device performs differently each time it is deployed.

Benthic fauna should be sampled quantitatively. That is, a known volume of sediment from beneath a known area can be obtained in a consistent manner time after time from an area of interest. The sampling process is usually destructive, as animals collected are ultimately killed during processing. Benthic ecologists consider additional samples collected from the same general area within, say, one or a few or sometimes even tens of meters apart, as replicate samples. Sampling from ships makes it hard to lower the collecting device to the exact same place on the bottom. Due to the inherently uneven distribution, or patchiness, of organisms in nature, so-called replicate samples can be very different, adding considerable variability to measurements of organism abundance or biomass.

Quantitative benthic sampling devices are designed to obtain a consistent volume of sediment from beneath a known surface area. Replicate samples should be taken with the same device before making statistical comparisons between samples. This rule is often disobeyed, however, because organism abundance can be measured using many different types of quantitative sampling gear. Thus estimates of abundance from core tube samples to a depth of 15 cm into the sediment can be compared to those made from counting samples taken with cores of different diameters, so long as they collected sediment to the same 15 cm depth horizon. Counts from different sampling devices are then simply uniformly extrapolated from whatever area (and volume) was actually sampled, say perhaps from an area of 0.02 m^2, to a standard area, usually on a per square meter basis for macrobenthos. Counts of smaller benthos are also extrapolated to larger areas, always using a simple multiplication factor. A square meter is the standardized area

used for expressing macrobenthos abundance, i.e., #/m^2. It is usually #/10 cm^2 for meiobenthos and #/cm^3 for microbenthos. Megabenthos are quantified as # visible or identifiable per unit transect length. Transect lengths surveyed vary greatly in length, and long (hundreds of m to km) transects are often broken into shorter segments that can serve as pseudo-replicates. Investigators should always provide exact information about the size of their sampling device, including the area and/or volume of sediment sampled by the device, with maximum sediment depth specified and number of replicates analyzed as well. Unfortunately, this is not always the case in the published literature. Too often, counts of organisms made from several replicate samples are lumped together and reported only as an average or mean value with no indication of error about the mean.

Core tubes open on both ends, rectangular straight-sided boxes with no top or bottom, or variations on this theme, such as grab samplers, are typically used to sample the benthos quantitatively. Some devices are more efficient (collect more of what's actually there) than others by capturing animals living deeper within the sediment (Smith and Howard, 1972). Hand-held cores seem to be the gold standard for sampling shallow water benthos down to SCUBA-accessible depths (generally no more than about 30 m), whereas remotely deployed core tubes pushed into the mud are usually used when taking samples with ROVs or submersibles. Ship-deployed samplers are sent to the bottom on the end of a cable where they penetrate the sediments under the force of gravity, often with an assist from added weights. One major problem concerns the fact that many organisms live in the topmost layer of the sediment, and a device being lowered remotely to the bottom on a cable can cause this soupy surface layer of sediment to be swept away by the "bow wave" present in front of the device before it hits the bottom.

The best quantitative samples of soft-bottom benthos in deep water are those taken with box cores, heavy metal devices that sample a known surface area to a consistent depth and that deploy a horizontal blade that encloses the sample at the bottom to seal it from any winnowing during retrieval. Box cores have the added benefit of not producing bow waves, as they are sent to the bottom while open on both the top and bottom, are slowly held in position above the bottom by a large, rigid frame and then slowly penetrate the sediment without "crashing" into the bottom like grab samplers do. Box cores upon retrieval will typically contain extremely clear water on top of the sediment, an indication that the device did not disturb the bottom's surface before it was sampled. Once back on board the ship, large box core samples may be sub-sampled by hand using replicate cores within the box core. Such replicate sub-samples are not, however, true replicate samples of the bottom.

Once sediment samples have been collected, they are sieved at the appropriate size intervals, fixed using formalin, stained using Rose Bengal, and, if necessary, preserved in alcohol. The processing of benthic organisms is a necessary part of any collection program. Not only are methods of sample collection quite different among studies, but also the manner in which different investigators process samples can make large differences when attempting to compare collections.

6.2.1.3 Ecological Role and Diversity of Soft-bottom Benthic Organisms

As noted by Gray and Gray (1981) and Gray and Elliott (2009), almost three-fourths of our planet is covered by sediments that are covered by water, and all of these sediments harbor benthic communities. The benthos is very important in maintaining the health and welfare of the Earth and its diverse denizens.

Understanding what roles benthic organisms play in the marine environment requires knowledge of their taxonomic composition, where they live, how they feed and reproduce, what they eat, what eats them, and how they impact and are impacted by their physical surroundings and other organisms. Benthic organisms are important in an ecosystem context because they perform many critical ecological functions (Figure 6.1). Under normal circumstances, the benthos moves, captures, deposits, and mixes sediment particles by feeding upon, burrowing, or building tubes in it in a process called bioturbation (Graf and Rosenberg, 1997). These activities serve to "ventilate" sediments that might otherwise go anoxic (become void of dissolved oxygen). The activities of benthic fauna also assist the microbial process of nutrient remineralization by stimulating the growth of bacteria on the seafloor. The general scenario is that when particles of organic matter sink to the sea floor, they become part of the food web or decompose. The benthic bacteria are the active agents of this decomposition process which releases nutrients as a flux back up out of the seafloor (Marinelli et al., 1998). Benthic organisms are integral parts of marine food webs as well, and many of the fisheries products extracted from the ocean depend in their earliest life stages on eating bottom-dwellers for their nourishment and growth, demonstrating the nursery function of the benthos as promoters of energy flow. Benthic animals are also ecosystem engineers, physically modifying the environments where they live (Bledzki, 2010). Last, benthos are an essential component in biogeochemical cycles, greatly influencing the rates of important chemical reactions that occur in seawater, the rates at which sediments accumulate on the bottom, and the fluxes of nutrients and other chemical compounds. Pollutants that enter sediments are redistributed by benthic fauna whose activities may also ameliorate pollutant impacts.

In studies of benthic communities, it is local, within-patch species diversity (called alpha diversity) that is most commonly measured. Most of these numerical measures incorporate not only counts of the number of different species present, but also counts of the number of individuals within each species identified from relatively small-scale (tenths to thousandths of a square meter) quantitative samples of the community. "Species richness" refers to the number of species present; the term "evenness" refers to how many individuals are counted within each species. High evenness occurs in communities that have similar numbers of individuals within each species found. Within a given habitat type, species diversity will increase as more area is sampled, but only up to a point. Generally speaking, benthic communities are more diverse when they have a low biomass per unit area and become less diverse as biomass increases where only a few species dominate the community (Figure 6.2). Because no habitat has ever been sampled completely, we do not know how many different species exist. The deep-sea benthos are very diverse, and investigators typically cannot identify a significant fraction (40–50%) of the animals

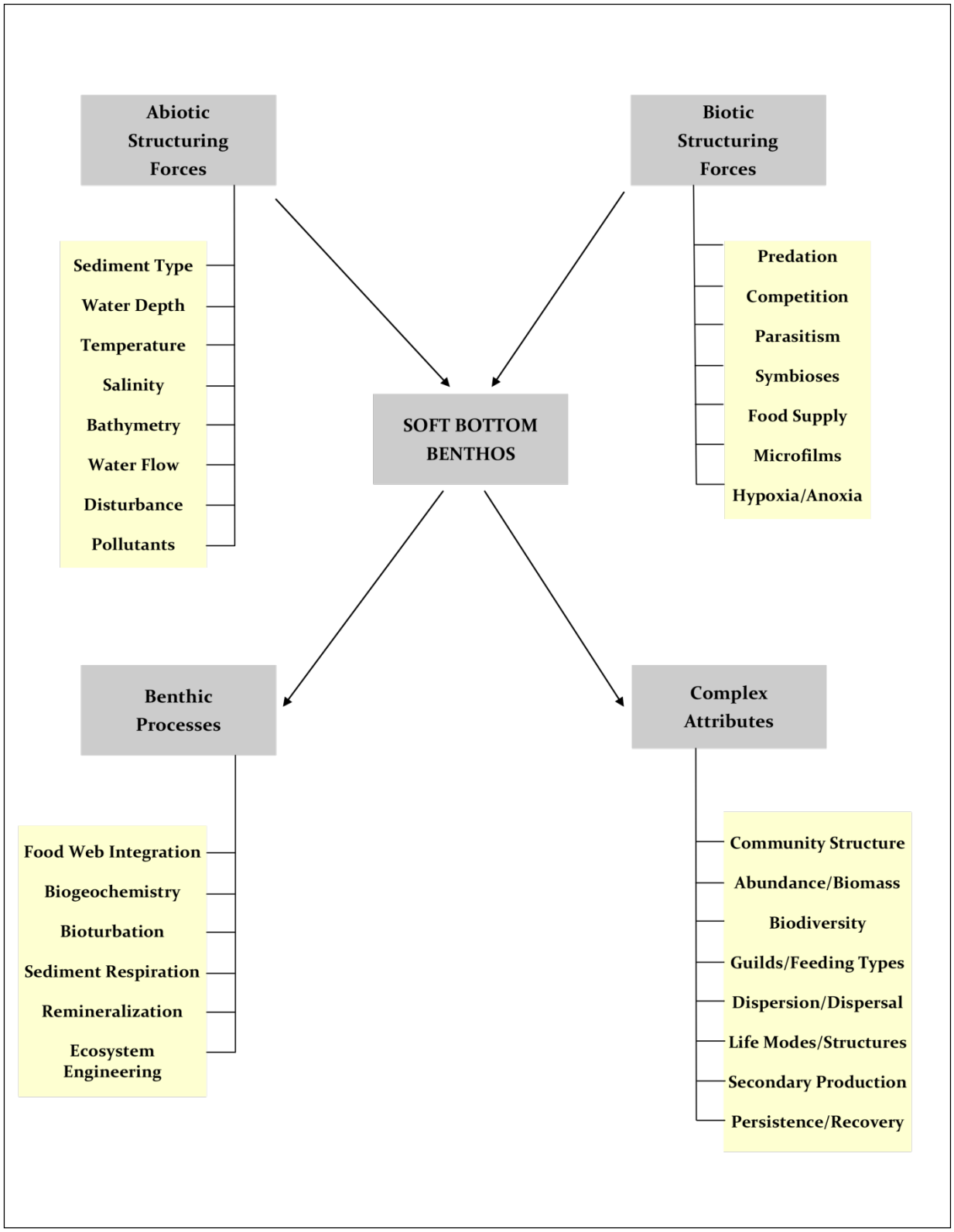

Figure 6.1 Conceptual overview of the ecological role of soft-bottom benthos in coastal waters.

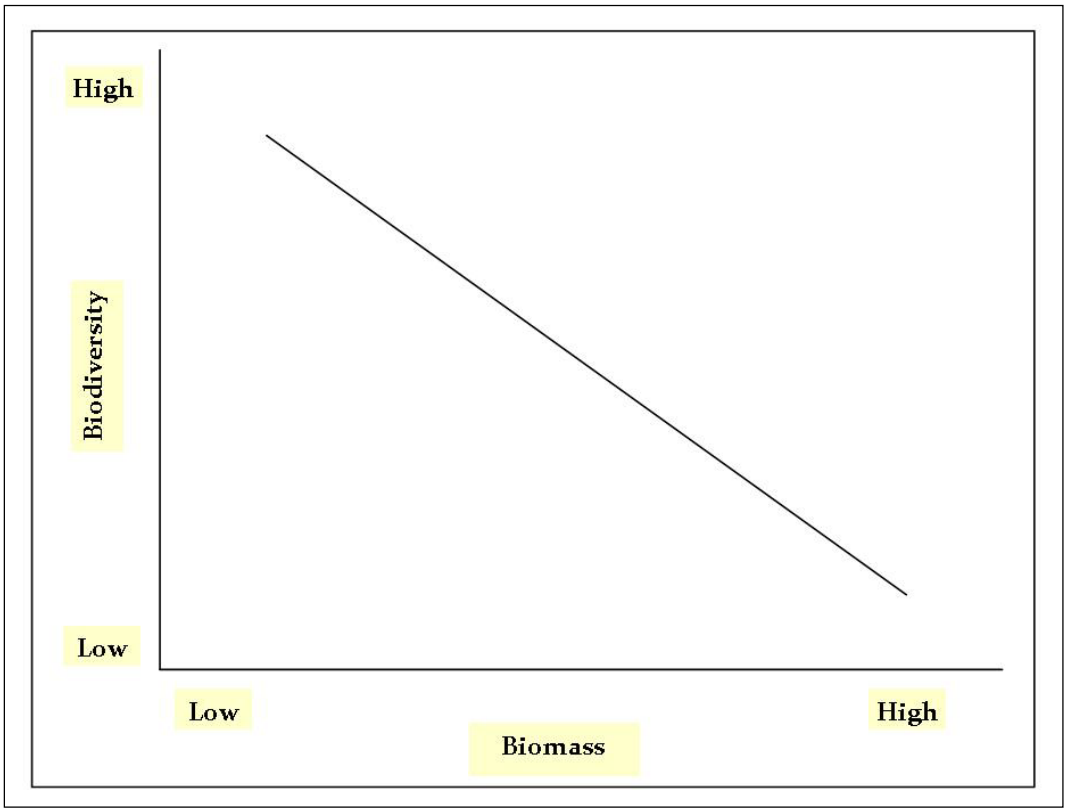

Figure 6.2 Benthic communities with high biomass generally have lower biodiversity, being dominated by fewer species than species-rich, low-biomass communities.

collected there. It has been estimated that up to 10 million species may inhabit the deep sea (Grassle and Maciolek, 1992; Snelgrove, 1998), although others suggest a lower total (May, 1992; Poore and Wilson, 1993).

Many factors have been hypothesized to affect species diversity in benthic communities:

- Time, in the evolutionary sense–more time begets greater diversity;
- Productivity–more food allows more different species to exist;
- Spatial heterogeneity–more habitats or ecological niches, more species;
- Environmental stability–unchanging habitats beget specialization;
- Competition–more competitive pressure induces more specialization;
- Predation–this can reduce abundance of top competitors, allowing more specialization among the less-targeted; and
- Pollution–generally reduces species diversity as vulnerable species get eliminated. Surviving species become dominant.

Howard Sanders, a pioneer in measuring changes in marine benthic communities in several different habitats, championed the "Stability-Time Hypothesis" that incorporates many of these factors (Sanders, 1969). He found empirical evidence in soft-bottom communities that suggested

that shallow, more stressful, marine environments (e.g., continental shelves) are less diverse than those that remain within a narrow range of environmental conditions (e.g., the deep sea). It has also been demonstrated that tropical environments, by virtue of their being geologically older (and having had no recent glaciations) and of having greater productivity (longer growing seasons, smaller temperature ranges, ample precipitation, higher primary productivity), are more diverse than polar environments. On the continental shelf, species diversity seems to increase with distance from shore, with less physical disturbance and habitat variability (tides, runoff, human impacts) offshore.

Given these broad indicators, there are several things to consider when discussing or attempting to compare the species diversity of different benthic communities or even the same types of communities in different benthic habitats. Chief among them are:

- Taxonomic level. Benthos from different studies may not be identified to the same level as available taxonomic expertise varies greatly. The most reliable studies are those that identify each animal to the species level, but virtually no studies have done this successfully. Many similar-looking animals are tentatively identified as Species A, B, C, etc. and must be shipped off to professional taxonomists. This creates many problems for comparing the diversity of different communities, because many investigators can only identify organisms to the genus or family level. Taxonomic methods and difficulties vary depending on organism size.
- Sampling method, quantitative vs. semi-quantitative vs. qualitative. Sampling devices are not equally efficient in capturing benthic fauna and this makes inter-study comparisons difficult. Nor are sampling devices all the same size, and how they are deployed can make a difference (e.g., remotely from shipboard, from a submersible or by ROV, by hand using SCUBA).
- Extrapolations from small sampled areas to larger, un-sampled areas. The effort and cost for collecting and analyzing benthic samples are so great that results from collections made with devices that sample only a fraction of a square meter of sediment surface are typically extrapolated to larger areas such as density, $\#/m^2$. This adversely affects some, but not all, mathematical measures relevant to measuring community structure.
- Non-uniform distributions of benthos in space and time. There is no such thing as a homogeneous benthic community, because at some spatial or temporal scale, patchiness exists. This means that many replicate samples must be collected to minimize this source of variability. However, to reduce expenses, investigators typically collect far fewer replicates than they ought, leaving it more difficult, for example, to detect statistically significant differences in abundance or diversity among samples at different sites even when they exist (Figure 6.3).
- Vertical distributions of infauna are poorly known. Many studies report benthos densities on a per square area basis without taking into account that not all the animals collected live at the same depth within the sediment. Some sampling devices dig deeper than others, hence volumes of sediment collected can be highly variable for comparative purposes.

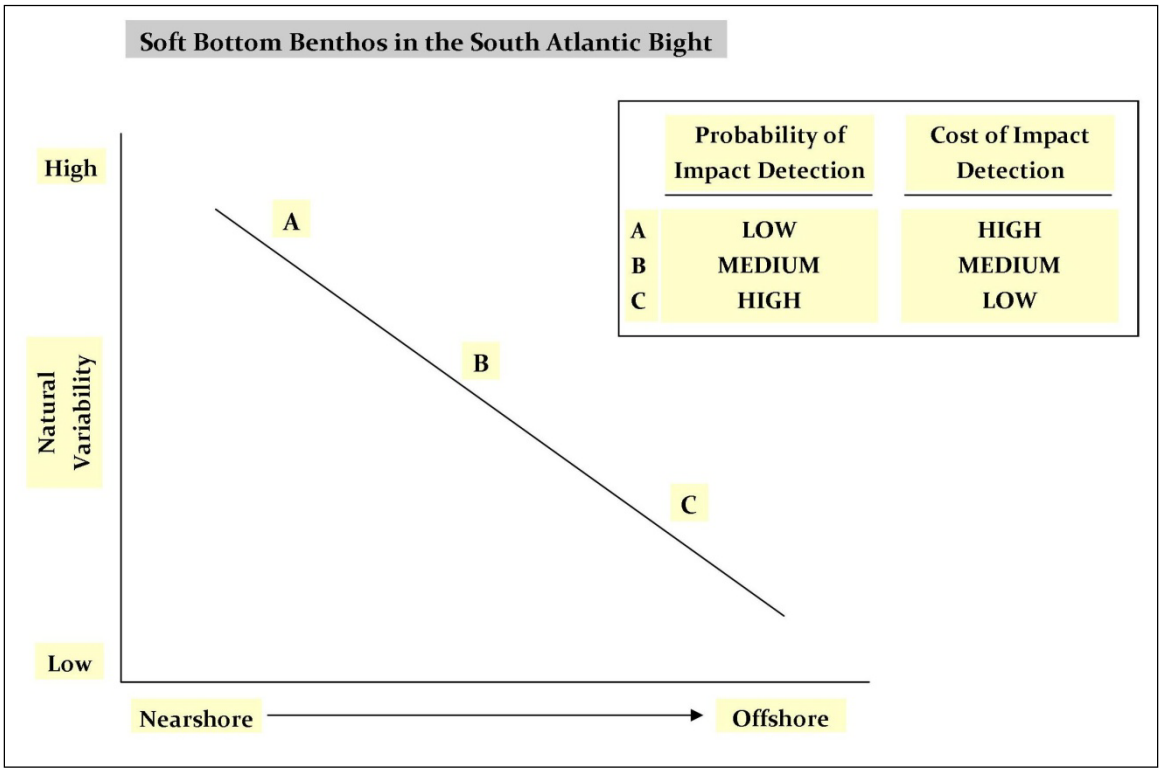

Figure 6.3 Disturbance events occur more frequently and intensely nearshore, creating greater spatial variability in benthos abundance, biomass, and biodiversity on the inner shelf (A) than on the middle (B) or outer shelf (C). Natural variability in benthos abundance, number of species, and biomass is higher in disturbed habitats and lower in more stable habitats.

- When, during the year, samples are collected makes a difference. Because there are seasonal variations in abundance and diversity, one should not attempt to compare collections made at very different times of year. The same can be said for inter-annual variations (year-to-year differences). Figure 6.4 illustrates that if benthos abundances change regularly over time with low sampling variability (Case I), differences between seasons during the year can be readily detected. In Case II, however, sample-to-sample variability is so great over time that no seasonal changes can be detected, and that is typical of areas where physical disturbance of the habitat is great, e.g., from storm events. In Case II the benthic community is frequently in a state of recovery.
- Age of organisms collected is variable. Benthic animals in a sample of the sediment will be encountered as larvae, juveniles, or adults. Most larvae and juveniles cannot be identified to the species level or to any known taxon, and this is where genetic identifications can eventually help immensely.
- Absence of raw data. Many publications, mostly for space-savings and cost, report only average abundances with some statistical measure of variability such as a standard deviation, standard error about the mean, or, rarely, the mean with 95% confidence intervals. The actual counts of organisms are often lost or contained in inaccessible archives. Raw data are often needed to make useful comparisons.

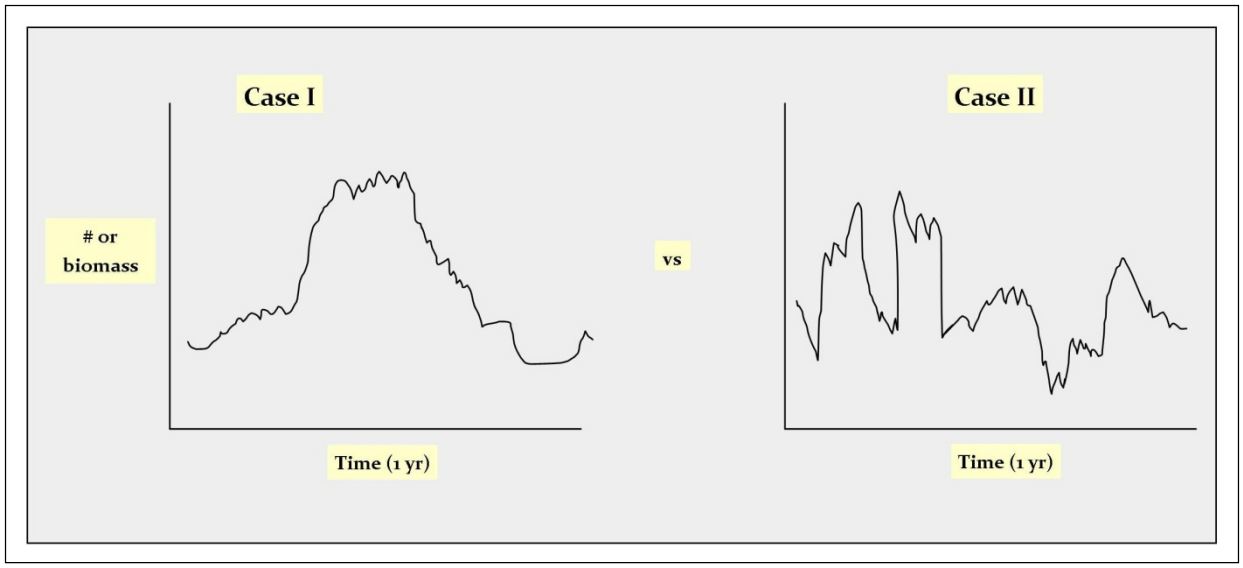

Figure 6.4 Examples of temporal changes in benthic biomass or abundance. Case I depicts regular, seasonal or annual trends, whereas Case II depicts irregular change over time typical of highly disturbed communities.

- Lack of voucher specimens. Most samples are identified and then discarded without preservation of the animals collected so that taxonomic accuracy can be verified. Mis-identifications happen too often.
- Lack of taxonomic identification keys. It is a luxury to find marine areas where local experts have published accurate diagnostic aids. Most of the time an investigator must use keys from some similar area or send samples off to experts for identification.
- Frequent occurrence of unidentified or unidentifiable species. These situations happen all the time, so researchers will use their own methods of lumping similar-looking animals together into one category and call it species A, B, or C or some other unique label for accounting purposes.
- Only when similar collection and processing and identification methods are used by the same investigators/technicians over time will you get the most reliable comparative measures of species diversity in studies of the benthos.

Numerous publications discuss the mathematical and philosophical nuances involved in measures of species diversity in the marine environment (e.g., Snelgrove, 1999; Levin et al., 2001; Gray, 2000; 2002; Snelgrove and Smith, 2002) and others that consider the diversity of benthos in the context of conservation policy (e.g., Carney, 2007). These should be consulted before interpreting such measures or using them as metrics for documenting environmental change or recovery of disturbed benthic communities.

Delineation of benthos distributions (where certain types of populations exist, their population boundaries, and depth zones) is necessarily based on estimates of abundance, estimates that are subject to the same types of biases and sampling problems that exist for measuring species diversity (e.g., Cerame-Vivas and Gray, 1966; Day et al., 1971). For that matter, any calculations

that use benthos abundance data (e.g., secondary production, population growth rates, size distributions or age structure of populations, etc.) bear the same constraints.

Deeper benthic fauna on continental margins consist of species extending down from the continental shelf, species extending up from the abyss, and species restricted to the slope (Carney, 2005). Their distribution is regulated by depth zonation, and this phenomenon has been documented globally. It is not simply cold temperatures, high pressures, or limited food availability that causes this pattern, as controls hypothesized remain conjectural (Carney, 2005).

6.2.2 The South Atlantic Planning Area as a Productive Region in the Carolinian Zoogeographical Province

Cape Hatteras, North Carolina is the southern terminus of the Virginian coastal province and marks where the continental shelf becomes shallower, wider, and more distant from the Gulf Stream. Southward from Cape Hatteras to the northern east coast of Florida, an area of the coastal margin called the Carolinian Province, consists of a coastal ocean region that is bordered by numerous barrier islands and begins its transition to a subtropical regime (Cerame-Vivas and Gray, 1966; Alongi, 1998; Engle and Summers, 1999).

Are estuaries and the coastal ocean strongly coupled systems? This is an open question, although evidence, e.g., Dame et al. (2000), suggests they are indeed coupled strongly. This paper makes the point that southeastern estuaries are understudied, sufficiently so that long-term trends about their ecological state are difficult to define. Such is also true, even more so, for the continental shelf off the southeastern US coastline. It is evident that the South Atlantic Planning Area is tightly connected to the nearshore/estuarine habitats on the western edge of the region. Dame and Allen (1996) affirm connectivity between the nearshore/estuarine area and the coastal ocean, with transport of materials and exchanges between estuaries and the sea due to river flow, tidal exchanges, wind forcing, and movements of water in the hydrological cycle, e.g., evaporation allows input from sea to estuary. Coastal development is an impending problem along the entire southeast coast, with northern Florida particularly over-developed. Thrush et al. (2004) and Lohrer et al. (2004; 2006) show how changes in land use and coastal development affect sediment loading in coastal waters with subsequent impacts on benthos and other components of coastal ecosystems.

The South Atlantic Planning Area can be considered event-driven, because wind-induced movements of water masses can impact the primary producers for considerable periods of time (see Chapter 5: Plankton Communities). Particulate materials, dissolved nutrients and organic matter emanating from the coast are constrained to remain inside a semi-permanent salinity front that extends only 10–20 km offshore (see Chapter 4: Chemical Oceanography), and for this reason most of the South Atlantic Planning Area shelf is nutrient-poor, or oligotrophic. Episodic large storm systems and hurricanes can have dramatic impacts on this front, but it has been difficult to measure them (for obvious reasons). If large storm events flood coastal lands, increased runoff will flood seaward and propel estuarine mud into coastal waters where it can persist in suspension (higher turbidity) for many months (Bell and Hall, 1994).

Nutrient- and sunlight-fueled primary production in the overlying waters of the shelf and on the shallow bottom (if enough light is there) serves as the base energy source for bottom-dwelling

organisms in the South Atlantic Planning Area. Much of this organic matter is consumed by plankton before it settles to the bottom and is converted into benthic biomass. Benthic biomass is consistently highest in the middle shelf (20–40 m depths), and latitudinal gradients in biomass at a given depth are slight or non-existent. The outermost shelf has low benthic biomass, and benthos throughout the shelf undergo seasonal changes in community composition (Tenore, 1985). Benthic processes of respiration, consumption, metabolism, and nutrient recycling have variable rates depending on temperature and the flux of organic matter to the bottom (Hopkinson, 1985). Input of terrestrial organic matter and organic carbon diminishes with distance from shore and depth (Moran et al., 1991), but humic substances derived from terrestrial vascular plants can be found far offshore in shelf waters (Moran and Hodson, 1994).

Harvests of living resources on the shelf are intimately linked to estuarine nursery grounds. Many commercially relevant species reproduce and release eggs and larvae on the shelf that are transported shoreward to grow and mature before they move seaward once again and enter the fisheries (Shanks, 1995). Penaeid shrimp and finfish harvests in the South Atlantic Planning Area are lower, however, than more productive coastal fisheries in the Gulf of Mexico and in the Mid- and North Atlantic states. Blanton et al. (2004) and Wenner et al. (2005) note that white shrimp spawn offshore and that their planktonic larvae are moved back towards shore to settle into estuarine nursery grounds. Much of this transport of shrimp larvae occurs during coastal circulation patterns that emphasize downwelling, i.e., surface water moving towards shore. This is but one of many studies that emphasizes the connectivity between inshore and offshore biological communities in the South Atlantic Planning Area. The paper by Blanton et al. (1995) speaks to the role of coastal circulation (up- and downwelling regimes) in movement of blue crab and other marine invertebrate larvae towards the coast from offshore. Blue crabs are epibenthic organisms that recruit as plankton from offshore nursery areas in the water column and move to nearshore settlement areas where they moult and become small crabs that live in association with the bottom.

Samples of benthos collected farther offshore from the continental margins on the Blake Plateau and along the continental slope and rise (Blake and Grassle, 1994; Hilbig, 1994) illustrate the importance of annelids, crustaceans, mollusks, and echinoderms, the most dominant taxa at these greater depths, much the same as they dominate shelf depths. Slope and rise depths are much better studied off North Carolina where circulation patterns generate dynamic confluences and mixing resulting in high productivity that enhances benthic biomass and abundances, especially off Cape Hatteras (Hecker, 1994; DeMaster et al., 1994). Circulation is not as dynamic in the South Atlantic Planning Area, with some exceptions like the bathymetric high Charleston Bump that induces persistent eddies as the Gulf Stream passes by (see Chapter 3: Physical Oceanography and Air-Sea Interactions).

A special portion of the South Atlantic Planning Area, off the coast of Georgia in waters about 20 m deep, was designated in 1981 as Gray's Reef National Marine Sanctuary (GRNMS). It has a mixture of bottom types including both hard-bottom (rocky) and soft-bottoms (unconsolidated shell hash and sand). The benthos inside the boundaries of GRNMS has been studied extensively by many investigators (Cooksey et al., 2004; Hyland et al., 2006; Balthis et al. 2007; Kendall et al., 2007) and is quite diverse. The GRNMS illustrates how the mixture of sediment/habitat types contributes to biocomplexity and partially explains why the area harbors such a rich community

of interacting species. Kendall et al. (2005) used sonar and diver verification to classify the benthic habitats (sediment or seabed surface) within the GRNMS. See Kracker et al. (2008) for the characterization, as it describes sonic methods that can be used elsewhere in the region, useful because remote sensing with satellites and other methods don't work nearly as well in the relatively turbid coastal waters of the South Atlantic Planning Area. Significantly, they found that, despite the obvious differences in classification schemes used by other researchers to classify habitat in the same area, the percentages of each habitat type differ considerably among investigations, presumably because the habitats change over time due to tidal reworking, waves, currents, and storms/hurricanes that frequent the area. Thus no habitat classification (as % coverage in the area under consideration) can be considered as definitive, only generically correct, and subject to change over time as conditions dictate.

6.2.3 Early Studies of Benthos in the South Atlantic Planning Area

Dozens of investigators have collected benthos in the South Atlantic Planning Area over the past six decades. Excluding work done in estuaries and on intertidal beaches in the region (see Fox and Ruppert, 1985 for descriptions of most nearshore benthic macrofauna of South Carolina), some of the earliest looks at nearshore soft-bottom habitats were done as Ph.D. dissertation or post-doctoral projects by Frankenberg (1971), Leiper (1973), and Dorges (1977) a few kilometers offshore from Sapelo Island, Georgia. Because high benthic diversity had been found in the deep sea in the 1960s, the impetus for these continental shelf studies was the popular interest in understanding factors that control the types and diversity of communities that develop in different marine habitats (Sanders, 1969). The South Atlantic Bight Program was initiated by the Bureau of Land Management (BLM) and conducted by Texas Instruments, Inc. in 1977 (BLM, South Atlantic Benchmark Program, OCS Environmental Studies, July 1979). This company contracted several studies by benthic ecologists and specialists in the region, including investigators from the Skidaway Institute of Oceanography (Tenore and Sen Gupta) and the Belle W. Baruch Institute for Marine Biology and Coastal Research at the University of South Carolina (Coull) who performed collaborative studies that provided the initial views of benthic communities in the SAB. In subsequent years a number of studies were contracted by MMS involving examination of impacts from sand dredging and beach nourishment (Nairn et al., 2004) and other offshore resource-oriented foci as well as larger programs such as the Atlantic Continental Slope and Rise program (Blake et al., 1985, 1987). State-supported natural resource agencies also initiated various impact studies to examine effects of dredging waste disposal (Zimmerman et al., 2003), fishing activities, and other resource acquisition-related activities. The Coastal Ecology Program at the Center for Coastal Environmental Health & Biomolecular Research (Charleston, South Carolina) is a partnership between NOAA, USEPA, various coastal states, academic institutions, and the private sector designed to conduct assessments of the status of ecological conditions and potential stressor impacts at multiple spatial scales in US coastal waters. This program is an extension of the USEPA's Environmental Monitoring and Assessment Program (EMAP) that monitors estuary health. It uses a probabilistic sampling design so that conditions at both regional and national scales can be reliably compared. An element of the program concerns an evaluation of how well the nation's National Marine Sanctuaries and National Estuarine Research Reserve Systems are faring relative to their surrounding non-managed waters. Samples of benthos and fishes are collected for evaluation in the Coastal Ecology Program (Cooksey et al., 2004; 2010). The 2004 effort sampled 50 stations in the SAB, including the Gray's Reef National Marine Sanctuary, from about 1 nm offshore out

to the shelf break (100 m water depth). The Ocean Margins Program has also contributed significantly to our knowledge of how the Middle and South Atlantic Bights are involved in the global carbon cycle (Verity et al., 2002; Aller et al., 2002).

Unfortunately, much of what is known about the seabed in the study area is unpublished or exists in file cabinets and agency reports that are inaccessible. It is reasonably certain that not every study conducted has been reported in a retrievable form, much less been published. Additionally, the US Navy and US Coast Guard have collected numerous types of data in the South Atlantic Planning Area that cannot be accessed without official clearances.

Overall, the pace of benthic exploration in the South Atlantic Planning Area has been much slower than in areas offshore of North Carolina where the prospects for offshore oil resources has stimulated or been the impetus for many more studies there. Recent interests in energy-related resources, such as natural gas and methane hydrates, may, likewise, stimulate additional work in the South Atlantic Planning Area in the near future.

A literature survey undertaken by the South Carolina Wildlife and Marine Resources Division (Knott and Wendt, 1985) reviewed information then known about benthic invertebrate communities of the continental slope in the South Atlantic Bight, including the meiofaunal, macrofaunal, and epifaunal components. There has been additional research activity since their survey that is relevant to benthic communities in the South Atlantic Planning Area, and newer studies are incorporated in the following synthesis/overview.

6.2.4 Microbenthic Communities

Benthic microorganisms are single-celled protozoans, mostly bacteria, forams, and ciliates. Viruses are too small to be included in this size-class. Members include animals that have a wide range of sizes. Although bacteria are typically the most numerically abundant microbenthos, foraminiferans ("forams") are also an abundant and trophically important component of the size-class. These small calcareous protozoans live on bottom sediments from shallow muds in estuaries to the deepest parts of the ocean. Their feeding ecology has been described by Lipps and Valentine (1970), with bacteria, small diatoms, and detrital particles smaller than about 50 microns (μm) forming the majority of their diets. In sandy-bottom shelf communities, their food source is reduced and thus their abundances are lower there as a result. Forams are also consumed by deposit-feeders of all sorts, being captured and ingested along with the surface sediment and those slightly deeper. Douglas and Woodruff (1981) describe deep-sea benthic foram distributions and should be consulted for details about this fauna and how it is collected, with relevant problems discussed. All of their information is relevant to shallower living forams such as found in the South Atlantic Planning Area. Table 6.1 provides a summary of studies on microbenthos in the study area.

Table 6.1
Time trajectory of soft-bottom microbenthos surveys in the SAB or adjacent areas

Period	Fauna	Location	References
"Early"	Foraminifera	SC and FL shelf	1
1960s	Foraminifera	NC shelf	2
1970s	Foraminifera Micro-, meio-, macro-	GA shelf GA Bight	3 3a
1980s	Foraminifera	Eastern US coast	4
1990s	Micro-	NC, SC shelf	5
2000s	Foraminifera	SC shelf	6

1 Cushman's "southern lines" (1947 unpubl. report, summarized by Todd, 1979)
2 Wilcoxon (1964)
3 Kilbourne (1970); Sen Gupta and Kilbourne (1971; 1973; 1974; 1976); Sen Gupta and Hayes (1977); Sen Gupta (1979); Todd (1979); Sen Gupta et al. (1981)
3a Tenore et al. (1978)
4 Buzas and Culver (1980); Hanson et al. (1981); Culver and Buzas (1981; 1983); Sen Gupta and Strickert (1982)
5 Cunningham and Ustach (1992)
6 Abdul et al. (2006); Skalit et al. (2006)

6.2.4.1 Shelf Microbenthic Communities

Perhaps the earliest studies of living foram distributions in portions of the southeast coast were made by Cushman (unpublished report at Woods Hole Oceanographic Institution, 1947), with additional work by Wilcoxon (1964), Kilbourne (1970), and Sen Gupta and Kilbourne (1971; 1973; 1974; 1976). Schnitker (1971) studied North Carolina shelf forams, an assemblage similar to that found on the South Atlantic Planning Area shelf. Numerous studies of relict and/or total (living and dead) forams are available but not reported here.

The Cushman samples and accompanying typescript have been summarized by Todd (1979). Todd describes the Cushman collections from the so-called "Southern lines" where a specially modified dredge was used to collect samples at 77 stations running from the coast out to the shelf edge along four transects: off Onslow Bay, North Carolina; Charleston, South Carolina; Jacksonville, Florida; and Cape Canaveral, Florida. The Charleston transect comprised 10 samples from the inner shelf at depths between 12–22 m; 9 from 25–43 m on the inner shelf; 3 from depths between 50–76 m; and 2 samples from the upper slope at 99–120 m depth (24 total samples). The inner (2 at 20 m), middle (15 between 23.5–41 m), shelf edge (1 from 50 m), and Blake Plateau (3 between 800–850 m) were sampled off Jacksonville (21 total samples), while the middle shelf (6 between 23–45 m), edge (1 at 68 m), and upper slope (2 from 142 m) were sampled off Cape Canaveral. Twenty-three samples came from the Onslow Bay transect. Altogether 233 species and varieties were described, including relict species, as the dredge cut to depths of about 7.5 cm into the bottom. Todd (1979) states that it was only possible to present a crude picture of present-day species from the collections. Diversity increased with depth seaward, with about 30 species on the inner shelf and 50 at greater depths. Her Appendix B lists species likely to be found as characteristic, dominating, or rare. Cushman (1918–31) also

suggested the existence of a faunal boundary for forams off the coast of Cape Hatteras, and Schnitker (1971) found a 60 m boundary between a central shelf thanatotope (groupings of species) and a deeper shelf-edge thanatotope.

Wilcoxon (1964, cited in Sen Gupta, 1979) examined the relative abundance of foram species from the North Carolina shelf and found four depth-related assemblages: a beach fauna (0–1 m), inner shelf (1–15 m), middle shelf (15-61 m), and outer-shelf/upper-slope (61–183 m). There was an increase in the number of species seaward, and agglutinated species were most abundant on the middle shelf where hyaline species dominated in general. The porcelaneous group was most prominent nearshore.

Kilbourne (1970) sampled forams on the Georgia shelf and recognized a 1–15 m nearshore *Ammonia-Elphidium* faunal zone, a 15–35 m *Asterigerina-Planorbulina* faunal zone, and a 35-100 m *Placopsilina-Textularia* faunal zone. Based on this master's thesis work, Sen Gupta and Kilbourne (1971; 1973; 1974; 1976) expanded the study to cover the entire Georgia continental shelf (78 box cores taken in a stratified random design). They found that species diversity rose nearshore at depths <12–15 m but was nearly constant or "steady" across the shelf out to the shelf edge. No north-south latitudinal gradient was found. Sen Gupta and Kilbourne (1976) documented common, abundant species in water <20 m (*Elphidium excavatum forma clavatum* and *Ammonia beccarii*), in 15–30 m (*Asterigerina carinata* and *Planorbulina mediterranensis*), with four species at depths > 40 m (*Planulina exorna*, *Islandiella subglobosa*, *Textularia conica*, and *Bigenerina irregularis*). These species formed the basis for three thanatotopes. Altogether Sen Gupta and Kilbourne found 187 species in their Georgia shelf study. Sen Gupta and Hayes (1977) went further with the analysis and found 13 recurrent species groups, the largest having 33 species in it. Interestingly, one of the groups was based on just 5 species that occurred at a single upper slope station. Ten of the "groups" contained only two or three species, while most of the species in the total assemblage did not occur in any recurrent group at all.

Also cited in Sen Gupta (1979) were studies by Arnold (1977) who recognized three thanatotopic boundaries: shelf edge, 50–100 m isobath, and some relict species at 100–165 m.

From the same box cores taken by Tenore (1979) and Coull (1979), Sen Gupta (1979) took pairs of 3 cm deep subcores and used Sudan Black B to stain the foram specimens that were separated from sediment using a 0.063 mm mesh sieve. He identified numbers of both living and dead specimens, examined a microsplitter fraction of the sample for species frequencies, and calculated the frequencies of all living species. The density of the foraminiferal assemblage collected ranged from 1–6,542/cm^2, equivalent to #/cm^3, hence the need to examine only some quantitative fraction (split) of many samples. The average from all samples collected was 36 tests (the shell of an individual foram), with high variability both between stations and between different box cores taken within the same station. Abundance increased with depth, and seasonal variation was generally low. *E. excavatum forma clavatum* and *Ammonia beccarii* comprised a significantly larger fraction of the inshore shelf, and these two species dominated the assemblage more in winter samples than at other seasons. The most widespread species of the shelf, *Planulina exorna*, was found preferentially on the middle and outer shelf. The largest population of any species found was that of *Bolivina lowmani*, not found nearly so abundant earlier by Sen Gupta and Kilbourne (1976). He surmises that, because the samples were treated differently in

the 1976 study, they may have been too greatly damaged to be identified. The forams at station 7E on the shelf edge/slope were quite different in abundance and species composition from the rest of the sampling set, dominated by one abundant species, *Brizalina subaenariensis var. mexicana*. Overall, Sen Gupta characterized the living fraction of the foram assemblage was typical of the Carolinian province, and seasonal changes were not significant. Sen Gupta concludes his 1979 paper with recommendations for future examination of the forams, suggesting that just 50 stations sampled in one year "leaves room for substantial improvement." Additional year-long studies are needed, especially in the 50-500 m depths, and a follow-up on these same seven transects would allow temporal comparisons.

Buzas and Culver (1980) cataloged all known accounts of foram distribution along the entire eastern continental margin of the US east coast, from Newfoundland to the Bahamas. The 876 species found at 542 stations were subjected to cluster analysis using 350 of the stations containing 791 species. They found seven large marginally overlapping areas or provinces, with a major latitudinal change occurring near Cape Hatteras. The Carolinian Province, from Cape Hatteras to Cape Canaveral and defined by the distribution of molluskan, crustacean, and bryozoan macrofauna, was represented by a shelf and slope foraminiferan community. No single environmental variable could account for all the variability in the foram distributions, although water masses and current patterns may be very important. An expanded version of this study is presented in Culver and Buzas (1981).

Sen Gupta and Strickert (1982) summarized collections from 18 stations located on 7 transects along the Hatteras-Florida slope that started at depths from 50–80 m and extended to the depth where the slope merges with the Blake Plateau (>500 m). They found 165 different living species amongst the samples taken during four seasons in 1977. Abundances varied from 1 individual per 3 milliliter (mL) wet sediment volume (= #/cm^2 to a depth of 3 cm) to an astounding 3,132 individuals at a station off Daytona Beach, with mean values generally in the 10s to 100s per sample. There were five dominant species in the seasonal samples. There was no conspicuous latitudinal faunal zonation, but one boundary defined by depths of ~100 m between the upper and middle slopes. Thirty species were present with a 5% or greater abundance in one or more samples. The 100 m depth defined a shift in diversity, which was higher in shallower water. It is suggested that wind-induced upwelling has a strong influence on foram populations in this area. Sen Gupta et al. (1981) provide details about the high abundance station off Daytona Beach (Station 7E on the Florida slope) they sampled in 1977.

In a zoogeographic analysis of benthic foraminifera along the shelf break in the Gulf of Mexico and along the North American continental margin, Culver and Buzas (1983) recognized large-scale distribution patterns based only on species occurrences without taking their abundances into account. This suggests that it is possible to produce the same distributional patterns using abundance data or presence/absence data.

Lueck and Snyder (1997) examined stained benthic forams in Onslow Bay, North Carolina, sampled at several stations across the continental shelf, and found no vertical partitioning of the sediment by this community of organisms. They suggested that, because they found no direct relationship between observed 4X differences in abundance of forams at two stations (23-Mile Site and Frying Pan Shoals) due to water depth, water mass characteristics, sediment grain size,

and sorting or mineralology, the differences might be explained by differences in flux rates of groundwater onto the shelf from beneath the sediments. Their hypothesis remains to be tested.

In a multi-institutional, multidisciplinary study examining nutrient effects on micro-, meio-, and macrobenthos on the Georgia Bight, Tenore et al. (1978) looked at the probable impacts of two sources of nutrients: coastal runoff and Gulf Stream upwellings/intrusions. They used box cores from which subsamples were taken for various analyses at nine stations off Georgia in depths from 13 to 44 m, three stations per transect with one each in the inner-, middle-, and outer-shelf regions. The sediment was mostly medium-sized, moderately sorted sand with very low C and N contents (<0.09 and 0.008%, respectively). Microbial activity was examined by measuring heterotrophic potential as glucose uptake, N fixation activity, biomass as ATP (adenosine triphosphate) content, and denitrification potential as nitrous oxide reduction. Heterotrophic activity was generally higher at inner and outer stations than at middle stations, decreasing north to south. Microbial biomass increased at the shelf-slope break from north to south but did not vary with latitude along the inner and middle portions of the shelf. N fixation was lowest in the southern part of the shelf where intrusions occur most frequently.

Cunningham and Ustach (1992) used epifluorescent microscopy to analyze sediments taken with box cores (0.06 m^2) from three random sub-cores (0.64 cm^2) to a depth of 1 cm, fixed in 2% formaldehyde. They found a basic decline in the numbers of ciliates, amoebas, flagellates, forams, and bacteria with depth along a four-station transect as depth increased from a shelf station off North Carolina to deeper stations off South Carolina (Table 6.2). They estimated the biomass of these organisms by first estimating the volume of the animal and then calculating its biomass assuming they had a specific gravity of 1.0. Because sediments had to be diluted extensively to make counts, the variance-to-mean ratios for these counts are very high, often exceeding 2,000. Ciliates dominated at all depths, and there was no correlation between the numbers of protozoans and the numbers of bacteria.

Table 6.2
Microbenthic community abundance and biomass data from Cunningham and Ustach (1992) and biomass data from Hanson et al. (1981)

Station	Depth (m)	Bacteria (#/cm^3)	Protozoans (#/cm^3)	Biomass (mg/cm^3)
1	135	2.39×10^{10}	165	2.2×10^{-4}
2	2,411	1.35×10^{9}	570	2×10^{-3}
3	3,409	1.08×10^{8}	347	3.3×10^{-3}
4	3,833	9.03×10^{6}	964	2.7×10^{-3}
Mean abundance of microorganisms in sediments, as μg C/cm^3 (Hanson et al., 1981) are:				
Sediment Depth (cm)		Inner Shelf	Middle Shelf	Outer Shelf Break
1		3,100	1,200	1,525
5		650	800	350
10		288	223	273

Clearly, microbenthic fauna are more abundant nearshore in the South Atlantic Planning Area and decrease in abundance and biomass with increasing depth. As these organisms are fueled by detrital-based organic matter, the trend in their depth distribution both with distance from shore and depth in the sediment appears to track the abundance of this food resource. Many more measurements are needed, however, because the error bars around these estimates are very large. This imprecision is evident in that typically only order-of-magnitude differences are considered significant for estimates of bacterial abundance.

As part of the College of Charleston's Transect Program (Skalit et al., 2006), samples of sediments at stations along the Charleston transect at eight stations (11–96 m depths) were collected over a two-year period. Between 25 and 39 foram genera were identified on each of the four cruises made during this period, with 8 dominant genera (Abdul et al., 2006). There was considerable cross-shelf assemblage variability, however, and they suggested that further studies are required to conclusively map the distribution of benthic foraminiferal assemblages along the southeastern continental shelf.

Bornmalm et al. (1997) maintained and observed living forams in the laboratory to understand more about their movements and behavior on the bottom. *Cibicidoides pachyderma*, a calcareous foraminifer, and *Ammodiscus anguillae*, an agglutinated foraminifer, were collected live at 220 m depth on the Charleston Bump. They were maintained in aquaria at 12°C and 1 atmosphere in the laboratory on a thin veneer of sediment. Their rates of movement varied between 1 and 23 mm/day across the sediment and *A. anguillae* moved between 1 and 10 mm/day within a 0.5 cm layer of sediment. Both species moved in and out of the sediment, suggesting that they are epifaunal and/or shallow infauna. Their rates of movement are about the same as measured for other deep-sea forams but among the slowest for shallow-water forams. They moved both vertically and horizontally in meandering patterns, though with predominantly straighter patterns in the vertical plane.

6.2.4.2 Benthic Microalgae

Part of the benthic community on the continental shelf of the South Atlantic Planning Area where sufficient light penetrates to the bottom includes the benthic microalgae, including diatoms. The relative importance of benthic primary production, compared to levels of water-column primary production, is an active area of investigation in coastal zones around the world (Gattuso et al., 2006). These investigators suggest that net community production is positive (produce more oxygen than is consumed) on about 33% of the global shelf area. Their model of this process, however, has many limitations.

Benthic marine algae have been surveyed and cataloged on the continental shelf in the Long Bay region off Myrtle Beach, South Carolina and in Onslow Bay, North Carolina. Of the 152 taxa identified, a majority (106) were Rhodophytes, 40 of which were found in Long Bay (Schneider, 1976). Searles and Schneider (1980) reassessed the distribution of benthic marine algae off North Carolina, the northern limit for many tropical species. They state that "The South Carolina coast has only 95 species reported and is not important as either a northern or southern limit of seaweed distribution." There are many more species in North Carolina (289) than the mere 95 that occur in South Carolina waters. The Cape Fear, North Carolina deep-water seaweeds (30 and 42 m depths) were studied by Peckol and Ramus (1988) who found variable rates of

photosynthesis for species having different morphotypes (e.g., thin flat species vs. those with branched or thick thalli). They suggest that nutrient-laden intrusions of Gulf Stream water and the N flux from sediments are the main nutrient sources for these seaweeds.

Hanson et al. (1981) measured benthic algal biomass in the top 1 cm from replicate box cores in the Georgia Bight. They found chlorophyll a (Chl a) values were lowest off Florida and mean values increased northward, with inner- and middle-shelf sediments containing about twice as much as shelf-break sediments. The highest amounts of degraded chlorophyll (phaeopigments) were found in the southernmost sediments of the Georgia Bight, where values were 0.5–2.0 micrograms (μg) Chl a/gram of sediment.

The traditional view of linkages between benthic habitats and their overlying waters has focused on fluxes of organic matter, energy flow, nutrient remineralization, and production, both primary and secondary. Marcus and Boero (1998) remind us that species' life-cycle attributes are also an important part of benthic-pelagic coupling because they can have important impacts on community structure in and above the sediment. Many planktonic species of both phytoplankton and zooplankton have benthic resting phases as part of their life cycles. Dinoflagellates, diatoms, rotifers, copepods, and several other taxa create resting cysts that can emerge during favorable conditions. These cysts are part of the microbenthos, despite their inactivity. Cysts and resting eggs from these species can thus act as seeding agents for plankton blooms, including noxious or harmful algal blooms. Organisms that spend a portion of their life cycle in the benthos or a portion in the plankton can be called members of the merobenthos and meroplankton, respectively. Copepod resting eggs are abundant in coastal sediments and are subject to predation in the water column as well as in the seabed. Our traditional view of the manner in which benthic and planktonic communities overlap needs to include these dynamic aspects of how coastal benthos affects coastal plankton and vice versa.

Nelson et al. (1999) measured sediment chlorophyll concentrations (as a proxy for microalgal biomass) at depths of 14–40 m off Georgia's coast and 20–40 m off the NE coast of Florida. The algae living in the top 0.5 cm of the sediment generally exceeded the amount living in the water above the bottom by a factor of 4–6. They found pigments of diatoms as deep as 2–3 cm in the sediment, with mixing to these depths probably due to bioturbation, grazing by benthic fauna, storm mixing, and resuspension of sediment. This may be a significant source of non-detrital food for the benthos. Cahoon and Laws (1993) collected benthic diatoms from the continental shelf off North Carolina using SCUBA to depths of 35 m. Benthic microflora biomass ranged from 16–97 mg Chl a/m^2, with pennate diatoms being most abundant. Cahoon et al. (1994) looked at the vertical distribution of chlorophyll concentrations in sediments collected with box cores from 16 sites off Cape Hatteras. They found viable diatoms as deep as 14 cm in the sediment, a finding that suggests the area is one of high rates of deposition and bioturbation by maldanid polychaete worms.

For several years, Richards et al. (2006) have been monitoring benthic primary production at a depth of 27 m in the Coastal Ocean Processes Program study area in coastal Georgia and measuring light availability on the seafloor (see Jahnke et al., 2008). They are attempting to see whether the amount of light incident on the bottom can be used to predict benthic primary production levels. Generally they found that benthic chlorophyll concentrations do not vary

markedly over the year and increase substantially only during warm quiescent periods. Richards et al. (2002) have also measured the flux of dissolved materials in porewater at the same depth.

6.2.4.3 Slope Microbenthic Communities

The Florida-Hatteras slope just east of the coast running from Savannah, Georgia to Charleston, South Carolina was sampled with a box dredge at depths from 45 m at the shelf edge to 675 m at the edge of the Blake Plateau by Arnold (1977) to examine foram distributional patterns. Major influences were sediment type near the shelf edge and the Gulf Stream's influence at the middle and upper slope depths. Station 2 exhibited exceptionally high abundances of forams on the Florida slope; see Table 6.1 in Cunningham and Ustach (1992) and Station 7E in Sen Gupta et al. (1981).

Gooday et al. (2001) and Smart and Gooday (2006) examined forams collected at three sites on the 850 isobath off North Carolina, the former emphasizing living organisms in the macrofaunal size range, the latter non-living species. Both studies found high densities of organisms, high species diversity, and considerable differences in the foram communities at each of the three sites. Some of the dominant species found also occur in shallower waters on the shelf. The slope species appear to be opportunistic, tolerant of low-oxygen stress, and respond in their population dynamics more closely to organic matter input than metazoan macrofauna found at the same sites.

Analysis of magnesium:calcium ratios in the tests of forams can provide information on past temperature regimes and paleoclimate. Measures of this and other trace element ratios in living forams collected from the shallow slope near the Charleston Bump by Blanks et al. (2006) can shed light on how biological processes (e.g., food supply, calcification rates, metabolic rates, etc.) can affect these ratios. They reported nearly a six-fold increase in foram abundance between 2001 and 2006, from 6 to 34 indiv/cm^3.

6.2.4.4 Summary for Microbenthos

Early studies of microbenthos in the South Atlantic Planning Area emphasized qualitative foraminiferan species distributions in an attempt to delineate foram paleocommunities, and it was not until the late 1970s that quantitative estimates of microbenthos were made. There appears to be a biogeographic boundary at Cape Hatteras, North Carolina that separates the Carolinian province from the Virginian province to the north. Because it is hard to tell living from dead forams without the use of modern staining techniques, the early studies did not distinguish between recent and relict species. There seem to be some recurrent groups of foram species across the shelf, but there is no latitudinal gradient in species in the South Atlantic Planning Area. Abundance generally increases with depth, but no significant seasonal variation occurs. It was not until the 1990s that non-foram microbenthic organisms were quantified in any part of the South Atlantic Planning Area, and they can be quite abundant. The degree to which microbenthic organisms participate in heterotrophic processes is quite variable, with greater activity nearshore than offshore where organic matter substrates are in lower supply for the bacteria. A trend towards lower rates of substrate uptake from north to south on the shelf needs to be verified by additional studies of these processes. Slope forams seem to occur in greater abundance off Florida than elsewhere. Microbenthic fauna are more abundant and have greater biomass nearshore than on the seaward portions of the shelf, a trend also likely fueled by a

greater food supply nearshore. Far too little work done has been done on benthic primary producers to characterize their biodiversity or abundance/biomass. Chlorophyll concentration, a surrogate measure for algal biomass, is higher in surface sediments on the shelf and is bioturbated to depths of 10+ cm in the sediment. The microbenthos of the South Atlantic Planning Area is woefully undersampled.

6.2.5 Meiobenthic Communities

Offshore meiobenthic studies in the South Atlantic Planning Area began with the BLM Benchmark Program managed by Texas Instruments, Inc. in the late 1970s. Of the taxon-level information available, Coull (1972) and Tietjen (1976) provide information on harpacticoid copepods and nematodes, respectively. They found distinct zonation patterns traversing the shelf, slope, and abyssal plain off the Carolinas. Both the harpacticoid copepods and nematodes had a <100 m shelf assemblage that was different from the slope (100–1,000 m) and abyssal (>1,000 m) assemblages. The sandy-shelf meiofauna community they sampled was essentially homogeneous. Because so many species identifications for any meiofaunal taxa are lacking for the region, it is not possible to make any assessments of meiofaunal community structure. Table 6.3 provides a list of studies on meiobenthos in the study area.

Table 6.3
Time trajectory of soft-bottom meiobenthos surveys in the SAB or adjacent areas

Period	Fauna	Location	References
1970s	Harpacticoid copepods, nematodes, polychaetes	NC, SC, GA shelf	1
1980s	Micro- and meiofauna	-	2

1 Tietjen (1971); Coull (1972); Tietjen (1976); Tenore et al. (1978); Coull (1979)
2 Tietjen (1980); Coull et al. (1982)

6.2.5.1 Shelf Meiobenthic Communities

Meiofauna were sampled by Tenore et al. (1978) by taking three 1.5 cm subsamples from three box cores per station. A 0.044 mm mesh was used to retain meiofauna after coming through a 0.5 mm mesh. Nematodes accounted for 60% of the individuals but only 36.5% of the biomass, while copepods and polychaetes made up 33% and 15% of the biomass (dry weight), respectively. Mean meiofauna density was 945/10 cm^2 along the northernmost transect, 790/10 cm^2 along the middle, and 505/10 cm^2 along the southernmost. Densities at inner-shelf stations were higher than at middle- and outer-shelf stations, with total meiofauna biomass lowest at outer stations (292 µg/10 cm^2) compared to inner stations (406 µg/10 cm^2). Nematodes were negatively and harpacticpoid copepods positively correlated with increasing mean grain size, and most copepods were interstitial forms. Meiofauna were similar in density and biomass to reports from elsewhere, while macrofauna were lower.

Hanson et al. (1981) collected meiofauna off the Georgia Bight along four seaward transects (from Savannah, Georgia to St. Augustine, Florida). John Tietjen, the nematode specialist in their research team, found the dominant taxa to be nematodes (61%), copepods (24%), polychaetes

(4%), and foraminifera (3%). Mean middle-shelf densities of nematodes were significantly lower (209/10 cm^2) than at inshore (432/10 cm^2) and shelf-break stations (314/10 cm^2). Copepod densities, however, were higher at middle-shelf stations (242/10 cm^2) than at the inshore (112/10 cm^2) and shelf-break stations (170/10 cm^2). The dry weight of nematodes only accounted for 23% of the total meiofauna biomass along the four transects. Copepods comprised 50% of the biomass, while polychaetes, the largest meiofaunal organisms present, accounted for 22% of the biomass. No relationship was found between total meiofaunal densities and grain size or with the amount of chlorophyll in the sediments. Both nematode and copepod biomass was inversely related to macrobenthos biomass.

Coull et al. (1982) is one of only very few descriptive studies concerning meiobenthos in the shelf/slope regions of the South Atlantic Planning Area. Sampling was done at 50 stations along 7 transects (6–9 stations per transect). Four transects were sampled in each of four seasons, while the other three were sampled only in winter and summer. Depths sampled ranged from 10 m across the shelf to just over 500 m on the continental slope. Animals were collected with a box core (the same one used by Tenore [1979] for collecting macrobenthos) that was sub-cored three times with a 2.5 cm diameter core to 15 cm depth. The three sub-cores were each partitioned transversely into four vertical sections, although the depth distribution of meiofauna within the sediment was not addressed in this paper. Animals were preserved in the field and then sieved after elutriation through a 0.5 mm mesh onto a 0.062 mm mesh. Meiofauna were identified to major taxon and counted, with the first 100 nematodes and first 100 harpacticoid copepods identified to the family taxonomic level at each station. Meiofauna were dominated by free-living nematodes and copepods, comprising 51% and 19%, respectively, with harpacticoids being >90% of these small crustaceans. The gastrotrichs were the third most abundant taxon, at nearly 7% of the total meiofauna. Densities (#/10 cm^2) ranged from 7 to 2,645, with a mean density on the shelf in depths <100 m of 957 and 364 in depths >100 m. The highest densities were encountered at stations between 20 and 100 m deep, and in virtually every station the animals exhibited a clumped spatial distribution at the scale sampled (between replicate subcores within box cores). In general, meiofauna were most abundant on the middle shelf and in the three northern-most transects–one off North Carolina and two off South Carolina, with lowest values off northern Florida. Five variables (median grain diameter, sorting, total organic carbon [TOC], depth, and latitude) were examined for correlations with meiofaunal densities using multiple regressions, but only depth (27%) and latitude (17%) could explain any of the station-to-station variability. Five of the 34 total families of nematodes accounted for 38% of all free-living animals counted and all five decreased in abundance with depth and latitude. The five dominant harpacticoid families also decreased with depth and latitude. Many of the copepods were interstitial forms, living between sand grains within the sediment. Based on the few studies on continental shelves elsewhere in the world, the finding that meiofauna were most abundant on the middle shelf was unexpected, as was the occurrence of several mystacocarids that are typically found on sandy, intertidal beaches. Seasonally, meiofauna were lowest in abundance in spring and highest in winter, presumably due to more reproductive activity in spring into the fall and with overwintering population losses accounting for the lowest numbers. Overall the authors felt that the faunal assemblages encountered were typical of those found elsewhere on sandy shelf sediments having low organic carbon content. Additional studies with identifications to the species level are required to measure the community structure of meiobenthos in the South Atlantic Planning Area.

6.2.5.2 Slope Meiobenthic Communities

Knott and Wendt (1985) reported a lack of quantitative data documenting the role of meiofauna on the shelf and slope of the southeastern US They noted that most of the non-foraminiferal work done is based on identification of meiofauna only to the level of order or higher taxon, a level inadequate for determining the dynamics of meiofaunal community structure. This general lack of species-level identifications still exists.

Tietjen (1971) sampled the meiobenthos off North Carolina where the edge of the Blake Plateau impinges upon the continental slope. This is north of the study area, but included here because these are the dataset from the continental slope closest to the South Atlantic Planning Area. The shallowest stations (50 and 100 m) were medium and coarse sands. Between 250–500 m, the sediments were comprised "almost exclusively of planktonic foraminifera remains." At 600 and 750 m, the sediments changed to sandy silts; deeper stations (800, 1,000, 1,250, 1,500, 1,750, 2,000, and 2,500 m) consisted of clayey silts, with many macrobenthic brittle stars present in this depositional area. Twenty-one meiofaunal taxa were collected (0.044 mm mesh); most common were nematodes, harpacticoid copepods, foraminifera, polychaete worms, gastrotrichs, and ostracods. Highest abundances occurred at 250 m, lowest at 400–500 m. Nematodes, sorted out for identification to species, were dominant from 50–500 m, with forams dominant deeper, especially at the 1,000–2,000 m depth range. Twenty-three families and 212 species of nematodes were identified. About 95% of the meiofauna occurred in the upper 1–2 cm of the sediment, regardless of sediment type. Meiofauna densities decreased significantly with depth, and at stations shallower than about 250 m, population densities were an order of magnitude higher than at greater depths. Nematodes were the dominant taxon at all depths. The types of meiofauna present depended on the grain size, with archiannelids, gastrotrichs, and halicarid mites, as well as markedly reduced numbers of harpacticoids, disappearing as the sands became more silty. Grain size also correlated well with organic content of sediments, and deeper sediments had elevated levels (1–2%). Among the nematodes, deposit feeders dominated between 50–500 m (50% of nematodes), but 40% of them were epigrowth feeders. From 500–2,500 m, about 80% of the nematodes were deposit feeders, 8% epigrowth feeders, and 12% predators/omnivores. With bacteria and detritus or benthic microalgae as food, meiofauna distributions were likely strongly influenced by the Gulf Stream currents. More information on relationships between microbes and meiofauna is presented in a review paper by Tietjen, a globally-recognized expert on free-living marine meiofaunal nematodes (Tietjen, 1980). Typical densities of meiofauna found in the South Atlantic Planning Area in Table 6.4 are presented as ranges because of the high spatial variability encountered by meiobenthologists in their samples.

Table 6.4
Typical range of abundances of meiobenthos (#/10 cm^2) in the South Atlantic Planning Area. Data summarized from references in Table 6.3.

Area	Dominant Taxa		Foraminifera	Total Meiobenthos
	Nematoda	Copepoda		
Inner shelf	500–900	10–100	10–100	500–1,300
Middle shelf	50–300	100–200	30–80	500–1,000
Outer shelf	200–300	100–200	50–100	400–600
Slope				200–500

6.2.5.3 Summary for Meiobenthic Communities

The meiofauna were not sampled intensively in the South Atlantic Planning Area until the 1970s, and only a few transects were made across the shelf or out on to the slope. The investigators identified the organisms sampled to only a major taxon level, so there are no data on meiobenthic species diversity. The work done was of the highest quality, but with so few samplings in a relatively small window of time, it would be unwise to presume that the spatial and temporal variations seen then persist now. It is highly likely that the benthic habitat has undergone some changes in the ensuing four decades. Abundances and biomasses found were typical of coastal shelves and other slope areas sampled elsewhere in the world, and the predominance of nematodes and harpacticoid copepods is entirely in keeping with these other studies. Because no meiofauna have been sampled since these original studies, meiobenthic communities in the soft-bottoms of the South Atlantic Planning Area remain grossly undersampled through both space and time. Nor do we know to what degree the meiobenthos participates in coastal shelf food webs where so many harvestable species likely feed on meiofauna in their larval or early juvenile developmental stages.

6.2.6 Macrobenthic Communities

Coastal soft-bottom macrobenthic organisms in the South Atlantic Planning Area are generally impoverished compared to other areas on the US east coast. Most of the soft-bottom species are rapid growing and short lived, thus able to maintain populations in response to dynamic, storm-induced changes in the sediment that move and displace benthic fauna. Winds that move sediments make it difficult for benthic communities to attain high levels of productivity (Emerson, 1989). These populations also indirectly take advantage of stochastic, unpredictable short-term (days in duration) influxes of nutrient-rich deep water from below the Gulf Stream during wind-induced upwelling events that enhance productivity needed by the benthos. Despite relatively low numbers and biomass, the benthic communities can achieve high levels of species diversity, especially in less-disturbed hard-bottom areas. Mallin et al. (2000) provide an informative descriptive comparison of similarities and differences between the North and South Carolina coasts. Table 6.5 identifies studies on macrobenthos in the study area.

Table 6.5
Time trajectory of soft-bottom macrobenthos surveys in the South Atlantic Bight or adjacent areas

Period	Fauna	Location	References
1970s	> 1.0 mm	GA shelf	1
	> 0.8 mm	GA shelf	1a
	> 0.5 mm	GA shelf, SC slope	1b
1980s	> 1.0 mm	SC shelf	2
	> 0.5 mm	SC, GA. FL shelf	2a
	> 0.3 mm	NC, SC slope	2b
1990s	> 0.5 mm	SC shelf	3
	> 0.3 mm	SC slope	3a
2000s	> 0.5 mm	SC, GA, FL shelf	4

1 Smith (1971; 1973); Frankenberg (1971); Leiper (1973); Frankenberg and Lieper (1977)
1a Dorges (1977)
1b Cutler (1975); Tenore et al. (1978); SCWMRD (1979); Tenore (1979)
2 Wenner et al. (1983)
2a Hanson et al. (1981); Knott et al. (1983); Tenore (1985); Baca and Lankford (1987); Van Dolah et al. (1983); Winn et al. (1989)
2b Blake et al. (1987); Maciolek et al. (1987a,b)
3 Van Dolah et al. (1992; 1993a; 1994a; 1997); Jutte et al. (1999); Jutte and Van Dolah (1999); Barry A. Vittor and Associates (1999); Lotspeich and Associates (1997)
3a Brown (1991); Schaff et al. (1992); Hilbig (1994)
4 Jutte and Van Dolah (2000); Jutte et al. (2001); Hyland et al. (2001; 2002); Cooksey et al. (2004); Hyland et al. (2006); Rexing (2006); Bergquist et al. (2009a); Zarillo et al. (2009); Zarillo and Reidenauer (2008); Zimmerman et al. (2002)

6.2.6.1 Shelf Macrobenthic Communities

From a study conducted 3.85 km (nearshore) and 38.5 km (offshore) east-southeast off Sapelo Island, Georgia, Frankenberg (1971) reported on collections made with a Smith-McIntyre bottom sampler from December 1963 to November 1964. Sediments were "fine" nearshore and "coarse" offshore. Ten samples were collected at each station and were eluted through 1 mm^2 screens. The offshore station was dominated by a cephalochordate (*Amphioxus*), amphipods, a mysid, polychaetes, a sipunculid, a cumacean, pelecypods (bivalves), and echinoderms, each taxon comprising at least 1% of the total specimens collected. An additional 219 species were collected but comprised only 19% of the total (235 species). The seasonal pattern offshore showed a dramatic increase in the number of Branchiostoma (*Amphioxus*) from less than 100/m^2 in December–March to 1,300/m^2 in May–July and back to 100/m^2 or less in September–November. The inshore station was not dominated by a single species, rather a cumacean (*Oxyurostylis smithi*), a spionid polychaete (*Spiophanes bombyx*), a bivalve (*Tellina texana*), and a crustacean (*Pinnixia chaetopterana*) all made up over 5% of the collection, with many other species present as well (175 total species). At this shallow station, the community changed dramatically during the year; *Spiophanes*, *Tellina*, and *Oxyurostylis* made up 60% of the community from February to March but less than 10% from June to November. A community dominated by *P.*

chaetopterana, *Hemipholis elongate*, *Magelona*, and *Callianassa* comprised less than 10% of the fauna from December through May, but greater than 40% between June and November. Based on findings by Smith (1971), this replacement pattern is not the same from year to year. However, some of the common inshore species did have similar patterns from 1963–64 and 1969–70, specifically *S. bombyx*, *T. texana*, and *O. smithi*, all abundant between June and January each year. Other species showed great variability in abundance over this time interval. The seasonal aggregation of *Branchiostoma caribaeum* offshore was unusual and had not been found anywhere else. Frankenberg concluded by stating that single-season samples are inadequate for describing benthic community ecology in the subtropics, and seasonal variation is an important characteristic of these communities.

Macrobenthic fauna were sampled off Sapelo Island (7 m depth) by Smith (1971; 1973) using a USNEL Spade Corer from July 1969 to June 1970. Ten replicate cores were taken each month for ten months during this period. Smith found 103 species from 10 phyla; polychaetes were dominant (36 spp.), followed by mollusks (31) and crustaceans (21). Abundances remained stable through summer and fall and increased in December, and reached a maximum density in March of 14,213/m^2 and a low of 744 in June. Two species, a polychaete (*S. bombyx*) and a cumacean (*O. smithi*), became very abundant between December and May. The macrobenthic biomass steadily increased from December to March, reaching a maximum of 20.2 g/m^2 in March. Echinoderms dominated the biomass from July to December and were replaced in dominance by mollusks from January through June. The numerically dominant taxa, polychaetes and crustaceans, were never prominent in terms of biomass, only once comprising 32% of the total biomass in March. When species were most abundant, species diversity was lowest. Most organisms lived in the surface sediments, but some burrowed as deep as 50 cm (Smith, 1971).

Leiper (1973) also studied nearshore shelf macrobenthos sampled with 0.1 m^2 Smith-McIntyre grab samplers off Sapelo Island, Georgia in the same vicinity as Smith (1971). His emphasis was on detecting seasonal changes in the abundance and diversity of the benthic community at three stations there: A at 8 m, B at 9 m, and C at 10 m depth. He took twelve grabs per month, each sampling to a sediment depth of 8–10 cm, and the sediment was screened through a 1.0 mm mesh. Four species of polychaetes dominated abundances, with a crab, a shrimp, a bivalve and a gastropod species the other four most abundant organisms during any month of the year-long study. *S. bombyx*, a spionid polychaete, reached its greatest abundance in late winter/early spring, maxing out at a mean of 11,849/m^2 in April. The most species were found in early spring as well. Compared with the abundances found by Frankenberg (1971) and Smith (1971), both of whom also used a 1.0 mm mesh to separate organisms from the sediment, Leiper's study found highest abundances at the same times of year (late winter/early spring) and lowest numbers in late summer. Station A had a total macrobenthos abundance of 20,584/m^2 in April; Smith found 14,213/m^2 in March and Frankenberg 4,419/m^2 in February. The three studies spanned almost eight years, so there seemed to be consistent seasonality over that time period.

Nearshore salt marshes, tidal creek point bars, the Ogeechee estuary, tidal flats, shoals, beaches and shallow shelf areas off Georgia were investigated by Dorges (1977). Samples were collected with an iron core (0.2 m^2 surface area) in shallow tidal waters and with a modified Reineck box corer in waters below 3–5 m depth. Sediments were sieved through a 0.8 mm mesh, then fixed in formalin. Sediment sampling depth was not stated. Two transects were sampled in 1969; a

northern one off Sapelo Island with 51 stations found 179 species from 12 major taxa, mostly polychaetes, mollusks, and crustaceans. Abundances and number of species (taxa?) increased dramatically starting about 1 km offshore and stayed high until about 8–10 km offshore, due to an increase in the fine component of the sediments. From 8–20 km offshore, abundances and number of species was greatly reduced. A southern transect with 36 stations was sampled parallel to the northern transect. Dorges (1977) found 144 species in 10 major taxa, mostly polychaetes, crustaceans, and mollusks. In both transects, the ten most common species accounted for 86% of the total number of individuals. The southern transect crossed various shoals and troughs not present along the northern transect. Offshore, 100 stations were sampled on the shelf, where the sediments consisted of medium to coarse relict sand sediments. The benthic community composition of the area was similar but conspicuously different from that in the nearshore waters. Only 119 species were found out to a depth of 180 m, with tube-dwelling polychaetes, bivalves, bryozoans, lancelet (*Branchiostoma virginiae*), and echinoderms dominant. Several species in each taxa are named. Dorges (1977) lists the "most important and characteristic" species found in each of the habitats sampled from inshore to the shelf edge. On the shelf the following are listed: *Owenia fusiformis, Spiochaetopterus oculatus, Moira atropos, Branchiostoma virginiae, Discoporella umbellate, Petaloproctus socialis, Onuphis eremite, Polydontes lupine, Potamilla cf. reniformis, Mesochaetopterus taylori, Macrocallista maculate, Laevicardium laevigatum, Chione cancellata, Amphiura fibulata, Chione intapurpurea, Dentalium spp.,* and *Scolecolepidis viridis*.

The study of Frankenberg and Lieper (1977) demonstrated that seasonality is an important aspect of the abundance and species composition of benthic communities off Georgia. Samplings in 1963–64 and 1969–70 were compared. The high variability found calls into question whether "communities" exist in subtropical benthos. Two stations (F-1 and F-2) were sampled with 0.1 m^2 Aberdeen grabs (10 replicates) during December 1963 to November 1964, whereas three different stations (A, B, C) were sampled (12 reps at each) in December 1969, and in January, February, April, June, August, September, and November 1970. Sediments were washed live through a 1 mm^2 mesh and then preserved. The inshore area consisted of fine sand and silty sediments and 12–33 ppt brackish turbid light-limited waters, with outer shelf consisting of coarse sediments and 33–36 ppt and clear water. Stations ranged from 3.5–21 m depth. A nearby inshore station was sampled by Smith (1971; 1973). Faunal densities were generally highest late winter/spring and lower during summer/fall. Mean densities of total macrobenthos at the inshore suite of stations ranged from a low of 258/m^2 to a high of 20,584/m^2, with individual species having as much as four orders of magnitude differences in abundance. The total number of species at these inshore stations ranged from a low of 47 in May 1970 to a high of 107 in April 1970. The overall dominants included a polychaete (*S. bombyx*), tellinid pelecypod bivalves, a cumacean crustacean (*O. smithi*), with several other taxa dominant at various times over the year (amphipods, magelonid polychaetes, other pelecypods, some nemertean worms, and barnacles that had settled on empty shells lying on the sediment, also colonized by a sabellarid, tube-building, polychaete). At station C, there was no clear seasonal change, with the cyclostomate ectoproct (*Cupuladria doma*) dominant throughout the year. At the offshore station, sampled for only a year beginning in December 1963, the coarse-sand assemblage was dominated by a cephalocordate, amphipods, and the glyceriid polychaete, *Glycera capitata*. *Branchiostoma caribaeum*, the cephalachordate, became most abundant in the summer months; amphipods and polychaetes were dominant the rest of the year. Species abundance was highest (83 species) in

March and lowest (39 species) in October 1964. Mysid crustaceans (*Gastrosaccus johnsoni*) became abundant from May to December in 1964. Some major findings of this study were: 1) 3–4 order of magnitude changes in average abundance occurred at a single inshore station over time in 1970, with similar ranges in density occurring between stations only 5.5 km apart; 2) faunal density variation, in both time and space, was typical in the area; differences in faunal density among replicate grab samples was also high, as they usually differed from one another; 3) replicate grab samples varied less from one another than from samples taken at other times or other stations–between replicate sampling variability is a problem; and 4) causes of variability may be due to reproductive events, fish predation, natural longevity losses, migrations, and navigational error (sampling different places at the "same" station over time).

Tenore et al. (1978) collected macrobenthos with fifteen box cores at each station (10x20x15 cm deep), sieved through a 0.5 mm mesh on board ship and then preserved. Total wet weight biomass was measured in the laboratory. Values ranged from about 3 to 22 g/m^2 and were lowest at inner stations compared to middle and outer, but all were lower than reported elsewhere on the US east coast continental shelf.

Knott et al. (1983) characterized intertidal and subtidal benthic infaunal assemblages off Murrells Inlet, South Carolina. They established three transects from the beach at mean high water. The subtidal stations on these transects were at 1–2 m depth (= nearshore), 2 m depth at 0.5 km from shore (= midshore), and 4–5 m depth at 1 km from shore (= offshore). They took three replicate Van Veen grab samples at each station during November 1977, February, May, and August 1978. Sediments were washed through a 0.5 mm mesh screen before fixation and processing. Polychaetes dominated the subtidal stations at all depths, both numerically and in number of species. Along with amphipod crustaceans and pelecypods (bivalves), these three taxa accounted for more than 95% of the individuals and 70% of the species collected; the ten most abundant species comprised nearly 82% of the total fauna collected in their study, intertidal plus subtidal stations. Subtidally, *S. bombyx* (a surface deposit-feeding spionid polychaete) was numerically dominant, making up 45% of the collections. This species was most abundant between November and February and had highest densities at the outermost, deeper, fine-sand stations. Another polychaete, *S. squamata*, was also abundant but at the shallow stations. Six species of amphipods were common throughout the year as well. *Donax variabilis* (coquina clam) was common at the nearshore and midshore stations. The sizes of these animals were measured to provide clues as to whether reproductive events had happened at various times over the year. Species numbers and species richness increased seaward along each transect. Measures of species diversity, evenness, and richness varied from season to season at a given station, such that consistent seasonal patterns were not clearly reflected by these indices. Fauna at the nearshore and midshore stations clustered together, and the offshore stations comprised a distinguishably different cluster, neither cluster being similar to the two intertidal station clusters found. Species groupings showed several distinctions as well when their constancy and fidelity at all the stations were considered. The investigators attributed the relatively high species diversities to the moderate wave activity in the lee of the jetty under construction at the inlet. More energetic wave activity in other areas resulted in lower diversities and less dominance by polychaetes (Roberts, 1974).

Probably the most complete and comprehensive description of macrobenthos (>0.5 mm) in the South Atlantic Planning Area in existence is by Tenore (1985). The study was based on four seasonal sampling events with a quantitative box core (0.06 m^2) to 15 cm depth at 6 or 7 evenly spaced, depth-defined stations, six cores per station, across the shelf on seven different transects. There were two transects across the north Florida shelf, two across the Georgia shelf, and three across the South Carolina shelf, each transect encompassing the inner (20–50 km offshore, 13–15 m depth), middle (50–90 km, 23–28 m, and outer 90–150 km, 37–200 m) regions of the shelf/upper slope. Subsamples from each core were analyzed for sediment grain size and TOC. Benthic organisms were identified to major taxonomic group (echinoderms, polychaetes, bivalves, mollusks, and miscellaneous), with many to the species level. Additional data were collected for dry weight biomass and AFDW determinations. Samples were compared on the basis of abundance per unit area sampled as well as upon their total biomass per unit area (and volume) sampled using stepwise multiple regression. Similarities between stations were assessed using species data for those that accounted for more than 0.2% of the samples according to season. High species diversity, low abundance, and coherent groupings according to station depth were found. The inner-shelf stations were most distinct from the other regions of the shelf, and their communities persisted throughout the year. Organisms at the middle- and outer-shelf regions changed seasonally as a function of settlement of new, water-borne recruits during the year. The outermost shelf/upper slope stations were unique, unlike each other and unlike stations closer to shore. Polychaetes dominated the communities in each region at all times of year, typically comprising 50% or more of the abundance and biomass. Most species of polychaetes found were rare, comprising less than 0.2% of average abundance, as was true for other taxa. Spionid polychaetes dominated the sediment-dwelling benthos, as they are adapted for living in such dynamic environments: shifting sands, wide temperature ranges, and periodic upwelling events that provide new nutrients to oligotrophic water masses with subsequent settlement of organically rich particles to the sea floor. Because sediment characteristics in the shallow waters of the shelf are determined by the influence of tidally driven and storm- or wind-driven scour, most benthic species were motile surface-dwellers, as opposed to stationary or less mobile, burrowing fauna. Because the sediments are low in organic carbon (= food), organism abundances and their standing crop biomasses were low. The types of organisms present were those that feed on the surface of the sediment where newly settled organic matter occurs or where microalgae grow in situ. There was no latitudinal gradient but rather a consistent inner-, middle-, outer-shelf delimitation of the benthic communities, similar to findings elsewhere in the Middle Atlantic Bight. Homogeneous is a term that can be used to characterize the fauna within these three regions, although great heterogeneity in abundance and biomass exists throughout all regions of the South Atlantic Planning Area.

Tenore et al. (1978) sampled nine stations off Georgia in early spring (March 1976) to examine differences among the benthic communities on the continental shelf relative to the hydrodynamic regime there. Three transects were sampled: off Wassaw Sound, St. Catherines Island, and Jekyll Island. The inner shelf (20–50 km), middle shelf (50–90 km), and outer shelf/upper slope (90–150 km) regions were sampled with a box corer as well as with Niskin bottle water samplers at the surface (1 m depth) and bottom (1 m above sediment). Groups of investigators examined various components of the collections: sediment and suspended particulates, chlorophyll a in water and sediments, the microbial community, N fixation, ATP analysis, denitrification, microbenthos, meiobenthos, and infaunal macrobenthos. This suite of measurements revealed an

impoverished benthic community with low biomass due to sediment scour from wind and tides and low nutrient input. Higher biomass of macrobenthos at middle and offshore stations suggests that intrusion-related biological productivity enhances communities there. This comprehensive study illustrates the strength of multidisciplinary investigations that can elucidate important shelf processes. Key findings included: medium size, moderately sorted quartz sand; low sediment C and N values; a general decrease in suspended particulate matter offshore; increasing levels of chlorophyll in bottom waters offshore; a significant decrease in the rate of glucose uptake by heterotrophic microbes with distance offshore; N-fixation higher in inner- and outer-most stations than in middle stations and decreased north to south; variable rates of denitrification with highest in the middle shelf; decreasing microbial biomass with distance from shore; higher heterotrophic activity in the outer shelf at the two southern stations (from intrusions?); microbial biomass (ATP) increased southerly but invariably along a N-S transect of inner and middle stations; low N-fixation activity; macrobenthos biomass (0.5 mm mesh) lower at inner stations and low overall compared to other east coast shelf stations; nematodes and harpacticoids dominated the meiofauna, having N-S and inshore-offshore gradients in density; and sediment granulometry may control meiofaunal distributions.

Tenore (1979) sampled 50 stations along seven transects extending from inshore to the outer shelf/slope, from just south of Cape Fear, North Carolina to Daytona Beach, Florida. At each station, six replicates were taken with a box core (0.06 m^2) and sieved through a 0.5 mm mesh screen aboard ship. Samples at 25 of the stations were collected on four seasonal cruises during 1977. Formalin-preserved samples were sorted in the laboratory. Preserved wet weight and AFDW biomass were estimated for whole taxa: polychaetes, arthropods, echinoderms, mollusks, and miscellaneous. Subcores from each box core were taken for sediments analyses (size, sorting, silt-clay fraction, skewness, and TOC). The Shannon-Weaver (H') diversity index was calculated based on measures of abundance and numbers of species found in the samples. The results indicated low organism densities and low biomass but quite high diversity, with H' values exceeding 3.0 at 89% (133) of the season/station data sets, with 33 stations (22% of the whole set) having values >5.0. There was little variation in the percentage distribution of the diversity index with seasons. Polychaetes dominated the macroinfauna, accounting for over 50% of total density and biomass in most samples. When polychaetes were not abundant, the samples contained large megabenthic organisms. Some of the polychaete species (*S. bombyx*, *Unicola B*) showed seasonal variation in their mean numerical composition (as % relative abundance averaged over all 25 seasonal stations) as great as a factor of almost 30. For example, *S. bombyx* comprised 0.3% of the total infauna in the fall but 5.3% in winter and 7.3% in spring. *Unicola B* had relative abundances of less than 0.2% in fall and winter but 6.0% in spring. The highest mean total macrobenthos density found in any of the stations was 1,416 per box core or 23,600/m^2. However, most mean abundances during the study were in the range of a few hundred organisms per box core; mean numbers of taxa per core fell between 11 and 325, mostly around 125–175. Only 18 species were present in numbers equal to or exceeding 0.2% of the total catch in one or more seasons. The outermost stations on the slope had the lowest densities and diversities. Seasonally, mean densities and biomass (#/core, AFDW) per transect both varied seasonally about as much as they varied between transects during the year. The same can be said for the number of taxa per core. Jaccard similarity analyses (based on presence/absence) found a clustering for the inner-most shelf stations, a middle-shelf cluster, but the outer, deeper, heterogeneous stations did not cluster even with each other. Thus water depth, not latitude,

seemed to be the primary community delimiter. By dividing biomass by density, Tenore calculated the mean weight per individual and found that organisms in the nearshore region, although fewer in number, were larger than those on the middle shelf and slope, particularly in summer and fall. Mean weight per individual was similar for the middle shelf and slope.

Hanson et al. (1981) performed a comprehensive study of the benthos in the Georgia Bight in relation to Gulf Stream intrusions and the outwelling of nutrients from estuaries in the region. Their study was conducted in June 1977 and can be readily compared with the early spring studies of Tenore et al. (1978). Hanson et al. (1981) sampled twelve stations spaced along four transects off Savannah River, St. Catherines Island, St. Augustine, and Daytona Beach. Depths and distances sampled ranged from 13–18 m and 20–30 km for inshore, 25–31 m and 30–70 km for the middle shelf, and 39–68 m and 70–100 km for the outer shelf. Sediments collected with a box corer to a depth of 20–25 cm. The following parameters were measured: sediment granulometry, benthic algal biomass, benthic metabolism, microbial activity and biomass, meiofaunal density and biomass, and macrofaunal biomass–essentially the same as measured by Tenore et al. (1978). Once again, the sediment was mostly well-sorted, medium-grained sand. Organic C and N values increased offshore and southward in the shelf sediments, with the inner shelf showing the highest latitudinal variation for organic N content. Macrofaunal biomass was generally low, but higher than found in the spring by Tenore et al. (1978), and highest in the fine sediments found off Florida. Where Tenore et al. (1978) reported low macrobenthos biomass inshore during spring, no such relationship was found in the summer sampling. The macrobenthos of the Georgia Bight is characterized by small species with short generation times, and its low, patchily distributed biomass reflects the overall oligotrophic status of the region. However, off Florida the biomass is higher and reflects the influence of nutrient-rich Gulf Stream intrusions that fuel the production of particulate organic matter that settles to the bottom. Nutrient inputs from the coast enhance the benthos only to a distance of about 20 km from shore due to the presence of low-salinity fronts that constrain nutrient export to the middle and outer shelf.

Hyland et al. (2006) authored a hallmark paper regarding the state of macrobenthos off Georgia. A survey was done in 2000–2002 at twenty different stations within Gray's Reef National Marine Sanctuary and along an additional three transects across the continental shelf in Georgia at mean depths ranging from 8.1 m inshore, 10.5 m inner shelf, 19.2 m middle shelf, and 105 m outer shelf/shelf break. The inner- and middle-shelf stations were 12 and 42 km from shore, respectively. The three transects allow an examination of broad spatial patterns in the benthic assemblage, plus they measured sediment contaminant loads at each station. They used a Young grab (0.04 m^2) to collect three replicate grabs per station that were sieved through a 0.5 mm mesh. Q-mode cluster analysis with an unweighted pair-group method employing Bray-Curtis similarity analysis was used to classify stations based on double square-root transformed abundances from combined replicates at each station. Rare species were excluded from the analyses. They also used canonical discriminant analysis in conjunction with cluster analysis to determine whether clusters could be explained by any physical measures or environmental variables. Interestingly, they also examined the seafloor landscape ("benthoscape") as a possible source for observed spatial patterns found. The number of species, H' diversity, total faunal density, and density of numerical dominants were calculated. Sediments consisted mostly of sand and shell hash/gravel lacking a fine component. The bottom was classified as sand plain or flat

sands, rippled sand (the dominant type at 67%), sparsely colonized hard bottom, and densely colonized hard bottom. Overall, benthic infauna were least abundant and least diverse in flat sands. Rippled sands supported the most diverse and moderate density fauna, with live bottom supporting the highest densities and moderately high numbers of species. There were clear groupings of benthic fauna along each transect according to distance from shore. Mean total densities were highest inshore (11,743/m^2) and lowest at the shelf break (1,550/m^2), with numbers of taxa/species highest (50) at middle-shelf sites. The number of taxa per grab sample ranged from 27 to 64, indicating a highly diverse benthic assemblage in terms of species richness, quite possibly due to high topographic complexity. TOC was low throughout the survey area, only 2.1–4.1 mg/g. Of the 349 taxa identified at the 20 stations in 2000, polychaetes comprised 45% by species and 16% by abundance, mollusks 27 and 67%, and crustaceans 22 and 7%. These three taxonomic groups represented 90% or more of the fauna both by % of species and % of abundance. The highest densities found in the study (50,258/m^2) occurred within GRNMS. When six stations were sampled again in 2002, species that had been present in 2000 were usually found there again, but their rank order by abundance changed, with some very abundant species (e.g., some bivalves and some polychaetes) completely absent in 2002, demonstrating how temporally dynamic these assemblages can be on the Georgia shelf. Long-term repeated observations are clearly needed to understand the structure and dynamics of benthos in the area.

Parts of this same study were reported earlier in Hyland et al. (2001; 2002) and Cooksey et al. (2004). This latter document contains color pictures of fauna and provides a much less technical report of the effort. Its major findings were that vast stretches of sands throughout the sanctuary support a highly diverse infaunal community and are not "biological deserts," and there were notable differences cross-shelf in species diversity, with stations farthest offshore having the greatest number of species. Also, temporal differences in benthic community structure were detected between years in spring (2000 compared with 2001). These differences were not, however, as great as the differences seen across-shelf, but must be taken into account when any sampling effort is made in the future to monitor long-term changes due to human or natural disturbances. The cross-shelf patterns in community structure were related to sediment granulometry, depth, and the proximity of estuaries, especially with regard to recruitment by estuarine species. Cooksey et al. (2004) have reproductions of two poster presentations that address sediment quality and the condition of benthic fauna in the sanctuary in 2000 and 2001.

Sedberry (2007) made submersible observations and infaunal collections from 55 to 1000 m, an extension of previous work along the same transect, but out to only 55 m. Fish observations, habitat descriptions (bottom types), analysis of infaunal invertebrates collected with a Young grab by the submersible, analysis of fauna inhabiting some sponges and tunicates, and analysis of the isotope composition of coral samples to determine paleooceanographic conditions and coral growth rates. Benthic samples were studied by Dr. J. Hyland, C. Cooksey, and J.D. Dubick of the NOAA Center for Coastal Environmental Health & Biomolecular Research in Charleston, South Carolina. Eight stations were sampled in 2004. Samples were live-sieved (0.5 mm screen) and fixed with 10% buffered formailin. They were later transferred to 70% alcohol for long-term preservation. Compared to earlier work by Hyland et al. (2006) along the shelf portion of the transect and within Gray's Reef National Marine Sanctuary, the findings in this study were consistent with the trends of increasing H' diversity across the shelf, higher species richness at

middle-shelf stations, and low density overall. Only two stations were examined in detail (B1 with 2 replicates at 515 and 526 m depths and B4 with three replicates at 738, 722, and 720 m depths). At Station B1 they found 650 and 200 individuals per m^2, while at B4 only 50, 50, or 75 individuals per m^2 were found. Shelf densities reported by Hyland et al. (2006) ranged between 1,550 and 11,743 per m^2. The deeper slope stations were inhabited mostly by annelids and crustaceans, with dominant polychaetes at B1 being *Lumbrinereis latreilli*, *Mediomastus ambiseta* and other species in the genus, as well as members of the families Onuphidae and Sabellidae. Crustacea at B1 included Leptognathia sp. and *Rildardanus laminose*. B4 was dominated by tubificid oligochaetes, the polychaete *Scoloplos rubra*, crustaceans of the family Melitidae, and an aplacophoran mollusk. Several of these organisms are typically found in disturbed or impaired benthic assemblages, but it was not possible to provide an accurate interpretation of these findings with such a limited data set.

The National Benthic Inventory web site is a dynamic quantitative database on benthic species diversity, abundances, and distributions–along with associated environmental data–collected during NOAA/National Centers for Coastal Ocean Science and partnering institutions. A corresponding taxonomic reference collection of preserved benthic organisms is also available.

In a study of macrobenthos in the GRNMS, Rexing (2006) analyzed data from samples of sandy sediments taken by SCUBA at various distances from reef structures to see whether benthos-feeding fishes living in association with the reef caused a "halo" effect of reduced benthic prey density with proximity to the reef. Ancillary to testing the question of interest, Rexing found clear differences in flat sand and rippled sand bottom benthic communities, both in macrobenthos densities, species dominance, and diversity (all higher in rippled sands). Such a finding illustrates how complex it is to measure community structure in seemingly uniform soft-bottom habitats and how much more information is needed about how different benthoscapes affect benthic communities. As for the halo effect, no significant differences in macrobenthic abundances were found with increasing distance (sampled 1, 10, 25, and 75 m away) along four transects from the reefs examined. Fish-gut contents analyses found numerous prey, especially those with hard bodies like crustaceans that came from the reef environs in higher proportions in guts than in sediments in several fishes examined. However there was no overall definitive clear signal that any prey taxa were selected disproportionately to their abundance in the sampled areas. Prey abundance, however, is not necessarily a good measure of their availability to predators, so this finding was not unusual. Soft-bodied prey like polychaete worms are more easily digested and may have been disproportionately under-represented in fish stomach samples. Significantly, Rexing demonstrated clearly that benthic fauna are important prey for a wide variety of reef-dwelling fish species in this habitat. This extensive Master's thesis provides species/taxon lists and measures of density for all samples. There was great concordance between these findings and the more extensive study by Hyland (2006). Reef-halo effects have also been studied by Posey and Ambrose (1994) and Steimle et al. (2002). Kendall et al. (2003) contains underwater photos of the rippled and flat sand bottom studied by Rexing.

Knott et al. (1983) sampled sandy beaches and nearshore areas up to 5 m depth for macrobenthos near the high-salinity Murrell's Inlet, South Carolina. Abundant subtidal species included *S. bombyx* and *S. squamata* (polychaetes), *Protohaustorius deichmannae* and *Acanthohaustorius millsi* (amphipods), and the bivalve *Tellina* spp. Polychaetes dominated both the intertidal and

subtidal areas, especially in areas sheltered by a jetty that was constructed during the course of the study.

An e-mail query was sent to Dr. W. Savidge, a researcher at the Skidaway Institute of Oceanography, concerning his recollections and/or collegially based knowledge of benthic studies in the Georgia Bight. His response (24 Jan 2010) mentioned only cursory knowledge of J. Blake's slope studies off North Carolina: J. Howard's samplings in river mouths of Georgia, J. Hyland's GRNMS studies, and L. Sautter's Transects Program at the College of Charleston. His own studies at the R2 tower (GRNMS, 27 m) with "tubecore-able fauna" have found (from rough sortings) a sparse fauna, small, dominated by errant polychaetes (as opposed to sedentary worms, errant worms move around a bit), and pericarid crustaceans. He also has found, "Lots of predatory polychaete forms (polynoids, goniadids, etc.). Magelonids are encountered regularly. There are many 'threadlike' polys that I do not recognize. Mollusks are rare. Large polys are rare. I've only cored echinoderms as newly settled individuals, but adults show up on video. Small lancelets are ubiquitous." His epibenthic sled samples from bi-monthly cruises in 2007 and 2008 have not yet been analyzed, nor have plankton tows. This is a very typical, though somewhat detailed, response from among several others solicited face-to-face or by telephone. Most investigators suggest they have some work in progress or temporarily "on the back burner" as other priorities dictate. Clearly, benthic studies take a long time to bring to completion and publication.

The Charleston Ocean Dredged Material Disposal Site (ODMDS), located 14 km southeast of the entrance to Charleston Harbor, has been sampled periodically since August 1978 (SCWMRD, 1979; Winn et al., 1989; Van Dolah et al., 1997). In 1993 and 1994, Van Dolah et al. (1997) performed a detailed study of benthic fauna in the site by collecting grab samples within and in two strata surrounding the disposal area. Because the innermost and next closest stratum were much more likely to be unrepresentative of the natural benthic community in the area, only the findings from the outermost stratum are mentioned here. With ten grabs taken (August 1993, July 1994) in each of eight rectangular cells of the stratum, the benthos were sieved using a 0.5 mm mesh before processing. Polychaetes, pelecypod mollusks, and amphipods dominated, with 65% of the individuals collected coming from these three major taxa, and this was essentially the same composition as was found in previous summer samplings in 1978 and 1987. Comparisons between the earlier two samplings (1978 and 1987) and those from 1993 and 1994 were compromised somewhat by the fact that a shallower penetrating grab (Smith McIntyre) was used rather than the 0.04 m^2 Young grab in the 1993/94 study. The Smith McIntyre grab does not penetrate as deeply, hence less sediment per sample was collected by that device. Faunal abundances cannot be compared with great confidence as a result. Nonetheless, there were about three times more infauna in 1993/94 than in the earlier collections (~5,200–6,800/m^2 vs. ~1700–1850/ m^2) as well as about twice as many species (~160 vs. ~80). Once again, these count differences may be gear-related. In general, however, about the same number of total taxa was found in each of the four years (~500). Some species varied considerably between years, especially a spionid polychaete. Spatially, the 1993/94 replicate samplings came from within a larger bottom area in the stratum and may thus be more representative of what was there. A large number of very informative figures, tables, and appendices provide an opportunity to understand their findings in great detail. Perhaps one of the most useful outcomes from this study concerned a statistical power analysis. Given the variabilities found in abundances of

individuals and species, Van Dolah et al. (1997) found that 10 replicate grab samples was enough to detect changes on the order of 20% over time and/or space. This provides an excellent baseline for future sampling protocols. Another significant finding was that, for proper comparisons to be made, collections made from the same sediment type (e.g., sandy, muddy, shell hash) should be examined, because all three of these types exist within the boundaries of the disposal site's study area. Benthic community structure is fundamentally related to sediment type; typically there more deposit-feeders in mud, more suspension-feeders in sand (Gray and Gray, 1981), although it should be noted that both feeding types often co-occur, and many benthic animals exhibit both feeding modes.

Zimmerman et al. (2002) conducted a study in 2000 midway during a disposal "event," the removal of sediment from Charleston Harbor to deepen the channel, a project that started in 1999. Data on benthic communities in and around the offshore disposal site, a 10 km^2 area of fine-grained sands at a 13 m depth 11 km miles southeast of Charleston, were compared to samples collected prior to the deepening project in 1993/94. The site was gridded into a central quad that was surrounded by an inner stratum of eight strata and that surrounded by an additional outer eight strata, each of the twenty strata measuring a 2.5 km^2. A grab sampler (0.043 m^2) was deployed ten times within each of the twenty strata, and a subsample for sediment analysis was taken from each grab sample and sieved with a 0.5 mm mesh. Only the samples from the inner and outer zones are reported here. Mean density per ranged from 1415 to 9323/m^2, with an average of 3939/m^2 individuals. There were between 22 and 51 species, mean 34, in each grab sample. Polychaetes comprised 56% of all organisms collected, amphipods 13%, and mollusks 10%, with "other taxa" at 21% (nemerteans, etc.) Eleven taxa made up 47% of the abundance in the 2000 samples: spionids, sabellids, etc. Densities were lower wherever sediment impacted the bottom. Comparing non-impacted areas in 1993–94 (the baseline) and 2000, no differences in density were found. This study is useful for its species list in the non-impacted areas. A more detailed account of the study is given in Zimmerman et al. (2002).

Jutte et al. (2005) summarized their previous studies of the disposal site. Because they found impacts to the benthic community that resulted from changes in the sediment, they recommended that continued post-disposal monitoring be conducted in the same manner as the impact studies had been conducted.

Zarillo et al. (2009) mention that the Jacksonville, Florida ODMDS had been surveyed by Barry Vittor and Associates (1996) in 1995 and 1998 just inshore of shoal A4, an area that was also surveyed, again by divers using hand-held core tubes, by Lotspeich and Associates, Inc. (1997), both of whom report that the inner-shelf infauna are dominated by polychaete worms in both abundance and species richness. They found amphipod crustaceans, bivalves, and gastropod mollusks, as well. These communities exhibited both spatial and seasonal variability.

The Barry Vittor and Associates (1999) study 1.6 km west from shoal A4 off Florida used divers with hand-operated cores at depths of 10–15 m on a sand bottom. Polychaetes (33.8%), bivalves (26.9%), gastropods (15.0%), and malacostracans (14.7%) dominated the total assemblage numerically, with polychaetes making up 34.3% of the total number of taxa, malacostracans 28.8%, bivalves 14.3%, and gastropods 11.3%. Dominant polychaetes were surface deposit-feeding spionids.

The most recent published broad sampling effort in the South Atlantic area of interest is by Cooksey et al. (2010), who provide a report on the condition of estuaries and coastal waters from Point Henry, VA to the Indian River lagoon, Florida. The study was part of the USEPA National Coastal Assessment program, done in collaboration with NOAA and the five Southern US Coastal States (Virginia, North Carolina, South Carolina, Georgia, Florida). Their findings on estuarine conditions will not be mentioned here. Open shelf waters were sampled between Nags Head, North Carolina and West Palm Beach, Florida for soft-bottom benthos at 50 stations in March–April 2004, with one station in Gray's Reef National Marine Sanctuary. The other stations were selected using a generalized random-tesselation stratified sampling design that insures adequate areal coverage of the area of interest despite having actual stations selected at random within strata. This design is a decided strength compared with the typical transect sampling designs used by most coastal investigations. Additional samples were also collected to measure sediment contaminants, organic carbon content, percent silt/clay vs. sand, and other relevant general habitat conditions. Sediments were collected with a modified Young grab sampler (0.04 m^2) that had to have been at least 75% full, else it was discarded for estimates of benthic community structure. Two "replicate" grab samples were collected at each station for benthic macroinfauna. Samples were sieved live on the ship through a 0.5 mm mesh, fixed in formalin, and stained with Rose Bengal.

Because only 28 of the 50 total stations were located strictly within the boundaries of the SAB, some of Cooksey et al.'s (2010) findings-based generalizations are influenced by data from the other 22 stations. Water depths ranged from 9–68 m, and coastal stations uniformly had euhaline waters with salinities near 35, bottom temperatures of 6–24°C, and high concentrations of dissolved oxygen. Waters were only weakly stratified during the sampling period. All the coastal stations were >80% sand by grain size weight, most over 90% and <5% silt-clay. Stations at shelf-break depths had the highest organic carbon content, probably related to intrusions of nutrient-rich waters that promote higher levels of water-column primary productivity. Shallower stations had an average of only 3.5 mg/g TOC, characteristically low as found by many other investigators. Coastal ocean sediments were relatively uncontaminated at low background levels, with very low concentrations of pesticides, herbicides, PCBs, and PAHs. Only a few stations had mildly elevated metal concentrations (cadmium, silver, arsenic).

Cooksey et al. (2010) were able to identify 313 of the 462 total different organisms collected to the species level in their 50-station coastal waters sample set. Most of these were polychaete worms, 47% by taxa and also 47% by abundance. Crustaceans were the next most dominant taxon (28% by taxa, 30% by abundance), mostly amphipods with several shrimps, ostracods, isopods, and cumaceans. Mollusks were the third dominant taxon (17% by taxa, 9% by abundance), mostly bivalves and gastropod snails, with Echinoderms fourth (2% by taxa, 2% by abundance), with a nearly even mix of brittlestars, sea stars, urchins, and sea cucumbers. By comparison, 948 different taxa were collected in their 746 estuarine sampling sites in the region, but per unit sampling effort (# taxa per grab sample of 0.04 m^2), almost twice as many taxa were found offshore. To re-emphasize the taxonomic difficulties typically encountered in sampling the soft-bottom benthos, these experts were able to identify only 545 of these 948 taxa to species. Thus the offshore benthic community is much more diverse than the estuarine community, but it is not possible to say by how much with any high degree of accuracy because of the species identification issues. Both inshore and offshore were heavily dominated by polychaete worms,

however, accounting for 37% and 47% of the total identifiable taxa found with a grab sampler in the estuarine and coastal waters, respectively.

With regard to abundance, Cooksey et al. (2010) found no identifiable trends with latitude or with water depth at their 50 offshore coastal stations, despite the fact that Hyland et al. (2006) had earlier found large differences with depth in offshore Georgia, where inner- and middle-shelf stations had about three times as many infauna as outer-shelf stations. Again, the lack of abundance patterns described by Cooksey et al. (2010) was based on the entire 50-sample set, so direct comparisons of abundance trends found within the smaller, restricted area (Georgia waters) is tenuous. By examination of their 50-station offshore sampling map (their Figure 2.1.1), it would appear that only seven stations were collected offshore Georgia. Given the high variability in abundance typically encountered with replicate grab samplers and so few stations in the same coastal area, it is neither unusual nor surprising that they found no similar trends. All 50 of the offshore stations contained infauna, with densities ranging from 275 to 23,650 organisms/m^2. Because the sampling unit was 0.04 m^2, this means that they found anywhere from 11 to 946 organisms per grab sample, an almost three orders of magnitude difference from station-to-station. These abundances are about the same as found in Georgia earlier by Hyland et al. (2006). Interestingly, the densities encountered at their 746 estuarine stations ranged over almost six orders of magnitude, from 0 to 103,350/m^2. The most commonly occurring species or taxa in the offshore samples are listed in Cooksey et al. (2010; Table 3.4.3) with five of the top ten being polychaetes. Over 90% of the 50 offshore stations sampled had infaunal densities exceeding 635 organisms/m^2, and over 50% had densities exceeding 2,350 organisms/m^2.

Species richness was calculated by Cooksey et al. (2010) as number of taxa per grab sample for their calculations of H' biodiversity. Thus their "species" richness ranged from 10 to 114 taxa per grab sample at the 50 stations, averaging 38 taxa per grab, with a total of 462 taxa found in the offshore survey. In comparison, the estuarine average of 16 taxa per grab was less than half that found offshore, illustrating the higher biodiversity of offshore benthic communities, being highest in the deeper waters of the shelf. No non-indigenous species were found offshore. Furthermore, none of the offshore sites in the SAB showed any degree of degradation with respect to contaminants or other measures of habitat quality. All stations were regarded as subject to the normal suite of environmental forcing functions that determine benthic community structure (Figure 6.1).

6.2.6.2 Slope Macrobenthic Communities

Cutler (1975) sampled 197 deep stations (150–2,500 m) with trawls and dredges off Cape Hatteras, North Carolina and south to below Cape Fear in South Carolina waters. Infaunal organisms were collected from two benthic taxa (sipunculan "peanut" worms and worm-like pogonophorans) to establish whether there was a zoogeographical barrier on the continental slope in this sampling region. This study found evidence, based on similarities and differences in 27 different species' distributions in the region, of a "partially effective zoogeographical barrier around 34^{o}N latitude" that separated northern from more southern species. Because dispersal of these animals depends on reproductive release of larvae that do not migrate to or swim at the water's surface (they remain close to the ocean floor), Cutler (1975) speculated that bottom currents probably affect their dispersal, most notably those generated by the Gulf Stream or those in the southerly flowing Western Boundary Under Current.

Knott and Wendt (1985) state that there is a lack of information on macrobenthic community structure on the continental slope where polychaetes generally dominate everywhere. They were able to document a trend towards decreasing macrobenthos abundance with depth but no such trend for species diversity with depth. They suggest that the literature available then supported existence of a northern slope community somewhat distinct from the more southern portions of the slope in the South Atlantic Bight. Latitudinal changes in species composition were not as great as those that correlated with bathymetry. The zoogeographic "barrier" at 34°N was recognized, as was a seasonal component of change in the southern South Atlantic Bight shallow slope compared to less seasonality in the more northern slope region.

Blake et al. (1987) conducted a two-year sampling program on the slope and rise along four transects ranging from depths of 600–3,500 m off South Carolina and North Carolina. Box cores collected over 1,200 species, almost half of which had never been described before. They found higher species diversity at 600 m near the Charleston Bump and lowest at 3,000 m on the rise, with annelids (polychaete worms) dominating virtually everywhere.

Schaff et al. (1992) examined the macrobenthos and microbial communities of the continental slope (850 m deep) 177 km east of Charleston, South Carolina as part of a larger study in the Middle Atlantic, including an additional two sites off North Carolina at this same depth. Site I had lower rates of carbon flux (0.6 g C/m^2yr) than Sites II (20 g C/m^2yr) and III (>70 g C/m^2yr) off North Carolina. The bottom appeared to be current swept, with only arborescent foraminifera and burrow openings visible on the bottom. Mounds and pits occurred at densities of 1 and 7.9/m^2, respectively. Samples from these microhabitats were combined for reporting results of community inventories. Galatheid crabs and a variety of other burrowing, bioturbating megafauna (sipunculans and sea cucumbers) found in core samples were likely responsible for constructing these features. Other megafauna present at Site I included echinoids, eels, anemones, and rattail fishes. Four Ekman-style box cores were taken and analyzed at Site I (August/September 1988, June 1989, October 1989, and August 1990) using submersibles. The cores were retrieved to the surface and subcores taken for analysis of microbes and several other relevant parameters of interest. Two subcores for benthic infauna were collected from each box core, with the cores sliced vertically at 0–2, 2–5, 5–10, and 10–15 cm. The top two segments were sieved with a 0.063 mm mesh, the bottom two with a 0.300 mm mesh before preservation and processing. The hemipelagic sandy mud sediments at Site I consisted of 72% carbonate by weight and 1.2% TOC content. Microbial abundances in the uppermost 6 cm layer of sediment ranged generally from 0.3–2.5 x 10^9/ml sediment slurry and typically decreased with depth in the cores. Macrobenthic biomass (g wet wt/m^2 ± 1 SD) at Site I (7.19 ± 5.5) was not significantly different than at Site II, but both were more than 6X lower than the anomously high biomass found at Site III off Cape Hatteras. Sixty-seven percent of the macrobenthic animals were found in the 0–2 cm section of the sediment at Site I; only 7% occured deeper than 5 cm. The deeper-dwelling animals were oligochaetes and polychaete worms. Taxonomically, annelids dominated at all three sites, but were less dominant at Site I (only 42%), where coelenterates, mollusks, and arthropods comprised greater proportions of the community than at Sites II and III. Echinoderms, nemertean and sipunculan worms, and turbellarians occurred similarly at all three sites. Thirty-three polychaete species were collected at Site I, together representing 43% of the macrofauna. Polychaete diversity was similar at Sites I and II and much lower at Site III where infaunal abundance was very high (>55,000/m^2). Most of the polychaetes were subsurface deposit-feeders

at these depths. Interestingly, no filter-feeding polychaetes occurred at Site I, although some solitary filter-feeding corals were found there. There was a higher proportion of carnivorous polychaetes at Site I. Great differences found in the community structure of the benthic communities at these three sites could most likely be ascribed to differences in the effects of a variety of factors, mostly related to availability of food. These factors included carbon flux rates, sediment type, sedimentation rates, Gulf Stream-induced upwellings, and even mass-wasting processes. Although the three sites had significant differences in macrobenthos abundances, there were similarities in their microbial counts, polychaete species composition, and polychaete dominance and diversity patterns. Only polychaetes were identified to the species level in this study. In contrast to the homogeneous macrobenthic community structures found by Tenore (1985) at slope depths, the slope communities off North Carolina (including Site I off South Carolina) showed marked spatial heterogeneity with modest changes in latitude over distances of just 150 km. For comparative purposes, the comprehensive study by Aller et al. (2002) of benthic communities on the slope off North Carolina should be consulted. It is a model of the types of studies still needed to characterize slope environments in the South Atlantic Planning Area.

Brown (1991), using sample processing techniques described by Blake et al. (1985; 1987) and Maciolek et al. (1987a,b), measured the biomass of macrobenthos collected with a box corer at depths ranging from 583 to >2,000 m off South Carolina. A 0.300 mm mesh was used to screen sediments collected after they first passed through a 2.0 mm screen. There were no significant differences in wet weight biomass from 500–2,000 m, but there was a sharp drop, nearly an order of magnitude, in depths of 3,000–3,500 m, averaging from about 10–12 g/m^2 before dropping to about 0.8–1.0 g/m^2 in the deepest stations. Because so few stations were sampled to make AFDW biomass measurements, no comparisons of changes in standing stock biomass with depth were possible. However, along the 2,000 m isobath in the study area that extended from South Carolina northward off North Carolina, AFDW biomass was generally between 0.5 and 0.6 g/m^2. Despite their small individual sizes but because of their great abundances, most of the biomass was from polychaetes and other worms. Echinoderms, mostly brittle stars, dominated the biomass whenever they became abundant. These are among the first measurements of macrobenthic AFDW made in the deep sea.

6.2.6.3 Summary for Macrobenthic Communities

Macrobenthos sampling in the South Atlantic Planning Area began in the 1970s as doctoral dissertation projects in Georgia's nearshore coastal waters. Shelf-wide transect sampling with quantitative grabs was begun in the late 1970s with support from the BLM through Texas Instruments, Inc. as primary contractor for meio- and macrobenthos abundance, taxon characterization, and biomass determinations. These soft-bottom surveys found a normal meiobenthic community dominated by nematodes and benthic-dwelling copepods but a depauperate macrobenthic community (low abundances, low biomass, low diversity) that was dominated everywhere by fast-growing polychaete worms and a variety of small crustaceans, bivalves, gastropods, and other taxa of non-polychaete worms. These types of organisms are characteristic of physically dynamic habitats that undergo frequent disturbance events and that have relatively low inputs of organics, i.e., the coastal benthos is oligotrophic. These classic surveys are now over 35 years old, and it is likely that neither the samples themselves nor the raw data still exist in a retrievable electronic format. The published literature does not include raw data, only averages. Between then and now, the South Atlantic Planning Area has had

numerous storm events, hurricanes, and subsequent coastal floodings that have released vast amounts of organic materials and potentially toxic compounds into coastal waters of the South Atlantic Bight. In addition, several beach renourishment and dredging projects throughout the South Atlantic Planning Area have had high local impacts at borrow and dumping sites. A marine sanctuary (Gray's Reef) has been designated off the Georgia coast and now serves as a relatively unperturbed "control" site with which other portions of the sandy-bottom community in the South Atlantic Planning Area can be compared. Fortunately, state and federal agencies have commissioned various studies of benthos during this intervening time, generating a reasonably good and recent (early 2000s) inventory of soft-bottom benthic fauna at widely dispersed locations in the South Atlantic Planning Area. However, these more recent samplings have been insufficient in both spatial coverage and temporal frequency to adequately characterize gradients in benthic community structure across the shelf or with latitude along the shelf. Any such gradients identified from earlier samplings have likely changed over the intervening years. Broader-scale, long-term regular and standardized sampling programs are required to establish a baseline benthic community profile against which future impacts of resource development on the OCS can be assessed. All size-based components of the benthos (micro-, meio-, macro-, and mega-benthos) and all depth and distance-from-shore-defined habitats (inner, middle, outer shelf and slope) are grossly undersampled for such purposes.

6.2.7 Megabenthic Communities

Transect video surveys are done to capture evidence of the presence or relative abundance (e.g., # seen/transect length) of different types of large, highly motile organisms, many of which cannot be accurately identified to species without capture and direct examination of a specimen. Before portable video cameras became available, examination of photographic images (snapshots taken from above the bottom) were the basic means by which the distribution of megabenthic organisms was mapped (e.g., Wei and Rowe, 2009). These authors point out that the Global Positioning System and Geographic Information Systems software make it much easier to construct organism distribution maps and to correlate them with other characteristics of the environment.

6.2.7.1 Shelf Megabenthic Communities

Most studies of megabenthos in the South Atlantic Planning Area have been conducted as photographic video camera transect surveys conducted by oceanographic training programs ("Transects Program" in Project Oceanica) or by proprietary submersibles (Johnson Sea Link) and/or ROVs used to investigate areas of interest to state resource managers, particularly for fisheries management. These transects typically emphasize so-called "live bottoms" on the continental shelf and have minimal coverage of soft-bottom habitat in the South Atlantic Planning Area.

Because they are generally smaller than "live-bottom" fauna, the soft-bottom benthic organisms are not as visible in photographic/videocamera surveys, except for some annelids tube structures and bivalves siphons. Popenoe and Manheim (2001) summarized published and unpublished data from various bottom photographic surveys and from cruises by the US Navy NR-1 submersible in the Charleston Bump area. GRNMS is well characterized with color photographs in Gilligan's (1988) Sea Frontiers article. Megabenthic fish communities were examined from video footage made by submersible dives (Johnson Sea-Link) on the Charleston Bump and Blake Plateau by

Wieber (2008). The soft-sediment and coral rubble habitats on dives deeper than 740 m were both dominated by *Synaphobranchus* spp. and, in general, fish species diversity was twice as great over hard-bottoms than over soft-bottom sediments.

Wei and Rowe (2009) re-examined bottom pogo camera photos taken of large epibenthic megafauna off North Carolina in the 1960s using geo-referenced mapping methods. This study confirmed earlier estimates of faunal distribution and is important because it illustrates that modern mapping systems can be powerful tools for understanding where megafauna exist in the South Atlantic Planning Area. Perhaps someone will take on the immense task of bringing all available bottom photo data in the South Atlantic Planning Area together into a geo-referenced system that would be very useful to resource managers. Zajac (2008) echoes these sentiments with respect to seafloor landscape structure and macrobenthic biodiversity.

Jumars (2007) provides a review of the ecological role of a difficult-to-study group of shrimp-like small crustaceans called mysids. These animals tend to school and are best captured with epibenthic sledges. They move vertically from the sediment surface up into the water column, usually at night. Mysids are eaten by numerous predators, figuring prominently in the diets of small fishes in the 3–15 cm length category; they are ingested by invertebrates as well. Mysids eat a variety of meiofauna, microphytobenthos, and detritus as well as zooplankton, meaning they are omnivorous organisms that connect the benthos with the water column through the food web–a phenomenon Jumars calls "habitat coupling." The major problem with gaining a more complete understanding of the mysid taxon is our inability to sample their populations and obtain good measures of their abundance at different locations at different times. Acoustic methods may be most appropriate for making a reliable census of mysids on the continental shelf where they may have a much more important trophic role than can be determined at present. In addition to the Jumars review, the mysids known specifically from the South Atlantic Planning Area have been published by Heard et al. (2006). They present identification characteristics with comments on distribution and ecology of each of the eighteen species known to occur in the South Atlantic Bight. Most are epibenthic. Mysids are also known as "opossum shrimp" because females carry their eggs in a brood pouch prior to hatching. Again, mysids figure prominently in the diets of numerous fishes and invertebrates, thus forming a significant link between the seafloor and overlying waters.

Another difficult-to-sample group of organisms in the benthos of the South Atlantic Planning Area is the burrowing shrimps, the so-called mud and ghost shrimps, in the infraorder Thalassinidea. These animals construct burrows that can extend as deep as 2 m in the sediment, which makes them very elusive to most benthos sampling devices. The burrowing shrimps that live at water depths from inshore out to 200 m in the South Atlantic Planning Area have been reviewed taxonomically by Heard et al. (2007). It would not be unreasonable to characterize these animals as mega-bioturbators, with some species of *Callianassa* ghost shrimps re-working as much as 2.5 kg of sediment per square meter per day while feeding and burrowing. These animals filter-feed upon detrital material, scavange, and also ingest herbivorously. They may occur at densities of a few hundred per square meter in shallow coastal habitats. Approximately eight different species were known in the South Atlantic Bight before 1984, but the list has now grown to a total of fourteen species, each characterized morphologically with keys and comments about their ecology and distribution (Heard et al., 2007). These animals occur mostly

in intertidal and shallow subtidal areas and are eaten by stingrays and other bottom-feeding fishes like hake. Their impacts on benthic community structure and biogeochemical properties of sediments is likely very large but very incompletely studied and/or understood.

Although they emphasized characterization of the fauna inhabiting hard-bottom substrates in the inner, middle, and outer shelf, Wenner et al. (1983) used a modified Smith-McIntyre grab to collect benthic invertebrates at three outer-shelf stations (41–70 m depths). They sieved the sediments from five replicate samples with a 1.0 mm mesh. They pooled the data for their suction sampler and grab sampler for winter (January to March 1980) and for summer (August to September 1980) collections. Most abundant were polychaetes, amphipods, and an echinoderm. Winter collections from the outer shelf were unique in that no single species was represented by more than 50 individuals at a station, perhaps because the grab sampler used was much less efficient on hard substrates. One serpulid polychaete, *Filograna implexa*, was very abundant in the samples at all three outer shelf stations. Clear from this study is the demonstration of higher species diversity on hard substrates compared to soft-bottoms, a likely result of greater habitat complexity and existence of numerous microhabitats on hard bottoms. Elizabeth and Charlie Wenner and their colleagues have sampled large epibenthic faunal communities using trawls pulled over large areas of the bottom. These organisms are generally not collected with sediment corers and include various crabs, shrimps, and stomatopods, including the golden crab (*Geryon fenneri*) that has harvest potential in the South Atlantic Planning Area (Wenner et al., 1987; Wenner and Barrans, 1990). They have also examined factors that help transport penaeid shrimps, especially the white shrimp, *Litopenaeus setiferus*, from offshore spawning grounds into estuaries of the South Atlantic Planning Area (Wenner et al., 2005).

Wenner and Read (1982) sampled epibenthic crustaceans with a trawl at 476 stations throughout the South Atlantic Planning Area from 1973 to 1977. Six depths ranges (9–18, 19–27, 28–55, 56–110, 111–183, and 184–366 m) were sampled with the trawl that had a 1.3–cm-mesh collecting bag. The trawl was pulled at 5–6 knots but was equipped with devices that held it slightly above the bottom to prevent snagging. For this reason the authors suggest that it probably under sampled the epibenthic community compared to trawls that actually dig partially into the bottom as they collect. Nonetheless, they collected 184 species of decapod crustaceans (shrimp, crab, lobster), with ten dominants comprising over 70% of the total number of individuals collected. Penaeid shrimps comprised 42% of the collection, while portuniid crabs comprised 11%. Winter and spring collections contained the fewest species, with more found in summer and fall. The deepest stations sampled did not contain any of the ten most abundant species in the survey. *Sicyiona brevirostris*, the rock shrimp, was the most abundant organism collected, occurring in 31% of the 476 total stations sampled. Ignoring any year-to-year variability that may be present in these communities, each of the dominants was most abundant in specific depth strata at specific times of year. Not all strata were sampled in the same season in each year. Cluster analysis of the data found three cohesive species groups: inner shelf, middle to outer shelf, and upper slope. Certain species were usually collected at the same time in the same depths (constancy and fidelity). Diversity (H') showed little variation with season or depth. The greatest numbers of individuals and species occurred at depths of less than 100 m. Only a few species were relatively abundant.

Arnold (1995; 2000) provides information on the calico scallop (*Argopecten gibbus*) fishery that exists mostly on the middle shelf off northern Florida. Concern is expressed for sustainability of the fishery given the tendency for over-exploitation and the potential for damage to the fishing grounds where the scallop is found. Trawls not only impact the bottom but also collect a considerable amount of incidental by-catch.

6.2.7.2 Slope Megabenthic Communities

Wenner and Barans (2001) examined the upper- and middle-continental slope on the north side of the Charleston Bump (185–220 m depths) from a submersible to characterize benthic habitats used by fish and sessile invertebrate communities–coral mounds, high- and low-relief features, and cohesive muds. They noted numerous burrows in the soft sediments that were made by the tilefish, *Lopholatilus chamaeleonticeps*.

Mills et al. (2005) made surveys from a submersible of the megafauna at 2,000 m on a methane hydrate seep on the Blake Ridge Diapir about 320 km off Charleston, South Carolina. The dominant megafauna there were vesicomyid clams and mussels. These bivalves derive their nutrition from bacteria that live in their gills symbiotically. The bacteria grow in a chemoautotrophic fashion, obtaining their energy from methane and/or sulfides emanating from the seep. There was evidence of "massive mortalities" of the clams at the site, possibly due to parasitic infections rather than to any changes in the supply of sulfides coming from the seep.

Analysis of camera transects along the bottom on the continental slope off Cape Hatteras, North Carolina were subjected to several classification/comparison/clustering schemes using reciprocal averaging ordination by Hecker (1994). No similar study was done in the South Atlantic Planning Area.

6.2.7.3 Summary for Megabenthic Communities

The largest members of the soft-bottom epibenthic community are motile crustaceans, slow-moving gastropod snails, sea stars, urchins, and brittlestars that have not been quantified in any systematic way in the South Atlantic Planning Area. There is no regular assessment program in existence for characterizing megabenthic fauna in the South Atlantic Planning Area. Surveys have been opportunistic, sporadic, and localized. Most have been conducted for purposes related to resource development or commercial harvests and have focused on hard- or live-bottoms rather than soft-bottom habitats.

6.2.8 Benthic Processes

Compared to offshore, deep-sea habitats, the coastal sea floor is close enough to the water surface to interact in numerous ways directly with the overlying water column that supplies the bottom with particulate organic matter. Benthic-pelagic coupling is thus a significant role for the benthos in coastal shelf waters as it receives this detrital rain. As this material is oxidized through respiration, its organic content is transformed through incorporation into the food web or remineralized into essential nutrients that fuel primary production. Benthic organisms participate either directly in these processes or indirectly by facilitating them through their burrowing or general bioturbating activities. All of these processes, however, require an organic, carbon-based substrate (food supply) and are typically rate-limited by temperature. Benthic process studies are few and far between in the South Atlantic Planning Area, so some nearby studies are cited as

examples of the kinds of process-related work that are needed. For example, Aller et al. (2002) looked at the carbon supply from the shelf to the continental slope of North Carolina. However, no similar study has been done on the continental slope anywhere on the South Atlantic Planning Area.

One of the few new research projects that involve the sediment-water interface in Georgia's coastal waters is reported by Savidge et al. (2008). This is the BOTTOMS-UP Project, an observatory 65 km east of St. Catherine's Island, Georgia in 27 m depth, or a Synoptic SAB Offshore Observational Network that is focused on sediment dynamics. They track sand ripple migrations and measure photosynthetically active radiation (PAR) continuously in situ. This paper shows how, in shallow shelves with a high area-to-volume ratio, the seabed's importance increases with respect to pore-water solute and particulate exchange across the sediment-water interface. Storm-driven alterations change these dynamics, and changes can persist for a long time. Their study suggests the need for long-term observations of sediment-water exchanges.

6.2.8.1 Sediment Respiration

Benthic communities in a given area of the sediment, along with their associated bacteria, can be viewed and studied as a pseudo-organism itself that undertakes many of the same metabolic processes that individual organisms do. Dissolved oxygen consumption (= uptake) by the seabed, or sediment respiration, has been measured by placing a small chamber over the bottom and tracking changes in the concentration of dissolved oxygen inside the enclosure using oxygen electrodes. Some of the respiration is due to uptake by the bacteria, some to the benthic fauna, and some due to simple chemical oxidation reactions that operate independent of organisms. It is more difficult to tease these components out if there are autotrophic algae or bacteria inside, but in depths where sunlight does not reach the bottom or by using a dark or opaque chamber, one can measure respiration of heterotrophic bacteria and benthos. Because it takes a known amount of O_2 to fuel the combustion of each gram of the organisms' organic carbon body content to produce energy (= metabolism), the amount of O_2 uptake can be equated to and expressed in terms of C uptake or utilization per unit area of sediment surface over short time periods (usually hours extrapolated to a full 24-h day). Aerobic metabolism can be considered as the opposite of photosynthesis, a process during which O_2 is actually produced by autotrophic organisms. Respiration, then is simply the reverse of photosynthesis, and is the process by which organic carbon is converted to CO_2 and energy that is used by the organism to stay alive and grow. Carbon budgets and cycling rates can be readily balanced if both productive and consumptive processes can be expressed in this common currency.

It has been found that a core of sediment carefully extracted intact from the sediment can be placed at in situ temperatures on board ship where it is more convenient to measure O_2 uptake rates. Because the short-term data obtained in shipboard cores are the same as those found in direct measurements made on the bottom itself, this is typically how sediment respiration rates are now measured.

To measure benthic community respiration, Smith (1973) took spade cores to a depth of 40 cm in sublittoral water of 7 m depth offshore from Sapelo Island, Georgia. The cores were incubated in chambers held at ambient temperatures with the overlying water stirred to prevent oxygen stratification over the surface of the core. Smith used Winkler titrations to measure changes in

oxygen concentration in the overlying water for one hour, and a formalin-killed control was run along with each month's measurements. To partition the total respiration measured, the macrobenthos retained on a 1 mm mesh was sorted and respiration of specimens was measured in glass respirometers using an O_2 electrode for each species. Bacterial respiration was measured by subtraction after killing the microbial community with antibiotics. The meiofauna/ microfauna/microflora's respiration was measured by subtraction from the other components measured. The portion unaccounted for was ascribed to sediment chemical oxygen demand (COD) based on uptake in the formalin-killed control chambers. The sediment was a fine sand and had a silt-clay fraction of 4–8%, with a carbon content ranging from 1.2 to 3.2% over the year. Community respiration ranged from 92.7 (July) to 53.9 ml $O_2/m^2/hr$ (January) and was positively correlated with temperature. The five most dominant macrofauna were measured individually each season, usually polychaetes (*Notomastus*, *Glycera*, *Nephthys*), an echinoid sand dollar (*Mellita*), an anthozoan (*Haliactus*), a burrowing shrimp (*Callianassa*), or a bivalve (*Abra*). Polychaetes and crustaceans accounted for 40–60% of total macrofaunal respiration, with mollusks and echinoderms most of the rest. Annual macrofaunal respiration was 12.1% (5–26% range) of total community respiration. Bacterial respiration was most prominent in warmer months and decreased greatly in winter but comprised 50.5% (30–60% range) of total annual community respiration, while the meiofaunal/microfaunal/microfloral fraction comprised 37.4% (25–58% range) of the total over the year. Chemical uptake accounted for 5–9% of total uptake. These measurements of total benthic community respiration were higher than those measured elsewhere in Long Island Sound, Puget Sound, and Woods Hole, possibly because of the high productivity of the Georgia coast. COD was higher than elsewhere as well, possibly because of the high porosity of the sand and relatively high amounts of reduced (not yet oxidized) organic matter in the sediment fabric. Bioturbation could also enhance rates of COD.

Hanson et al. (1981) also measured benthic respiration. Although no statistically significant trends were seen in the rates of total O_2 uptake, mean values suggested a trend for rates decreasing across the Georgia shelf and increasing from north to south. Chemical oxygen uptake was 25% of total O_2 uptake. Glucose flux (= uptake) at three depths in the sediment increased significantly across the shelf and in the N-S direction, with lower fluxes deeper in the sediment. Carbon oxidation (= CO_2 production) in the surface sediment decreased across the shelf and decreased also in the N-S direction at the shelf break. N-fixation and denitrification showed similar relationships in the 5–10 cm layer of the sediment.

Hopkinson and Wetzel (1982) measured benthic respiration and nutrient fluxes in the shallow coastal waters 3 km off Sapelo Island, Georgia at essentially the same place where Smith (1971; 1973) worked. They used acrylic hemispherical chambers on the bottom placed carefully by SCUBA divers and incorporated appropriate controls using dark-bottle incubations. They also measured sediment and pore-water nutrient profiles in undisturbed cores taken with a Reineck box corer. They found that dissolved nutrient concentrations were always higher in the top 25 cm of the cores than in the water just above the bottom. The basic pattern was regeneration of ammonium, nitrite, nitrate, and phosphate, uptake of dissolved organic nitrogen, and no net exchange of dissolved organic phosphorus with the overlying water. Benthic respiration was 2.9 g $O_2/m^2/d$, high compared to estuarine and marine environments in summer, and comparable to the rate of oxygen uptake found by Smith (1973). These results supported the suggestion by

Nixon (1981) that coastal systems appear to be sinks for nitrogen, making nitrogen the major limiting nutrient for primary production in coastal waters.

Benthic and pelagic metabolism and nutrient fluxes were measured on a hard-bottom site in Gray's Reef National Marine Sanctuary by Hopkinson et al. (1991). There was only a thin veneer of sand covering the site and, consequently, community respiration was dominated by the epibenthic fauna and flora, especially sponges and corals. They found that the benthic community was overall heterotrophic, consuming twice as much organic matter as was produced on the bottom. This is possible because of the import of organic matter from outside the study area. They suggest that most of the hard-bottom macrofauna is ungrazed by predators.

Using divers, Hopkinson (1985) deployed benthic respiration chambers 1.6 km off Sapelo Island, Georgia and measured uptake rates that varied with temperature, 0.6 g $C/m^2/d$ in January and 1.5 $gC/m^2/d$ in August. Smith (1971) had earlier measured benthic respiration rates of 1.2 g $C/m^2/d$ in summer (0.72 due to bacterial uptake) and 0.7 g $C/m^2/d$ in winter (0.21 due to bacterial uptake) at a site a few kilometers away from Hopkinson's study area. Hanson et al. (1981) measured a mean uptake rate of 0.32 g $C/m^2/d$ in June in deeper water on the inner shelf, with average rates of 0.23 in cores taken from the middle and outer shelf.

These few measurements have been combined with measures of carbon production in the water column in an attempt to determine whether this region of the South Atlantic Planning Area is a net producer or consumer of organic matter, but the issue is complex and unresolved, although the consensus of available data from other segments and portions of the shelf suggests that respiration exceeds primary production. A major problem has been trying to account for inputs of additional organic matter from rivers and marsh habitats, and the intermittent input of nutrient-rich intrusions from the Gulf Stream that fuel above-normal rates of primary production, some of which settles to the bottom to fuel the benthos, some of which is consumed by herbivores in the water column, and some of which is exported from the shelf area to the slope and beyond.

Additional measurements of benthic respiration by Meiggs et al. (2008) over a two-year period in the Satilla River and on the Georgia shelf outside the river mouth indicated increased respiration in the benthic chamber in the late summer and early fall months, with heterotrophy on the shelf being controlled by temperature, the supply of organic and inorganic substrates to the microbiota, and hydrology.

For additional information concerning the question of whether coastal waters export organic matter to deeper offshore basins, see Falkowski et al. (1988), Rowe et al. (1986), and Rowe (1987). Exchange of materials, dissolved and particulate, as well as living organisms occurs frequently between estuaries and coastal waters, but organismic flux rates are largely unknown (Dame and Allen, 1996).

6.2.8.2 Nutrient Regeneration/Remineralization

Aller (1982) elegantly describes how the chemical properties of sediments and the overlying water are affected by benthic fauna. Many reactions are involved in the decomposition of organic matter: aerobic respiration, nitrate reduction, manganese reduction, iron reduction, sulfate

reduction, methane production, and fermentation. These processes take place beneath the sediment surface on soft-bottoms where the distribution and activity of benthic organisms occurs. The macrobenthos influences these reactions variously by translocating and reworking sediment material between reaction zones as they feed, burrow, and construct tubes. Their fecal pellet formation creates biogeochemical microhabitats, their mucous secretions serve as reactive organic substrates in the sediments, and their feeding/metabolism impacts microbial populations. Rowe et al. (1975) held that regeneration of nutrients in sediments is the major factor supporting high rates of primary productivity on continental shelves. Carpenter and McCarthy (1978) suggested otherwise, that nutrients moved from deeper water at the shelf's edge offshore are more important. This lively debate includes a rebuttal from Rowe (1978). The question of whether continental shelves export carbon productivity offshore has been examined during the Shelf Edge Exchange Processes (SEEP) experiment (Rowe, 1986; 1987). He suggests that there is little export, with most phytoplankton-derived detritus used on the shelf, a conclusion also made by Falkowski et al. (1988). Although the SEEP study area was in the northeast US coastal margin off Long Island, NY, these types of questions are relevant to the South Atlantic Planning Area where considerable productivity occurs. Verity et al. (1993) suggested that shelf primary and secondary production is used within and recycled within the water column overlying the shelf of the South Atlantic Planning Area.

Hopkinson and Wetzel (1982) made direct in situ measurements of benthic oxygen uptake and fluxes of N and P between the bottom and the overlying water in the Georgia Bight. They used acrylic hemispheric chambers deployed by SCUBA divers in water only 3.7 m deep where the sediments were 96% fine sand. Dark-bottle controls were measured in situ as well. They also measured sediment and pore-water profiles from undisturbed cores collected from a Reineck box corer. Benthic respiration in July was 121 mg $O_2/m^2/h$. Nutrient exchange measured showed regeneration of ammonium, nitrite, nitrate, and phosphate, uptake of dissolved organic nitrogen, but no net exchange of dissolved organic phosphorus. Oxygen uptake by the sediment was equivalent to 1.1 g $C/m^2/d$. Substantial denitrification took place. Through extrapolation from short-term measurements to a 24-h basis, they estimated that 55% of water-column net primary production was mineralized by the benthic community at this site. They concluded, in agreement with other investigators, that denitrification was an important sink for fixed N in this coastal region, resulting in nitrogen being the major nutrient limiting primary production in coastal waters.

The highly permeable sands of the middle shelf at a depth of 27 m support denitrification rates that are sufficiently high enough to impact the global N budget if other shelves have similar rates. This supply of "new" N to the water column is useful for benthic primary producers as well as those in the water column above (Rao et al., 2007). More primary production generally increases the abundance of benthos, but no such connection was made or inferred in this study. The degree to which varying oxic and anoxic sediment conditions might impact their measurements requires further study, as do the bacterial communities involved in N transformations.

Vance-Harris and Ingall (2005) measured organic matter oxidation processes that use nitrate and/or nitrite as electron acceptors (= denitrification) in sediments collected with cores off the Georgia coast. Denitrification is the one of the largest sinks of oceanic N, with heterotrophic

microbial communities taking up the fixed N. They found very low rates of N production in coarse-grained sediments at a depth of 27 m, two orders lower than rates in muddy-bottom areas of the shelf. Their study was part of the SAB Synoptic Offshore Observational Network (SABSOON) and included samples from a depth of 40 m at the R4 Tower. They suggested that organic-poor sands cover 70% of the area. They found no evidence for many denitrification processes and only very low rates of heterotrophic denitrification, about two orders of magnitude lower than occurs in fine-grained shelf sediments. This process is what causes organic matter oxidation using nitrate or nitrite as electron acceptors rather than oxygen, i.e., it is an anaerobic process. These results are thus indicative of a sediment community that does not take up very much nitrogen by denitrification. Rather the area is largely oxic and, therefore, nitrification is the more dominant process in the area.

Jahnke et al. (2000), based on studies at 14–40 m depths on two transects across the shelf off Georgia and Florida, found that perhaps as much as 84% of the bottom area receives sufficient sunlight to promote photosynthesis by benthic microflora. Resuspension of sediments by storms reduces water transparency to varying degrees. As nutrients are released by the bacterial decomposition of organic matter inside the bottom sediments, the enriched pore water then moves upward to cross the sediment-water boundary layer. Marinelli et al. (1998) showed that this happens from depths of up to 10 cm in the sediment. Jahnke et al. (2000), however, suggested that the important role of sediment pore water in nutrient exchange processes with the overlying water, the net benthic flux of nutrients, still requires additional investigation because methods used to measure these fluxes may have flaws.

Jahnke et al. (2008) reported results from a seven-year time series of benthic chamber studies as part of the SABSOON program. Using benthic chambers to measure changes in oxygen concentration over time, they were able to measure rates of benthic primary production and light levels on the bottom at a depth of 27 m. They determined that light-limited photosynthetic benthic flora contribute significantly to oxygen production on the shelf and that ship-based measurements of PAR are biased toward making clear-water measurements. The long-term, in situ bottom measurements were sufficiently good that predictions of benthic primary productivity can be made based on light level measurements. Studies such as this further illustrate the importance of benthic processes in the coastal shelf ecosystem.

6.2.8.3 Food Web Integration

The trophic ecology of benthos is better known in shallow estuarine waters where these fauna provide sustenance for numerous estuarine-dependent predatory species as well as resident fauna. Shelf and slope water trophic dynamics are dominated by publications involving the prey of recreationally and commercially important species (e.g., Ross, 1982 on gray tilefish diets; see Chapter 7 for more examples).

Benthic suspension feeders, such as oysters, clams, and mussels, can alter the composition and dynamics of phytoplankton, especially in shallow waters, because they remove particles from the water. Corals and sponges also remove particulate matter from the water when it passes through and around them.

Because food for benthic fauna at shelf and slope depths arrives mostly as settling organic matter from above, measures of the TOC in the sediment can give an idea of how much benthic biomass (and diversity) might be able to be supported in an area on the sea floor. Generally, both biomass and diversity (species richness) decline as TOC concentrations decline, and TOC generally declines with increasing depth and distance from shore.

In a comparative study of the organic carbon content of sediments, Hyland et al. (2005) examined data from seven different coastal regions of the world, including the southeast US. If organic loading becomes too high in an area, the benthos will suffer reduced species richness, and these authors suggest that stress from organic loading will not be appreciable in areas having less than about 10 mg/g of sediment. At concentrations above 35 mg/g, excessive organic loading will have major impacts on species richness, primarily due to the increased biological oxygen demand imposed on the organic matter as microbial degradation occurs. In the southeast estuaries considered in the study, these same trends were seen, lending credence to the conceptual model proposed by Pearson and Rosenberg (1978). Some caution is necessary, however, because stress on benthic community structure can come from a variety of stressors (e.g., chemical contaminants), hence measures of TOC loading alone are not sufficient as an indicator for the health of soft-bottom benthic communities.

Pace et al. (1984), after an examination of information on food webs in coastal shelf waters, attempted to simulate the flow of energy in such habitats. Their simulation ties together a variety of food-web components (from primary producers to bacteria) and infers much about the connections between, for instance, the benthos and fish. What emerges from such an exercise is the realization that some components of the web are less or more dependent on other components (sinking zooplankton feeding pellets may not be so important to benthos productivity, for example) and that we need to revise many of our assumptions about the efficiency with which organic matter and energy are transferred between components of continental shelf food webs. Hofmann et al. (1981) had previously modeled the concentrations and vertical flux rates of zooplankton fecal pellets to the bottom in shallow areas like those on the southeast continental shelf. Almost all of the pellets produced get consumed and/or degrade before reaching the bottom, such that only about 0.02% of the daily primary production reaches the bottom. Once again, low rates of food input contribute to the "impoverished benthos" of the South Atlantic Planning Area.

6.2.8.4 Bioturbation and Bio-irrigation

Alongi (1985) performed a laboratory study showing that small-scale disturbance of surface sediments has little impact, if any, on infaunal or meiofaunal food webs. Brenchley (1981) experimentally demonstrated the effects of macrobenthos bioturbation on sediments as they feed, tunnel, and burrow, and also how these activities affect benthic community structure. Lohrer et al. (2004) experimentally manipulated the density of a heart urchin and found that its bioturbation activities were extremely important to the proper functioning of coastal benthic communities, especially remineralization. The notion that bioturbation may promote the resistance to invasive species in the benthos has been tested experimentally by Lohrer et al. (2008).

Diaz et al. (1994) took x-ray images of sediment profiles collected from the continental slope off Cape Hatteras, North Carolina. Benthic fauna there actively mixed the sediment to depths of 20 cm, with some burrowers going down to 30 cm depths. They suggested that, given lower rates of sediment deposition and accumulation that occur hundreds of kilometers south of Cape Hatteras, sediments on the continental slope there are not as thoroughly mixed or biologically active.

Levin et al. (1997) investigated the degree to which some polychaetes can re-work sediments as they construct tubes. Using stable isotope tracers they measured, in situ on the North Carolina continental slope, how quickly organic matter deposited on the sediment surface is transported to depth by maldanid polychaetes (a family-level taxon that builds tubes in soft sediments). Material was transported to depths of 10 cm or more into the sediment column over a 1.5-day period. Although the downward mixing/transport was not uniform–there were some smaller patches of intense mixing among less-mixed areas–they suggested that species whose life-style activities move sediments vertically could rapidly redistribute organic matter within the seabed. This would have a strong impact on the structure of benthic communities and the pace of biogeochemical processes in the sediments.

Gaston (1987) also examined animal-sediment relationships with polychaete worms that feed on/in/around soft-bottom sediments. Using simple gut-content analyses, he found that the proportions of surface-deposit feeders, carnivorous species, subsurface-deposit feeders, and sessile forms changed across the Middle Atlantic Bight shelf. The surface-deposit feeders were numerically dominant in most areas; however, they decreased in abundance moving deeper across the shelf until increasing in abundance at the shelf break where production of organic matter in the surface water was higher. Subsurface deposit feeders, on the other hand, steadily increased in abundance with depth across the shelf, having greatest abundances in fine-sediments that have higher amounts of organic carbon within them. Sessile species were found mostly in stable habitats that had less severe water movements. As is usually the case, the abundance and distribution of deposit-feeding polychaetes seems to be regulated by food resources that sink to the bottom as detritus. Woodin and Marinelli (1991) also describe how some "below-sediment deposit feeders" (= subsurface deposit feeders) modify the sedimentary habitats in which they live. Not only do worms biogenically modify the bottom, but also bivalves. Dauer (1983) describes the functional morphology of a surface deposit-feeding spionid polychaete, *Scolelepis squamata*, which is abundant in the South Atlantic Planning Area. His description of how this animal feeds brings clarity to our understanding of the important role that this particular feeding guild plays in cycling organic matter and carbon on soft-bottoms. A large variety of bottom fishes, shrimps, and crabs also disrupt the sediment surface with their daily activities.

6.2.9 Consensus Overview of the Literature on Soft-bottom Benthos

Tenore et al. (1978) concluded that Georgia's continental shelf has an impoverished benthic community dominated by small, mobile, surface-dwelling forms that can survive in the wind-induced and tidally scoured sediments. With lower biomass inshore, benthos at the middle and outer regions of the shelf are likely enhanced by nutrient enrichment from Gulf Stream intrusion-related biological productivity. Microbes, however, seem able to respond to all short-term nutrient fluctuations in this environment.

The Executive Summary of the BLM Benchmark Program (Volume I, 1979) about benthic community structure findings for micro-, meio-, and macrobenthos does not do justice to the extraordinary amount of information gathered by their investigators. They summarized as follows: "The dynamics of benthic community structure on the shelf varied with physical factors (temperature, depth, sediment texture) as well as with population factors (natality, mortality, recruitment, migration). Generally there was north-south homogeneity, with marked cross-shelf zonation, correlating with changes in hydrographic conditions and depth. In general, benthic species diversity was quite high in the study area. Although community assemblages were characteristic in the nearshore and mid/outer-shelf zones, no single meiofaunal, macroinfaunal, or invertebrate epifaunal species or small group of species could be considered to be dominant." The population factors mentioned in the Executive Summary quoted above (natality, mortality, recruitment, migration) were not addressed by the benthic ecologists who undertook the studies except in their discussions of what may be causing observed changes. All of these factors need to be addressed directly with many more studies before we can ascribe cause-effect to them, though undoubtedly they are all important to some degree relative to physical factors. The point is, they were not studied as part of the contracted benthic work in the BLM Benchmark program. An extensive review and evaluation of MMS's Outer Continental Shelf Environmental Studies Program (National Academy Press, 1992) provides many recommendations about the types of studies needed to assess impacts of future development activities. These will be emphasized in Section 6.2.10.

Knott and Wendt (1985) provided an extensive, excellent review of samples collected and studies made along the continental slope of the South Atlantic Planning Area. Their literature review includes maps (with coordinates) of these collections. Their review includes microbenthos, meiobenthos, and macrobenthos portions, already mentioned above as Knott and Wendt (1985) and was a useful starting point for this present review. Notably, they caution about comparing studies from investigators that have used different sampling and processing methods. This caution applies still.

The review article by Brooks et al. (2006) and the detailed report (Brooks et al., 2004) were written in response to the need for information about the impacts of sand mining on the OCS. Their extensive literature review of the western and eastern Gulf of Mexico and of the southern (North Carolina to Florida) Atlantic coast did not find any review paper that synthesized southern Atlantic fauna. What few papers they did find for the region are readily available and on hand. Their major findings for the east coast southern region in summary form were that:

- Polychaetes, bivalves, and archiannelids dominate the fauna, with *Spiophanes* and *Prionospio* the dominant genera, with *S. bombyx* listed in 44% of the surveys.
- Other polychaete genera (e.g., *Chone*, *Clymenella*, *Lumbrinereis*, *Nephtys*, *Nereis*, and *Tharyx*) were found in >10%, or at least 4 of the 32 east coast studies.
- Aricidea, Sabellariidae, and Syllidae were also commonly listed families of polychaetes.
- *Unicola irrorata*, an amphipod, was listed in 22% of the surveys, with several other genera listed.
- Dominant bivalve genera included *Ensis*, *Nucula*, *Tellina*, and *Astarte*.

- There was no consistent relationship between macrofauna abundance and water depth, but most studies found a decrease with depth on the shelf.
- Numerous sedimentary habitats exist, over a wide range of grain sizes, within which abundances, biomass, and diversity vary widely, as well as feeding types.
- Deposit or suspension feeders dominate the soft-bottom benthos.
- Abundances are highest in late spring and summer, but this varies with location.
- In sand mining areas, infaunal densities declined in areas impacted by dredging, but no consistent pattern of faunal response was found in the literature reviewed.
- Polychaetes and amphipod crustaceans colonize impact areas most rapidly, mollusks much more slowly.
- The southern Atlantic coast needs more study, and they recommend studies over narrower depth ranges with identifications to the species level if possible.
- Because different studies used different measures of biomass, for instance (wet compared wtih dry, with and without shell weights), inter-comparisons between studies are not possible.
- "Recovery" in impacted areas can occur within three months to three years.

Most noticeable for the South Atlantic Planning Area is the fact that so many of the descriptions of soft-bottom benthic communities have resulted from product-oriented studies about resource-acquisition concerns, rather than process-oriented studies, done under contracts by state agencies, private industry, and academic institutions, typically with well-trained staffs and/or in collaboration with academic scientists. This lack of curiosity-driven, process-oriented study (with few exceptions) reflects an early stage of maturity in our understanding of how this dynamic coastal ecosystem functions. Because it resides between estuaries on one side and the Gulf Stream on the other, the South Atlantic Planning Area benthos are in many respects a transitional community that responds rapidly to seasonal changes on either side–input of nutrients from both sides (river runoff and upwelling events), and wave disturbance events emanating from the Gulf Steam side or from the Gulf of Mexico and Caribbean (storms and hurricanes). Hence, the benthos may be in a perpetual transitional state of response, alternating between existence in or recovery from a disturbed state and existence in relatively short periods of environmental stability. There may be a gradient of disturbance intensity from high in shallow water to less as depth increases. The unique dynamic physical character of the South Atlantic Planning Area presents numerous opportunities to test both existing ecological theory and to generate new paradigms about the benthos and its linkages to other components there. Unlike the study of oceanic provinces far from shore, the proximity of the South Atlantic Planning Area to so many shore-based research facilities is a decided plus for such studies.

There does not seem to be anything unusual about the state of the benthos in the South Atlantic Planning Area. It is just as patchily distributed as benthos elsewhere, although the actual scales at which organisms in the different size classifications are patchy may be different. It has not been subjected to any large-scale major insults. The soft-bottom benthos of the region are diverse and robust, able to withstand disturbances and insults from small-scale man-made causes as well as intense storms that frequent the region. It has lower biomass than many other well-studied coastal margins, likely because the supply of organic matter to the bottom is less than in these

other areas. Soft-bottom community structure, however measured, always points to dominance by polychaetes and other annelids, bivalves, and crustaceans, and each taxon is exceedingly rich in its number of species. These taxa have short life histories and have adapted to the rapid changes that occur in the types and amounts of their food supply. Other major benthic taxa (e.g., echinoderms, nemerteans, etc.) are also well represented, but species diversity is generally much higher in areas with hard-bottom and reef communities.

The benthic communities on the continental slope of the South Atlantic Planning Area appear to be quite different from those on the slope farther north in the Mid-Atlantic. Although populated by many of the same taxa as exist elsewhere, their abundance and diversity is lower. This, again, is quite possibly due to the effects of scouring deep currents rather than a current structure that results in bringing deep nutrients to the surface as happens off the North Carolina coast. Hecker (1994) found unusually high densities of megafauna (benthic fishes, foram tubes, etc.) off Cape Hatteras, North Carolina where particulate matter input to the bottom is much higher than in the South Atlantic Planning Area at slope depths.

A large number of fish and other commercially important living resources depend on the benthos for nutrition and for spawning habitat. Despite its dynamic nature, the benthic communities of the South Atlantic Planning Area must be allowed to persist and thus continue to support these harvests. Management of protected areas may or may not mitigate threats from resource-acquisition activities (mining, trawling, dredging, and spills), and the existence of the Gray's Reef NMS provides additional opportunities for researching connections between harvested and non-harvested areas.

6.2.10 Potential Impacts of OCS Development on Soft-bottom Benthic Communities

There is a vast body of applicable literature on the impacts of offshore oil and gas field development and the extraction of sand and gravel resources for beach nourishment. Unfortunately, the soft-bottom benthos has often been somewhat neglected in the extent to which it has been studied in these venues, with a lack of long-term follow-up assessments as well as a lack of uniformity in the manner in which assessment studies have been performed. The offshore wind energy industry is, by comparison, relatively new, and the amount of information about its impacts is thus considerably less than exists for oil, gas, and mineral recovery operations.

6.2.10.1 Oil and Gas Exploration and Development

The biological impacts of exploration and offshore production of oil and natural gas have been studied extensively (e.g., Neff, 2005). It should be noted, however, that most field studies of offshore platform effects have been conducted in places other than the southeastern US coast (e.g., the North Sea, Baltic Sea, Gulf of Mexico, off southern California, Mediterranean Sea, etc.). Briefly stated, impacts on the soft-bottom benthos from platform release of drilling muds and cuttings of various types are generally confined to the near-field proximity of the drilling platform itself. Some drilling muds are more toxic than others and can contain varying amounts of metals and various types of lubricating substances. Some drilling mud components are more bioavailable than others and can also bioaccumulate to varying degrees. Plumes of fine-grained particles from drilling mud and cuttings released to offshore waters are rapidly diluted and disperse quickly. The larger-sized particles in the sediment plume settle to the bottom down-

current from the platform and, depending on their composition, form a mound of material that seldom extends more than a few hundreds of meters from the release point (depending on water depth and current velocity). Physical burial of surrounding benthic communities is the most deleterious impact of these sediment releases. Should the mound be thick, the sediments within it can become anoxic as bacterial degradation of its contained organic materials takes place. Re-oxygenation of the anoxic layer will occur slowly over time (months to years) as settlement of new benthic larvae eventually leads to an active, bioturbating, infaunal soft-bottom benthic community. Gray et al. (2002) review the effects of hypoxia and anoxia on marine organisms. Terlizzi et al. (2008) studied macrobenthos at different distances from platforms off Italy to test the hypothesis that there were no differences among the stations sampled with a Van Veen grab. There was so much station-to-station variability in abundance and species composition that they could not detect, either univariately or multivariately, any strong gradients of differences due to the presence of platform structures. They suggested that more stations would need to be sampled to detect any differences that may exist and bemoaned the poor state of taxonomic expertise for the fauna collected.

The foundations of oil and gas production platforms act as hard substrate that is attractive to all types of marine organisms, creating a fouling community with the potential for "reef effects" that diminish with distance from the structure (e.g., Page et al., 1999). Montagna et al. (2002) sampled meiofauna near and around oil platforms in the Gulf of Mexico and found that changes in their abundance and community composition were due more to reef effects than to any effects of contamination. Wilson-Ormond et al. (2000) found that the effects of proximity to gas-producing platforms on the reproductive status and parasite loads of larger types of motile epibenthic megafauna (e.g., shrimp, crabs, stomatopods, starfish, scallops) were overwhelmingly site-specific and highly variable. The ability to detect impacts of the offshore oil extraction industry was confounded as well in a study by Hernandez Arana et al. (2005), who found that variability in abundance of macroinfauna was greatly influence by natural disturbance events. They did, however, detect that abundances, biomass, and community composition of soft-bottom benthos were reduced near platforms compared with those at greater distances away from them.

Exploration and production platforms are usually located on soft-bottomed areas of the seabed, so the hard structure serves also as a settling habitat for the water-borne larvae of organisms that inhabit hard-bottom substrates as adults, the so-called meroplankton, many members of which are adapted for opportunistic lifestyles. The earliest settlers on foundation structures soon become replaced via succession when longer-lived organisms take over and dominate the biomass attached to the structure (Whomersley and Picken, 2003). The attached communities are typically dominated by bivalve mussels and sea anemones. Mussels and other bivalve species can have large impacts on benthic community structure (e.g., Norkko et al., 2001). These hard structures may also serve as stepping stones for larval forms that would otherwise die were it not for the presence of these "way stations." They may also serve as a means by which exotic or non-indigenous species gain entry into areas where they previously did not exist (Page et al., 2006; Glasby et al., 2007). The fouling community on platforms also releases organic material into the surrounding region of the seafloor, likely enhancing the biomass of the soft-bottom benthos there (Wolfson et al., 1979; Terlizzi et al., 2008).

The more commonly used drilling muds that are water-based (i.e., mixed with freshwater or seawater) have been found to have essentially no impacts on marine fauna and flora beyond the close proximity of the platforms. Barite and bentonite, two common minerals that are mixed into drilling muds to alter their density, can have impacts on larval forms of invertebrates and fishes, because their inert fine particles physically cause damage to sensitive tissues of these delicate organisms as they unavoidably contact, ingest, and pass the particles (Raimondi et al., 1997). Most laboratory bioassays conducted with drilling muds have tested macroscopic fauna (e.g., mysid crustaceans and polychaete worms), with very little field work on smaller organisms like meiofauna (e.g., Montagna and Harper, 1996). These authors found that nematode worms and harpacticoid copepods were more abundant around offshore platforms, likely influenced by organic enrichment in the vicinity. Meiofauna will colonize hard substrates as well (Atilla et al., 2003).

The most relevant work done with drilling mud that relates to the south Atlantic coastal area is that of Starczak et al. (1992), who tested barite's impact on a capitellid polychaete worm, *Mediomastus ambiseta*, that occurs extensively throughout the southeastern Atlantic region. They found that *Mediomastus* actively moved away from sediments that were highly enriched in barite, but that their ingestion, defecation, and growth rates were basically unaffected by the presence of barite in the test sediment. Maurer et al. (1981) found no change in the types (trophic guilds) of polychaetes that inhabited sediments around drilling rigs in northeastern coastal waters, though it is questionable whether a similar finding would occur in the warmer waters of the south Atlantic coast. Clearly more work needs to be done to test whether oil and gas recovery operations in the study area will have significant impacts, negative or positive, on soft-bottom benthos. The long-term impacts of such activity cannot be known in this region until a suitable baseline study of natural benthos fluctuations is conducted for the area.

In an assessment of the US Outer Continental Shelf Environmental Studies Program (National Academy Press, 1992), a working group assigned to benthic processes evaluated shortcomings of the program for oil and gas exploration activities and identified future information needs to MMS. The larger panel identified six major objectives of obtaining information for evaluating these activities: 1) characterization of major habitat types; 2) identification of representative species or major species groups in the area of interest; 3) description of seasonal patterns of distribution and abundance of representative species, e.g., spawning and feeding grounds; 4) acquisition of basic ecological information on key representative species, e.g., trophic relationships, habitat requirements, reproduction; 5) determination of basic information on factors that determine the likelihood that various populations and communities would be affected by OCS activities and the potential for their recovery; and 6) determination of potential effects of various agents of impact (e.g., spilled oil, operational discharges, noise, and other disturbances). The first three are needed prior to leasing, while the last three are needed in site-specific areas after leasing. It would be useful if early monitoring studies were able to establish natural rates of change of benthic communities and processes before undertaking oil and gas exploration and production. The panel found that MMS had expended resources sufficiently well to characterize major benthic habitats of the OCS such that detailed site-specific studies can be supported, although characterization of the spatial and temporal variability in continental shelf habitats is limited. They recommended that MMS focus on specific scientific hypotheses in developing its strategies for the acquisition of ecological information, resulting in less fragmented studies and

establishment of a better data management system. With respect to benthos, they recommended that future research focus on process-oriented programs designed to evaluate mechanisms that control the distribution of populations and communities, such as trophic links between benthic and pelagic communities. The research should be conducted at appropriate spatial and temporal scales, especially for determining the rates at which populations recover from disturbance, an area of study that has a critical lack of understanding at present. MMS should also expand cooperation with other organizations to help support long-term studies of reproductive ecology that are now developing data on population and community processes. This report was dated 1992, but it could just as easily have been dated 2011 because there is still a need for what the panel recommended nineteen years ago. As has happened in other offshore areas of the US, now that there is more interest in the energy potential that exists in the South Atlantic study area, it is likely that more collaborative studies with BOEM and among stake-holders will emerge in the near future.

6.2.10.2 Sand and Gravel Extraction

Sand and gravel extraction activities result in the removal of sediments from an offshore borrow site (dredging) and the placement of sand onshore in areas requiring build-up for attenuation of erosion (sometimes with temporary storage of sand in nearshore areas). Several beach nourishment projects using OCS borrow sites have been carried out in the nearshore portion of the South Atlantic Planning Area. Pre-dredging conditions are sometimes assessed at the actual dredging site but may be based on the pre-dredging conditions that exist at a similar, non-dredged site or sites. However, conditions at these other sites may not adequately reflect seasonal and inter-annual variability that can occur. Recovery is measured a variety of ways, including percent organic matter content of refilling sediments, organism abundances and species or taxon compositions, and others related to sediment grain size and bathymetry. Recovery to control conditions is often an ill-defined situation, because the typically variable baseline data in control sites may indicate that the control area is undergoing changes itself.

Baca and Lankford (1987) studied the impacts of beach nourishment on Myrtle Beach, South Carolina. They found no difference between control beaches and nourished sites (sampled with cores) during the first year of the three-year project. *Scololepis squamata* (Spionidae), *Donax*, *Haustorius*, and *Emerita* dominated the beach's benthic macrofauna, as expected. In a series of Technical Reports, Van Dolah et al. (2006) and Bergquist et al. (2009b) provide an overview of the estuarine and coastal habitats of South Carolina that summarizes what their state agency has found regarding dredging activities and other aspects of resource utilization. Their conclusion suggests that impacts have been low and good for the state's economy but that additional long-term, longitudinal study is necessary.

Lotspeich and Assoc. (1997) performed pre- and post-dredging benthic faunal surveys at a borrow site 11 km off Atlantic Beach, Florida at 11 stations in depths of 12–15 m. Polychaetes represented 35.3% of the benthic assemblage's numbers, mollusks comprised 33.6%, and arthropods 18.8%. Total number of taxa was dominated by polychaetes (51.6%), followed by arthropods (23.4%), and mollusks (16.1%). They found seasonal changes in species richness, abundance, and community structure in both the dredged and control sites that were greater than the spatial variation found within sites. Year-to-year variations in species richness and abundance was also found, being higher in June 1995 than in either February or September 1996,

in both the control and borrow sites. They found that, relative to the control site, gastropods disappeared following dredging and that bivalves and annelids declined, but crustaceans increased. Recovery took two years before species richness and abundance had returned to pre-dredging levels. A hurricane in 1996 complicated their ability to measure longer-term effects. Once again, this is strong evidence that soft-bottom communities in the South Atlantic study area are likely in a perpetual state of recovery from disturbance events and that basing full "recovery" on a shifting baseline or non-existent climax community is extremely difficult. Long-term baseline studies are clearly necessary and needed.

Jutte and Van Dolah (1999) conducted a study of a sand borrow project off Hilton Head Island, South Carolina. They sampled a dozen sites in a control area, taking ten Young grab samples at each site. Grab samples were subsampled once for sediment characteristic measurements and the rest of the sample was then screened through a 0.5 mm mesh. The two borrow sites (Joiner and Gaskins) underwent a variety of changes in benthic community structure, including the number of major taxa present, organism abundance, species present, and species diversity measurements that persisted for up to 17 months after dredging operations began. The control site remained amphipod-dominated while the two borrow sites switched from amphipod- to mollusk-dominated, presumably as a result of dredging operations. After two years of study, the control sites were still the same and the Joiner Bank was not dissimilar, but the Gaskin Banks area remained different. This was possibly because the sediment refilling rates were different in the two borrow sites and also because of a huge increase in the numbers of a gastropod, *Acteocina candei*, that showed up in the Gaskin Bank borrow site after dredging operations ceased there. Some other changes in benthos abundance were tentatively ascribed to predation by white shrimp. The two borrow sites were dredged at different times, however, and may simply have been at different stages of recovery. A major problem was the loss of the pre-dredging samples from the borrow sites. A complete list of the species collected included 138 taxa. The earlier studies of Van Dolah et al. (1992; 1993a; 1994a) in the Hilton Head area were mentioned prominently in this 1999 report for the first year post-operations. Follow-up studies were conducted the next year (26–29 months post-dredging; Jutte and Van Dolah, 2000), but were confounded by the effects of sediment transport and other changes that occurred from two hurricanes that passed by the area between the studies. The benthic community at the Joiner Banks borrow area was similar to the control study area two years after dredging operations ceased. The benthic community at the Gaskins Bank site was still different from both the control and Joiner Bank sites two years later but had higher abundances and diversity and actually most resembled the control site community that was studied earlier there in 1990 (Van Dolah et al., 1992). It was recommended that bathymetric surveys be continued in the dredged areas to determine when the area had finally refilled with sediment.

Van Dolah et al. (1993b) describe a MMS-funded effort to evaluate sand, gravel, and hard-bottom resources off the South Carolina coast. This entailed a literature review and a mapping effort to identify potential sand sources within the nearshore area (0–16 km). Van Dolah et al. (1998) made recommendations about future dredging activities based on results from six such projects in the central and southern portions of South Carolina. Repeated borrowing from previously dredged sites may not usually be possible because in-fill rates are quite variable (several years required) and the new deposition material often is too fine grained. This change of sediment type also causes benthic communities to change dramatically. In this particular case,

they suggest that, to better match sediment grain sizes, borrow sites be located on the nearshore depositional end of barrier islands and not too far offshore as was the case for the Gaskin Banks borrow site off Hilton Head Island. Given the relative water depth and proximal coastal location, these recommendations may be applicable only to the specific location.

The Myrtle Beach nourishment (40 km of beach with 4.5 million m^3 of sand) took place in three phases starting in the Cherry Grove area and progressing southward in the next two phases. The Cherry Grove borrow site (Phase I, see Jutte et al., 1999) was dredged with a hopper device that removed shallow linear furrows (grooves) of sediment and left relatively undisturbed sediment between furrows. The other borrow sites were dredged with a siphoning pipeline that basically removed sediments to much greater depths. For Phase II, Jutte et al. (2001a) report that quarterly benthic sampling started two years before dredging began at the Cane South borrow site and a reference site in summer 1997 and continued for a little over two years afterwards. Another borrow site, Cherry Grove, was also sampled because a different type of dredging was employed there (hopper versus the usual pipeline dredging method). The sampling plan consisted of ten Young grab samples randomly collected and sieved using a 0.5 mm mesh. Statistical comparisons were made on the ten most abundant taxa. Over 70,000 organisms were collected and identified as belonging to 508 different taxa. The ten most numerically and frequently sampled dominants comprised 60% of the collections: polychaetes, polygordid worms, a cumacean, and bivalves. Abundances of macrobenthos ranged from 1,950 to 17,000/m^2, with lowest densities in summer and fall. Time-series plots were generated; however, no error bars were included, so one cannot readily tell visually whether the differences seen are statistically significant. Species diversity did not differ greatly between reference and borrow sites and was often higher in the borrow site. Seasonal changes in abundance occurred at both sites as well, often accounting for greater changes in the benthic community than could be accounted for by the dredging activity or site-to-site differences. Polychaete worms made up half the community in both sites. Comparisons of polychaete abundances at the two sites through analysis of variance on transformed counts detected significant between-site differences but no significant date or date/site interactions during the monitoring period. Such a finding indicates that sampling variability was high in all aspects of the benthos sampling program–this is usually the case, however, and illustrates how difficult recovery is to detect even when a large number of replicate samples are collected on each sampling date. The authors suggested that dredging activities impacted the benthic community (abundance and numbers of species) for only a short period of time–recovery was rapid. There were differences in the infilling rates between hopper-dredged and pipeline-dredged sites as well, but additional studies were recommended to study the differences more completely.

Phase III of the nourishment project along the Grand Strand of Myrtle Beach used a borrow site off Surfside Beach/Garden City, South Carolina (Jutte et al., 2001b; 2002). The top 10 most abundant taxa made up 60% of the animals collected, with polychaetes, bivalves, and crustaceans prominent. They suggested that neither infaunal abundances nor numbers of species were impacted for a significant period of time post-dredging. Because a hopper dredge was used in Phase III as well, the investigators were able to conclude that although bathymetric/grade recovery was slow with both dredging techniques, biological recovery was faster with the hopper dredge.

The borrow site for the 2007 Folly Beach nourishment project was studied by Berquist et al. (2009) who used a sampling design similar to that used by Jutte and Van Dolah (1999). By making comparisons of benthos abundances and community species composition in both the dredged site and at a suitable reference site, they found that removal of 3.5 m of sand had major impacts on the benthos, with a shift to much finer sediments post-dredging during the natural fill-in process. They sampled the borrow area 6 months ahead of dredging, immediately before dredging, and then again 6 and 12 months post-dredging. Because the borrow area had filled back in with finer sediments than had been there originally, the infaunal benthic community had not recovered one year after dredging ceased. Bergquist et al. (2008; 2009a) describe other aspects of dredging/nourishment projects that involved assessments of benthic macrofauna impacts. A major problem with studying recovery of impacted communities is that there are never any long-term baseline, control, or parallel studies of similar areas with which benthic community structure can be compared post-dredging. The estimation of recovery is also itself an inexact science because soft-bottom benthos in relatively shallow coastal areas are typically always in some state of recovery from physically induced disturbance events, and the characteristic spatial and temporal patchiness of this community attests to the magnitude of this challenge. The soft-bottom benthos in the South Atlantic study area is not likely to ever reach its "climax" state, and community recovery will necessarily have to be assessed against a naturally ever-changing, event-driven community state. The community of benthic organisms that repopulates dredged areas may not attain the same structure (e.g., species numbers, abundances, biomass) that existed before dredging but may nonetheless function biogeochemically and biologically in support of living resources and other ecologically desirable attributes.

Zarillo et al. (2009) and Zarillo and Reidenauer (2008) conducted benthos studies on Florida's northeast coast to examine the potential impacts of utilizing offshore borrow sites for beach nourishment south of St. Augustine inlet. About 3.7 million yd^3 of sand were removed for the project. They used a Smith McIntyre grab to take 161 samples and sieved to 0.5 mm in five study areas during their 2005 and 2006 surveys. The first "identification" was into four different taxa (polychaetes, crustaceans, mollusks, and others), with identifications to the lowest practical taxonomic level after this initial sorting was done. Their definition of recovery was that the dredged area would return to similar species composition as existed in non-dredged areas nearby at some future point in time. This practical nuance was necessary due to the high incidence of storms and disturbance events in the region that keeps benthic communities in a non-steady state, and thus "recovery" can happen relatively quickly in such areas. The benthic community changed considerably following dredging, as compared to nearby control stations. Gastropods disappeared, crustaceans increased, and both annelids and bivalves declined. Species richness and organism abundance declined "dramatically" after dredging, probably because of hurricanes that passed by the area post-dredging. Two years after dredging, however, abundance and species richness of the benthic community had returned to pre-dredging levels.

Comprehensive studies and syntheses of dredging impacts from gravel extraction in the United Kingdom have been performed for MMS (e.g., Hitchcock et al., 2002; Oakwood Environmental Ltd., 1999); however, their results are not directly applicable to the sand-dominated habitats of the South Atlantic Planning Area. Seiderer and Newell (1999) investigated the relationship between particle-size composition of sediments and biological community structure off southeastern England. They found that, although sediment modification from marine aggregate

dredging activity typically results in arrival of new "opportunistic" species of benthos, there was no reason to require sediment restoration as a prerequisite criterion for re-establishment of biological communities comparable to those that occurred in the deposits prior to dredging. The implication here is that there are many factors involved besides sediment composition and particle-size distribution that affect or even control benthic community structure. This finding is consistent with findings in the South Atlantic Planning Area with recovery of sand borrow sites in that opportunistic (r-selected) species, especially polychaete worms and small crustacean amphipods, move into disturbed sites whose grain size has become finer after dredging activity ceased. Whether sediment characteristics are less important than other factors as controllers of benthic community structure in the South Atlantic Planning Area cannot be stated with certainty. Although borrow sites are selected more for sand-sized particles and not fines, granulometry studies are needed to examine the explicit role of sediment grain-size recovery in the disturbed area as part of the total benthic community recovery process.

Greene (2002) discusses findings from a number of dredging projects undertaken for beach nourishment that provide information on recovery rates after these types of activities. Every study was different, but what stands out is that the recovery process generally happens relatively quickly (months to years) rather than over decade-scale time periods. Brooks et al. (2006) found similar conclusions about recovery rates. Impacts include large decreases in abundance, and diversity and recovery can take anywhere from about 1 to 10 years, depending on whether just density and species composition or function is looked at. It is not well-known which factors are most important for the prediction of recovery rates in a given area; however, if a borrow area is populated mostly by r-selected, fast-growing, opportunistic species, then it is more likely that recovery will take place faster than if the area originally included k-selected, slow-growing species. Recovery, per se, is typically based on measures of organism abundance or biomass and various measures of diversity and community dominance. These diversity measures will always be problematic as long as taxonomic resolution (species identifications) remains elusive. The indices themselves are meaningful but, until we are able to make better identifications, especially of juvenile benthos, they will remain only marginally useful for determining whether communities have recovered after disturbance events such as dredging. Whether a "recovered" benthic community functions similarly to undisturbed communities also remains uncertain. The key question is: Do the new benthic communities fill the same or a quantitatively similar trophic function and provide the same energy transfer to higher trophic levels, as did the original communities? If they do not, then the potential for long-term and cumulative ecological impacts of sand dredging may be greater than predicted. The difficulty with such questions is that we currently know far too little about what drives benthic-pelagic coupling and the underlying biogeochemical/secondary productivity processes that support food webs on continental shelves. Much more study is required (Raffaelli et al., 2003; Marinelli and Williams, 2003).

6.2.10.3 Renewable Energy Development

Development of energy harvesting technology on the continental shelf in the South Atlantic Planning Area will impact the soft-bottom benthos in a variety of ways. Some impacts are well known whereas others have potential impacts that lack verification from field-based experience or research. Peterson and Malm (2006) and Michel et al. (2007) provided synthesis of these impacts on benthic communities, based on monitoring of existing offshore wind parks and other related studies. Most published studies of and experience with the impacts of offshore wind

development and/or operations come from northern European offshore habitats that are vastly different from the South Atlantic Planning Area, both in physical and biological settings. Using such literature to inform managers about potential impacts is therefore fraught with uncertainty derived from making necessary, but untested, extrapolations and assumptions. The following narrative must serve primarily as a guideline because of these limitations.

A comprehensive review of ecological research on offshore wind energy development was compiled by Zucco et al. (2006). A chapter in their document by Meissner and Sordyl (2006) is a literature review of research done with respect to benthic habitats and communities. They identified noise and vibration, temperature, electromagnetic fields, disturbance, and contaminants as potentially having impacts, but most of the suspected problems with these factors are derived through analogy or modeling approaches. That is, the studies cited are either theoretical in nature or inadequately or incompletely address the issues. They state that relevant studies for the effects of wind parks on benthos are "quite limited." They included literature derived from studies of other offshore industries (e.g., oil and gas, telecommunications, marine aggregate extraction). At the time of their report, they were able to find information on benthos from pre- and post-construction phases on only three wind parks in Denmark, one each in Sweden and Ireland, and two in the UK

The South Atlantic Fishery Management Council (draft only, SAFMC, 2008) expressed concerns for benthos with regard to energy-related natural resource development in the region. They specifically mention reef habitat (mostly for its value as spawning and essential fish habitat) as an area of concern for disruption by sediment disturbances that occur during construction and cabling activities that occur in virtually all energy development projects in the OCS. Bottom disturbance during construction, sediment suspension, pile driving noise, habitat loss from emplacement of foundations and cables, habitat disturbance during cable laying, introduction of hard substrate, and scour are mentioned for the construction phase. Operational sound and vibration, antifouling contaminants, and introduction of new communities to the area from fouling organisms are mentioned as of concern during the operation phase of these facilities. The SAFMC document clearly attempts to express generic, all-inclusive concerns so that virtually any type of activity licensed in the offshore marine environment must take essential fish habitat as an entity of concern.

Concerns emerging from an examination of other available literature include some that can have long-lasting direct impacts (e.g., habitat loss from sediment removal, noise and vibration, or release of contaminants) and others that are probably important only on a small, local scale and may recover relatively quickly (e.g., sediment disturbance during cable laying, hard substrate additions). Other impacts may occur only indirectly as a consequence of physical alterations to the habitat. Some of these impacts are known to occur, whereas others can only be surmised as to their importance and spatial scales. There are considerable gaps in our knowledge and research base about most of these impacts, whether known or potential. These are listed below.

Known Direct Impacts to Soft-bottom Benthos:

Negative Effects:

- Digging, dredging, water jet trenching, removal/suspension/burial of fauna during cable laying activities and foundation emplacements, and cable servicing activities
- Burial of fauna by settling sediments suspended by trenching activities via decreased densities and reduced biodiversity, also fouling the feeding mechanisms of suspension feeders
- "Reef effects" and "Halo effects" as newly attracted predators forage adjacent to hard structures
- Loss of soft-sediment habitat, replacement with hard or modified substratum
- Shading effects of towers on benthic microalgae on surrounding sediment surface
- Hydrodynamic changes in current flow around hard structures that may alter feeding modes of epibenthic feeders and surface- and sub-surface deposit feeders and also alter grain size distribution and organic content of affected sediments
- Creation of unauthorized construction debris fields around wind turbine structures
- Chemical contamination of sediments around/downcurrent of structures
- Habitat fragmentation
- Structures act as fish aggregation/attraction devices, with increased boat traffic and the negative impacts of increased recreational activities
- Tower lights that attract plankton and their predators

Positive Effects:

- Formation of fouling communities on foundation structures where none existed before, hard-bottom habitat created, biodiversity increases, biomass increases
- Increased organic matter input to sediment from fouling communities
- Lack of trawling, if prohibited in vicinity of towers, reduces physical disturbance of sediments
- Area may become a *de facto* Marine Protected Area
- Increased predator abundance may promote biodiversity in an area.

Possible, Mostly Unstudied, Effects:

- Less or more visitation by fishes and marine mammals (potential benthic predators), more benthos
- Decreased communication or changed behavior due to increases in noise and vibrations, less efficient foraging by epibenthic predators (e.g., smaller or fewer shrimp and flounder)
- Electromagnetic forces that may affect organism behavior, feeding, reproduction, survival
- Sediment heating by transmission lines/cables resulting in increased metabolic activities of benthos and microbial community
- Hard structures becoming stepping stones for invasive species' habitat expansion
- Cathodic fouling preventive measures that may alter settlement of pelagic larvae to benthos
- Turbine noise altering settlement of pelagic larvae to benthos

Updates to the review by Michel et al. (2007) by "pathway" of exposure to soft-bottom benthic communities are summarized below.

Noise and Vibration

With so little research conducted on noise and vibration resulting from construction activity and operation of offshore wind energy projects, most reviews conclude that apparently these factors are not regarded as having a significant impact on benthic organisms. Several sources of noise have been identified and measured with >200 decibels (dB) (e.g., large vessels in deep water, small vessels in shallow water, air guns used in geophysical surveys, explosives, pile driving) and >145 but <200 dB (e.g., drilling, trenching, turbine noise). It is suggested that wind turbine operational noise has the lowest potential for environmental effects, and that avoidance might be the most common response to underwater noise. Because the benthos is predominantly non-motile, avoidance is probably not a common response to underwater noise.

Several recent studies have been conducted in Australian waters and elsewhere with the planktonic or pelagic larvae of invertebrates and fishes in regard to their noise recognition abilities (Milius, 2011). These studies have demonstrated that larval reef fishes that can be widely dispersed recruit back to their natal reef, being attracted by reef noise. Experimental manipulations using light traps and pre-recorded sound suggest that reef organisms, like snapping shrimp and fish, make noises that are readily detected by larvae and act as a cue for settlement of reef fish larvae (Tolimieri et al., 2000; Simpson et al., 2004; 2005; Mann et al., 2007) and possibly decapod crustacean larvae (Montgomery et al., 2006). Evidence for sound detection and orientation behavior in these organisms led to the hypothesis that invertebrate coral larvae might also demonstrate an auditory response to reef noise that could facilitate their finding suitable habitats for settlement and subsequent growth. Vermeij et al. (2010) conducted several experiments using free-swimming coral larvae inside containers and found that the larvae displayed directional movement, both horizontal and vertical, towards underwater speakers broadcasting reef noise. This is the first demonstration of an auditory response in organisms from the phylum Cnideria (jellyfish, anemones, hydroids, corals). Their experiments were conducted in such a manner that cues from photoreceptors, mechanoreceptors, and chemoreceptors were eliminated as responsible for the observed responses. These studies are extremely relevant to offshore wind energy development because the introduction of additional noise "pollution" to the marine environment from wind turbines might threaten the abilities of numerous benthic invertebrate and vertebrate marine larval forms to settle to the bottom successfully. Study of this phenomenon is needed.

Temperature Effects

Buried or surficial cables that transmit electricity produce heat, with greater increases closer to the cable. An increase in temperature can change the physicochemical properties of sediments by altering redox, oxygen, sulfide, and other chemical profiles as well as increase the activity of microbes. These changes can lead to anoxic conditions in the sediment. Unfortunately, no studies of these purported impacts have been conducted. Theoretical calculations of suspected heat output from buried cables indicate only moderate temperature increases on the order of only a few degrees Kelvin if buried a meter deep. Given the relatively small volumes of sediment that would surround buried cables, thermal effects could easily be relegated to insignificance for soft-bottom benthos. However, no studies have been done to support such a contention.

Koller et al. (2006) raises concerns about heating of the sediment from submerged cables and subsequent impacts on benthic fauna, but suggests that the wind park they studied for five years between 2001 and 2006 was benign, having had little environmental impact. The primary reasoning behind this opinion is that both the study and control sites underwent similar changes in fluctuations of benthic taxa and individuals, with some sites having higher numbers in 2006 than existed in earlier surveys.

Electromagnetic Fields (EMF)

Gill et al. (2005) extensively reviewed what is known about EMF, with emphasis on elasmobranches which are the fish most sensitive to EMF. However, there remains very little information available on this topic with respect to benthic marine invertebrates. Internal grids (inter-turbine cables) are usually alternating current lines that deliver power to a collection point for transmission of power to shore. Perfectly shielded submarine cables do not generate electric fields outside the cable.

The only published study to-date of EMF impacts on benthic organisms is the work of Bochert and Zettler (2004) who conducted a laboratory study using brown shrimp, *Crangon crangon*, a crab (*Rithropanopeus harrisii*), the edible mussel (*Mytilus edulis*), a flounder (*Plathichthys flesus*), and an isopod crustacean (*Saduria entomon*). For exposures of 1–3 months, survival in the test groups was the same or higher than in control groups. The mussel's gonad index showed no differences between test and control animals. Artificial magnetic fields used were considerably higher than occurred naturally at the location of the study (Rostock, Germany). Their findings will be difficult to compare with others for several reasons: differences in field strength tested, whether alternating or direct current power is transmitted (they generate different types of electromagnetic fields), and experimental conditions employed. Hydroids and guppies are the only two other aquatic organisms mentioned by the authors as having been tested elsewhere by other investigators. Because of such limited actual measurements, there is insufficient information to make reasonable statements about the possible effects of EMF on benthic marine invertebrates, but any effects would likely occur only close to the cables. Recently Normandeau (2011) examined the literature to summarize what is known about the effects of EMF on marine organisms. Although it has been shown that some elasmobranch fishes and other magnetosensitive species like the spiney lobster may react to the presence of electromagnetic fields, they felt it was difficult to draw conclusions about the ecological significance of EMF in the marine environment. They identified three major gaps for research about EMF effects: 1) immediate and long-term responses of marine organisms; 2) data on electrosensory and magnetosensory biology in marine organisms; and 3) more data on the natural history of potentially affected organisms. Because the soft-bottom benthos are overwhelmingly populated by invertebrates, it was informative to see only the case study of the spiny lobster, a priority species in the Gulf of Mexico, cited in their report. This is a species that undergoes migrations, and it is known that there are magnetosensitive components that form part of their navigational abilities. EMF could interfere with the spiny lobster's abilities to navigate by interfering with its magnetoreceptors. There are no other studies on invertebrates cited that might be relevant to benthic invertebrates in the South Atlantic study area. The authors state "No direct evidence of impacts to invertebrates from undersea cable EMFs exists."

Disturbance Impacts

Physical disturbance, damage, displacement, and removal usually occur during the construction and decommissioning phases (site preparation, foundation installation/removal, and cable grid installation/removal). Changes to benthic habitat and subsequent changes in benthic community composition will result from such disturbances, but they will likely occur locally and downcurrent of disturbance activities, i.e., near-field rather than remore- or far-field. Direct habitat loss from foundation emplacement or cable burial will occur in only a very small fraction of the area occupied by an offshore wind project. Therefore, impacts from habitat loss will be minimal. Sediment scour has been incompletely studied, whether near-field or far-field. Scour protection can be placed at the bases of turbines to reduce scour effects, although this will result in more direct habitat loss depending on the scale of such preventive measures. Scour pits are known to be colonized by benthic fauna that differ from those infauna found in the natural surrounding sediments. Once again, there is insufficient knowledge about disturbance effects of offshore wind energy projects on benthos to unequivocally state that effects would be confined to only a local scale, as most studies and environmental assessment suggest will be the case.

There is one study in the region that studied the effects of sediment disturbance after Hurricane Hugo hit Charleston, South Carolina in September 1989. Bell and Hall (1994) dove on 19 artificial reefs in depths of 10–33 m six weeks after the storm. In the hurricane's path, shallower reefs were moved by the storm, but the largest impact was due to deposition of muddy sediments that had arrived from land/nearshore. Mud burial, up to 65 cm depth, and subsequent resuspension over several years occurred. Sand also moved and buried reef structures. Troughs in sand ripples/waves were filled in with mud. Water turbidity increased, with loss of diver visibility and, by inference, decreased input of sunlight to the bottom. Only qualitative assessment of epibenthic invertebrate communities was possible. There was minimal impact to epibenthic communities and sessile invertebrates on most reef structures, although horizontal surfaces on one reef remained covered by 0.5 to 2 cm of mud one year after the storm. This removes usable hard surface as suitable habitat. Commonly found mollusks, echinoderms, small crabs, and polychaete worm tubes were encountered by divers less frequently four months following Hugo than before the storm. Eight months after the storm, benthic invertebrate species on two reefs in the storm path in 15–20 m depth appeared to be in pre-storm abundances, except where pockets of soft mud remained. There was no clear evidence of large-scale negative effects of Hugo on artificial reef biotic communities, but they concluded that long-term studies were needed to detect any longer-lasting effects on reefs. Thrush et al. (2004) address the issue of muddy waters from sediment input to coastal waters that can adversely affect biodiversity and function of coastal shelf communities.

Introduction of New Hard Substrate

Lemming et al. (2007) suggest that, based on experiences with Danish and British offshore wind parks, it is the introduction of hard substratum (foundations and scour protection with rocks) that has the greatest effect on benthos. The new fouling community on these hard surfaces increases biodiversity and biomass of benthos in the area and, when it matures, will also attract fishes. These were deemed to be positive effects; no negative effects concerning benthos were mentioned. Other scour-protection schemes that reduce flow around objects may also be appropriate, but their impacts on surrounding benthic communities will need to be studied.

Benthic species having planktonic larvae will likely be the first to colonize artificial hard substrates at an offshore wind facility. Succession of colonists will result in replacement of fast-growing species by those that have more competitive abilities for the space and food available on these structures. A fully developed fouling community will take about 3–4 years to develop and will be diverse and dense, with different species (fauna and flora) at different depths on the structures (vertical zonation). A very large literature exists on colonization rates of artificial reefs in the marine environment and generally indicate that communities develop that are similar to those that occur on natural reefs nearby. How reef development affects the surrounding area falls under the general topic of "reef effects." Sediments surrounding artificial reefs will change in grain size, organic matter content and, depending on the types of predators emanating from the reef, benthic species composition and density. There are only a few studies of how macro- and/or meiofaunal communities change with distance from artificial reefs and none that have examined how this dynamic changes over time. Wai (2009) and Cheung et al. (2009) provide the most recent overview of reef effects.

In perhaps the only benthos-related experimental study on the South Carolina shelf, Van Dolah et al. (1988) placed plates made of Plexiglass™ on the bottom to serve as hard-substrate onto which planktonic larvae of benthic organisms could settle. They tested the effects of substratum orientation, length of exposure, seasons, and proximity to natural hard-bottom habitat. Season had a greater effect on settlement than orientation or proximity to hard-bottom. Two different types of communities were established on the plates after a year in the water: colonial species dominated those plates that were placed over hard-bottom, and solitary species developed on plates emplaced over sand bottom. Thus proximity to hard-bottom habitat had the greater effect on fouling community development in this experiment, one of the only such studies performed in the South Atlantic Planning Area shelf environment.

Boehlert and Gill (2010) proposed that introduction of manmade structures into the marine environment will have the greatest impact on benthic habitats and ecosystems due to the structural changes that occur as well as changes to water circulation and currents. Addition of hard substratum to an area previously lacking it becomes colonized by a variety of sessile benthic organisms and motile macroinvertebrates (a fouling community) whose presence then attracts nektonic biomass and may act as stepping stones for invasive species (Wilhelmsson and Malm, 2008; Byrne O'Cleirigh Ltd., 2000). Predators associated with these artificial human-made "reefs" are known to forage on benthic invertebrates in adjacent soft-bottoms, although this may result in an increase in the number of prey species in the area, depending on spatial scales involved (e.g., Thrush et al., 2001; Langlois et al., 2005). Barros et al. (2001) selected three natural rocky and one artificial rocky reef to sample for soft-bottom macrobenthos at varying distances (1 to 11 m away) from these structures in Botany Bay, NSW, Australia. They found several differences in species composition, abundance and diversity that could be correlated with reef proximity but stressed that a manipulative approach is necessary to demonstrate the mechanisms by which such differences might accrue. Benthic assemblages close to reefs had greater spatial variability than those farther away. Sediment grain size was larger close to the reefs than farther away. Species were more abundant close to the reef than farther away, but syllid polychaete worms were more abundant farther from the reefs. They hypothesized that predation from fishes attracted to or living on the reefs had a greater impact on benthos close to the reefs, i.e., predation pressure was greater close to the reefs than at farther stations along the

transects sampled. Despite this study's rigorous experimental design, the differences found were highly variable due to differences found among different reefs, among transects within reefs, and among stations within transects within reefs. There were no consistent patterns related to reef proximity that held for all reefs examined.

Indirect Effects

If offshore wind parks become areas where trawling is prohibited, then one might expect benthos in the area to remain productive and serve as normal strong trophic links between the bottom and organisms that dwell in the overlying waters, including demersal fishes. Trawling severely disturbs the habitat used by soft-bottom organisms, especially those types of trawls that dig into the bottom sediments ahead of the trawl net itself. Impacts on the organisms range from direct mortality to lesser impacts such as simple displacement or disruption of detrital food availability. The loss of habitat structure from trawling has been shown to have negative effects on the biodiversity of soft-bottom benthos (Thrush et al., 2001).

Tingley (2003) describes the effects of offshore wind facilities on birds that, when killed, may just float away or sink to the bottom and influence the benthos in the area. Dead birds on the bottom would provide a new source of organic matter to benthic infauna or attract predators to the area that would not otherwise visit except for the presence of odor-trails from this avian biomass as it degrades on the bottom over time.

Bauer et al. (2008) conducted field surveys of bottom debris, including derelict fishing gear, at the Gray's Reef National Marine Sanctuary off the Georgia coast. Most debris was concentrated at the center of the sanctuary and was most frequently associated with ledges on the bottom rather than on other types of bottoms. If wind turbines attract fishermen, there will likely be an associated increase in the amount of anthropogenic debris falling to the bottom in these areas.

In summary, the known direct and indirect impacts of offshore wind energy development are likely to be site-specific and will depend on many factors such as sediment type, the natural disturbance regime from waves and storms, the type of infaunal community present, and the intensity, duration, and spatial scale of the wind energy development. Impacts are generally deemed greater and longer lasting on macrobenthic communities than on meio- or microbenthic communities primarily because macrobenthic organisms grow and reproduce more slowly. Megabenthic organisms are generally motile enough to move away from disturbance events.

6.2.11 Data Gaps in the State of Knowledge for Soft-bottom Benthic Communities with Regard to OCS Development

There are many gaps in our knowledge of soft-bottom benthic communities in the South Atlantic Planning Area. Much of our knowledge is based on decades-old surveys, and there is no reliable record of long-term trends in benthic community structure and seasonal dynamics in the area. A lack of standardized collecting and sample processing criteria makes inter-study comparisons tenuous at best. Taxonomic challenges are great for micro-, meio-, and macrobenthos, less so for megabenthos, hence measuring changes in biodiversity of these communities is premature at best. Research programs dedicated to understanding the relative importance of community structuring forces are needed, and these can be designed and achieved with stronger interactions

between government, private industry, and academic institutions. Broad areas of research needs for the South Atlantic Planning Area follow below.

6.2.11.1 Benthic Habitat Mapping

When any area of the ocean floor is designated for use, it is most helpful to have a detailed map of the area with habitat and sediment types and benthic communities noted along with bathymetric features. Which classifications may be most useful to managers depends on many extrinsic variables, but consistent definitions are essential (Costello, 2009). Very few large areas exist where resource managers have such information available, and the southeastern US coast is no exception. Recognizing this state of affairs, a theme session entitled "Sediment-Biota Interactions and Mapping Marine Habitats" was held at the ICES Annual Science Conference in Halifax, Nova Scotia, Canada, in 2008. Presentations were given on multiple uses of the seabed (e.g., aggregate extraction, dredging, fisheries, wind turbine facilities). Norji et al. (2009) report highlights from the meeting; talks included topics on various benthos mapping and sampling approaches, including acoustics. They note, however, that even these advanced technologies require ground-truth sampling to characterize habitats. One talk focused on ecosystem processes and sediment-biota interactions as regulators of community structure and biodiversity, a theme that resonates well with concerns for the potential impacts of wind energy development on continental margin benthos. Duly noted by the authors was the fact that "although the composition, abundance, and functionality of benthic communities are dependent on sediment character, the systematic role of sediments as regulators of the benthic communities is still elusive."

Zajac (2008) suggests that soft-sediment benthic landscapes (or "benthoscapes") are, in general, poorly understood for purposes of good stewardship. He calls for coordinated efforts to develop sea floor mapping technology, quantifying benthoscape structure, development of and integration of ecological theory for these systems, and making empirical studies towards these ends. The South Atlantic Planning Area would certainly qualify for such efforts.

By using high-resolution side-scan sonar, Ojeda et al. (2004) developed a surface map of the seafloor in Long Bay, South Carolina. The ability to produce such maps will make decisions about use of sand resources and impacts of dredging on benthic fauna much easier. The side-scan sonar images they collected were analyzed for texture and the textures were classified using a neural network. Of the 686 km^2 area imaged (at depths ranging from 6 to 14 m), surficial sand covered virtually all of it. Bathymetric highs were classified and corroborated by divers as sand bottom ridges (41% of the area surveyed), while flat areas were hard-bottoms (59%). Many more such detailed data are needed in the region.

6.2.11.2 Life History and Seasonal Dynamics of Benthic Fauna

Many of the data gaps identified for benthos of the South Atlantic Bight in the BLM Benchmark program (1979) remain. Many areas have still not been sampled adequately to describe extant communities. Few of the infaunal species have been sampled sufficiently to understand their life histories, reproductive biology, or feeding behaviors. Although the former CaroCoops ocean weather buoys (part of Carolinas RCOOS) are replaced approximately every six months to be cleaned, no study has been made of the fouling communities that might colonize these hard structures emplaced on the shelf. The continental slope communities are simply understudied.

Distributional patterns for most benthic fauna are unknown, as are the primary factors that affect benthos distributions and their variations. Microbenthic fauna are grossly understudied, especially the dynamic bacterial communities that are so important to this ecosystem. Benthic processes involving meiofauna have not been studied. There are no real long-term sampling programs for soft-bottom benthic fauna in the South Atlantic Planning Area. Even in shallow estuarine habitats where it is relatively easy to sample benthic communities on a regular basis with the same sampling methods over time, there are not enough time-series datasets in existence, with very few exceptions (e.g., a 30-year record in the Baruch database, long-term macrobenthos and meiobenthos studies in the North Inlet estuary, South Carolina). Repeated sampling within the GRNMS will be helpful in understanding the temporal (and spatial) dynamics of this community–a sustained effort of sufficient length there is not yet available for long-term management purposes.

6.2.11.3 Manipulative Experiments

Peterson (1993) illustrates how basic ecological tenets can be applied to examine environmental problems in coastal areas, emphasizing the importance of multi-species, multi-factor contexts. He also identifies several common fallacies in environmental assessment and advocates use of manipulative studies. Noticeably absent in this literature review are experimental studies conducted in shelf or slope waters. The review by Brooks et al. (2006) found the same lack of studies that can identify and elucidate fundamental controls on community structure, be they due to biotic or abiotic factors or an interacting blend of both. Quijon et al. (2008) experimentally manipulated the detrital food supply to macrobenthos in a 20 m deep soft-bottom fjord environment in Newfoundland. They found that inputs of organic matter were used rapidly with little impact on the diversity of the benthic community, suggesting that food supply alone may not have persistent effects on benthic community structure. This illustrates again how difficult it is to understand, much less predict, what factors are fundamentally more or even most important for structuring soft-bottom benthic communities.

6.2.11.4 Standardized Procedures for Field Assessments

Meissner and Sordyl (2006) concluded that detailed predictions about the impacts of offshore wind development on benthic communities cannot be made due to a lack of studies and the necessity of drawing conclusions by analogy. Local changes will dominate, especially with creation of artificial reefs as turbine foundations and scour protection devices are introduced to the environment. They consider impacts from noises and vibration and electromagnetic fields will not be of great significance, but that the effects of heat emission from power cables remains controversial. The need is great for fundamental research and long-term monitoring studies. They provide an overview of the so-called German Standards for Environmental Impact Assessments as they apply to offshore wind projects. Many of these standard requirements also make sense for the development of offshore wind facilities in the US and should be consulted by regulatory agencies. Zucco and Merck (2004) reached the same conclusion about the "large ecological research deficits on the effects of offshore wind parks on benthic habitats, their biocoenoses and on the fish fauna."

The Baltic Environmental Forum Group (2009) gives a good overview of concerns that should be monitored before and after an offshore wind energy project is built. For sampling the benthos, they recommend using Van Veen grab samplers and/or SCUBA cores, depending on depth of

emplacement. They also recommend that benthic biomass be measured as dry weight (g/m^2) and that statistical treatment of data include community analysis using PRIMER v6, a statistical package developed by Clarke and Gorley (2006). Clarke and Green (1988) and Clarke (1993) offer conceptual approaches for monitoring changes in community structure involving multivariate techniques. Underwood (1993) also recommends several ways to detect environmental impacts that may not be detectable using Before/After, Control/Impact sampling methods and how to optimize sampling at different spatial scales as well as recommendations on how to proceed when no data are available before a disturbance. In addition, Hewitt et al. (2005) also concluded that a multivariate approach was more successful than any of five diversity indices in defining changes in community structure because the information can be examined for changes in individual species or changes in biomass/size structure.

Michel et al. (2001) proposed numerous protocols for the development and design of biological monitoring of the impacts of offshore sand dredging operations on the continental shelf for the MMS Marine Minerals Program. The basic conceptual approach described therein involved measuring temporal and spatial changes to benthic communities as they might impact their secondary productivity and transfer of benthic biomass to higher trophic levels, specifically fishes. The sampling gear, processing methods, stratified random sampling design for assessing abundance, biomass, and community composition of benthos outlined in that report is appropriate for such purposes and dredging operations. Because sand dredging activities are so inherently different in scale and potential impact from most offshore wind development activities, these recommendations are not the most appropriate for, nor are they directly translatable to, monitoring the construction, operations, and decommissioning of offshore wind facilities. However, several individual components of the benthic sampling design proposed are appropriate and translatable, and these should be integral parts of any program designed to measure impacts of offshore wind projects.

6.2.11.5 Benthos Condition: Assessment and Community Change Metrics

An essential part of understanding whether human activities cause ecological impacts is a benthic sampling program optimally designed for such purposes. There are many references on the statistical efficiency or power of various designs to detect changes, but both Norris (1995) and Osenberg and Schmitt (1996) provide overviews of approaches to this problem that are particularly relevant to benthic communities. Norris (1995) calls for renewed efforts to develop appropriate multivariate change metrics so that we may enable predictions to be made about the future state of benthic communities subjected to various stressors. He also calls attention to the need for more international cooperation in this effort. Given that the US lags behind other countries in the development of offshore wind energy, there is much to learn based on the collective experiences of other countries. Osenberg and Schmitt (1996) critiques several types of field assessments that have been used in the past, including the Control-Impact and the Before-After-Control-Impact sampling designs. They also make clear the distinction between field assessments and manipulative field experiments, the latter having little to do with assessing changes. Manipulative experiments are best used to understand how systems function and the control processes involved. Their contention is that most field assessments are inadequate to the task and suggest that efforts towards making predictions a goal of environmental assessment are where we need to expend more effort.

Nickell et al. (2009), regarding benthic indicators for the impacts of a large cod farming operation in Scotland, suggest the use of several indices for data collected with Van Veen grab samplers. These include the AZTI's Marine Biotic Index, the Infaunal Trophic Index, and Margalef's D, a measure of species richness. They created a correlation matrix of theses biotic indices and several abiotic sediment measurements (e.g., particle size analysis, organic content, Eh redox values) to calculate Pearson's product-moment correlation coefficient, r. They also used Multidimensional Scaling with PRIMER version 5.2.9 (Clarke and Gorley, 2006). They employed some modeling procedures to determine impacts at different scales–near field and intermediate field. Unfortunately, they were unable to support use of any single universal or even just a few environmental variables that gave predictive information. Rather they found that the Pearson and Rosenberg (1978) paradigm of organic matter enrichment was followed, making it desirable to continue to monitor a range of traditionally measured parameters. This is not good news for future benthic studies on the continental margin; no critical meaningful types of data or indices or models were identified that might provide a short-cut for assessing environmental impacts on benthos in these regions of the ocean.

Sediment organic carbon content is an important indicator of potential food resources for benthic fauna. Carbon content, however, can sometimes include inorganic (non-food) forms, especially in foram-rich sediments. Milliman (1994) suggests that, because of the problem with calcium carbonate carbon interference in measures of organic C in sediments, organic nitrogen can be used as a reliable indicator of their organic content. The relation between mineralogy, grain size and organic content must be better delineated, since mineralogy may be a more important determinant than grain size. All of these parameters can be extremely important determinants of benthic community structure.

Warwick (1993) suggested that it may be more pragmatic to work at high taxonomic levels and more easily detect biotic community responses to human perturbations above the "noise" of natural variability. Somerfield and Clarke (1995) and Terlizzi et al. (2003) also make a case for using higher-level taxonomic identification of organisms for detecting anthropogenic impacts. Warwick and Clarke (1991) categorized various methods used for analyzing changes in community structure under three general headings: univariate, graphical/ distributional, and multivariate. When applying these methods to benthic community structure, they concluded that: 1) similarity between times and sites based on their univariate or graphical/ distributional properties is different from their clustering in multivariate analyses; 2) species-dependent (multivariate) methods are more sensitive than species-independent (univariate and graphical/distributional) methods in discriminating between sites or times; 3) when more than one component of the fauna has been studied, univariate and graphical/distributional methods may give different results for different components, whereas multivariate methods tend to give the same results; and 4) key environmental variables responsible for community change may be identified by matching multivariate ordinations from subsets of environmental data to an ordination of faunistic data. Their collaborative research on methods for detecting changes in community structure resulted in creation of the statistical package PRIMER v6. (Clarke and Gorley, 2006), which is now used globally by researchers in the marine environment and increasingly more in other non-aquatic environments.

Borja et al. (2010) review the concept of recovery from impacts to estuarine and coastal marine communities. They warn that the recovery of degraded estuarine and coastal marine ecosystems may take 15 to 25 years for the original biotic composition to be reached again, and the recovery of diversity may take even longer. More studies are needed (e.g., Schaffner, 2010) in coastal waters to better define recovery rates, patterns, and community trajectories of benthos after disturbance events, whether natural or anthropogenic in origin. Borja et al. (2010) also examine the utility of several biotic indices as measures of recovery for benthic communities. Their review points mostly to the need for more research on the issue of what constitutes recovery of such ecosystems.

6.2.11.6 Summary State of Knowledge

Conceptual models of human activities (bottom-up effects) in the ocean and their top-down consequences (effects and impacts) are offered by Elliott (2002) using the example of offshore wind power. He shows a concept map model of the exploratory and construction phases of offshore wind power generation and the operational phases of power generation. These figures (dubbed "horrendograms" because of their complexity) illustrate the cascade of effects that must be considered by permitting and regulatory agencies and offer a plethora of hypotheses for testing. With regard to the benthos, most hypothesized impacts are negative, and involve habitat loss, prey disturbance, and consequent changes in fisheries. Elliott (2002) suggests that the number of potential interactions between the subjects in the concept maps is so great that they will never all be tested or quantified, requiring "best (expert) judgment" in decision making.

Gill (2005) states that any impacts to benthic communities from offshore facilities will have to be assessed relative to the area's natural disturbance regime and the stability and resilience of communities in that area. His literature review regarding benthos was only marginally complete, but based on the available material examined, his summary of the situation remains succinctly accurate today: "Ecological factors are not being considered properly and are under-represented in any discussion of the costs and benefits of adopting offshore renewable energy resources." A lack of appropriate knowledge also contributes to our inability to integrate ecology into the planning and decision-making process for developing offshore energy resources.

6.2.11.7 Precautionary Concerns Relative to Data Gaps

Several documents referenced above recommend that certain types of studies are needed to provide "definitive" answers to fill in data gaps about various potential wind energy impacts on benthic organisms. Caution should be taken when such suggestions are made because:

- No controlled study can replicate field conditions
- Benthic communities have naturally high spatial and temporal variability that cannot be eliminated with any known sampling methods, hence signal-to-noise ratios are typically very low
- Results from one study may not necessarily be reliably extrapolated to other areas at other times
- A definitive result is nearly impossible to achieve because so many externalities change dynamically; the baseline is always in a state of flux
- Results for one (or a suite of) species may not apply to a different species

- Research findings typically raise more questions than they answer
- Statistical uncertainty and probability are part of any study and are typically high in studies of benthos
- An acceptable level of risk in one situation may not be acceptable in others

6.2.11.8 High Priority Research Needs

Motion and noise are among several well-recognized types of signals in the biological world. Color, contrast, and other visual and physically sensed cues are some others. An interesting line of research currently in its infancy involves the noises and vibrations made and perceived by organisms that live in association with the sea floor. Burrowing, digging, and other bioturbations produce signals that can be perceived by other organisms sufficiently close to or having sufficiently sensitive receptors. But the signal must be distinguishable from other noises or vibrations in the ambient environmental regime. Wind energy development may alter the thresholds for signal-to-noise ratios at various distances from the turbines and other machinery involved in wind energy operations. It would be useful to know whether benthic fauna suffer changes to their reproduction, survivorship, growth, or behavior in sediments surrounding these energy production facilities. Do fish have a more difficult time finding benthic prey around wind parks? Are burrowing organisms less susceptible to epibenthic predators like shrimp and flounders near wind parks? How benthic fauna behave and/or are sensed by predators or potential mates are not well known. More studies on predator-prey interactions are needed to determine whether noise affects benthic and/or epibenthic food webs.

Because insects are generally absent from the sea, species diversity of the oceans is typically lower than for habitats on land. However, at higher taxonomic levels (phyla within the Bacteria, Archaea, and Eukarya) the ocean environment is more diverse than terrestrial habitats. The eukaryotic "kingdoms" include protists, animals, plants, and fungi, all present in abundance in the sea. Nearly half the animal phyla occur only in the sea (e.g., sea stars and other echinoderms), but only one animal phylum (the velvet worm Onychophorans) occurs exclusively on land (Duffy, 2010). There is thus a great need for more taxonomic expertise in identifying marine benthic fauna, especially for juvenile forms which often numerically dominate benthic communities. Standardized sampling methods and gear, as well as sample processing protocols, need to be established so that studies from different areas and times can be more reliably compared.

Because we do not yet understand the relative importance of biotic and abiotic forces that influence soft-bottom benthic community structure even in well-studied inshore waters, it is imperative that hypothesis-driven experimental manipulative studies be conducted offshore before decisions are made concerning the potential impacts of offshore development on benthic communities. Seitz (1998) and Tenore et al. (2006) provide conceptual and modular approaches, respectively, to understand the forces regulating soft-bottom benthic communities.

6.2.11.9 List of the Data Gaps and Research Needs for Soft-bottom Benthos

- Population dynamics of offshore benthic organisms: life histories, reproductive capacities, growth rates, especially for numerically dominant species
- Maps of sediment types, bathymetric landforms, and benthic communities

- Taxonomic keys, especially for juvenile benthos
- Determination of the relative roles of biotic and abiotic factors in regulating benthic community structure using hypothesis-driven experimental manipulative research methods
- Consensus-driven determination of what constitutes significant impact and recovery that is both practicable and statistically rigorous in the light of natural variability
- Standardized sampling methods and sample processing protocols for each size-class of benthos (mega-, macro-, meio-, micro-benthos)
- Impacts of electromagnetic forces in and around electrical cables
- Impacts of turbine noise and vibration on organism behavior and life history
- Experimental, manipulative quantification of "reef effects" on benthos
- Long-term sampling programs in different sediment types (hard vs soft-bottom, inner, middle, outer shelf, slope, rise)
- Ecological value of Marine Protected Areas (MPAs) or no-harvest zones to commercial fisheries
- Stronger linkages between government, private industry, and academia, especially for training a technically-proficient workforce

6.3 HARD-BOTTOM BENTHIC INVERTEBRATE COMMUNITIES

6.3.1 Hard-bottom Benthic Invertebrate Community Types and Distribution

The South Atlantic Planning Area encompasses a large geographic region that can be divided into the relatively shallow inner, middle, and outer continental shelf, and the deeper areas (beyond 200 m), including the Florida Hatteras slope, Blake Plateau, Blake Escarpment, and Blake ridge. Struhsaker (1969) was one of the first to categorize bottom types in this region and document that hard or "live" bottom habitats supported large populations of commercially and recreationally important fishes. However, much of the early work on the continental shelf and slope of the study region was conducted in response to oil and gas exploration interests as well as federally funded fishery surveys, many of these appearing only as project reports (gray literature). Surveys for geologic hazards, such as sediment instability, fault lines, and gas pockets, were routinely conducted before drilling operations, using various acoustic instruments (see Reid et al., 2005). These survey records were interpreted not only for potential hazards, but also for the presence of ecologically sensitive hard or live bottom, which were protected from the immediate deleterious effects of fossil fuel operations (USDOI, 1978). Although there had been a great deal of research concerning estuarine and other soft-bottom nearshore areas, these large, federally funded projects were among the first that included offshore ecosystems (Roberts, 1974; Continental Shelf Associates, 1979; Texas Instruments, Inc., 1977; Henry, 1981; Henry and Giles, 1979; SCWMRD, 1981; SCWMRD and GDNR, 1982; 1984). These projects were, however, limited (with a few exceptions) to shelf habitats at water depths of less than 100 m. The deeper zones of the continental slope were included in some early mapping and bottom sampling efforts (Avent et al., 1977; Boesch et al., 1977; Barans and Henry, 1984; Blake et al., 1987), but have also been the focus of more recent work using sophisticated technologies, which facilitate more comprehensive ecosystem assessments (Parker et al., 1983, Reed, 2004; Reed et al., 2005; 2006; Koenig et al., 2005; Ross, 2006; Ross and Nizinski, 2007; Partyka et al., 2007). Early

studies reported that hard substrates were present throughout the continental shelf but were limited in extent (Boesch et al., 1977; CNA, 1977); however, more recent mapping efforts (Van Dolah et al., 1994b; SEAMAP-SA, 2001; Arendt et al., 2003) indicated that hard bottom is locally extensive, but knowledge of composition and distribution of different habitat types and benthic faunal assemblages, especially the invertebrates, on the shelf is still incomplete.

Hard-bottom habitats have been classified using relief, morphology, and location within the shelf zone (Henry and Giles, 1979; Miller and Richards, 1980). Hard-bottom habitats include a variety of bottom types, ranging from areas with little or no vertical relief (Figure 6.5), which support patchy communities of sessile benthic fauna and flora, to areas of high-relief, rocky outcroppings (Figure 6.6), and abundant invertebrate and algal growth (Figure 6.7). Knowledge of the distribution and extent of hard-bottom habitats has expanded considerably since the early studies (Van Dolah and Knott, 1984; Stender et al., 1991; Maier et al., 1992), as has characterization of their associated invertebrate and fish faunas (Miller and Richards, 1980; Powles and Barans, 1980; Grimes et al., 1982; SCWMRD and GDNR, 1981; 1982; Wenner et al., 1983; 1984; Sedberry and Van Dolah, 1984; Barans and Henry, 1984; Quattrini and Ross, 2006).

Figure 6.5 Example of low relief habitat off Gray's Reef National Marine Sanctuary (GRNMS). Photo courtesy of GRNMS.

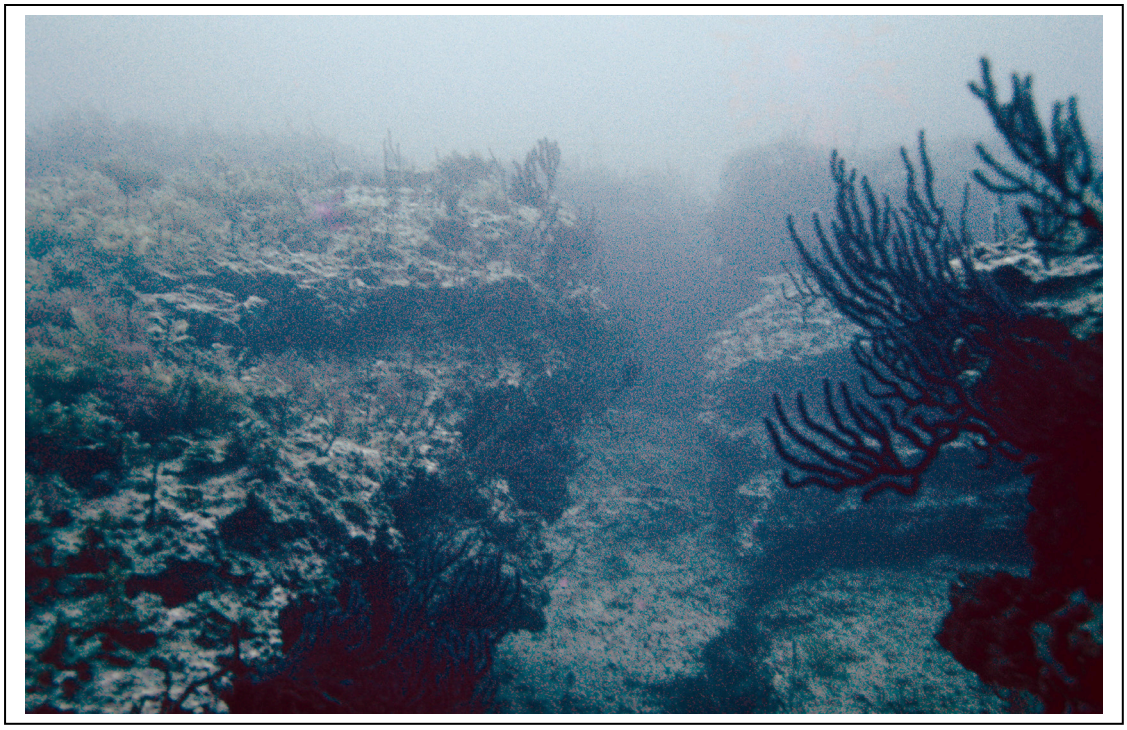

Figure 6.6 A high relief rocky ledge habitat; some of these support lush growth of sponges and gorgonians like the one to the right of the photograph. Courtesy S.W. Ross, University of North Carolina-Wilmington (UNCW).

Figure 6.7 Dense cover of sessile benthic fauna (especially octocorals) on high-relief hard-bottom. Image courtesy S.W. Ross, UNCW.

In 1985, the MMS commissioned a literature study for benthic communities in two areas of the South Atlantic Bight. These areas were adjacent to the OCS area previously investigated (SCWMRD and GDNR, 1981; 1982) and comprised a large northern area bounded by the 200 and 2,000 m depth contours and 31°N (Brunswick, Georgia) to 34°30' N (Cape Lookout, North Carolina). A second, much smaller, area was located in shallower depths (80–200 m) off

northern Florida, between 29°45'N and 30°30'N. Within this region are three major provinces: the continental shelf, the continental slope, and the Blake Plateau. Early studies of shelf and slope communities contained more information on soft sediment than hard-bottom communities, but each contained sites of hard substrate and so have some distributional and taxonomic information on hard-substrate fauna. The results of these and other studies will be discussed in more detail in subsequent sections.

In the late 1980s, interest in the distribution of hard-bottom habitats expanded because of concerns about increasing fishing efforts and the impacts to reef fish populations (SAFMC, 1990). To assess the size of reef fish populations, it was necessary to quantify the amount of habitat available for the species of interest. Determining locations of reef habitats is also of concern to a variety of other users of marine resources, including private companies, the research community, and state and federal agencies charged with protecting and preserving important habitats. The recognized need for better habitat classification prompted a multi-year effort, funded by NOAA, to establish the SEAMAP habitat database (Ross et al., 1986; Van Dolah et al., 1994b; SEAMAP-SA, 2001; Arendt et al., 2003). This effort summarized the occurrence and distribution of reefs and hardgrounds on the shelf between Cape Hatteras, North Carolina and the Florida Keys; to date there is no better regional summary of hard-bottom habitat on the area (Figure 6.8). An inventory of data sources for deep water bottom typing beyond 200 m was assembled by Arendt et al. (2003), but data were not analyzed nor were maps produced for the slope as had been done for the shelf (SEAMAP-SA, 2001).

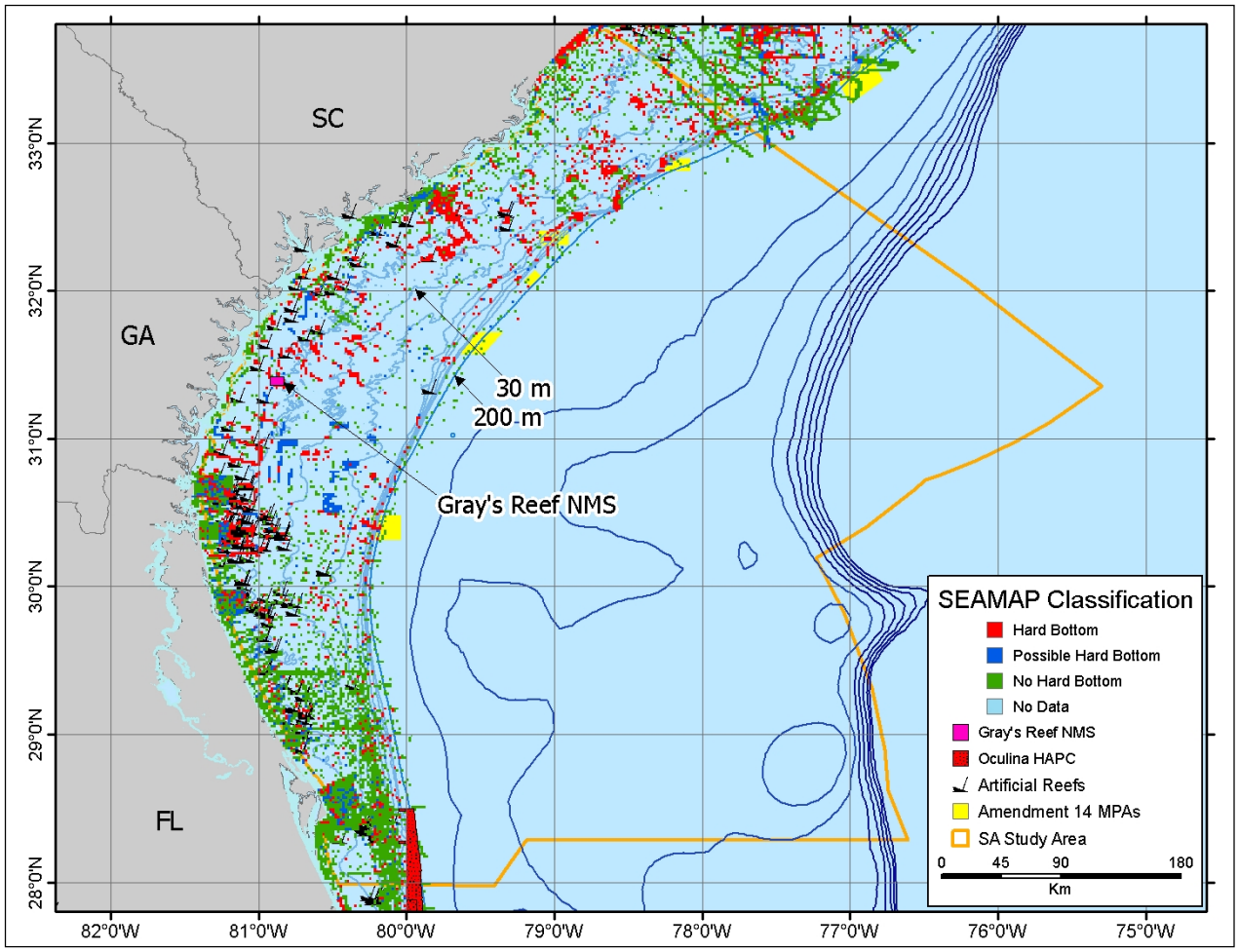

Figure 6.8 SEAMAP-SA classification map, with additional areas of sensitive hard-bottom habitat (Gray's Reef NMS, Oculina HAPC, and shelf edge MPAs). Map modified by S.W. Ross and M. Rhode, UNCW.

6.3.2 Zoogeography

Zoogeographic provinces along the US east coast have been analyzed in various ways by a number of researchers. Despite some varying results, depending on how data were analyzed, the two major and well-recognized zoogeographic breaks in this region are around Cape Hatteras, North Carolina and Cape Canaveral, Florida (Briggs, 1974). Johnson (1934) recognized four marine provinces along the Atlantic Coast of North America: 1) Arctic; 2) Boreal (Nova Scotia to Cape Cod); 3) Trans-Atlantic (Cape Cod to Cape Canaveral); and 4) Caribbean (Cape Canaveral south). The Trans-Atlantic was later divided into two provinces called the Virginian (Cape Cod to Cape Hatteras, also called cool temperate) and the Carolinian (Cape Hatteras to Cape Canaveral, also called warm temperate), primarily defined by temperature boundaries (Hutchins, 1947; Ekman, 1953; Bumpus and Pierce, 1955; Hall, 1964; Briggs, 1974). Early zoogeographic research by Cerame-Vivas and Gray (1966), using primarily soft sediment fauna, showed that the fauna on the inner and middle shelf from Cape Hatteras, North Carolina to Cape Canaveral, Florida represents the Carolinian province, but tropical province fauna dominate the outer shelf. Subsequent studies indicated that, while the soft-bottom fauna may belong to the Carolinian province, hard-bottom fauna are mainly tropical, probably carried north on the Gulf

Stream and supported year round by moderate bottom water temperatures (Pearse and Williams, 1951; Menzies et al., 1966; Schneider, 1976; Schneider and Searles, 1991). Although a large number of tropical invertebrate species can survive as far north as Cape Hatteras, North Carolina (and in many cases as far north as New England), it is not known whether these reproduce and form continuous populations or whether they constitute a seasonal sink of recruits that perish in the winter. For many fishes, on the other hand, tropical species occupying hard-bottoms do spawn in the region and apparently maintain permanent populations; therefore, it seems likely that many invertebrates do as well. Over 400 invertebrate species were recorded from hard-bottom in the Carolinas (Pearse and Williams, 1951) and found to be predominantly (74%) southern fauna; the sponges, ascidians, bryozoans, decapods, polychaetes, amphipods, and echinoderms have the strongest southern affinities. Other studies also concluded that the zoogeographical affinities of the southeastern US hard-bottom-associated taxa were primarily tropical to sub-tropical (Caribbean/West Indian) (Bayer, 1961; Abbott, 1974; Wiedenmayer, 1977; Cairns, 1978; Giammona, 1978; Meyer et al., 1978; Burgess et al., 1994).

In deeper slope waters, Rowe and Menzies (1969) described the bathymetric distribution of epibenthic megafauna (hard and soft-bottom) on the continental margin off Cape Lookout, North Carolina based on bottom photographs and trawl samples. They concluded that species had narrow depth ranges, resulting in ribbons of assemblages parallel to depth contours. On the upper continental slope (200–800 m), these faunal zones correlated with marked changes in sediment size and temperature variations related to movements of the Gulf Stream. Below 1,000 m, some zonation continued, apparently in response to small differences in temperatures. On the upper slope (>200 m) and northern Blake Plateau (to 1,200 m), the megafaunal species assemblages are essentially identical to that of the upper continental slope of the Middle Atlantic Bight (Boesch et al., 1977). The zonation of the deep-sea benthic fauna off the southeastern U.S. is further discussed by Menzies et al. (1973) and Texas Instruments, Inc. (1979). The composition and zonation of the slope epibenthos were very similar to that described by Grassle et al. (1975) for the slope south of New England. The zonation on the Carolina slope around 2,000 m was affected by the southward flowing Western Boundary Undercurrent. Along the contact zone between the slope and upper rise (3,000 m), three species unique to this zone were the soft coral *Anthomastus grandiflorus* and the holothurians *Pelopatides gigantean* and *Euphronides depressa*. Deeper than 3,000 m only *Parapagurus pilosimanus*, *Amphiophiura bullata*, *Euplectella suberea*, and the sea pen *Umbellua lindahli* were found.

Sessile macroalgae are also a significant component of marine benthos that occurs within the photic zone. The benthic macroalgae species of the continental shelf between Cape Hatteras and Cape Canaveral belong to either the cold water New England/Canadian province (distributed southward by the Labrador current) or the warm water Caribbean/West Indian province (distributed northward by the Gulf Stream); there are probably no truly endemic species in this area (Humm, 1977). The continental shelf between Cape Hatteras, North Carolina and Cape Canaveral, Florida is colonized by the eurythermal (tolerant to wide temperature ranges) members of these two floras, resulting in an overlap of cold-water and warm-water species in this region; however, the warm water species are dominant (Searles and Schneider, 1980; Schneider and Searles, 1991). Another transition zone occurs around Cape Canaveral as a result of cool water upwelling north of the Cape, which creates an environmental boundary for the distribution of benthic algae (Humm, 1969).

6.3.3 Continental Shelf Hard-bottom Invertebrate Communities (shore - ~200 m)

The continental shelf break in the South Atlantic Planning Area is relatively shallow at 50–80 m (Macintyre and Milliman, 1970; Uchupi, 1967). Nearshore habitats are influenced by terrestrial runoff (Atkinson et al., 1978) and the offshore habitats by Gulf Stream intrusions and cold-water upwellings (O'Malley et al., 1978). The general circulation consists of an offshore northerly current flow (Gulf Stream), with nearshore water moving south and a cross-shelf tidal movement of both surface and bottom waters (Bumpus, 1973; Bane et al., 2001). Bottom topography is generally unstructured sediment with a shallow step-wise series of fossil carbonate ledges on the inner, middle, and outer shelf, some with localized patches of ahermatypic and hermatypic corals (Huntsman and Maclntyre, 1971). Nearshore sediments are fine-grained terrestrial sands, whereas the middle and outer sediments are coarser and carbonate dominated (Henry and Hoyt, 1968; Milliman et al., 1972). Parker et al. (1983) estimated live bottom to comprise 23% of the shelf, while live bottom >1 m relief comprised only ~7%, which is compatible with other estimates of 3–10% (SCWMRD and GDNR, 1981; SEAMAP-SA, 2001). It is difficult to estimate the amount of live-bottom habitat that occurs in the continental shelf of the South Atlantic Planning Area because of the patchy and discontinuous nature of its distribution. Generally the quantity of hard-bottom area is lower off Georgia compared to the Carolinas and Florida. Several studies (e.g., Parker et al., 1983) have attempted to make assessments of live-bottom coverage, but the accuracy of these is uncertain. Henry et al. (1980) estimated the proportion of hard-bottom from Cape Fear, North Carolina to Cape Canaveral, Florida to be 4.3% of the total area surveyed, but they considered this to be an underestimate based on acoustic data that indicated an additional 16.2% of undetected hard substrate. Later studies (Parker et al., 1983) suggested that "rock-coral-sponge" habitat accounted for nearly 30% of the substrate between depths of 27–100 m from Cape Fear, North Carolina to Cape Canaveral, Florida (~7,400 km^2). This is the same order of magnitude (6,520 km^2) as estimated by Barans and Burrell (1976) for the same region for depths of 19–55 m. Despite these relatively high estimates, early studies on the shelf showed that bottom type was highly variable (SCWMRD and GDNR, 1981; 1982). The percent live bottom varied between 25–100% of the total area of the study sites, illustrating the patchiness of hard-bottom in the study area.

Seismic profiles within the South Atlantic Bight (Henry and Giles, 1979) were used to identify three general hard-bottom types: low-relief (<0.5 m) relatively flat hard grounds; moderate-relief (0.5–2 m) irregular, discontinuous rock outcroppings; and high-relief (>2 m) reefs, which occur near the shelf break south of Cape Lookout, North Carolina (Menzies et al., 1966) to northern Florida (Emery and Uchupi, 1972). There are no apparent trends in relief with depth across the continental shelf, except that higher profile reefs tend to occur farther offshore. All live-bottom habitats appear to have elements of different habitat types, rather than being entirely composed of a single habitat class (SCWMRD and GDNR, 1981). Even the most irregular shelf-edge topography typically contains a significant amount of low- and moderate-relief hard-bottom as well as high relief.

Sessile benthic fauna and flora can indicate the presence of hard substrate even when emergent rock is not visible; this often occurs on low-relief or flat hardgrounds that are subject to cyclic covering and uncovering by sand. This temporal variability in availability of low-relief hard ground may have a significant effect on faunal distributions (Powles and Barans, 1980), and the depth of the sediment may account for the patchiness of the epibenthic community. There is

generally more emergent hard-bottom further offshore as the sediment layer thins. Sessile fauna were limited to thin sediment layers (<8 cm); deeper sand or sediment did not support epibenthic fauna (Powles and Barans, 1980). Henry and Giles (1979) also attributed the patchiness of hard-ground distribution to sediment thickness. Moderate-relief reefs are common off north Florida, South Carolina, and North Carolina, occurring at inner- and middle-shelf depths from 15–30 m (Henry and Giles, 1979). Although many inshore reefs are low relief, an exception is the 40 km^2 area off Georgia known as Gray's Reef, which is mostly moderate relief. Shelf-edge reefs are discontinuous but usually well-defined, high-relief ridges (or series of ridges) at or near the shelf break (Macintyre and Milliman, 1970; Avent et al., 1977) and are characterized by blocky irregular rock outcrops with local relief up to 15 m (Henry et al., 1980; Henry and Hoyt, 1968; Ross and Quattrini, 2006).

6.3.3.1 Inner- and Middle-Shelf, Hard-bottom Invertebrate Communities (0–50 m)

Pearse and Williams (1951) did some of the earliest work on hard-bottom fauna off North Carolina and South Carolina. Over 400 species were recorded from hard-bottom habitats, including sponges, ascidians, bryozoans, decapods, polychaetes, amphipods, and echinoderms, most of which had southern rather than Carolinian zoogeographic affinities. Further south off Georgia, Hunt (1974) reported that soft corals, sponges, ascidians, bryozoans, barnacles, and algae were the dominant epifauna on Gray's Reef, a moderate- to high-relief hard-bottom area that later became the Gray's Reef National Marine Sanctuary. Areas of abundant growth were associated with exposed rock, moderate growth with rock thinly covered with sand, and sparse growth on rock with thick layers of sand. Sessile invertebrates included two species of ascidians (*Clavelina picta, Amaroucium stellatum*), five species of sponges (*Cinachyra cavernosa, Speciospongia vesparia, Homaxinella rosacea, Ircinia campana, I. fasciculate*), six species of anthozoans (e.g., *Titanideum frauenfeldii, Leptogorgia setacea, L. hebes*), and three species of soft corals (e.g., *Telesto* spp.).

In 1979, Texas Instruments, Inc. published the South Atlantic Benchmark Program report under the MMS Environmental Studies Program. Seasonal samples were acquired using an otter trawl from 50 sites, arranged along seven transects from the slope to the inner shelf at both deep (540 m) and shallow (11 m) sites. Sampling revealed a hard-bottom area at only one station, (site 2D: 27 m, 32o45'N, 78o56'W), although the presence of sessile epifauna and reef fishes were evidence of a reef-type substrate at two other stations (2E: 37 m, 32o40'N, 78o47'W and 6C: 30o23'N, 80o51'W). The otter trawl catch from the hard-bottom station contained tunicates (Styela plicata), soft corals (Titanideum frauendeldii and Telesto fruiticulosa), sponges, and the scleractinian coral Oculina spp. This station was also close to a bed of the scallop Astropecten gibbus, as evidenced by the >300 individuals in one of the samples. Although the majority of samples from this study were taken from soft-bottom infauna and epifauna, there were useful general observations on community structure. The shelf zones are roughly parallel to the shore and shelf break, and the mobile fauna divide naturally into the inner-shelf, middle-shelf, outer-shelf, and deep-slope zones, although their boundaries are not rigidly defined and species composition of the different shelf fauna overlap. There are seasonal shifts in the boundaries of the three major shelf zones as evidenced in the distribution of common invertebrates and fishes. The winter faunal assemblage generally dominated the inner shelf where environmental variables such as temperature, salinity, and wave action were the most variable. The middle- and outer-shelf mobile invertebrates exhibited seasonal variations, and these shelf assemblages were very

different from those of the slope assemblage. The shelf in this region is scattered with patches of hard-bottom that support high-diversity, high-biomass sessile fauna and reef fishes, but the overall epifaunal distribution appears to be controlled primarily by the Gulf Stream. The lack of accurate locality data for hard-bottom areas and the patchiness of their distribution resulted in inadequate sampling during the 1977 South Atlantic Benchmark Program.

A study of hard-bottom faunal assemblages (Continental Shelf Associates, 1979) was conducted on the continental shelf between Charleston, South Carolina and Jacksonville, Florida at depths of 13–165 m. The majority of the species found were decapods (seven species), anthozoans (six species), bivalves (six species), bryozoans (five species), and echinoderms (five species). The polychaete Phyttochaetopterus socialis was very abundant at one of the middle-shelf sites off Charleston and also created habitat for other fauna. Similar species were found on both the shallow- and middle-shelf sites, although there was a higher species richness and biomass associated with emergent hard-bottom compared to sand-covered hard-bottom. The following major taxa were believed to be associated primarily with the hard-bottom areas, as opposed to soft sediments, based on the species sampled: Porifera (sponges), Hydrozoa (hydroids), Anthozoa (scleractinians, antipatharians, gorgonians, anemones), Cirripedia (barnacles), Bryozoa (moss animals), Ascidiacea (sea squirts), and red, green, and brown algae. Certain species of polychaetes, mollusks, crustaceans, and echinoderms were also believed to be almost exclusively associated with hard-bottom substrates. Comparisons between the fauna collected in the Continental Shelf Associates (1979) study and shelf-edge studies to the north (Menzies et al., 1966; Cain, 1972) and south (Avent et al., 1977) revealed a large number of species in common. Unfortunately, because of the qualitative nature of these data sets, differing methodologies, and the variable amount of effort spent on collection and taxonomic identification among these three studies, the only conclusion that could be reached was that there were many species common to the different regions.

Powles and Barans (1980) studied two hard-bottom areas off Charleston, South Carolina on the inner shelf (16–24 m) and the middle shelf (29–32 m). The seafloor was generally flat and sandy with occasional rock or ledge protrusions up to 30 cm relief. The shallower ledges were often covered with a layer of sand, with sessile invertebrates protruding through from the hard substrate beneath (Figure 6.9A). Sponges and soft corals dominated the benthic assemblages in both areas; algae and hard corals were occasionally present. The three principal kinds of sponges were: white branching sponges such as Verongia fistularis and Axinella polycapella, unidentified encrusting sponges, and barrel sponges, such as Spheciospongia vesparium, Ircinia strobilina and I. campana (Figure 6.9B). Small, thinly branched gorgonians were tentatively identified as Titanideum sp. and Leptogorgia sp.; sea fans (Muricea pendula) were also observed as well as occasional small colonies of stony corals, such Solenastrea hyades (Figure 6.10A) and Oculina spp. Colonies of bryozoans and ascidians were also documented, often associated with the bases of sponges or soft corals. Although sessile invertebrate assemblages were similar at both study areas, there were more branching sponges and fewer soft corals in the deeper compared with the shallower area. Similar types of attached organisms have been collected from or observed in other live-bottom areas in the South Atlantic Planning Area. Struhsaker (1969) noted that sponges and sea fans were commonly found in trawl catches from live-bottom areas. Sessile invertebrates identified by Pearse and Williams (1951) included 25 species of sponges, and hydrozoans, soft corals, and bryozoans taken from rocky reefs in 4–17 m depth off the Carolinas.

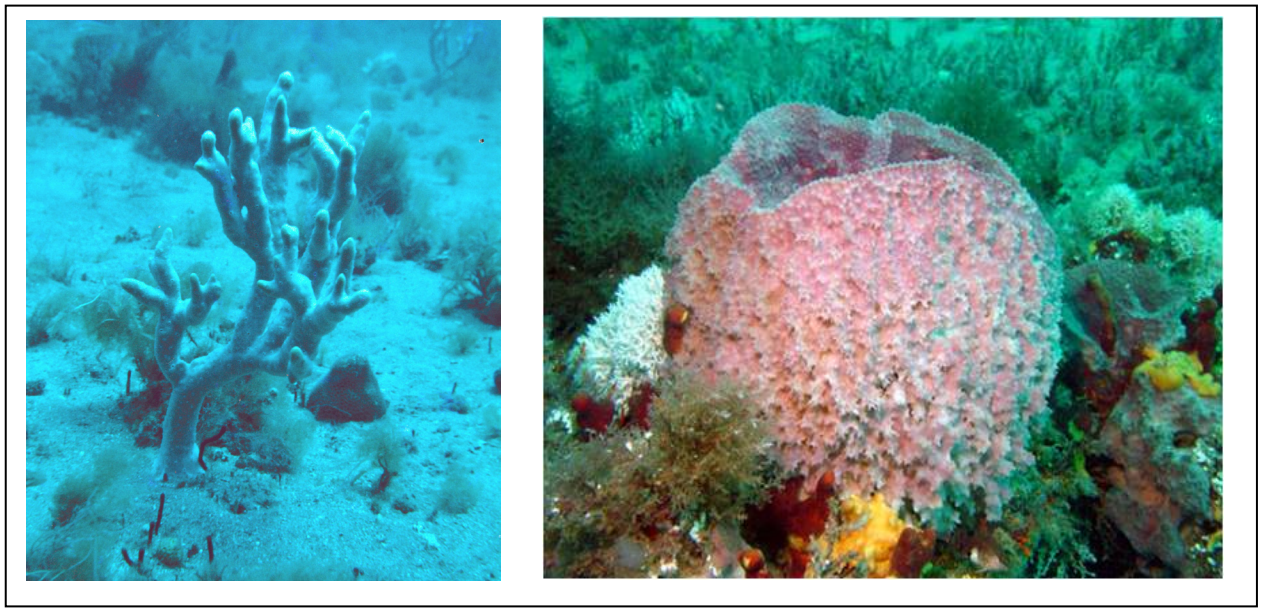

Figure 6.9 A) Well-developed sessile benthic communities can develop in areas where hard substrate is covered with several centimeters of sand; this is probably due to periodic movement of sand that exposes the substrate for settlement. Image courtesy S.W. Ross, UNCW. B) The vase sponge Ircinia campana, a common member of shelf hard-bottom communities in the South Atlantic Bight. Image courtesy Greg McFall, GRNMS.

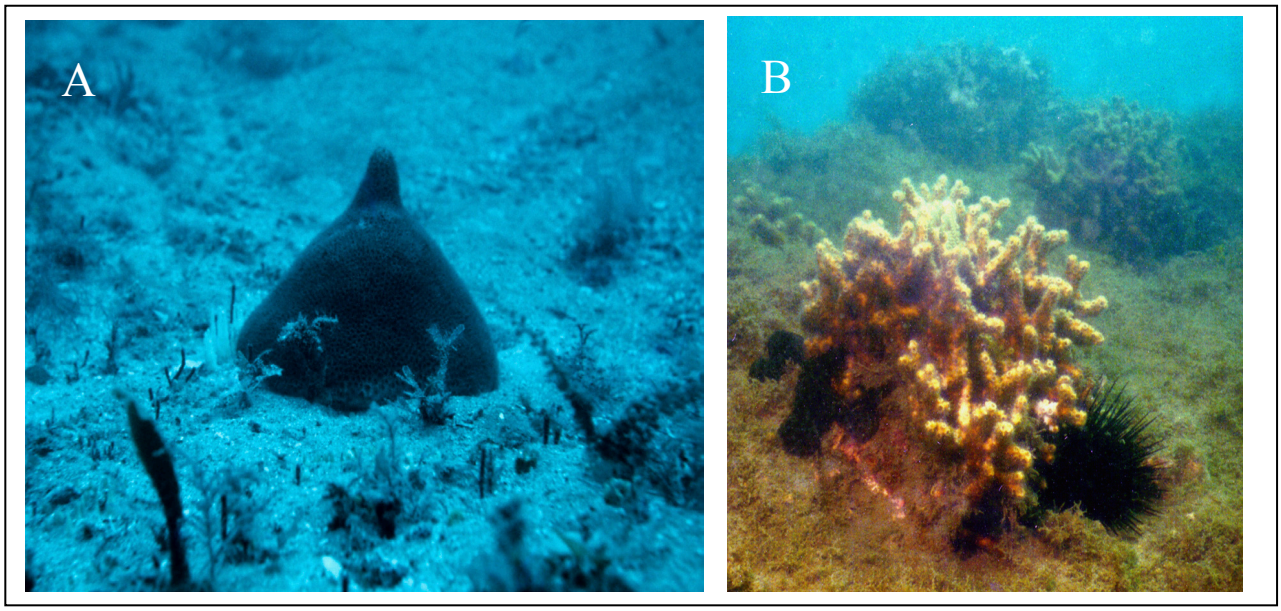

Figure 6.10 A) *Solenastrea hyades*is is one of the species of boulder corals that can tolerate the variable temperatures and turbid conditions common throughout the study area. Image courtesy S.W. Ross, UNCW. B) Colonies of *Oculina varicosa* on shallow ledges off central Florida. This is the most common genus of coral throughout the study area from the very shallow ledges to 100 m depth off Florida where it forms massive bioherms. Image courtesy S. Brooke, Marine Conservation Institute.

Coral heads, sea fans, algae, and sponges characterized the "coral patches" of Onslow Bay, North Carolina (Huntsman and MacIntyre, 1971); hard corals of the genera Solenastrea and Oculina occurred there, as in the Powles and Barans (1980) survey areas. McCloskey (1970) reported Oculina arbuscula colonies on ledges 3–25 m depth from Charleston, South Carolina to Cape Hatteras, North Carolina. This species is also found further south off the coast of Georgia, but in Florida O. arbuscula was replaced by O. varicosa and O. diffusa, which were locally abundant on limestone ledges from 4–25 m and form small (<30 cm diameter) hemispherical colonies (Reed, 1980) (Figure 6.10B).

In the early 1980s the BLM funded two large-scale studies with the objective of characterizing communities associated with hard-bottom areas from Cape Hatteras, North Carolina to Cape Canaveral, Florida over depths of 20–100 m (SCWMRD and GDNR, 1981). This initial study provided information on community structure, and a subsequent study the following year (SCWMRD and GDNR, 1982) filled data gaps on seasonal and depth variations. The first study compared three inner- (16–22 m), three middle- (23–38 m) and three outer-shelf stations (46–66 m) for differences in reef morphology, sediment deposition, and community assemblages. The second study included an analysis of season and bathymetric variation on benthic communities. The results of the inner- and middle-shelf stations will be discussed here, beginning with the outer shelf in the following section.

The inner-shelf stations ranged from low (<0.5 m) to moderate (0.5–2 m) relief and profiles varied with latitude, amount of emergent rock, sand veneer, and topographic irregularity (i.e., flat pavement to rocky outcroppings). Details on these stations are in the report but, given that they were so different from each other, it is not surprising that the amount and type of epibenthic fauna also showed considerable variability. At the low-relief site off Charleston, South Carolina the growth of sessile invertebrates was moderate to heavy, with a uniform distribution over the wide, sand-covered pavement. The second inner-shelf site was situated in the GRNMS and is an extensive area of moderate to high relief with rocky ledges and outcroppings covered in thick epifaunal growth. The third inshore site off North Carolina was an extensive series of high-relief (3–4 m) ledges that have some exposed rock, but coarse sand covered most of the flat tops of the ledges.

The middle-shelf sites off Georgia were in 23–29 m depth, with some low- to moderate-relief ledges and outcroppings with large expanses of sand-covered hardpan and moderate densities of epifauna. The South Carolina middle-shelf site was the largest in the study (9.8 km^2); it exhibited extensive patches of deep sand with isolated, small rock outcroppings of low to moderate relief and ledges with ~2 m vertical drop. The exposed hard substrates at this site often had very dense epifaunal growth. The middle shelf station off North Carolina had moderate- to high-relief ledges (up to 3 m) along an east-west axis, and frequent patches of sand and low ridges (0.5 m) were found away from the main ledges. The benthic community at this site was similar to the South Carolina site.

Results of the 1981 report showed that, as expected, the invertebrate fauna of the hard-bottom sites was more diverse than the surrounding sand fauna. Species composition was related more to station depth and topography than to seasonality, although species associations did vary from winter to summer. In 1980 (SCWMRD) and 1981 (GDNR) 1,175 taxa were collected during

winter and summer only, and in 1981 (SCWMRD) and 1982 (GDNR) 1,307 invertebrate taxa were identified from collections made across all sampling devices and seasons. These results emphasize the high diversity of these hard-bottom habitats. Most sites had large numbers of uncommon species (1–2 individuals); however, two species of polychaetes (*Filograna implexa* and *Pista palmata*) numerically dominated the middle- and outer- shelf sites off South Carolina and Georgia. Diversity was generally high during all seasons, with no statistically significant differences with depth, season, or latitude. The authors speculated that the higher species richness at middle-shelf sites may have been due to more consistent bottom temperatures and relatively high habitat complexity created by abundant large sponges and octocorals. Diversity differences between stations were attributed to between-station variations in topography and habitat heterogeneity. Sponges (porifera), bryozoans (bryozoa), and corals/anemones (cnidaria) were the most diverse taxonomic groups, with sponge diversity highest on the inner-shelf sites and less so on the middle and outer shelf, which had greater numbers of cnidarians and bryozoans. For all study areas, algal species occurred mostly during summer when red algae (rhodophytes) dominated collections. Except at the most northern inner-shelf station, algae were not as abundant on hard-bottom habitats off South Carolina and Georgia as they were off North Carolina. No significant differences in biomass were observed between seasons; however, in Georgia and South Carolina, there were differences across depth, with biomass being greatest on the inner shelf (probably a reflection of high sponge abundance on these sites). At sites off North Carolina, sponge biomass was highest on middle- and outer-shelf sites, suggesting latitudinal differences in sponge distribution and density. Site differences occurred among depths, with inner- and middle-shelf North Carolina sites being more similar to each other than to outer-shelf sites, but most species assemblages were not restricted to a particular depth zone. More specific taxonomic details on hard-bottom and other communities in these studies are in the reports (SCWMRD and GDNR, 1980, 1981, 1982)

A third phase of hard-bottom studies in the South Atlantic Planning Area, funded by MMS, was on the inner and middle shelf off South Carolina and Georgia (SCWMRD and GDNR, 1984). This study focused on six hard-bottom sites, four of which were very close to or the same as those in the previous SCWMRD studies, and which are described in greater detail in the study report. These sites were a combination of low- to moderate-relief hard-bottom with varying amounts of topography and sediment cover. As previously mentioned, hard-bottom areas supported a diverse assemblage of sessile fauna, including many large sponges and corals, which increase structural complexity and provide habitat for other fauna. In general, distribution of sponges and corals within a reef area is patchy and appears to be affected by sediment cover over the substrate (Jones and Endean, 1973, 1976; Storr, 1976; Taylor, 1977; Bak, 1978). Establishing sensitivity of corals and sponges to sediment exposure is important in areas where industry activities may disturb the seafloor or otherwise increase sediment load.

Surveys of these inner- and middle-shelf sites yielded ~5,000 sponges and corals in 597 quadrats (10 m^2), for an average density of ~1 per m^2. Hard corals (*Oculina varicosa* and *Solenastrea hayades*) were uncommon and found only at the inner-shelf sites with less than 5 cm of sediment cover. Five sponge species were observed at the inner stations, and four species were documented at the middle-shelf stations. The large vase sponge *I. campana* and the finger sponge *Haliconia oculata* were commonly observed, but other large sponge species that had previously been documented at these depths (e.g., *Spheciospongia vesparium* and *Cliona* spp.) were not. *I.*

campana and *I. ramosa* were common at both inner- and middle-shelf locations, usually in habitats with less than 7 cm of sediment cover. The finger sponge *Homaxinella* spp. and the flabellate sponge *H. waltonsmithii* were observed at all stations, but both species were much more abundant at the shallower sites with less than 5 cm of sediment cover. The other common sponge at the study sites was *Haliclona oculata*, the majority of which were found in less than 4 cm of sediment cover. Octocorals were much more abundant than sponges at all sites, and densities of both were greatest at inner-shelf stations. The most common octocoral at all stations was *Titanideum frauenfeldii*, with much higher densities at inner-shelf than middle-shelf sites. This species' distribution correlated with habitats having sediment thickness <5 cm. Similar patterns were observed for the whip coral *Leptogorgia virgulata*; this species was nearly always found at inner-shelf sites in sediment less than 2 cm depth. The only other large octocorals commonly found were the fan-shaped *Lophogorgia* and *Muricea pendula*. These were equally abundant at both depth zones, and most colonies were found in sediment regimes <5 cm thick.

Distribution of sediment along the reef tract was very patchy and ranged from 0–30 cm thick within a single transect. The sessile benthic fauna distribution reflected this patchy sediment distribution, indicating a clear relationship between sediment thickness and the presence of sessile species. Some studies have noted that corals and sponges are intolerant of high sediment cover (Bakus, 1968; Roy and Smith, 1971; Jones and Endean, 1973; 1976; Taylor, 1977; Bak, 1978); however, these studies do not define specific amounts that limit growth and distribution. Other studies mentioned the presence of corals and sponges in sediment-covered habitat, but do not document its thickness (Wells et al., 1960; Nicol and Reisman, 1976; Storr, 1976; Vacelet and Vasseur, 1977; Reed, 1980). Extensive gorgonian and sponge assemblages were observed in areas of (thin) sediment veneer; it was postulated that either those species can establish in sediment-covered areas, or their attachment sites were once exposed and subsequently covered as the sediment moved around the reef. Once established, these species may be able to tolerate shifts in sediment around the base as long as they do not bury the whole colony. This study indicated an inverse relationship between sediment thickness and density of sponges and corals.

In addition to general habitat description efforts, there have been several studies of specific taxa and/or communities associated with hard-bottom habitat in the study area. Continental Shelf Associates (2009) conducted a literature synthesis on the ecology of hard-bottom habitats off eastern Florida from Cape Canaveral to Miami. Most of the study was south of the South Atlantic Planning Area, and Brevard County (relevant to this study from Palm Bay to Cape Canaveral) had less hard-bottom (0.2 km^2) than the more southern counties; however, the general information is still relevant (see also SEAMAP-SA, 2001). Most hard-bottom off east Florida is composed of lithified sediment and mollusk shells (especially the coquina clam *Donax*) called Anastasia or Coquina limestone. These form ridges or "reefs" along the entire east Florida coast, but vary greatly in their extent, and patches of hard-bottom are interspersed with sandy soft sediment. The invertebrate, algal, and fish communities are moderately diverse with over 325 invertebrate species recorded from hard-bottom off Florida's east coast by the early 1990s (Gore et al., 1978; Nelson, 1988; 1989; Nelson and Demetriades, 1992), and amended later to 533 species (Continental Shelf Associates, 2009). The species richness of sessile species is greatest for cnidarians, bryozoans, and sponges followed by tunicates, polychaetes, and bivalves. In contrast, some sessile taxonomic groups are not highly diverse but may be locally abundant and, therefore, have high ecological value. For example, the colonial polychaete *Phragmatopoma*

lapidosa creates sand tubes that form massive reef-like structures in the intertidal and subtidal along the middle to northern east coast of Florida (Figure 6.11).

Like other complex structures, worm reefs provide habitat for numerous other invertebrates and fishes. Of the motile fauna, the crustaceans are the most numerous and diverse group associated with hard-bottom habitats along the Florida coast, and they are also the best-studied invertebrate taxa, although much of the research was done ~20 years ago (Continental Shelf Associates, 2009). There are >87 documented species of polychaetes that are likely to be very abundant, but more research is needed to confirm this (Continental Shelf Associates, 2009). There are also large numbers of gastropods, flat worms, and ribbon worms in nearshore hard-bottom habitats. To the northern end of the Florida coast there is a high abundance and biomass of echinoderms, especially the rock-boring sea urchins *Echinometra lucunter* and *Arbacia punctulata*. There are other invertebrate groups such as the brittlestars that may have high diversity and abundance, but their distribution has not been well studied.

Figure 6.11 This worm reef is constructed by thousands of *Phragmatopoma lapidosa* (polychaete worms) that use sand stirred up by the waves to construct their tubes and create these dome-shaped mounds.

On a large scale, invertebrate diversity and abundance vary greatly with latitude, depth, and often season; however, there also may be significant small-scale faunal assemblage variability due to differences in quantity and type of hard substrate, hydrodynamics, and other biotic and abiotic factors. The most diverse and abundant faunal assemblages frequently occur where sessile

benthic invertebrates enhance habitat by increasing habitat and trophic complexity. These structure-forming taxa include corals, sponges, reef-building polychaetes, some mollusks, and tunicates. The large algal growths off northern Florida and elsewhere may serve a similar function. Changes (natural or anthropogenic) in the abundance of these keystone or foundation species will impact the overall community biomass. Continental Shelf Associates (2009) summarized ecological information, such as distribution, diversity, trophic function, and reproduction, for selected major hard-bottom taxa, namely polychaetes, hydrozoans, tunicates, bryozoans, mollusks, crustaceans, echinoderms, corals, and sponges. For the most part, there was very limited information available for the invertebrates, especially the sessile structure-forming taxa, such as sponges and corals, despite the well-documented high diversity and ecological value of these fauna.

Marine flora, particularly macro-benthic algae, are an important component of the nearshore and sometimes the middle-shelf hard-bottom communities. Aside from the requirements of occupying the photic zone and having suitable hard substrate for attachment, temperature is considered the chief controlling factor in the latitudinal distribution of marine benthic algae (Setchell, 1920). Temperature varies seasonally, especially in the shallower shelf areas, and along the eastern US coast there are two major oceanographic currents that influence benthic temperatures. The cold Labrador Current flows south along the coast to Cape Hatteras, North Carolina where it swings out to sea and flows eastward. The warm Gulf Stream is the second forcing current, which flows north from south Florida to North Carolina, before heading eastwards into the Atlantic. Cape Hatteras, North Carolina is a boundary or transition zone for marine algal species distributions (Searles and Schneider, 1980). Another transition zone is in the area of Cape Canaveral, Florida where cold upwelling water creates a boundary for the distribution of nearshore benthic algal species (Humm, 1969; Searles and Schneider, 1980). The continental shelf between Cape Hatteras and Cape Canaveral represents an overlap of the northern cold-water and the southern warm-water provinces (Humm, 1969; Schneider and Searles, 1991). This overlap area contains the temperature-tolerant (eurythermal) species of benthic macroalgae and seagrasses from each province. Many of the southern species reach their northern limit (during summer) or the northern species their southern limit (during winter) in this area. Hoyt (1920) was the first phycologist to document the differences between nearshore shallow algal communities and those further offshore in deeper waters (15 to 65 m) of North Carolina. He characterized this flora as “predominantly southern” because almost all the species he encountered were from Florida and the Caribbean. This is due to the moderating influence of the Gulf Stream that maintains mild benthic temperatures offshore and allows tropical flora and fauna to persist. A thorough recent treatment of the benthic marine algae of the region was conducted by Schneider and Searles (1991).

The first regional guide to the benthic macroalgae of the area from Cape Hatteras, North Carolina to Cape Canaveral, Florida region (Hoyt, 1920) documented 133 different species and varieties; Cape Lookout/Beaufort, North Carolina was a major transition zone between the northern and southern species distributions. A later study by Schneider (1976) documented 150 species and varieties from North Carolina. Crustose coralline algae were not included in the study; this group is important in tropical coral ecosystems where they function as settlement cues for coral larvae. Of the North Carolina taxa, 38 were also found in South Carolina but only 2 others were collected just in South Carolina. These lower numbers of species are probably due to

the smaller area of hard substrate in South Carolina and perhaps lower sampling effort. According to Diaz-Piferrer (1969), nearly 80% of the 827 species of marine algae reported from the tropical western Atlantic also occurred in Florida or the Carolinas.

Schneider (1976) divided the shelf into three zones for benthic algae: the inner shelf from 0–25 km offshore, the middle shelf from 25–60 km offshore, and outer shelf from 60 km offshore to the shelf edge (90–130 km offshore depending upon latitude). This division appears equivalent to the bathymetric divisions employed by invertebrate biologists, but may differ in some locations. The largest number of algal species in a single zone was 93 (89%) found on the outer shelf with its great relief, high proportion of suitable substrate, and mild year-round bottom temperatures. Almost as many taxa, 89, (85%) were found on the middle shelf, which contained the highest occurrence of reef areas (SEAMAP-SA, 2001). The inner shelf had 66 benthic species (some species occur in more than one zone). The Gulf Stream maintains stable, moderately warm bottom temperatures offshore, whereas the nearshore is a more turbulent and seasonally variable environment (especially for temperature); therefore, most tropical species are restricted to offshore areas. The offshore habitat off Cape Lookout, North Carolina also appears to be the southern limit of distribution for temperate/polar algal taxa; thus, it is probably the area of greatest overlap in tropical and temperate species.

In contrast to Schneider's (1976) depth zonation, Gilmartin (1960) found no definite vertical zonation in the offshore flora in the Carolinas, but rather overlapping bathymetric distributions for green, brown, and red algae. Three groupings of algae were created based on bathymetric distributions: those exhibiting extremely narrow or stenobenthic (<10 m) depth ranges; those with intermediate or mesobenthic (10–30 m) depth ranges; and those with very wide or eubenthic (>30 m) depth ranges. Most of the species in the Carolinas are mesobenthic and eubenthic, with a maximum depth of <60 m, although in areas where light penetration is greater, the maximum depth of algal occurrence increases accordingly. Samples taken in the deeper waters off the shelf break produced only crustose coralline algae. It is not known whether this group serves the same coral recruitment role in temperate as in tropical reef habitats, but this would be an interesting research objective.

6.3.3.2 Outer-Shelf, Hard-bottom Invertebrate Communities (50–200 m)

The outer-shelf banks or reefs are a discontinuous series of ridges and ledges at 50–80 m depth that parallel the shelf break between Cape Hatteras, North Carolina and Cape Canaveral, Florida (USDOI, 1978). Several publications have described a series of moderate-relief, shelf-edge terraces and ledges along the South Atlantic Planning Area shelf edge (Moe, 1963; Pilkey and Giles, 1965; Uchupi and Tagg, 1966; Zarudzki and Uchupi, 1968). During visual surveys at 50–70 m, Henry and Hoyt (1968) observed lithified to semi-consolidated rocks ~1 m diameter encrusted with calcareous growth and partially covered by sand. Macintyre and Milliman (1970) surveyed topographic features near the shelf break between Cape Hatteras and Fort Lauderdale. Off North Carolina they discovered troughs, terraces, and poorly defined ridges parallel to the shelf break at depths of 50–150 m. Dredged rock samples were composed of highly bored, irregular fragments of limestone and sandstone. Between Cape Fear and Cape Canaveral, the topography was mainly smooth and undulating with an indistinct shelf break. Moderate-relief (6–10 m) ledges and rises (<5 m) occurred occasionally at depths of 50–70 m, and terraces occurred a little deeper at 70–110 m. The rock outcrops were composed of algal limestone,

quartz-rich calcarenite, and calcareous quartz sandstone. These shelf-edge features between Cape Hatteras and Cape Canaveral were primarily formed by calcareous deposition during the low sea-level stands of the Holocene transgression (Menzies et al., 1966; Rona, 1969; Zarudski and Uchupi, 1968). Average bottom temperatures at the shelf edge are warmer for longer duration than further inshore because of the influence of the Gulf Stream (Struhsaker, 1969); however, cold-water intrusions (caused by upwelling of deep water over the shelf) periodically decrease the outer-shelf bottom temperatures to 12°C or lower (Avent et al., 1977; Mathews and Pashuk, 1977; Leming, 1979). See SEAMAP-SA (2001) for maps of hard-bottom distribution in this region and depth zone.

Menzies et al. (1966) collected 170 species of invertebrates near a shelf-edge "algal reef" at 80–110 m off North Carolina. The fauna were numerically dominated by mollusks (45 species) and arthropods (34 species), but the hard-substrate bottom also supported sessile benthic invertebrates, such as corals and sponges. Cain (1972) identified 92 invertebrate species from three stations on the same reef, 37 of which were not previously known from that area. Macintyre and Milliman (1970) and Avent (1977) documented *Oculina varicosa* on shelf-edge features off north Florida, assemblages of the bivalve *Barbatia candida*, the echinoderm *Ophiothrix angulata*, and an additional 8 taxa of anthozoans, 32 decapods, 8 echinoderms, 16 (living) mollusks, and 26 bryozoans. Reed (1980) first described the biology of the shelf-break reefs and bioherms that are dominated by the branching scleractinian *O. varicose*. These high-relief ridges are most pronounced between 27°30'N and 28°30'N and form an almost continuous band of *O. varicosa* reefs near the edge of the continental shelf that are capped with live and standing dead coral colonies (Figure 6.12). The topography of this area was described in the 1970s (Macintyre and Milliman, 1970; Avent et al., 1977; Thompson et al., 1978), and the main tract of these coral reefs or bioherms has been documented from Fort Pierce to Cape Canaveral, Florida (Avent et al., 1977; Reed, 1980; 1981; 1983; 1992). In deep water, *O. varicosa* forms massive bushes of fragile colonies, creating continuous tracts of reef on the slopes and tops of pinnacles. The deep *Oculina* bioherms are the only known monospecific coral banks that occur on the North American continental shelf at less than 200 m (Ross and Nizinski, 2007).

The SCWMRD and GDNR 1981 and 1982 studies described in previous sections also included outer-shelf stations. The smallest of these (OS01) was a narrow strip (0.5 km^2) of low-relief hard-bottom located 120 km off the Georgia coast at ~60 m depth, and slightly inshore of a series of high-relief ridges that occur sporadically along the shelf break from Cape Hatteras, North Carolina to Fort Lauderdale, Florida (Henry and Giles, 1979). This station was adjacent to a "transitional zone" (Henry et al., 1980) between two pronounced scarps and had a sparse community of sessile benthic fauna. A second station (OS06) was located approximately 76 km off the South Carolina coast and was a large hard-bottom area (5 km^2) in 46–67 m water. This station comprised extensive "hummocks" of low to moderate relief with well-developed sessile benthic communities. This area is very close to hard-bottom sites (in MMS Lease Block 463) reported by Continental Shelf Associates (1979), who described the topography and bottom features in greater detail. In addition to scattered moderate-relief hard bottom, they described larger scarps and pinnacles from 5–8 m relief. Further north, the shelf-edge station (OS05) off North Carolina contained a gently sloping area mostly covered by sand and a steeper slope

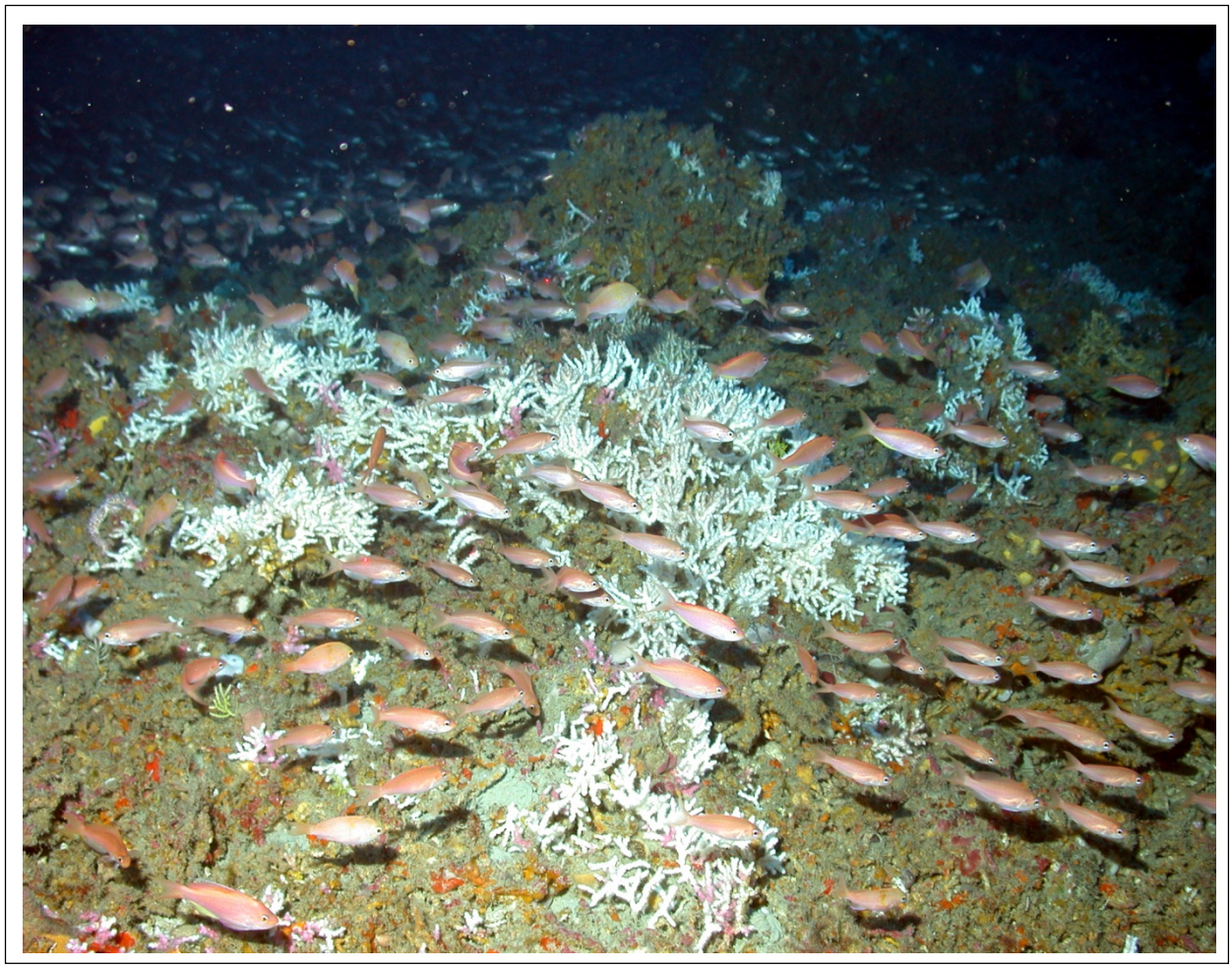

Figure 6.12 Live and dead *Oculina* colonies, which historically supported large numbers of fish, including commercially valuable species. Image courtesy of A. Shepard, UNCW.

between 70–100 m with frequent outcrops of rounded moderate-relief rocks, with a high-relief (5 m) ridge system at the deeper extent of the site (Figure 6.13).

Analysis of visual transects from the second year study (SCWMRD and GDNR, 1982) supported the distributions observed in the initial survey in 1980. Generally, large sponges were most common at middle-shelf stations and least common at outer-shelf depths. For example, occurrences of large barrel sponges *Spheciospongia vesparium* and the vase sponge *I. campana* were significantly greater at the middle- than the outer-shelf stations. The finger sponge *Haliclona oculata* was rare at the outer-shelf sites, but common at inner- and middle-shelf sites. Sponges were generally more frequent at stations off South Carolina and Georgia than North Carolina.

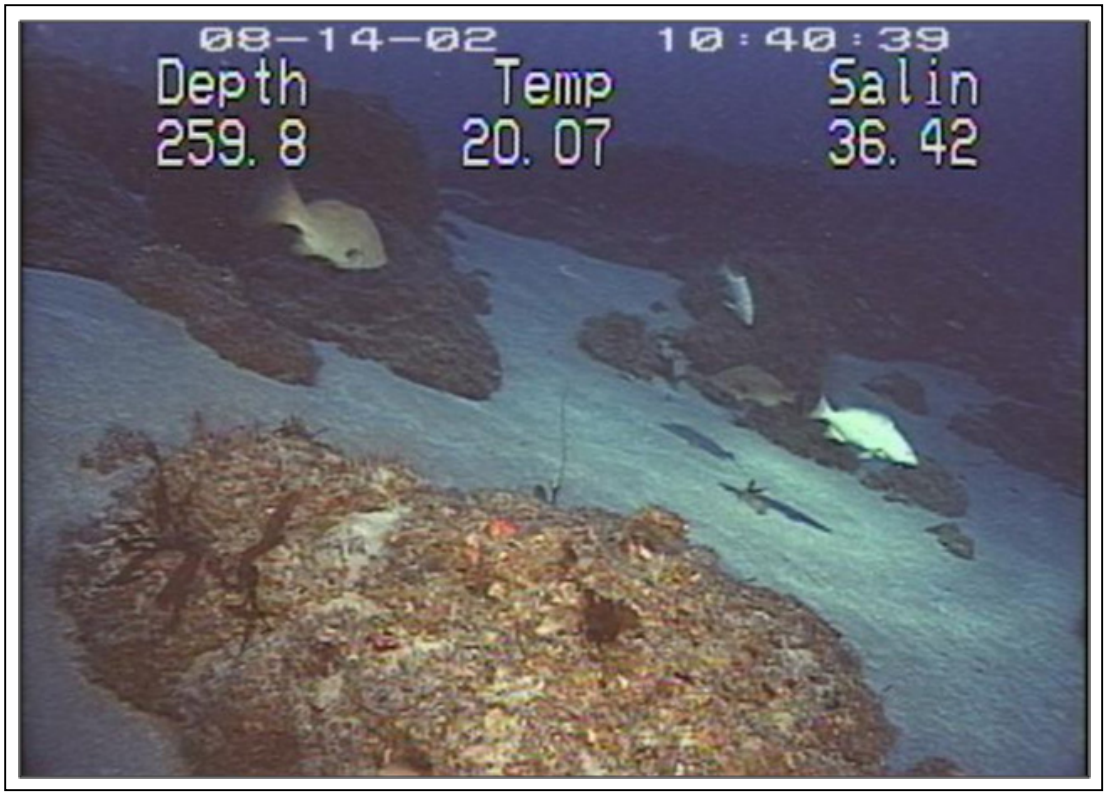

Figure 6.13 Deep shelf-edge habitat with rocky outcrops on sandy slopes. Courtesy of S.W. Ross, UNCW.

Octocorals at inner- and middle-shelf stations off South Carolina and Georgia were more common than sponges, but were absent or rare on the outer-shelf sites; only *Titanideum frauenfeldii* was observed at shelf-edge depths. This was the most frequently occurring octocoral species at all stations; significantly higher abundances occurred at inner and middle sites throughout the study range. The octocoral *Leptogorgia* spp. (mostly *L. virgulata*) was also common at inner-shelf sites, relatively rare on the middle shelf, but was not observed from transects on the outer-shelf sites. This pattern persisted for the fan corals *Lophogorgia* spp. and *Muricea pendula*; the former species was most common along the inner shelf and the latter was more common on the middle shelf. No fan corals were observed on outer-shelf transects, although they were collected there (rarely) by dredge and trawl. The octocoral distribution patterns described above were similar to those observed during the earlier (1980) study, except that all four genera were present at outer-shelf sites. In summary, based on two years of data, deeper live-bottom areas on the shelf break have a much lower incidence of large sponges and octocorals, especially the latter, than middle- and inner-shelf areas.

Benthic macro-algae were relatively abundant along the inner shelf during the summer, but were rare on the middle shelf and absent from the outer shelf. This is not surprising because algal growth is controlled primarily by light penetration, and the middle- and outer-shelf waters of the study region are deeper and frequently turbid.

Hard corals were rare in all habitats during the 1981 study. The more common stony corals in the region are species in the genera *Oculina, Siderastrea*, and *Solenastrea*, but these were seen very infrequently. For example, *Oculina* spp. was never documented from South Carolina and

Georgia, and the mound coral *Solenastrea hyades* was observed infrequently on inner- and middle-shelf sites. Off North Carolina, *Oculina* spp. was present in low abundance, and the mound corals were seen, but rarely on middle- and outer-shelf sites.

Black corals (Antipathidae) were only seen occasionally at offshore sites and were absent at inner- and middle-shelf stations off South Carolina and Georgia. A sample of one of these was identified as *Stichopathes* spp. (F. Bayer, National Museum of Natural History); however, Continental Shelf Associates (1979) identified a similar specimen as *Cirripathes* spp. Although visual surveys are an excellent non-destructive approach to community analysis, without supplementary sampling they do have taxonomic limitations.

Knott and Wendt (1985) published a literature synthesis of benthic studies conducted on slope areas of the Carolinas and northern Florida. MMS defined two areas of concern for this literature study. The northern area (divided into A and B) lies between the 200 m and 2,000 m contours from latitude 31°N (off Brunswick, Georgia) to 34°30'N (off Cape Lookout, North Carolina). The information for this area is summarized below in Section 6.3.4. The other area (area C) encompasses a shallower depth range (80–200 m) off northern Florida between 29°45'N and 30°30'N. The considerable variation in macrofaunal density between collections in this area (383–16,514 specimens per m^2) reflects the large temporal and spatial variability in faunal density that had been reported previously from continental shelf habitats (Tenore, 1979; SCWMRD and GDNR, 1981; 1982). The proposed causes of these differences varied between authors; Tenore (1979) suggested that patchy larval settlement created variation in density among soft-bottom areas, whereas SCWMRD (1982) attributed their observations primarily to differences in habitat complexity. Samples from hard-bottom sites had a much greater density range (15,282 per m^2) than those from the soft-bottom habitat (2,034 per m^2). As previously discussed, enhanced habitat complexity is the most likely cause of elevated species richness at hard-bottom stations compared with those with soft sediment. Information on macrofaunal biomass in the study area was limited to two stations and ranged from 4.8 to 28.6 g/m^2 (Tenore, 1979), which was similar to other outer-shelf stations in the South Atlantic Planning Area. There was a strong seasonal signal with much higher diversity values during the summer, probably due to the high abundance of the dominant structure-forming polychaetes (SCWMRD and GDNR, 1982). Bathymetric zonation may be an important determinant of species composition and community structure of macrofauna on both soft and hard-bottom habitats, and deeper stations on the outer shelf were dissimilar to the inner- and mid-shelf habitats. Samples collected from the study area are typical of a distinct outer-shelf/upper-slope faunal assemblage.

These previous studies mentioned a high degree of variation among different hard-bottom habitats; however, the relationship between habitat morphology and the richness and abundance of sessile invertebrates had not been specifically examined until a study by Fraser and Sedberry (2008). This study used video footage on eight different shelf-edge sites (50–70 m) from Jacksonville, Florida to northern South Carolina. The habitat types observed during video transects were divided into eleven different categories. The largest category was “low relief bioeroded habitat”; the smallest was “large boulders with sand,” and the scarps of northern Florida were the most well-defined hard-bottom reefs. The authors noted that bioerosion was a significant controlling force on hard-bottom morphology in the South Atlantic Planning Area, with sites off South Carolina being more eroded than those off Georgia and Florida. Bioerosion

can be caused by mechanical and chemical processes associated with algae, sponges, polychaetes, fish, and other organisms (Wilkinson, 1983), but the specific causes of the observed differences were not addressed. A study on similar habitats just north of the South Atlantic Planning Area also reviewed shelf-edge habitats, particularly in relation to fishes and Marine Protected Areas (Quattrini and Ross, 2006).

The transect analysis focused on the three species that accounted for ~90% of the individuals observed: the sponge *Ircinia campana*, the black coral *Stichopathes* spp., and the gorgonian *Muricea pendula*. The first two species were limited by temperature (>15°C) and depth (<70 m) and were most common in moderate-high relief structure with low-moderate sediment at 18–21°C. The gorgonian was found in all temperatures and depths but was most common at 21–24°C on low-relief structure with moderate sediment cover. None of the above species were found on low-relief, high-sediment transects. In general, those habitats characterized by high vertical relief and low-sediment cover had the greatest abundance and diversity of sessile benthic invertebrates; the greatest number of individuals were found at the St. Augustine Scarp, which is a very high-relief, low-sediment site (Fraser and Sedberry, 2008).

The Department of the Navy (2009) conducted an Environmental Impact Statement (EIS) for their Jacksonville Range Complex; this effort included a literature review for benthic and pelagic zones of federal waters between Wilmington, North Carolina and Daytona Beach, Florida. While this study reported similar hard-bottom, sessile benthic assemblages (sea fans, sea whips, ascidians, bryozoans, hard/soft corals, hydroids, anemones, and sponges) as had previous studies, they noted that not all hard-bottom habitats supported a rich benthic community (Kirby-Smith and Ustach, 1986; SAFMC, 1998). Also, despite mapping efforts by NOAA and other agencies in the South Atlantic region, much of the continental shelf from Cape Hatteras to Cape Canaveral has yet to be fully surveyed. The US Navy conducted multibeam surveys and habitat descriptions of the Jacksonville operations area, but this information is not publically available. Benthic surveys conducted in this study area revealed over 230 live/hard-bottom communities shoreward of 200 m depth (BLM, 1976). The highest concentration of hard-bottom communities on the inner shelf occurs off Cape Fear and between the area north of Jacksonville and Cape Canaveral. On the outer shelf, the highest concentrations of live/hard-bottom communities occur off South Carolina and northern Florida. The shelf break and several large offshore areas running parallel to the shelf break were also identified as additional potential locations of live/hard-bottom communities. Parker et al. (1983) estimated that hard-bottom represents 29.8% (7,403 km^2) of the substrate in depths of 27 and 101 m between Cape Fear and Cape Canaveral. Barans and Burrell (1976) estimated a slightly smaller area of 6,524 km^2 in depths of 19 and 55 m. See also SEAMAP-SA (2001) which identified areas of hard-bottom, possible hard-bottom and soft substrate between shore and 200 m depth (as shown in Figure 6.8).

Although the hard corals in the study region were dominated by branching corals and cup corals (e.g., *Oculina arbuscula* and *Astrangia danae*), there were also isolated patches of the hardier coral reef species (e.g., *Siderastrea*, *Solenastrea*) between 20–40 m depth in a few locations on the inner continental shelf southeast of Cape Fear (Macintyre and Pilkey, 1969; Huntsman and Macintyre, 1971). Farther south off the Georgia coast, the shelf-edge reef becomes the Savannah Scarp, a series of two or more parallel ridges in depths of 55–90 m. This is a popular location for recreational fishing for deep reef fish. Scientists from the South Carolina Department of Natural

Resources have documented more than 300 species of fish on shelf-edge, hard-bottom habitats (SCWMRD, 1985), and Quattrini and Ross (2006) documented fish associated with shelf-edge reefs off southern North Carolina. The large numbers of tropical, subtropical, and temperate species exist at these shelf-edge reefs because of the diversity of habitats (e.g., sand, hard flats, rocky ridges), and the proximity of both tropical (Gulf Stream) and temperate water masses. The hard substrate of the Savannah Scarp is dominated by moderate to heavy growth of sponges, bryozoans, and gorgonians (Barans and Henry, 1984), which provides shelter and other services to the abundant associated invertebrate and fish fauna. From Cape Canaveral to Fort Pierce, Florida, between depths of 50–100 m at the shelf edge and upper slope, bioherms are created by the branching scleractinian *Oculina varicosa*, and smaller colonies of *O. varicosa* also occur on low-relief pavement (Cairns, 1979; Reed, 1980; 1992). This area is known as the *Oculina* Banks and is discussed in Sections 6.3.5.1 and 6.3.6.2.

6.3.4 Continental Slope and Blake Plateau Hard-bottom Invertebrate Communities (~200 m – EEZ Boundary)

The dominant physiographic feature of the deeper parts of the South Atlantic Planning Area sea bottom is the massive Blake Plateau, which ranges offshore from east-central Florida northward to central North Carolina (see Chapter 2: Geological Oceanography). Its surface from 30°N to 32°N is covered with small features that were identified as coral mounds (Uchupi, 1967; Popenoe and Manheim, 2001). Instead of the soft sediments characteristic of the continental slope, the seafloor on the northern Blake Plateau consists of a hard pavement of cemented sediments and manganese-encrusted outcrops. The Gulf Stream flows along the Florida Hatteras Slope on the Blake Plateau's western flank, and strong currents prevent sediment accumulation. This hard-substrate, low-sediment, high-flow environment provides suitable conditions for the formation of deep-water scleractinian coral reefs (Cairns and Chapman, 2001; Ross and Nizinski, 2007; Roberts et al., 2009). To date, extensive deep-water coral bioherms and lithoherms of varying types and profiles have been documented from North Carolina to the Straits of Florida in areas deeper than 200 m (Stetson et al., 1962; Neumann et al., 1977; Reed, 1980; Paull et al., 2000; Partyka et al., 2007; Ross and Nizinski, 2007). Bioherms consist of caps of living coral on mounds of unconsolidated mud and coral debris (Reed, 2002a,b; Reed et al., 2006), whereas deep-water lithoherms are high-relief, lithified carbonate limestone mounds (Neumann et al., 1977; Paull et al., 2000) with attached coral colonies. Figure 6.14 represents a summary of deep coral areas from museum records and known coral areas sites along the slope of the South Atlantic Planning Area.

SCWMRD (1985) conducted a literature review on benthic invertebrate communities of the continental slope of the South Atlantic Bight; up to that time, there had been a number of studies on the continental shelf (see above), but the benthos of the deeper slope waters were relatively unknown. The deep portion of this study covered the 200–2,000 m depth interval from Brunswick, Georgia to Cape Lookout, North Carolina. They reviewed a variety of information (published and unpublished) from previous shelf and slope studies; however, in many cases comparisons among these studies were not possible because of differences in habitat type, sampling methodology, and data analysis. SCWMRD (1985) concluded that differences in species composition, density, and diversity were driven primarily by depth differences rather than differences in latitude or season. There was a general distinction between upper- and lower-slope communities, which were separated by a transition zone of rapid faunal change with depth.

Bottom currents, larval dispersal, and food availability undoubtedly influence the density, diversity, and distribution of benthic organisms on the continental slope. However, the greatest differences between epifaunal communities on the shelf and slope can be attributed primarily to substrate type. The epifauna that inhabit hard substrate are vastly different from soft-bottom fauna, regardless of depth. Hard substrate is not a common component of the slope, though there are localized topographic features that support areas of deep corals and sponges. The Blake Plateau is different in that much of it is composed of hard substrate, but from the limited information available, much of this is scoured by strong currents and is not populated by rich sessile benthic communities.

Early studies reported deep-water scleractinian corals on the continental slope between north Florida and Cape Hatteras, North Carolina (Stetson et al., 1962; 1969; Cairns, 1979; 1981; Ayers and Pilkey, 1981; Pinet et al., 1981). Cairns (1979) published a comprehensive review of the deep-water scleractinians from the Caribbean and adjacent waters, and included notes on the taxonomy and zoogeography of many species found in the present study area. The ecology of these deep coral ecosystems was not well documented in these early texts but, in the past decade, a significant amount of exploration and research has expanded understanding of deep coral ecosystems from North Carolina to south Florida (review in Ross and Nizinski, 2007).

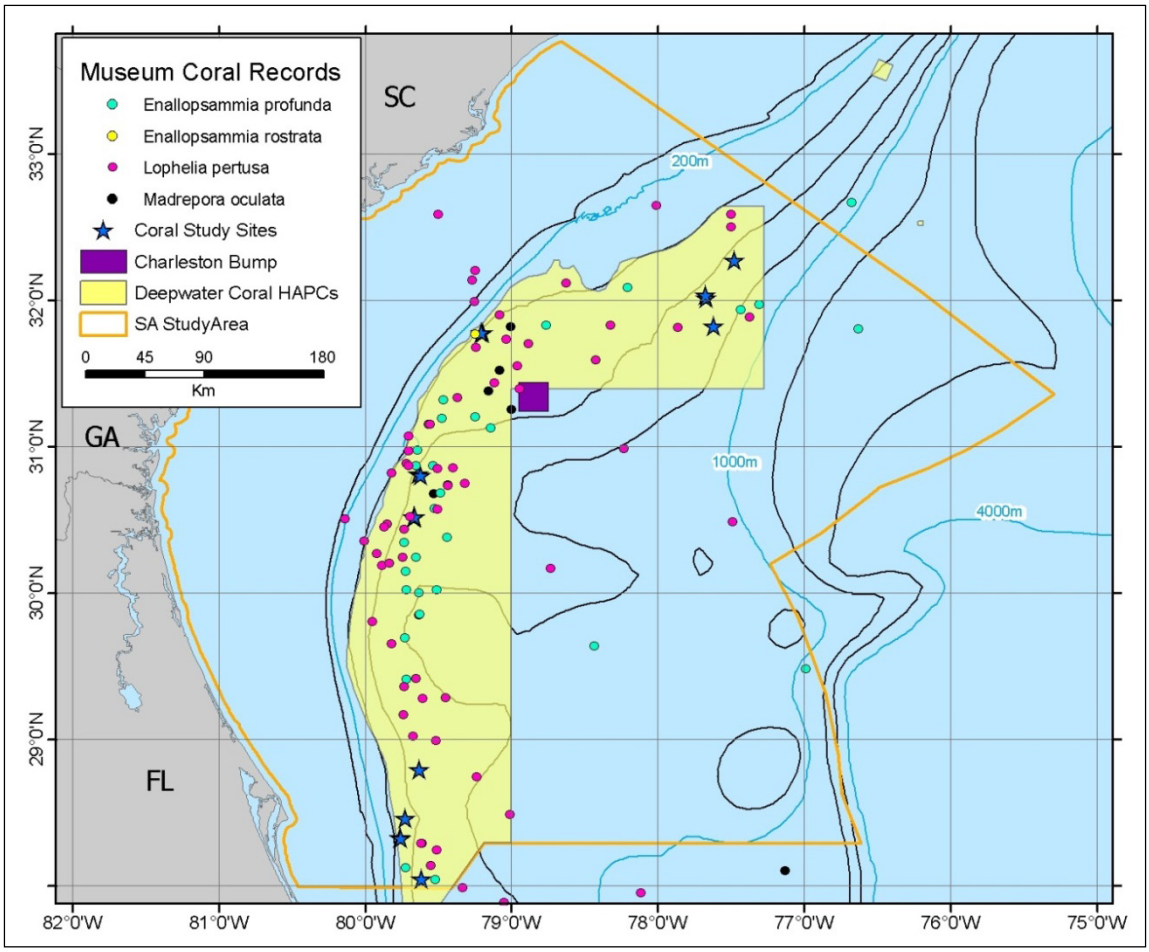

Figure 6.14 Known and potential deep coral habitats indicated by locations of museum records and study sites of recent research. Map courtesy S.W. Ross and M. Rhode, UNCW.

The structure-forming hard corals that dominate the slope depths (*Lophelia pertusa, Enallopsammia profunda*, and *Madrepora oculata*) (Figure 6.15) are different from those found on shelf-edge reefs (e.g., *Oculina varicosa*, *Siderastrea* spp., and *Solenastrea* spp.) and have distinct, non-overlapping depth distributions. Solitary corals were also commonly found in association with the deep framework-building species, including *Cyathoceras squiresi, Bathypsammia* spp., *Caryophyllia clavus,* and *Balanophyllia* spp. (Cairns, 1979; Pinet et al., 1981). The structure-forming corals create large bioherms or banks in some locations on the slope, with relief varying from 10 m to >100 m. Early studies described these coral ecosystems in some detail (Ayers and Pilkey, 1981; Pinet et al., 1981; Stetson et al., 1962), but were limited in their scope (mostly due to their sampling methods) relative to the information collected over the past decade on deep corals off the southeastern US.

The Department of the Navy (2009) EIS covered federal waters from North Carolina to Florida and included the deep slope areas >200 m out to the Exclusive Economic Zone (EEZ). This area contains substantial deep-sea coral habitat, particularly off Cape Lookout, North Carolina, South Carolina (Stetson Reefs), Georgia (Savannah Lithoherms), and east Florida *L. pertusa* reefs. The sites off North Carolina will not be discussed in detail as they are outside the study area; however, they are very similar in terms of structure and dominant associated fauna to the other areas detailed below (Partyka et al., 2007; Ross and Nizinski, 2007).

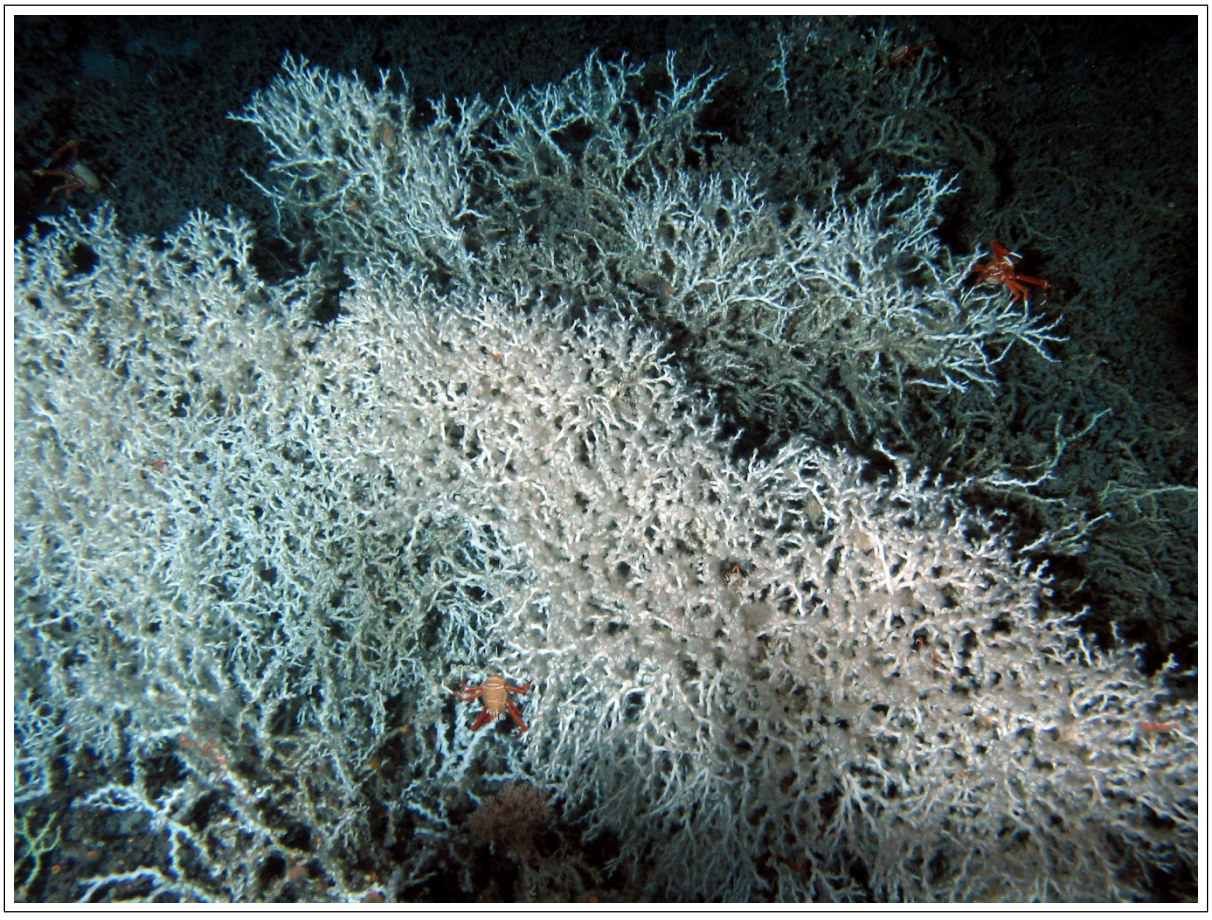

Figure 6.15 Large live colonies of *Lophelia pertusa* on the top of a bioherm off the north Florida coast (Brooke et al., 2005).

The Stetson Reefs are located on the eastern side of the Blake Plateau (Figure 6.14), approximately 220 km off the coast of South Carolina, and east of the Charleston Bump. This site ranges from 640–869 m depth and has an estimated 200 or more coral mounds (Stetson et al., 1962), which range in height from 46 to 102 m and encompass over 6,174 km^2 (Stetson et al., 1962; Reed et al., 2006; Partyka et al., 2007; Ross and Nizinski, 2007). The dominant structure-forming coral species was reported by Stetson (1961) as *Enallopsammia profunda*, with *L. pertusa* concentrated on top of the mounds. The heaviest coral growth was reported along an escarpment. Geological studies (Popenoe and Manheim, 2001) also indicated numerous features that could be corals mounds, but very few have been ground truthed. In 2002, two pinnacle areas in the Stetson region were explored, covering an area of 1.9 x 2.8 km (Reed et al., 2006). The benthos were dominated by Scleractinia (stony corals), Stylasteridae (hydrocorals), Octocorallia (soft corals), and Porifera (sponges). The primary structure-forming stony coral consisted of large colonies of *L. pertusa*, with some *E. profunda* and small quantities of *Solenosmillia variabilis* (Reed et al., 2006). This differs from Stetson's reports, but the relative dominance of each species can vary greatly within an area. Differences between observations from early and recent studies can also be affected by sampling gear; early studies surveyed large areas with sonar and other ship-based gear (trawls, dredges), compared with later studies using manned submersibles that studied smaller scale species' distributions (Reed et al., 2006; Ross and Quattrini, 2007; 2009). Small stylasters and solitary cup corals were common but do not contribute significantly to the complex reef structure. Dominant octocorals included species within the following families: Primnoidae, Paramuriceidae, Isididae (bamboo coral) (Figure 6.16A), and small colonies of Stolonifera and Nephtheidae (true soft corals). Sponges were also very abundant and diverse (eighteen identified taxa), especially on the steeper upper flanks of the features; some of these species are quite large (e.g., *Spongosorites* spp.) and provide habitat for other species. The most abundant taxa were Pachastrellidae, Corallistidae, Hexactinellida glass sponges, *Geodia* spp. (15–50 cm spheres), and *Leiodermatium* spp. The dominant invertebrate groups noted by Reed et al. (2006) included the decapods crabs, such as the squat lobster *Eumunida picta* (Eumunididae), the swimming crab *Bathynectes longispina*, and the commercially valuable golden crab *Chaceon fenneri* (Figure 6.16B) Dense populations of various brittlestars were visible within coral colonies (Brooks et al., 2007), and sponges were identified from videotapes.

The Savannah Lithoherms is a series of moderate-relief features located 165 km off Savannah, Georgia along the western edge of the Blake Plateau at depths of 490–850 m (Reed and Ross, 2005; Reed et al., 2006; Partyka et al., 2007; Ross and Nizinski, 2007). This area has been visited several times. Milliman et al. (1967) reported elongate coral mounds, approximately 10 m wide and 1 km long, oriented NNE-SSW with moderate slopes and 54 m relief. The mounds were dominated by small colonies of *E. profunda* and *L. pertusa.* Wenner and Barans (2001) described 15–23 m coral mounds with thickets of *Lophelia* and *Enallopsammia* near this area. In general, the high-relief *Lophelia* mounds in this region occur at depths of 490–550 m and have maximum relief of 61 m (Reed et al., 2006), but reefs in this area also seem to have a higher sediment cover than reefs in other areas (Ross and Quattrini, 2009). In addition to *L. pertusa*, there were other corals, such as black coral (*Antipathes* spp.), octocorals (bamboo corals and primnoid gorgonians), and abundant and diverse sponge species (10% of the total live coverage), similar to those noted above (*Phakellia* spp.*, Geodia* spp., Pachastrellidae, and Hexactinellida) found on the north faces (in the lee of the strong northerly current) of the high relief mounds.

The greatest coral development occurred on the upper peaks and ridges, with thickets of standing dead and live *L. pertusa* colonies. The south slopes of the lithoherms were less steep than the north slopes and primarily composed of dead *L. pertusa* rubble and coarse foraminiferal sand (Reed et al., 2006). Dominant motile fauna included decapod crustaceans (*C. fenneri* and galatheoids).

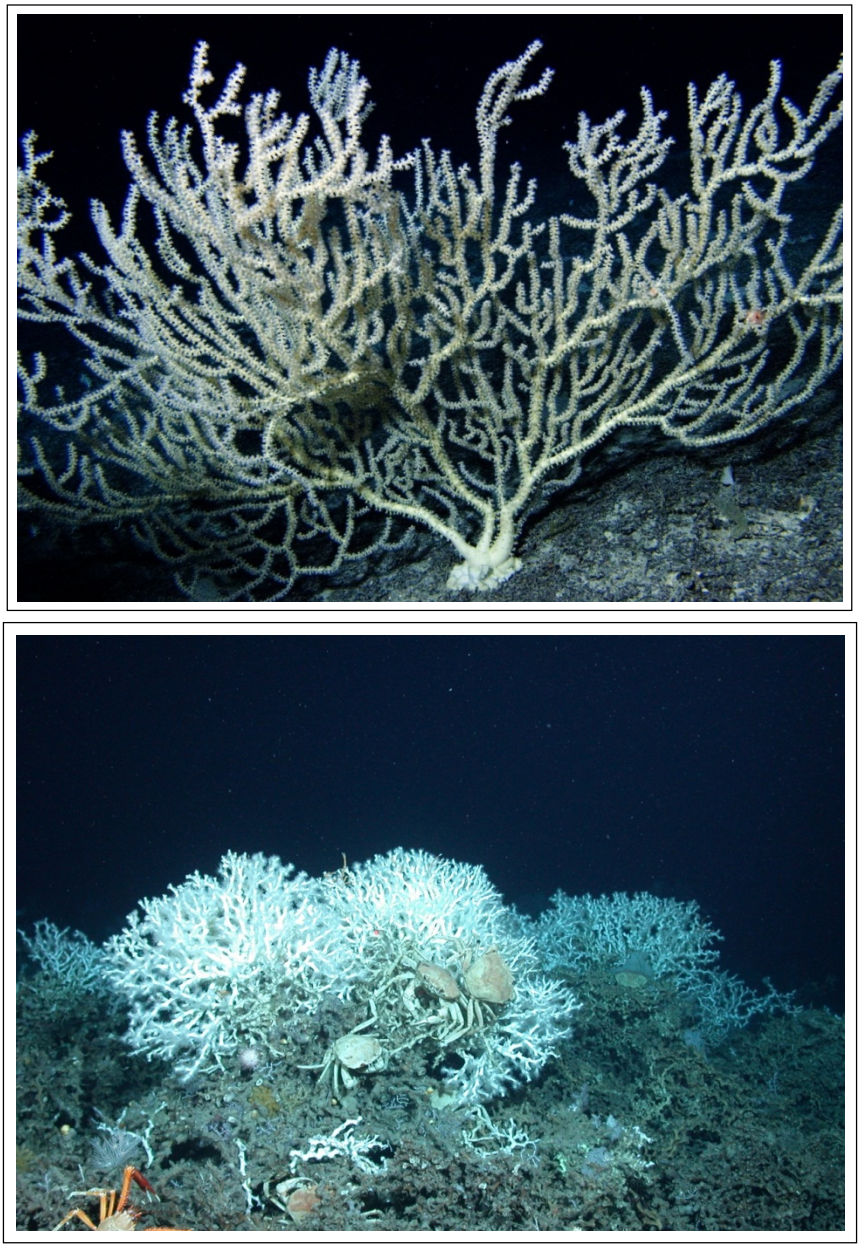

Figure 6.16 A) A very large colony of *Keratoisis* spp., a bamboo coral with the characteristic black and white skeleton visible through the tissue. Image from Brooke et al., 2005. B) Golden crabs associate closely with the deep coral habitat and are a commercial fishery species. Image from USGS (2010).

The Georgia and Florida deep coral reefs can be divided into two areas: Southern Georgia to Jacksonville, Florida (northern reefs) and St. Augustine to Jupiter, Florida (southern reefs), both of which occur within the 700 m to 800 m depth range (Reed and Ross, 2005; Reed et al., 2006; Ross and Nizinski, 2007; Ross and Quattrini, 2009). The northern sites are rocky pinnacles (lithoherms) with a cap of coral rubble and live coral thickets (Paull et al., 2000; Ross and Nizinski, 2007; Ross and Quattrini, 2009). In 2002 and 2004, Reed et al. (2006) documented ~300 mounds up to 168 m in height along a 222 km transect off north and central Florida from Jacksonville to Jupiter. At the northern end of this region they discovered a large feature (6 km long), which was comprised of several individual peaks. Submersible dives on the tallest of the peaks (107 m) revealed east- and west-facing slopes of sand, mud, and rock pavement with some coral rubble. The south (current-facing) slope, however, consisted of a series of terraces with dense thickets of dead standing and live *L. pertusa* along the terrace edges and the top of the peak where currents are accelerated. Other common sessile fauna included abundant bamboo corals (Isididae) and other gorgonians (*Placogorgia* spp., *Chrysogorgia* spp., and Plexauridae), soft corals (*Anthomastus* spp., *Capnella* spp.) and black corals (Antipathidae). Dominant sponges consisted of *Geodia* spp., *Phakellia* spp., *Spongosorites* spp., Petrosiidae, Pachastrellidae, and Hexactinellida (Reed et al., 2006).

Very little is known of the distribution or extent of deep corals between Jacksonville and Cape Canaveral, Florida; however, deep coral mounds in the Cape Canaveral region have been relatively well studied (Reed and Ross, 2005; Reed et al., 2006; Ross and Nizinski, 2007). The deeper of the coral mounds in this area are approximately 28 km east of the *Oculina* Banks Habitat Area of Particular Concern (HAPC). The deep features were first confirmed to be *L. pertusa* bioherms in 1982 using the CORD ROV (Reed, 2002b). These are some of the deepest coral mounds in the southeastern US and are formed from coral rubble and sediment capped with varying amounts of live and dead standing coral, with occasional dense thickets of *L. pertusa* and *E. profunda* on the crests and current facing slopes of the mounds (Partyka et al., 2007). The bases of the mounds were covered in scattered coral rubble and sediment. Other sessile benthic fauna included the scleractinian *M. oculata* and some stylasterid corals; dominant octocorals belonged to the families Primnoidae (gorgonians) and Isididae or bamboo corals (*Isidella* spp. and *Keratoisis flexibilis*), and the soft corals *Anthomastus* spp. and *Capnella* spp. Various sponge taxa were observed including several species of glass sponge (Hexactinellidae) and large demosponges (*Phakellia* spp. and Pachastrellidae).

In total, 30 Cnidaria and 18 Porifera taxa were documented by Reed et al. (2006) from these Cape Canaveral sites. Motile invertebrate fauna consisted primarily of echinoderms (several types of sea urchins and comatulid crinoids) and large decapod crustaceans (galatheoid crabs and the golden crab *C. fenneri*) (Reed et al., 2006). The shallowest documented *L. pertusa* bioherms were also found off Cape Canaveral, but further inshore (~60 km offshore) at approximately 400 m depth on the Florida Hatteras slope. These shallow features were first identified as *L. pertusa* bioherms as recently as 2005 (Brooke et al., 2005). Since then, four more bioherms have been discovered in the same small area, and all have an unusually high percentage of live coral thickets and a very diverse and abundant invertebrate and fish fauna (Brooke, Reed, Ross, Unpubl. data).

In response to research revealing the distribution, importance, and uniqueness of these deepwater coral habitats, the SAFMC and NOAA established five deep-water Coral Habitat Areas of Particular Concern (CHAPC) through the Comprehensive Fishery Ecosystem Plan Amendment (Figure 11.1 in Chapter 11: Areas of Special Concern). The final rule was published in the Federal Register on June 22, 2010 (75 FR 35330) and provided regulations to prevent bottom damage to the coral habitat from fishing activities. Within the CHAPCs, the possession of coral species and the use of all bottom-damaging gear, including bottom longline, trawls (bottom and mid-water), dredges, pot or trap, anchors and chain, grapples and chain, by all fishing vessels are prohibited. The total area of the CHAPCs is >60,000 km^2, and ~42,840 km^2 (300–1,100 m depth) of which are located within the Jacksonville and Charleston Navy operational areas; however, it is not clear how the CHAPC regulations will influence military operations.

The most current information on deep coral ecosystems in the South Atlantic Planning Area (Ross and Nizinski, 2007) reported a coral assemblage consisting of 114 known species of corals (Anthozoa and Hydrozoa), including 57 species of scleractinians (47 solitary and 10 colonial species), 4 antipatharians, 1 zoanthid, 44 octocorals, 1 pennatulid, and 7 stylasterids. This list will no doubt be increased as exploration and research continues.

The dominant structure-forming coral of the South Atlantic Planning Area is *Lophelia pertusa*, a cosmopolitan branching scleractinian species that occurs throughout the southeast US in depths of ~370 to 800 m. This species occurs as small, scattered colonies attached to various hard substrates but also forms complex, high-profile features. A typical *Lophelia* bioherm is formed from the growth of branching coral colonies, which over time become so large that the inner colony dies and bioerosional processes weaken the dead coral branches. These eventually collapse and fill with sediment, forming a sediment/coral rubble matrix. The outer living branches continue to grow, and new recruits may colonize the exposed dead core, creating rubble structures topped with almost monotypic stands of live *L. pertusa* (Wilson, 1979; Ayers and Pilkey, 1981; Paull et al., 2000; Popenoe and Manheim, 2001). As this process continues over thousands of years, these mounds and pinnacles can reach tens of meters in height, with the live coral forming a cover over the unconsolidated dead coral debris below. Along the sides and around the bases of the bioherms are rubble zones of dead coral pieces with occasional small live colonies, which may extend large distances away from the mounds. Conditions are not always appropriate for bioherm formation, and hard substrates can be colonized by large individual *L. pertusa* colonies, especially on the Blake Plateau where strong bottom currents may prevent sediment build-up (Popenoe and Manheim, 2001). Although *Lophelia* is the dominant hard coral off the southeastern US, other scleractinians, such as the colonial corals *Madrepora oculata* and *Enallopsammia profunda*, contribute to the overall complexity of the habitat. The branching coral *E. profunda* is similar in growth form to *L. pertusa* and sometimes forms mounds, especially further south off Florida; however, *M. oculata* only occurs as individual relatively rare colonies within or adjacent to *L. pertusa* or *E. profunda* mounds. Solitary coral species are often attached to coral rubble or underlying hard substrate. Most species appear to be either uncommon or rare, but local abundance of some species can be very high. For example, dense patches of *Thecopsammia socialis* and *Bathypsammia fallosocialis* cover dead coral branches on and near many reefs.

Black corals (Class Anthozoa, Order Antipatharia) are important structure-forming corals on the slope of the South Atlantic Planning Area. These corals occur locally in moderate abundances especially in the southern region, and colonies may become large (1–2 m) and provide structure for small mobile invertebrates, such as galatheoid crabs. Some of these coral "trees" may be hundreds to thousands of years old (Williams et al., 2006; 2007). The growth rings deposited by black corals are not only used to determine age and growth, but they also contain important chemical records on past climates, ocean physics, ocean productivity, pollution, and data relevant to global geochemical cycles. Gold corals (Class Anthozoa, Order Zoanthidae), which occur in the area, are also slow growing and long lived, reaching ages of up to 1,800 years old (Griffin and Druffel, 1989; Druffel et al., 1995) and may also be valuable archives of ocean history. Unlike most other corals, these do not settle on hard substrate, but use the skeletons of other species as initial structure and deposit their own skeletons over the top. These long-lived species in some places are harvested for jewelry. The *Gerardia* spp. are not common in the southeastern US but can be found on branches of *L. pertusa*, bamboo corals (*Keratoisis* spp.), or black corals (*Leiopathes* spp.). Like most other deep coral species, very little is known about the biology of these taxa, and their taxonomy is poorly understood, making identifications problematic if samples are not available.

The gorgonians (Class Anthozoa, Subclass Octocorallia or Alcyonaria, Order Gorgonacea) are by far the most diverse taxon on the slope of the South Atlantic Planning Area. There are 7 families, 16 genera, and 32 species currently known (see Ross and Nizinski, 2007 for full listing), and this is undoubtedly an underestimate. The most speciose family is the Primnoidae, but the bamboo corals (Family Isididae) are the best-known members of this group because of their larger size and distinctive morphology. Like the black corals, they can be locally abundant, reach ~2 m in height, and provide structure for other species. The true soft corals (Order Alcyonacea) are also octocorals, but they do not have the gorgonian skeleton as a support structure and are generally small (<30 cm). They are frequently seen on the rubble at the base or slopes of coral mounds rather than the dense coral habitat near the mound tops, with the exception of *Anthomastus agassizi,* a small mushroom-shaped red soft coral that can be very abundant on dead coral branches. Three families, Alcyoniidae, Nephtheidae, and Nidaliidae, comprise the true soft corals in the South Atlantic Planning Area, and only six species are known for this group. Stoloniferans, (suborder Stolonifera) are represented by one family (Clavulariidae) off the southeast region, with six species from four genera reported. One species, *Clavularia modesta*, is widespread throughout the western Atlantic; the other five species are known from North Carolina southward to the Caribbean.

Although stylasterids (Class Hydrozoa, Order Anthoathecatae) are not found in great abundances, stylasterids (lace corals) commonly occur in the South Atlantic Planning Area. Seven species representing four genera have been reported from the region. Individuals observed in situ are often attached to dead scleractinian corals or coral rubble. Abundance and diversity of stylasterids increase southward from the Carolinas. Other Hydrozoa from the deep reefs of this region were reviewed by Henry et al. (2008), who reported 35 species of hydroids, many of which were new records for the region. Hydroids are a diverse group of generally small cnidarians that commonly grow on dead coral rubble.

The other significant phylum of the deep-reef benthic fauna is the Porifera or sponges. Unlike shallow reefs, deep-water coral systems in the South Atlantic Planning Area have a great diversity and abundance of glass sponges (Hexactinellidae). Some of these are locally abundant, (e.g., *Aphrocallistes* spp., *Euplectella* spp., *Phaekelia* spp., and *Hertwigia* spp.) (Figure 6.17), and some are quite large. Small crustaceans are found living on or in the sponge structure, and a species of small yellow zoanthid populate the osculae of *Aphrocallistes* spp. at such high densities that the sponge appears yellow. Demosponges also occur on the deep reefs (e.g., geodid sponges) but the taxonomy of these and the glass sponges is very poorly described and represents an obvious gap in our knowledge of deep coral reef diversity of the South Atlantic Planning Area.

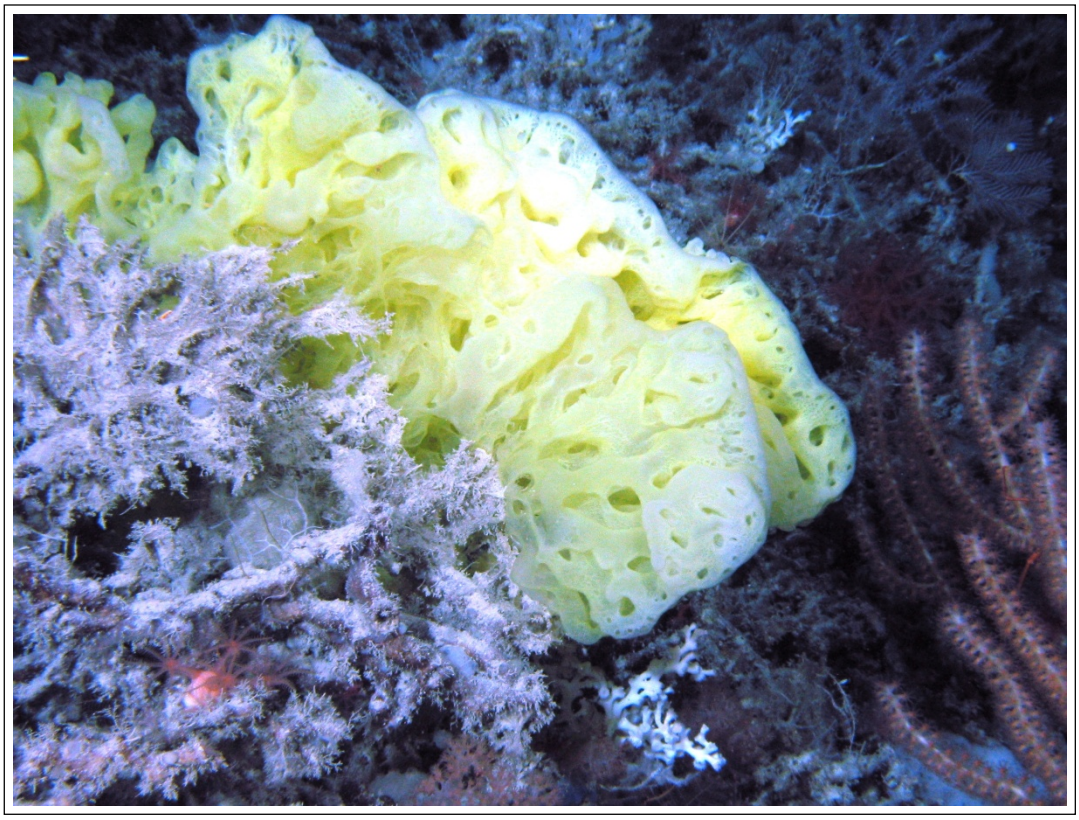

Figure 6.17 A bright yellow *Hertwigia* glass sponge from the deep reefs off the South Atlantic Planning Area. Sponges are very abundant and diverse components of deep reef ecosystems, but their taxonomy is very poorly known. Image from Brooke et al. (2005).

These coral reefs support an incredibly diverse and abundant invertebrate fauna (Reed et al., 2006; Ross and Nizinski, 2007; Henry et al., 2008). The squat lobster *Eumunida picta,* the brisingid seastar *Novodinia antillensis,* and cromalulid crinoids are especially ubiquitous, perched high on coral bushes presumably to optimize food supply transported by the currents.

The commercially important golden crab often occur closely associated with living *L. pertusa*, especially in the southern part of the area. Many different species of sponges, echinoderms, cnidarians (Messing et al., 1990), and crustaceans (Wenner and Barans, 2001) have been reported from deep-coral reefs off Florida, the northeastern Straits of Florida, and the Charleston

Bump region (Reed et al., 2006). Reed et al. (2006) provided a preliminary list of invertebrates, mostly sponges and corals, from some deep-coral habitats on the Blake Plateau and Straits of Florida; however, most taxa were not identified to species. Lack of data on the invertebrate fauna associated with deep corals is a major deficiency. See Chapter 7–Fish and Fish Habitat for more information on fishes associated with different hard-bottom habitats.

6.3.5 Ecology of Sessile Habitat Forming Taxa

This section provides a summary of available biological information on hard-bottom taxa in the South Atlantic Planning Area that increase structure for other species. It should be noted that while general distributional data, habitat coverage, and species richness are poorly known for the deep reef invertebrates of this region (despite the last decade of increased research), their biology and ecology are even less well studied. For many of the following sections, information is presented only for Florida. Equivalent information was not available throughout the study area.

6.3.5.1 Corals

Physical factors characteristic of temperate habitats may restrict the distribution of shallow coral reefs to tropical latitudes. Low and variable temperatures and elevated turbidity and nutrient levels may contribute to the latitudinal restriction of shallow stony corals and coral reefs (Crossland, 1988). Alternatively, Johannes et al. (1983) suggested that physical factors act indirectly through biotic interactions along the latitudinal gradient. For example, they hypothesized that seaweeds competitively exclude corals at higher latitudes because there are more nutrients available for seaweed growth. The primary restrictions on latitudinal distribution of coral reefs are probably a combination of physical and biological factors that vary spatially and temporally. Coral (anthozoan) diversity decreases sharply with latitude along the southeastern U.S. shelf; hard corals are rare north of Martin County, Florida, and species richness decreases, as well. The branching species *Oculina varicosa* and *O. diffusa,* and the small boulder-shaped *Siderastrea radians* and *S. siderea* can be found throughout the extent of the Florida coastline on nearshore and middle-shelf ledges, with occasional small colonies of *Cladocora arbuscula* and the cup corals *Phyllangia americana* and *Astrangia* spp. Species in the genus *Oculina* can be locally abundant on rocky ledges from Florida to North Carolina, in depths from the intertidal to the shelf edge and provide habitat for a diverse associated community, especially in deeper depths (Reed et al., 1982; Reed and Mikkelson, 1987; Brooke and Young, 2005). Various aspects of the biology and ecology of *Oculina* spp. have been investigated over the past several decades. Most of this research has focused on the deep *Oculina* bioherms that occur off east-central Florida (Reed, 1980; 1981; 1983; Reed et al., 1982; Reed and Hoskin, 1987; Reed and Mikkelson, 1987; Miller, 1995; Brooke and Young, 2003; 2005), whose ecological importance resulted in their being designated as a HAPC by SAFMC in 1984. McCloskey (1970) conducted a detailed study of shallow *O. arbuscula* from four study sites off North Carolina and South Carolina, which included an analysis of the species associated with eight moderate-sized coral heads. The diversity of coral-associated communities in this study correlated with the environmental regime, increasing with stability of temperature and decreasing with higher silt and sand scour but, remarkably, was not affected by seasonal changes. The dominant community members were generally not obligate coral associates, but often spent their entire lifecycles within the colonies. The structure of the community also changed with the age of the coral colony, with increasing boring and eroding species in older colonies. The majority of

the community consisted of deposit feeders. Overall the diversity of the community was "remarkably stable and predictable" (McCloskey, 1970)

There are relatively few studies on life histories of temperate or sub-tropical coral species, but *Oculina varicosa* is an exception. The *Oculina* spp. coral colonies provide habitat for other sessile and mobile faunal assemblages throughout the southeastern US, Caribbean, and Gulf of Mexico, but it is the large complex mesophotic reefs created by *O. varicosa* off east-central Florida that have stimulated interest in the biology and ecology of this species. The coral reproductive cycle begins in the early summer, and spawning occurs during late summer and fall, with large quantities of eggs (2,115–4,693 cm^2 skeletal surface area) and sperm released from separate male and female colonies (Brooke and Young, 2005). Reproductive cycles in broadcast-spawning species (those that release gametes into the water column) are all synchronous to some degree, which is necessary to ensure that the gametes are fertilized. Many tropical hermaphroditic species release gametes according to strict lunar schedules over a short period of time every year (e.g., Harrison and Wallace, 1990), but gonochoristic (separate sexes) broadcast spawners tend to have longer reproductive seasons and less tightly synchronized spawning periods than their hermaphroditic counterparts, with gamete release occurring over a number of weeks (Harrison and Wallace, 1990). Colonies of *O. varicosa* exhibited asynchronous gametogenesis and spawning, which provides the population with some security against releasing gametes into unfavorable water conditions or into currents that may carry them away from suitable settlement habitat. *O. varicosa* larvae (planulae) are small (~160 μm), can withstand a wide range of temperatures, and settle approximately 21 days after spawning (Brooke and Young, 2003; 2005). The larvae are active swimmers and can adjust their position in the water column; in laboratory cultures, *O. varicosa* larvae swam towards the water surface upon formation of ciliary bands and remained there for several hours, after which they began to swim throughout the water column or became demersal. This behavior has been reported in planulae from other species in the laboratory and attributed to changing phototactic or geotactic responses. This behavior was observed in *O. varicosa* larvae, even when embryos were kept in the dark, which implies a negative geotactic response.

For oceanic plankton, there is a risk of predation and unfavorable transport associated with the upper part of the water column. Conversely, staying near the reef also presents the risk of being consumed by adult corals or other benthic predators. The larvae may avoid the hazards of the reef by moving up in the water column, but ultimately they have to return to the benthos to settle. Temperature over the shallow Florida shelf habitats varies from 7 to 29.5ºC, partly from seasonal changes, but also because of periodic upwelling events that inundate the shelf habitats with cold deep-ocean water (Smith, 1981), subjecting both deep and shallow *O. varicosa* populations to rapid temperature fluctuations (Smith, 1981; 1983; 1987). Temperature can have a significant effect on mortality and metamorphosis in coral larvae; however, the investigation into the effect of temperature on larval survival and swimming speed shows that *O. varicosa* larvae can survive the temperature extremes that occur at the reef during the spawning season (Brooke and Young, 2005). Visibility on the shallow ledges generally ranges over 1–10 m but, during periods of phytoplankton blooms or storm activity, can be reduced to a few centimeters. Particles from the water column are deposited during calm conditions producing a thick layer of fine sediment on the substrate. Embryos and larvae of *O. varicosa* could, therefore, be exposed to a wide range of environmental conditions during their development. Physiological tolerances of coral dispersive

stages may strongly influence recruitment patterns and genetic exchange among *O. varicosa* populations. In general, *O. varicosa* larval characteristics are conducive to wide dispersal potential, but there is little information available on other important processes, such as larval supply, recruitment rates, and post recruitment survival. Studies of Florida shelf hydrodynamics (Smith, 1981; 1983; 1987) show that the strongest cross-shelf transport events occur during the late summer, when *Oculina* are spawning. It is unclear how much of the recruitment onto the Florida nearshore reefs comes from deep-water larvae, but the mechanism for transport exists in these upwelling events. Although the along-shelf water movement is dominated by the northerly flowing Florida Current, there are occasional current direction reversals that can potentially transport larvae north or south between along both deep and shallow reef tracts. Some gametes may be spawned into currents that transport the larvae to suitable settlement sites, whereas others may be carried to unsuitable habitat or out to sea and lost. A three-dimensional hydrodynamic model of the shelf and further information on larval behavior are required before informed estimates of larval dispersal can be made for this and other species.

Reed et al. (1982) analyzed the abundance and species richness of decapod crustaceans associated with *Oculina* colonies at four depths (6, 27, 42, 80 m) on the Florida shelf. The species richness was similar across depths, but the abundance of decapods was considerably higher for the deep colonies (even after standardizing for colony size). Relatively low numbers of species were found at all depths; from a total of 50 species (15 families), only 4 species (4 families) were common across the whole depth range. These data support previous observations on species "endemic" to the shallowest and deepest habitats, which suggest that there are two different communities occurring within *Oculina* habitats. The decapods represented only 11.5% of the total number of macro-invertebrates; amphipods, mollusks, polychaete worms, and tanaid crustaceans represented 20, 19, 15, and 12%, respectively (Reed et al., 1982). These were also the dominant groups on colonies of *O. arbuscula* from North Carolina (McCloskey, 1970), but decapod crustaceans represented only 1% of the total. Of the 50 decapod species found on *O. varicosa,* 12 species were also found on *O. arbuscula.* Numerically dominant decapods shared by both oculinid species include *Megalobrachium soriatum* (Porcellanidae), *Pagurus carolinensis, Mithrax forceps* (Majidae), and *Synalpheus fritzmuelleri* (Alpheidae). The decapod crustaceans (although taxonomically similar) are numerically less important in the more northern biotope off the Carolinas.

For most of the year, the majority of *Oculina* colonies are dark brown (colored by the symbiotic zooxanthellae), but this genus is facultatively zooanthellate, which means it can survive without zooxanthellae and colonies frequently occur fully or partially bleached. Unlike tropical reefs, which live in oligotrophic waters, the shelf of the South Atlantic Planning Area has relatively high nutrient levels, and there is sufficient plankton in coastal waters to compensate for the lack of zooxanthellae. Intact and partially digested crustacean skeletons were found in the gastric cavities of shallow *O. varicosa* samples on numerous occasions (S. Brooke, pers. obs.). A study of the distribution and growth of *O. arbuscula* under different light and temperature regimes (Miller, 1995) showed that highest growth rates occurred in higher light and warmer temperatures, similar to shallow tropical corals. Therefore, although *Oculina* can survive without symbionts, coral growth rates are enhanced by their presence (Miller, 1995; Brooke, 2002). Despite the apparently better growth conditions at shallow depths, coral abundance was greater in deeper, shelf-edge water where both light and temperature are reduced. The density of

macroalgae was also measured during the experiment and was found to be greater in the shallows. Thus, although conditions on the shallower ledges may favor the growth of both coral and algae, it appears that that the corals were being out-competed by the algae, which supports a hypothesis suggested by Johannes et al. (1983) that algae controls the distribution of corals at higher latitudes. Growth rates in zooxanthellate and azooxanthellate colonies of a temperate cup coral, *Astrangia danae,* were studied under different light and temperature regimes (Johannes et al., 1983). Photosynthesis was reduced and calcification and coral growth were dependent on plankton (heterotrophic) consumption at temperatures below 15°C. At even lower temperatures (<6ºC), feeding and growth both ceased. If these temperature thresholds are similar for *O. arbuscula*, heterotrophic consumption could be important to coral growth during much of the year, since inshore water temperature is consistently below 15°C for several months per year. These studies suggest that both biotic (food supply, competition) and physical factors (temperature, light) influence the distribution of corals in sub-tropical and temperate climates.

In addition to increasing overall habitat complexity, large sessile benthic organisms, such as corals and sponges, may provide microhabitat for smaller fauna (mostly invertebrates) living on or within their tissues and internal spaces. Abdo (2007) referred to these as "endofauna." Generally, the endofauna associated with sponges are dominated by polychaetes, amphipods, decapods, and mollusks that live either on the sponge surface as epibionts or within the canal system as endobionts (Pearse, 1932; Wendt et al., 1985; Voultsiadou-Koukoura, 1987; Duarte and Nalesso, 1996; Ribeiro et al., 2003). Octocorals lack the extensive canal system of sponges; however, the external surface area of their branches can support a variety of small invertebrates, such as amphipods, gastropods, and bivalves (Patton, 1972; Wendt et al., 1985). Of the many taxa inhabiting the reef epifauna, amphipods and polychaetes were by far the most abundant, representing 96% of the total endofauna, followed by gastropods, anthozoans, barnacles, and nematodes. For the sponges specifically, by far the most common endofauna species was the polychaete, *Haplosyllis spongicola*, followed by the amphipod, *Ericthonius*. Large sessile fauna of deep-water reefs also support very rich communities of invertebrates; faunal diversity on *Oculina* and *Lophelia* reefs is equivalent to that of many shallow tropical reefs (Ross and Nizinski, 2007). Over 20,000 individual invertebrates were found living among branches of 42 small *Oculina* colonies, yielding more than 350 different species (Reed, 1992; Reed and Hoskin, 1987; Reed and Mikkelson, 1987; Reed, 2000), many of which are important food sources for animals at higher trophic levels.

There has been a relatively large amount of research into the biology and ecology of deep corals from the South Atlantic Planning Area in the last decade (see Ross and Nizinski, 2007 for review), but information on the composition, biology, and ecology of the benthic deep-reef-associated invertebrates remains inadequate. Deep-water coral ecosystems that are composed of *Lophelia pertusa* or *Enallopsammia profunda* are very similar to the shallower *Oculina* reefs and form in the same manner. Individual colonies coalesce to form thickets, the inner areas stagnate and die, are bio-eroded, then filled with sediment, while the outer cap of live coral continues to grow. After thousands of years of growth and sediment infilling, bioherms form from a matrix of coral rubble and sediment with an outer layer of living coral. For an overview of carbonate mound formation, see Roberts et al. (2009). Although very few organisms can settle on the live coral with its batteries of nematocysts (stinging cells), the dead part of the coral colonies provide substrate for numerous other sessile species such as hydroids, gorgonians, soft corals, black

corals, sponges, and bivalves. The coral colonies also provide habitat for an abundant and diverse motile fauna including sea urchins, brittlestars, comatulid crinoids, sea stars, shrimps, galatheoid crabs, larger decapods, and fishes. The red galatheoid *Eumunida picta* is very common among *L. pertusa* and *E. profunda* colonies, and it is often seen in an ambush stance on the coral with its claws raised. The commercially harvested golden crab *Chaeceron fenneri* is also often seen in large numbers within or adjacent to the coral reefs. Knowledge of the species richness of deep coral reefs of the South Atlantic Planning Area (and elsewhere) is far from complete, and new species and range extensions are discovered with every research cruise (e.g., Henry et al., 2008; Mah et al., 2010). One of the few species that grows within the live part of the coral colony is the eunicid polychaete *Eunice norvegicus*. This worm can reach several centimeters in length and builds a chitinous tube attached to the live coral branches. The coral then overgrows the soft tube and creates a strong calcified layer around it, effectively providing a shelter for the worm. In return the calcified worm tubes help strengthen the coral branches. The worms are predatory, but their feeding relationship with the coral is unclear.

Of all the deep coral species, *L. pertusa* has been the focus of the greatest research efforts in both the eastern and western Atlantic (see review in Roberts et al., 2009). Several estimates have been made of the growth rates of this important species. Growth has been inferred from measurements of colonies growing on man-made structures, such as telegraph cables and oil platforms (Bell and Smith, 1999; Gass and Roberts, 2006). Growth estimates range from 6–35 mm/yr and, although natural variability may account for some of this range, this method generally underestimates growth rates. Linear and radial growth rates of *L. pertusa* have been estimated using skeletal stable isotopes of carbon (^{13}C) and oxygen (^{18}O) (Mikkelsen et al., 1982; Freiwald et al., 1997; Mortensen and Rapp, 1998; Rogers, 1999), and have also resulted in a wide range of growth rates (6–25 mm/yr). Direct measurements of coral growth measured in aquaria for *L. pertusa* (Mortensen, 2000; Orejas et al., 2008) yielded linear extension rates of 9.4 and 15–17 mm/yr, but there are obvious artifacts involved with extrapolating aquaria observations to field growth rates. The first direct measurements of in situ growth rates were from the Gulf of Mexico and produced an average linear growth rate of ~3.8 mm/yr (Brooke and Young, 2009). Experiments on environmental tolerances showed that *L. pertusa* is quite tolerant to high sedimentation rates (Brooke et al., 2009) and moderate temperature ranges. Reproductive biology of *L. pertusa* has been studied from the eastern (Waller and Tyler, 2005) and western Atlantic. This species is gonochoristic (each colony is a separate gender) and has an annual spawning season where colonies release eggs (~160 μm in diameter) and sperm into the water column to produce planktonic larvae. In the eastern Atlantic, this species spawns in late winter (Waller and Tyler, 2005), but in the South Atlantic Planning Area, spawning occurs at the end of September (S. Brooke, unpubl. data); the reasons for this offset are unknown but probably relate to differences in seasonal productivity. There is currently no published information on *L. pertusa* larval development, and this is an area of study that is greatly needed.

The large deep-water "tree" corals, such as antipatharians, gorgonians, and the precious gold coral *Gerardia* spp. (which is a parasitic zonathid), can be very slow growing and long lived. Recent radiometric work on samples from Hawaii and the Atlantic has estimated the lifespan of gold coral samples between 450 and 2,700 years (Druffel et al., 1995; Roark et al., 2006). Pink corals from Hawaii 70 cm in height were 80 years of age, and black corals from the Atlantic have been aged at hundreds to thousands of years (Williams et al., 2006; 2007). Bamboo coral

colonies from New Zealand with a trunk diameter of 1.4 cm were found to be several decades in age with an average radial growth rate (i.e., increase in size of the coral trunk) of 0.18 mm/yr (Tracey et al., 2007). A bamboo coral (*Keratoisis* spp.) from off the southeastern US was found to be about 400 years old (Sinclair et al., in press). Such age and growth characteristics mean that these kinds of coral ecosystems are very vulnerable to overharvesting (precious corals are used for jewelry) and other damaging human activities.

Tree corals have also been used recently to reconstruct historical climate conditions (Heikoop et al., 2002; Thresher et al., 2004; Sherwood et al., 2005). Black corals are abundant in deep-water, hard-bottom habitats off of the South Atlantic Planning Area. The skeletons of these long-lived species are formed from thin concentric bands of protein and organic material (Goldberg, 1991), whose isotopic signature reflects that of the water mass during the time of skeletal deposition. The isotopic composition of skeletal material from three antipatharian specimens from the South Atlantic Planning Area (estimated to be 200–500 years old) all showed enrichment in ^{15}N over the past 75 years, which is probably a result of increased terrestrial effluent (sewage and manure) reaching the offshore specimens (Williams et al., 2006; 2007). These ancient corals, therefore, represent a valuable archive of ocean conditions long before humans were recording environmental data.

6.3.5.2 Sponges

Sponges are an abundant and diverse component of hard-bottom habitats throughout the geographic and bathymetric range of the study region, and they serve multiple ecological functions. Most species provide shelter for various invertebrates, such as small crustaceans, worms, mollusks, and brittlestars. They are an important food source for many reef fish species (Pawlik, 1998), and as filter feeders they may also remove significant quantities of nutrients from the water column (Peterson et al., 2007; Bell, 2008). Freeman et al. (2007) identified three major sponge community habitat types (rocky scarp, plateau, and cryptic) associated with mid-depth (13–30 m) hard-bottom off Georgia. Each habitat type had a distinctive set of sponge species and growth forms, probably controlled by a combination of biotic (predation and competition) and abiotic (sedimentation and current regime) factors. The two dominant sponge growth forms were encrusting (40% of species) and amorphous/massive (25% of species), followed by branching, pedunculate, and digitate species. The scarp habitat, which was mostly hard substrate, was heavily colonized by encrusting or amorphous/massive sponges. The majority (66%) of species found on the sandy plateau areas were either digitate (*Raspailia* spp. nov., *Ciocalypta gibbsi*, *Aulospongus samariensis*, and *Axinyssa ambrosia*) or pedunculate (*Clathria carteri*, *Axinella waltonsmithi*, *Axinella bookhouti*, *Higginsia strigilata*, and *Clathria prolifera*). While this study did not investigate the causes of the habitat partitioning, previous observations indicated more spongivorous fish predators on scarp habitats (Ruzicka, 2005) and greater sediment stress on the plateau. The third major habitat type, the cryptic region, was the primary habitat for many of the rare sponges encountered by Freeman et al. (2007). They speculated that predation or competitive exclusion by faster growing species might restrict the rare species to cryptic habitats (Meesters et al., 1991; Wulff, 1997). Freeman et al. (2007) also identified fifteen sponge species that were new records for the Carolinian province and two species that were endemic to the area. The authors found a mix of temperate and tropical sponge species, which supports the hypothesis that this area is a transition zone between temperate and tropical Atlantic waters. This survey found a very different suite of sponge species from the study carried out by SCWMRD et al.

(1982a, 1982b) 25 years earlier. The discrepancy in findings may have been caused by different sampling techniques (i.e., different habitats were sampled by trawl/dredge in the earlier study versus scuba divers in the later work), taxonomic inconsistencies, or may reflect a real change in the sponge fauna over time.

Sponges can reproduce sexually and asexually, although the relative importance of these strategies to the population is unclear. It has been postulated that fragmentation may occur more in shallow water where wave-induced turbulence is higher than in calmer deep water (Continental Shelf Associates, 2009). Some vertical species such as *Aplysina* spp. and *Iotrochota birotulata* (both common off east Florida) may reproduce exclusively through asexual fragmentation (Wulff, 1991). Sexual reproduction in most sponges is by internal fertilization where embryos either develop within the sponge and crawl away on release, or are shed into the water column where they develop into lecithotropic larvae and settle after a short planktonic period (Lindquist et al., 1997; Maldonado and Bergquist, 2002). Very little information is available on reproductive timing, dispersal, or recruitment patterns for either shallow or deep-water sponges.

Sponges are major contributors to benthic community structure on temperate reefs and, although several studies have investigated how abiotic processes control sponge distributions on these reefs, the role of predation is less clear. Ruzicka and Gleason (2009) investigated the relationship between predators and the distribution of sponges on temperate reefs off Georgia and documented sponge species richness and abundance, and density of sponge-eating (spongivorous) fishes. They also examined the ability of nineteen sponge species to chemically and structurally deter predation by fishes. They found that sponges had greater chemical deterrents where there were more spongivorous fishes, and in other locations, the sponges had more structural (i.e., more spicules in their tissues) than chemical defenses. Predation appears to play a role in shaping sponge community structure on South Atlantic Planning Area reefs by restricting those species lacking adequate chemical defenses to habitats where there are fewer spongivores.

6.3.5.3 Hydrozoans

There are twelve identified species of hydrozoans along the east Florida coast (<200 m), which is lower diversity than the other dominant sessile invertebrates in the region. Some of the more common hydroid species along the coast include: *Thyroscyphus ramosus, Campanularia* sp*., Eudendrium ramosum, Lytocarpus philipinus, Pennaria* spp., and *Sertularella* spp. Some of the larger hydrozoans may provide shelter for small associates, but most probably serve a limited function as habitat. In addition, their generally small size and batteries of nematocysts (stinging cells) make it unlikely that they are an important food source in the benthic food web. Hydrozoans are colonial organisms with complex life cycles that can include polyps, medusae, and planula larvae. Reproduction can occur via asexual (budding or medusa production) or sexual (planula larvae) mechanisms. Medusae and planulae may drift in the plankton or crawl along the substrate, but most are short-lived so dispersal potential is low (Martin and Koss, 2002).

Henry et al. (2008) were the first to describe the hydroid community from shelf-edge (82–103 m) and deep-water (368–770 m) reef habitats from North Carolina to central Florida. Thirty-five

species of hydroids were identified, and, of these, ten species and one family were documented for the first time in the South Atlantic Bight. Latitudinal and depth ranges were also extended for 25 species. Sexually mature individuals of nineteen species were found during the summer-fall; most of these species (89%) release well-developed larvae, a strategy that may reduce the risk of dispersal to suboptimal habitats. Hydroids occurred across various substrate types including coral rubble, live corals, rock, and other organisms. Hydroid assemblages from deep-water coral habitats of the South Atlantic Planning Area were most similar to those from the Straits of Florida/Bahamas and Caribbean/West Indian regions (14 and 8 shared species, respectively).

6.3.5.4 Polychaetes

Diversity and abundance of polychaete worms are relatively high (>87 species) on hard-bottoms of the east Florida shelf (<200 m), but little is known about the biology or ecological function of most species. They are probably important components of food webs, both as consumers (most polychaetes are suspension feeders but some are deposit feeders or carnivores) and food sources for other fish and invertebrates. The most well-studied polychaete species is *Phragmatopoma lapidosa*, which lives in the intertidal and shallow subtidal from southern Florida to Cape Canaveral. This species uses sand to build tubes and create large colonies known as "worm rock" or "worm reef." The structure of the worm reefs provides habitat for a higher diversity and abundance of marine species than adjacent hard-bottom or soft-sediment habitats. These reefs have yielded >423 invertebrate species (Nelson, 1989; Nelson and Demetriades, 1992; Continental Shelf Associates, 2009) and >200 fish species (Gilmore et al., 1981; Lindeman, 1997; Lindeman and Snyder, 1999). Worm reefs were designated essential fish habitat (EFH) and a HAPC by the National Marine Fisheries Service (NMFS) because of their value as habitat for other species. Worm reefs also serve an important function in protecting shorelines from erosion (Multer and Milliman, 1967; Mehta, 1973; Kirtley, 1974). Polychaetes are likely also important to deep-water (>200 m) reefs, but there is very little known of them in these depths and reef habitats. The exception to this general observation is *Eunice norvegia*, a large predaceous species that builds chitinous tubes among the branches of live *L. pertusa*. The coral subsequently overgrows the tube, creating a hard calcified shell, which presumably provides protection for the polychaete. It has been postulated that the incorporation of the tube into the coral branches serves to strengthen the colony (Roberts et al., 2009).

6.3.5.5 Tunicates

Tunicates are quite abundant and diverse along the entire Florida coast; most are colonial (branching or encrusting) but some species are solitary, large, and abundant (e.g., *Phallusia* and *Mogula* spp.), especially under ledges and crevices. There is very little information available on the cross-shelf and latitudinal distribution of tunicate species. Most species probably do not significantly enhance benthic habitat, but may provide shelter for small crabs, amphipods, shrimp, worms, mollusks, brittlestars, etc. Their trophic role in the ecosystem is not well understood; however, because tunicates often produce secondary metabolites (i.e., potential toxins), it is not likely that they are an important food source for many other species, especially fishes (Pisut and Pawlik, 2002; Odate and Pawlik, 2007). These taxa are all hermaphroditic and reproduce sexually by releasing crawl-away larvae that quickly settle close to the parent colonies. They can also reproduce asexually by budding, thereby increasing colony size (Clooney et al., 2002). There is very little information on tunicate reproductive periods or

recruitment; some appear to recruit throughout the year, and others are sporadic and infrequent (McCarthy, 2001).

6.3.5.6 Bryozoans

Bryozoans are quite abundant and diverse (93 species) along hard-bottom habitats of the Florida coast. These taxa are colonial for the most part and commonly found under ledges and in crevices, occupying similar habitat niches to the tunicates. Branching bryozoans (e.g., *Bugula*) can provide shelter for small ophiuroids, crustaceans, etc., but do not significantly enhance structural complexity or increase community diversity. The trophic role of bryozoans is not clear for this region, but in general they are filter feeders that remove small plankton from the water column, and they are preyed upon by nudibranchs, sea urchins, sea stars, crustaceans, and mollusks. Bryzoans have a complex life cycle with different reproductive mechanisms. They can bud asexually (Seed and Hughes, 1992), or the hermaphroditic individual colonies can reproduce sexually using several different reproductive strategies, which are species dependent. Fertilization may be internal or external, giving rise to a planktonic larval form that spends extended periods feeding in the plankton, or short-lived, non-feeding larvae that settle soon after release. The dispersal potential of the planktonic larval form is much greater than the short-lived larvae, but there is very little information on recruitment rates. McCarthy (2001) recorded rare and sporadic settlement of three bryozoan species on settlement plates in south Florida. There is little information on distribution of bryozoan species by latitude or depth (Continental Shelf Associates, 2009).

6.3.6 Ecologically Sensitive Areas

6.3.6.1 Gray's Reef National Marine Sanctuary

GRNMS is located 32.4 km off of Sapelo Island, Georgia (Figure 11.1) in water depths of 18–20 m. This 58-km^2 sanctuary is the only NMS in federal waters in the South Atlantic Planning Area. Gray's Reef includes a large area of emergent hard-bottom ("live-bottom") which is the reason it was selected for a NMS, and this reef environment supports a rich assemblage of subtropical and temperate fauna. The rocky features are composed mostly of limestone and vary in profile from flat, smooth surfaces (most common) to vertical scarps and ledges, generally <2 m tall (Riggs et al., 1996). Hard substrates occur in variously sized patches throughout the Sanctuary. While sandy (quartz and carbonate mostly) habitat is abundant in GRNMS (about 75% of bottom cover), it is the complex, high-profile, hard-bottom habitat composing <1% of the bottom surface area (Kendall et al., 2005) that has attracted a diverse and abundant community of organisms. Bottom water temperatures can range from a summer high of 26°C to a winter low of 11°C. The winter low temperatures limit the long-term colonization of some tropical/subtropical species (Ruzicka and Gleason, 2009).

As with most of the marine waters off the southeastern US, the soft-bottom invertebrate communities of GRNMS are generally more completely described than the hard-bottom communities (e.g., Balthis et al., 2007). Even so, GRNMS contains one of the most studied hard-bottom habitats of the South Atlantic Planning Area. Gleason et al. (2005) provide a list and keys to invertebrates within the Sanctuary. The most comprehensive assessment of attached sessile organisms on the hard substrate of GRNMS was described in Kendall et al. (2007); however, dominant sessile organisms were only classified to major groupings (algae, sponges, corals,

gorgonians). The abundant epifaunal sponges and octocorals in turn serve as host to a variety of endofaunal organisms, with as many as 115 taxa occurring on three species of sponges and three species of octocorals (Greene, 2008). The Porifera (sponges) appear to be the best studied of the reef invertebrates from this area with studies ranging from sponge chemical defenses (e.g., Freeman and Gleason, 2010) to descriptions of the sponge fauna (Freeman et al., 2007). Freeman et al. (2007) listed 52 species of hard-bottom sponges from within or near GRNMS, 15 of which were new records for the region. These represented a nearly equal mix of temperate and tropical species, suggesting that this area off Georgia represented a zoogeographic transition zone. A new species of Ascidian was very recently described from the shallow hard-bottom of GRNMS (Sanamyan and Gleason, 2009). Fioravanti-Score (1998) found that bryozoa were the dominant early colonizers of various artificial substrates at GRNMS, with higher colonization rates for all invertebrates on hard-bottom areas compared with settling blocks placed on soft substrate. The scleractinian coral, *Oculina arbuscula*, apparently maintained its populations on Gray's Reef by sexually produced planulae that exhibited mostly local recruitment (Wagner, 2006).

6.3.6.2 Oculina Habitat Area of Particular Concern

In 1984, SAFMC designated 316 km^2 of the deep banks as the *Oculina* Habitat Area of Particular Concern (OHAPC) because of their importance to the life histories of many commercially valuable species. Mobile fishing gear and anchoring were prohibited to protect the delicate *Oculina* thickets. In 1994 the OHAPC was closed to all bottom fishing for ten years. This area was designated the Experimental *Oculina* Research Reserve (EORR), but was later renamed the *Oculina* Closed Area (OCA). In 2000, SAFMC expanded the OHAPC to 1029 km^2 to protect all known high-relief coral bioherms.

After the implementation of protective measures, the OHAPC was visited infrequently by researchers. In 1995 research cruises using a ROV and a research submersible (Johnson-Sea-Link) visited historical areas of known coral thickets. They found thick bushes of coral that had been reduced to rubble, evidence of trawling damage to coral habitat known to have been intact twenty years earlier, and the near complete loss of many reef fish populations (Koenig et al., 2000). Jeff's Reef, a small (4 hectare) area in the southern portion of the OCA, appeared in surveys to be the only intact coral area; however, the biomass and number of economically important fish populations were much lower than they had been twenty years earlier. In 2001, the Johnson-Sea-Link submersible was again used to survey the *Oculina* Banks to estimate the relative proportion of intact and rubble *Oculina* habitat and to evaluate reef fish use of natural and artificial structure within the EORR. This study found that only a small number of high-relief sites had intact live coral thickets. Overall, approximately 90% of the habitat surveyed appeared to be unconsolidated rubble while less than 10% contained intact coral colonies. This estimate was probably high, because ROV transects were directed at pinnacles and ridges that are known to support *Oculina* thickets (Reed, 1980; Koenig et al., 2000). The percentage of intact *Oculina* habitat on high-relief features is more likely between 1 and 10%. Thickets of *Oculina* are comprised of a dead understory of coral, with an outer cover of live coral; standing dead coral skeleton is valuable because it provides habitat for numerous other invertebrates and is a natural part of the reef construction. The relative abundance of live compared with dead standing colonies was highly variable, but the large live thickets occur predominantly on the south slopes facing the prevailing current (Gulf Stream) and tops of ridges and pinnacles where currents are accelerated. No additional coral thicket sites were found within the EORR, and

historical areas of coral thickets north of the EORR contained only coral rubble. There was virtually no indication of recovery in the areas that had been badly damaged, despite the high reproductive output of this species and larvae that have high tolerance to environmental variables and good dispersal potential. Unfavorable larval transport, insufficient suitable substrate, low natural recruitment rates, and continued disturbance from illegal fishing activity may all impede reef regeneration. Between 1996 and 2001, large concrete modules were deployed in damaged areas of the *Oculina* banks as part of a restoration effort (Brooke et al., 2006), but to date very little coral recruitment has been observed (Brooke, pers. obs.). Further research on *Oculina* larval settlement and a three-dimensional model of the complex hydrodynamic regime of the Florida shelf would enable prediction of larval transport and recruitment within and among *Oculina* populations.

6.3.6.3 Shelf Edge MPAs

In 2009, SAFMC implemented a series of eight deepwater MPAs in the South Atlantic region to protect long-lived, deep-water snapper and grouper species and their habitat from fishing pressure. Adults (and sometimes juveniles) of most snapper and grouper species are demersal associates of hard-bottom habitat of moderate to high relief. These MPAs supposedly represent areas of hard-bottom habitat that are important to the target snapper and grouper species, but some of the areas have not been fully surveyed. Images of the Snowy Grouper Wreck MPA show some fauna that are normally found much deeper (Figure 6.18).

The deepest part of this protected area is ~285 m, which is very shallow for these species. The interchange of complex geography and oceanography of within the South Atlantic Bight may provide appropriate environmental conditions for a mixing or transition between the shelf-edge and slope faunal assemblages. The shelf-edge seafloor of the South Atlantic Planning Area ranges from soft substrate, to high rocky relief with heavy encrustations of corals, sponges, and other invertebrate fauna. See Section 7.2.4.1.2 in Chapter 7: Fish and Fish Habitat for more information on these MPAs and Quattrini and Ross (2006) for a review of the Snowy Grouper Wreck MPA off southern North Carolina.

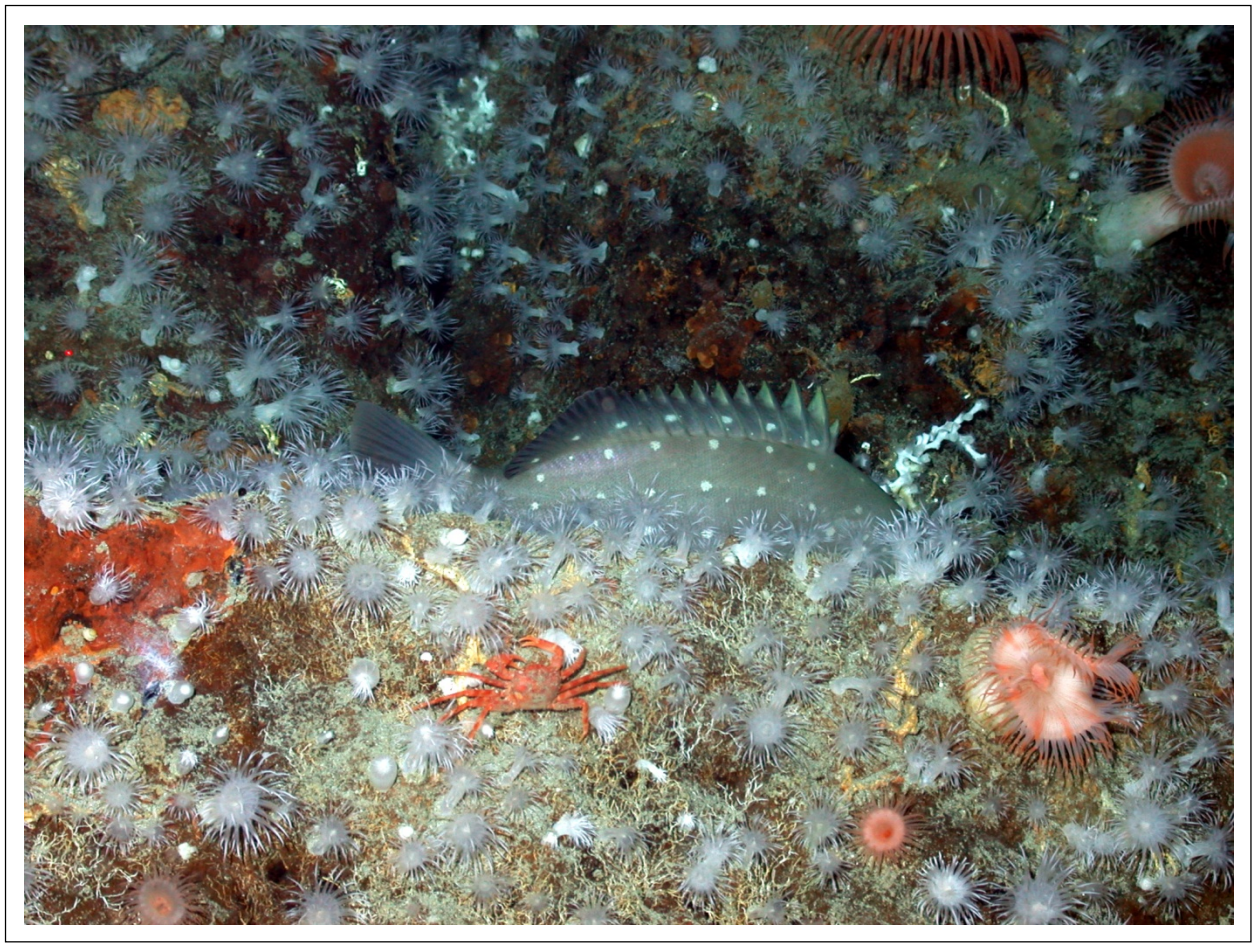

Figure 6.18 A juvenile snowy grouper hiding in a wreck, with small colonies of *Lopehlia pertusa* and venus flytrap anemone, which are characteristic of much deeper habitats. Image courtesy S.W. Ross, UNCW.

6.3.6.4 Deep Coral HAPCs

Deep-coral reefs are fragile and susceptible to physical destruction (Fossa et al., 2002). It is estimated that these deep reefs may be hundreds to thousands of years old (Neumann et al., 1977; Wilson, 1979; Ayers and Pilkey, 1981; Mikkelsen et al., 1982; Mortensen and Rapp, 1998). However, aging data are so limited (especially in the western Atlantic) that the age of coral mounds in the western Atlantic is unclear. Research in recent years has shown extensive and apparently pristine deep-water coral banks extending from North Carolina into the Gulf of Mexico. SAFMC recognized the importance of these areas and, in 2005, began the process of placing the deep reefs under protection as a HAPC. Working with regional scientists on the Coral Advisory Panel, they defined boundaries that encompassed the known extent of the deep reef systems from North Carolina to southern Florida. Two small-scale fisheries that worked close to the reefs: the golden crab trap fishery and the royal red shrimp trawl fishery. The Council worked with these fishers to define boundaries that would protect the reefs and permit the fisheries to continue (Figure 6.14). The HAPC was implemented 22 July 2010 and prohibits harvesting of corals or use of any bottom contact gear.

6.3.6.5 Charleston Bump

The Charleston Bump (see review in Sedberry, 2001) is a large elevated topographic feature intruding seaward onto the Blake Plateau off the coast of Charleston, South Carolina (Figure 6.14) whose size and location cause a deflection of the northward flowing Gulf Stream (Brooks and Bane, 1978). This geological and oceanographic phenomenon often creates a visible increase in sea surface height over the feature. The topography and geology varies considerably across the Charleston Bump (see Chapter 2: Geological Oceanography).

Blake et al. (1987) reported a diverse sessile benthic fauna in the vicinity of the Charleston Bump, dominated by corals and sponges. Consistent differences were found between the fauna inhabiting the upstream and downstream sides of the bump. The highest densities were found on top of the bump and on the first two ledges on the downstream side where the greatest quantity of exposed hard substrate occurred. The lowest densities were found in the trough behind the bump which was predominantly sandy substrate. Most of these taxa were sessile filter feeders, so the observed distribution was probably also influenced by current speed. The upstream side of the bump receives the full force of the Gulf Stream, which may preclude successful colonization and survival of fragile corals and sponges. Alternatively, the lower faunal densities in the trough, which is in the lee of the bump, may be related to current speeds that were too low to support filter feeders.

While most taxa were found throughout the region, they showed marked depth and location preferences. The most noticeable difference between the areas was that stylasterid hydrocorals dominated on the downstream side of the bump, while gorgonians dominated on the top, the upstream side, and in the trough. Structural differences between these two groups may explain this distribution. Stylasterids have a rigid, calcified skeleton and a dense branching pattern that results in a large surface area. In contrast, the skeleton of gorgonians is less massive, more flexible, and the branching pattern is sparser. Since filter feeders frequently orient themselves so their greatest surface area is facing the current, the bases of the rigid stylasterids would be subjected to greater current force than more flexible gorgonians. The low density of stylasterids in the trough behind the bump indicates that conditions are not suitable, possibly because of reduced current speeds or increased sedimentation.

Within these two dominant taxa (gorgonians and hydrocorals), certain species occurred in different habitat types and at different depths. The stylasterid *Stylaster complanatus* was most common on the shallow part of the downstream slope, while *Stylaster erubescens* was most common on the manganese-covered hard substrate slightly deeper. The other abundant stylasterid *Distichopora foliacea* was found in equal densities on the top and upper sides of the slope. The most common gorgonian found in the Charleston Bump region was *Swiftia casta*. This species was present in highest densities on top of the feature but was found throughout most of the area studied. Gorgonian species in the genus *Plumarella* were found in highest densities in the deeper portion of the upstream side and in the trough on the downstream side of the bump. *Plumarella pourtalesii* was found in comparable densities in both regions, while another species, *Plumarella* spp., preferred the upstream side. An unidentified species of the gorgonian *Swiftia* was found only in the trough.

Several of the other common taxonomic groups in this area also showed marked habitat and depth preferences. An unidentified bryozoan was confined to the depths above 600 m and was found in high densities only on the top and upstream side of the bump. In contrast, a small scleractinian, *Thecopsammia socialis*, was found only in the trough behind the bump. The dominant sponges inhabiting the Charleston Bump showed similar preferences. Depth and location appeared to be the dominant factors controlling community structure of benthic fauna on the Charleston Bump. The most pronounced faunal change occurred around 600 m depth; the shallower fauna differed substantially from those deeper than 600 m. Regions of rapid faunal change coincided with pronounced changes in topography and geology.

6.3.7 Anthropogenic Disturbance from Commercial Trawl Fisheries

Commercial trawl fisheries in federal waters of the South Atlantic Planning Area are limited to mainly penaeid shrimp fishing, the majority of which occurs over soft-bottom habitat. At various times there has been a trawl fishery for calico scallops in scattered locations, mostly off northern Florida and North Carolina; however, this fishery seems currently inactive. The indirect habitat impact to hard-bottom from trawl activity would be sediment suspension, which can damage sessile benthic fauna if severe and sustained, but otherwise would probably cause relatively minor short-term effects (Barnette, 2001). The exception to this is the rock shrimp fishery, as the target species are known to live close to hard-bottom features. SAFMC (2002) reported that rock shrimp fishers seek coral and sponge habitat and then trawl in the sandy areas nearby. Rock shrimp harvesting has been primarily focused on the deeper shelf habitats from ~40 to 80 m off east-central Florida, with limited occasional fishing off Georgia and the Carolinas. The greatest rock shrimp fishing intensity occurred off Cape Canaveral, Florida where it overlapped with the coral bioherms of the *Oculina* Banks. Large historical reefs have probably been destroyed by trawling, and there is no question that flat featureless coral rubble is far less ecologically valuable than intact colonies. Observations from research cruises show that sessile invertebrates have not colonized these impacted areas, and there are almost no fishes or mobile invertebrates associated with the rubble fields. The extensive physical destruction of the *Oculina* bioherms strongly suggests anthropogenic mechanical damage. Foreign trawlers fishing for red porgy on the east Florida shelf (Russian fishery technologist, pers, comm. to C. Koenig) likely caused some of the observed *Oculina* destruction until the late 1970s, when foreign fishing within US waters ended after the establishment of the US EEZ. Domestic fisheries for rock shrimp and calico scallop trawling continued inside the US EEZ, but were closed in part of the *Oculina* Banks in 1984 with establishment of the OHAPC (Koenig et al., 2000). Trawling continued along the northern portion of the Banks until 2000 when the OHAPC was expanded to encompass the known extent of *Oculina* habitat. The degree to which trawling in the OHAPC decreased after 1984 is unknown due to lack of surveillance and enforcement, but, based on the massive destruction of the coral bioherms, it is likely that considerable trawling continued illegally. Evidence that it has continued up to the present time includes broken experimental structures (Koenig and Brooke, pers. obs.), recent arrests of trawl vessels in the OHAPC, and recent observations of trawler boundary violations (Shepard and Brooke, pers. obs.). During World War II, US Navy ships used explosive depth charges against German U-boats west of the OHAPC (Cremer, 1986); these could have been responsible for some historical damage to these corals. However, this ended over 70 years ago and habitat recovery would be expected by this time unless: 1) other activities continued to damage the area, 2) the rubble is not appropriate habitat for re-colonization, 3) recruitment and spawning dynamics have changed due to changing

biology or changing oceanography, or 4) combinations of the above. World War II era wrecks near the OHAPC are well colonized by dense *Oculina* thickets (M. Barnette, pers. comm.), so recovery has not been limited by larval delivery or colony growth.

One of the difficulties with assessing damage from fishing gear is the lack of controlled experiments. Van Dolah et al. (1987), using a roller-rigged trawl,studied the effects of trawling on hard-bottom sponge and coral habitats off Georgia. They observed various levels of damage to most species of sponges (*Ircinia campana, Haliclona oculata*), octocorals (*Leptogorgia virgulata, Lophogorgia hebes, Titanideum frauenfeldii*) and stony corals (*Oculina varicosa*), but only the density of barrel sponges (*Cliona* spp.) was significantly reduced. After one year, the damage was no longer detectable. The authors attributed the rapid recovery to the single gear pass. Repeated trawling has a cumulative effect on the benthic fauna and prevents ecosystem recovery.

6.3.8 Potential Impacts of OCS Development on Hard-bottom Benthic Communities

6.3.8.1 Oil and Gas Exploration and Development

The potential impacts from fossil fuel exploration and subsequent production may occur as a result of normal operations, or from accidental oil spills and their mitigation actions. Normal operations include the physical displacement of sediment and bedrock when holes are bored to access oil and gas resources, anchoring of service vessels, rigs and platforms, pipeline placement, disturbance of sediments, and release of drill cuttings and drilling muds into the environment. Drilling muds are less toxic today than in the past when they contained heavy metal compounds, but muds, sediment, and drill cuttings can potentially smother or damage nearby sessile filter feeders. These activities are usually localized around operations and are of relatively short duration (<6 months) (National Research Council, 1985; MMS, 1987; Neff, 1987). Ecological theories based on recovery from natural disturbances were used to assess the potential recovery of hard-bottom communities from the impacts of fossil fuel operations (Lissner et al., 1991). Recovery of a damaged area depends, to a great extent, on the type of community that was removed or impacted. Those that are dominated by species with short-lived larval forms and asexual propagules will recover quickly (months, depending on size of damaged area) as neighboring individuals grow into open space and new recruits are supplied from adjacent undamaged individuals. Taxa such as cup corals (Gerrodette, 1981), hydrocorals (Ostarello, 1976), and octocorals (Sebens, 1983) probably fall into this category. Those communities that rely on long-lived dispersive larvae are subject to more unpredictable colonization processes. In the former, damage recovery was predicted to be relatively fast (on the order of months) whereas in the latter, several years were expected before the community recovered, also resulting in possibly a different species composition from the original. Longer recovery times in general were predicted for longer-lived, slower-growing deep-sea species (Lissner et al., 1991). These are theoretical predictions and, in reality, each ecosystem will respond differently to different damage levels. Controlled experiments on simulated damage would provide more insight into the recovery response of impacted species, but there is no information on these types of experiments relevant to the study region.

Fossil fuel operations can change the sediment regime in an area and re-suspend contaminants sequestered in subsurface layers. As with the physical disturbance discussed above, sediment disturbance and discharge of drilling muds and cuttings are of relatively short duration (<6 months) and localized in effect (reviewed in Neff, 1987). The greatest impacts to hard-bottom habitat from fossil fuel-related sediment and mud expulsion will occur in low-energy environments within a few hundred meters from the operations site. In low current regimes, the sediments and muds will not be readily swept away but may form long-term mounds, with associated fauna (reviewed in Boesch and Robilliard, 1987). In high-energy environments, the sediments and muds will be dispersed over a larger distance, with less focused impact. Potential impacts to hard-bottom communities could be avoided by locating oil and gas operations at least several hundred meters from natural hard-bottom habitats (Boesch and Robilliard, 1987; Neff, 1987). The effects of sediment disturbance by anthropogenic activities are similar to those observed during natural disturbance: suspended sediments can clog feeding and respiratory apparatus and heavy sediment deposition may bury or suffocate benthic fauna. Anthropogenic sediment disturbance may carry additional risks from toxic effects of drilling fluids or re-suspension of contaminated sediments.

The extent to which different ecosystems are impacted after an oil spill depends on how much oil is released, the type of oil, where it goes, and also how it is treated. The greatest recent example that illustrates all levels of oil spill impact occurred in 2010 in the Gulf of Mexico (*Deepwater Horizon* oil spill), and the ongoing management of the results of this spill should be closely monitored over the coming decade. Oil comes in many different forms, categorized by toxicity, volatility and viscosity, and each has a different set of physical and chemical properties, which influence its fate and toxicity once it is released into the environment.

Oil spill dispersants do not reduce the total amount of oil entering the environment; they change the chemical and physical properties of the oil, thereby changing its transport, fate, and effects on different components of marine ecosystems. Dispersants also contain potentially toxic compounds. Small amounts of oil will disperse naturally into the water column through the action of waves and other environmental processes. The objective of applying dispersant is to increase the amount of oil that physically mixes into the water column, reducing the potential that a surface slick will contaminate shoreline habitats and fauna, or impact organisms that come into contact with the water surface (birds, marine mammals, turtles, etc.). However, by promoting dispersion of oil into the water column, dispersants increase the potential exposure of water-column and benthic biota to spilled oil (Lunel, 1995). Dispersant application, therefore, will increase the hydrocarbon load on one component of the ecosystem (e.g., the water column), while reducing the load on another (e.g., coastal wetland). This trade-off reflects the complex interplay of many variables, including the type of oil spilled, the volume of the spill, sea state and weather, water depth, degree of turbulence (mixing and dilution of the oil), and relative abundance and life stages of resident organisms (National Research Council, 2005). The ultimate fate of dispersant-oil emulsions is poorly understood, particularly if they are applied at great depth as they were during the *Deepwater Horizon* oil spill response efforts (April–July 2010). The immediate impacts to water-column fauna and the long-term effects from sequestration in the soft sediment and hard-bottom benthos are unknown. The persistence and bioaccumulation of dispersant chemicals are also poorly understood, particularly in deep water where low temperatures can inhibit biodegradation.

Many biotic components of benthic ecosystems are sessile (corals, sponges, tunicates, bryozoans, hydroids) and, therefore, cannot move to avoid pollution. Benthic habitats are the ultimate repository for particulate material that falls out of the water column and may accumulate and persist in sediments or animal skeletons/tissues. While animals on or near the surface may suffer the acute effects of oil toxicity, the benthic communities could suffer less acute but long-term, sub-lethal effects that are much harder to measure. In deep-sea or high latitude areas where metabolic breakdown is slower, these effects may persist for a very long time. Some groups of benthic animals, particularly bivalve mollusks, lack the enzymes necessary for rapid metabolism of hydrocarbons and bioaccumulation may occur. Although the accumulation of aromatic hydrocarbons in adult mussels was not lethal (Donkin et al., 2003), their tissues were sufficiently burdened that extracts were toxic to juveniles of the same species. In addition to damaging the ecosystem, this bioaccumulation could lead to negative socio-economic impacts on fishing communities that are dependent on shellfish harvesting.

Much of the literature on the effects of oil on corals is over a decade old, and all studies focus on shallow hermatypic species; however, the work is still valid and apart from photo-inhibition, the same physiological mechanisms will apply to deep-water species. Direct effects of oil and oil/dispersant fractions on adult corals include tissue breakdown (Jackson et al. 1989), immediate abortion of planulae (Loya and Rinkevich, 1979), inhibition of fertilization, larval survival, and metamorphosis (Rinkevich and Loya, 1977; 1979; Heyward et al., 1994; Harrison, 1994; 1999; Negri and Heyward, 2000) and recruitment loss (Loya, 1975; 1976).

Corals exposed to elevated sediment loads, oil, and other toxins or stressors secrete large amounts of mucus in an effort to clean their tissues (Bak and Elgershuizen, 1976; Lewis and Price, 1976; Rogers, 1990). Mucus is rich in lipids (Benson and Muscatine, 1974; Harrison and Wallace, 1990), so continuous secretion places a substantial energetic burden on the coral and shifts energy allocation away from skeletal growth and reproduction (Bak, 1983; Bayne, 1985; Stearns, 1992). Such trade-offs were documented in experimentally injured corals on oil-polluted reefs, whose corals showed rapid tissue regeneration, in contrast to reductions in growth rates and fecundity (Guzman et al., 1993; Guzman and Holst, 1993; Guzman et al., 1994). A long-term study of the sub-lethal effects of an oil spill (60–100,000 barrels) off Panama (1986) showed that extensive effects on vital processes (growth, reproduction, and recruitment) were still apparent after five years, and were likely to be so for decades (Loya and Rinkevich, 1980; Bak, 1987; Eakin et al., 1993). Oil sequestered in fine sediments was repeatedly re-suspended and contributed to the continuing impacts (Guzman et al., 1994).

6.3.8.2 Sand and Gravel Extraction

The greatest threat to hard-bottom benthic communities from this activity is exposure to large quantities of resuspended sediment, which can clog delicate feeding and respiratory structures in sessile benthic fauna, or in worst cases, may bury the habitat completely. The speed at which sediment is removed after burial of emergent hard-bottom will determine the level of damage to the community. As documented in previous sections of this chapter, some sediment cover can be tolerated by corals and sponges, providing they have reached a size which allows their feeding and respiratory structures to remain exposed. The nearshore and middle-shelf hard-bottom is periodically swept with sediment in many locations so the effects of low to moderate sediment loads from anthropogenic activities would not be very different from natural processes. Severe

sediment deposition could bury the hard-bottom and cause widespread mortality. Sand borrow sites are usually located in sandy areas away from hard substrate, but this is not always the case. If the sand excavation re-suspends contaminated sediments, this could result in toxic effects. Much of the sand extraction is carried out to provide material for beach nourishment projects, which are usually a temporary fix for a larger problem created by shoreline modification. The nourished beach frequently washes away and much of the sand is deposited on the nearshore subtidal habitats, causing various degrees of damage. Much of the literature on impacts of beach nourishment focuses on the effects on turtle nesting and benthic communities at the excavation site, rather than impacts to adjacent hard-bottom habitats. Florida has established restrictions on placement of sand near hard-bottom habitats, but South Carolina and Georgia have not yet had to address this issue. Crowe et al. (2010) studied the impacts of the disposal of fine-grained dredged material at the Charleston Ocean Dredged Material Disposal Site on hardbottom reef habitats within 4 km of the disposal site. They reported that the hard bottom reef areas and their associated communities showed little evidence of degradation resulting from the movement of sediments from the disposal site during the study period.

6.3.8.3 Renewable Energy Development

Offshore wind energy extraction facilities are the most likely type of renewable energy development in the South Atlantic Planning Area. These will have varying degrees of direct and indirect impact to different hard-bottom benthic ecosystems. Most of these impacts result in either direct physical damage or involve sediment disturbance and the associated risk of smothering sensitive fauna. Vessels used during construction may cause anchor damage, sediment re-suspension and spillage of contaminants or other materials overboard (Michel et al., 2007). The construction phase can cause a great deal of seafloor disturbance. Current technology for foundations in soft substrates consists of large (4–5 m) diameter monopiles embedded up to 30 m into the substrate. For hard seafloor substrate, a gravity foundation can be used. These gravity foundations have a much larger footprint than the monopile type and require the seafloor to be cleared and leveled, which may potentially cause significant benthic impact. Conceptual designs for wind farms in deeper waters include floating turbines that would be anchored to the seafloor; these would have a much smaller footprint than either the monopile or gravity foundations. Driving monopiles into soft sediment could create significant re-suspension or if the substrate is hard and drilling is required, the sediment composition will be altered by the drill cuttings. The noise generated by these operations is a concern for vertebrate fauna, especially marine mammals; however, there is very little work on the effect of noise on invertebrates.

Laying cables between turbines also disturbs the substrate, but these are limited to narrow bands of disturbance around the cable and are of short duration. The impacts of this activity on hard bottoms would be limited to those associated with temporarily elevated levels of re-suspended sediments or methods used to attach the cables to hard substrates.

The foundations of the turbines can be surrounded by large rocks or other types of stable hard substrate, which support the foundation and prevent scouring around the base of the turbines. Artificial fronds may be used as an alternative to the rocks for scour protection in some environments (Cape Wind Associates 2007). Artificial hard substrates are known to attract communities of sessile benthic fauna. These communities may be abundant and very different from the nearby natural substrates (Carney, 2005; Dokken et al., 2000; Page et al., 2005;

Continental Shelf Associates, 2005), which has unknown consequences for the natural hard-bottom fauna (Carney, 2005).

A recent review of offshore renewable energy (Gill, 2005) noted that "Ecological factors are not being considered properly and are under-represented in any discussion of the costs and benefits of adopting offshore renewable resources." Although impacts can be estimated or predicted for different aspects of the marine ecosystem, these offshore wind facilities are a recent innovation and their environmental impact will probably not be well understood for several years after their deployment. In some European countries, where offshore wind parks are currently operational, monitoring programs have been implemented to study the environmental effects of the installations (Michel et al., 2007). These include collections of benthic infauna, epibenthic fauna, and fouling communities on the piling foundations. The longest monitoring program has been running at Horns Rev in Denmark, where two years of pre-construction and three years of post-construction data were collected. Much of the monitoring focused on benthic soft substrate infauna, but a study of fouling community development at Horns Rev wind park showed rapid increases in abundance (by 225%) and biomass (by 200%) in three years. According to IAPEME (2002), approximately five years was the estimated time for artificial substrates in temperate climates to reach a similar community state to natural habitats; the Horns Rev study supports this timeline. Studies from the Nysted wind park in Denmark also noted that mobile species, some commercial, increased in abundance around the scour protection structures, which was noted as a potentially beneficial development (Dong et al., 2006), but they also noted the presence of a feeding halo with increased predation on benthic infauna.

6.3.9 Data Gaps in the State of Knowledge for Hard-bottom Benthic Invertebrate Communities with Regard to OCS Development

In general, the studies that have focused on continental shelf, hard-bottom invertebrate communities in the South Atlantic Planning Area have been large in geographic scope but limited to descriptive work and were also limited in temporal coverage. Furthermore, because different methods were used in each study, direct comparisons of results are difficult, if not impossible. Despite multiple mapping and characterization efforts, the distribution of hard-bottom habitat in the study region is still relatively poorly described, especially for the deeper habitats out of SCUBA range. Shelf-edge or mesophotic habitats are poorly studied in general because they fall between SCUBA and deep submergence vehicle operating depths. This gap is also true of the study region; less information is available on the shelf edge than on the deep-coral habitats.

Life-history strategies and larval ecology are generally missing, particularly for non-commercial species. Larval dispersal, connectivity, and energy flows between and within habitats would help assess recovery potential from anthropogenic and natural disturbances. In the absence of this kind of research, our ability to assess the impact of human activities or potential recovery rates is quite limited. Deep-water submersible research efforts over the past decade have cumulatively covered quite a large geographic area, but given limitations on bottom time, relatively few dives were completed at each site. The research, however, has been intensive and has included biological studies on the dominant species, especially fishes, as well as habitat and community descriptive work. The reef invertebrate communities (deep or shallow) have rarely been address

in their entirety. Another critical fundamental gap that needs to be filled is the lack of comprehensive maps of habitat distribution throughout the region. Several efforts have been made at assessing the quantity type and distribution of hard-bottom habitat on the continental shelf (e.g., SEAMAP-SA, 2001), but these are not comprehensive; this is important because substrate type is the greatest driver of hard-bottom community type. Hard-bottom habitats frequently support populations of commercially valuable species, so understanding how the benthic invertebrate community affects these species would assist fisheries management decisions.

More comprehensive species inventories are needed, especially in mesophotic habitats and in deep water where species richness is extremely high and there is much left to explore. There is no doubt that many new species of invertebrates or range extensions are still waiting to be discovered from deep-water, hard-bottom habitat throughout the study area.

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CHAPTER 7: FISH AND FISH HABITATS

7.1 INTRODUCTION

The continental shelf off the southeastern US from Cape Hatteras to Cape Canaveral out to the edge of the EEZ, commonly known as the South Atlantic Bight, has diverse habitats that support complex ichthyofauna communities. Fish assemblages in the area are extremely dynamic, and their distributions are not only influenced by the topography of the shelf, but also by seasonal changes in water temperature, biological productivity, and circulation patterns moderated by the Gulf Stream (Miller and Richards, 1980; SCWMRD and GDNR, 1982; Sedberry and Van Dolah, 1984; Sedberry et al., 1998; Love and Chase, 2007; see Chapter 3–Physical Oceanography and Air-Sea Interactions).

The gradually sloping continental shelf is characterized by flat bottoms that are partially covered with sand and mud rich in carbonates, interdispersed with live/hard bottoms colonized by algae communities and sessile invertebrates (Struhsaker, 1969; Miller and Richards, 1980; Powles and Barans, 1980; Parker et al., 1983). These substrate types are found across relatively distinct areas of the continental shelf (coastal, open shelf, live/hard bottom, shelf edge, and lower shelf) (Struhsaker, 1969), which have unique biological and physical attributes that mediate species interactions and provide resources (shelter, food) and habitat for numerous fishes (Miller and Richards, 1980; Chester et al., 1984; Sedberry et al., 1998; Walsh et al., 2006; Ross and Nizinski, 2007). Areas beyond the continental shelf (>200 m) on the continental slope and the Blake Plateau (see Chapter 2: Geological Oceanography), also have unique benthic habitats that support a less well-known fish community, markedly different from that of shallower areas (Sedberry et al., 2001; Sedberry et al., 2006; Ross and Nizinski, 2007; Ross and Quattrini, 2009).

The purpose of this chapter is to synthesize the peer-reviewed and non-peer reviewed literature on fishes and fish habitats of the South Atlantic Planning Area, which covers a significant portion of the South Atlantic Bight. The area also extends beyond the 200 m isobath, generally considered the outer boundary of the continental shelf, out to the edge of the EEZ and including the continental slope and the Blake Plateau. Some of the studies included here include areas north to Cape Hatteras, North Carolina; therefore, the term "South Atlantic Bight" is used to describe a larger longitudinal extent than that covered by the South Atlantic Planning Area. This chapter also describes the fish assemblages associated with areas that are deemed important for the long-term sustainability of fish populations, or that are particularly susceptible to degradation (biologically sensitive areas). Some of these areas have been designated as Habitat Areas of Particular Concern (HAPC), a subset of federally designated Essential Fish Habitat (EFH), which are considered particularly important to the long-term productivity of populations of one or more managed fishery species, or to be particularly vulnerable to degradation. This synthesis also provides information on the current knowledge concerning fish species' trophic and ecological interactions and highlights information gaps requiring further attention.

7.2 CONTINENTAL SHELF

Fish communities on the continental shelf can be generally grouped into five zones: coastal, open shelf, live/hard bottom, shelf edge, and lower shelf (Struhsaker, 1969). Other zone classifications stratify the continental shelf based on depth: inner shelf <18 m; middle-shelf 18–55 m; and outer shelf 55–183 m (Miller and Richards, 1980), because each of these shelf areas have unique physical and climatic dynamics (Atkinson et al., 1985; Blanton et al., 2003) that support distinct fish assemblages (Marancik et al., 2005). For the purpose of this synthesis, fish communities are defined based on their locations on the shelf following Struhsaker (1969), although the approximate bathymetric range of each zone (Miller and Richards, 1980) is provided as a guide.

7.2.1 Nearshore Coastal Zone

The nearshore coastal zone (≤18 m; inner shelf) of the South Atlantic Planning Area is characterized by a low-salinity front strongly influenced by the diluting effect of freshwater discharge, tidal mixing, and local wind forcing, and is subject to seasonal atmospheric changes. Nearshore surface and bottom water temperatures fluctuate from ~14ºC (winter) to ~28ºC (summer). In these waters phytoplankton biomass and productivity, which are influenced by river discharges throughout the year, benefit during the summer from episodic subsurface intrusions of waters from the Gulf Stream (Atkinson et al., 1983; Blanton and Atkinson, 1983, Yoder et al., 1987, Barnard et al., 1997; Pomeroy et al., 1993). Seasonal changes in water temperature, photoperiod, and productivity influence the spatial and temporal distribution of nearshore fishes.

The nearshore fish assemblage is comprised of over 100 species, many of which use offshore waters during parts of their life cycles (Table 7.1). This assemblage fluctuates seasonally in composition, abundance, and biomass, reflecting the migration patterns of the dominant species and the recruitment of juveniles to coastal and estuarine nursery areas (Figures 7.1 and 7.2) (Boylan, 2006; Dahlberg, 1972; Dahlberg, 1975; Huntsman and Manooch, 1978; Miller and Richards, 1980; SEAMAP, 2000-2008; Wenner and Sedberry, 1989). The assemblage is largely dominated (both in number and biomass) by a relatively small number of temperature-tolerant species, mostly year-round coastal water residents (e.g., Atlantic croaker, Atlantic menhaden, kingfishes, pinfish, spot, summer flounder, southern flounder, silver seatrout, striped mullet) (Wenner and Sedberry, 1989). Many of these species spawn offshore from fall through early spring, and their larvae are transported by currents to estuarine and nearshore nursery areas starting in winter (Yoder, 1983; see Chapter 5: Planktonic Communities, and Section 7.4.2 Water Column). During unfavorable water-temperature conditions (winter and spring) and when many species have migrated to offshore deeper and warmer waters or to spawning grounds, the nearshore fish assemblage has a lower species diversity and richness than deeper shelf waters (Huntsman and Manooch, 1978; Wenner and Sedberry, 1989; SEAMAP, 2000b; Boylan, 2006; Rowe and Sedberry, 2006). Warmer water temperatures and increased primary production during summer and fall allow increased habitat use of inshore waters by a wider number of species (Figure 7.2; Wenner and Sedberry, 1989).

Table 7.1
Partial list of species that use nearshore/offshore areas during part of their life cycle.

Common Name	Scientific Name	Spawning	Nursery	Distribution	
				Juvenile	Adult
American butterfish	*Peprilus triacanthus*	O	N	E, N, O	E, N, O
American eel	*Anguilla rostrata*	O	F, E	F, E	F, E
Atlantic bumper	*Chloroscombrus chrysurus*	N		N, O	N, O
Atlantic croaker	*Micropogonias undulatus*	O	E, N	E	N, O
Atlantic menhaden	*Brevoortia tyrannus*	O	E, N	E	N, O
Atlantic sharpnose shark	*Rhizoprionodon terraenovae*	E, N	E, N	E, N	E, N, O
Atlantic spadefish	*Chaetodipterus faber*	N	N	N	N, O
Bay anchovy	*Anchoa mitchilli*	E, O	E	E	E,N
Black sea bass	*Centropristis striata*	N, O	N, O	N	N, O
Blackcheek tonguefish	*Symphurus plagiusa*	E, N	E, N	E, N	E, N, O
Blueback herring	*Alosa aestivalis*	F	E	F, E	E, N, O
Bluefish	*Pomatomus saltatrix*	N, O	N, O	N	E, N, O
Bullnose ray	*Myliobatis freminvilli*			N	N, O
Butterfish	*Peprilus triacanthus*	O	E, N	E, N	E, N
Cobia	*Rachycentron canadum*	E, N	E	E	N, O
Florida pompano	*Trachinotus carolinus*	N, O	N, O	N	N
Fringed flounder	*Etropus crossotus*			E, N	E, N, O
Gag	*Mycteroperca microlepis*	O	E, N	E	N
Gray snapper	*Lutjanus griseus*	E, N	E, N	E, N	N, O
Greater amberjack	*Seriola dumerili*	O	O	N, O	N
Gulf flounder	*Paralichthys albigutta*	O	E, N	E	E, N
Gulf kingfish	*Menticirrhus littoralis*	N, O	N, O	N	N, O
Hardhead catfish	*Ariopsis felis*	E, N	E, N	E, N, O	E, N, O
Inshore lizardfish	*Synodus foetens*	N	N	N, O	N, O
King mackerel	*Scomberomorus cavalla*	N, O	N, O	N	N
Ladyfish	*Elops saurus*	O	E	E, N	E, N
Northern kingfish	*Menticirrhus saxatilis*	N, O	N, O	N	N, O
Northern sea robin	*Prionotus carolinus*				N, O
Pinfish	*Lagodon rhomboides*	N, O	N, O		N
Round scad	*Decapterus macarellus*	O			N
Scup	*Stenotomus chrysops*	O	N, O	N	N
Sheepshead	*Archosargus probatocephalus*	N, O	N, O	N	N
Silver seatrout	*Cynoscion nothus*	O	E		N
Smooth dogfish	*Mustelus canis*	N	N	N, O	N, O
Southern flounder	*Paralichthys lethostigma*	O	E, N	E	E, N
Southern kingfish	*Menticirrhus americanus*	N, O	N, O	N	N, O
Spanish mackerel	*Scomberomorus maculatus*	N, O	N, O		N
Spiny dogfish	*Squalus acanthias*	O			N, O
Spot	*Leiostomus xanthurus*	O	E, N	E	N, O
Striped mullet	*Mugil cephalus*	O	E, N		N
Summer flounder	*Paralichthys dentatus*	N, O	N, O		N
White grunt	*Haemulon plumieri*	O		N	N

F= freshwater, E=estuarine, N=nearshore, O=offshore waters; bold= pelagic species.
Sources: Dahlberg (1972; 1975); Greene et al. (2009); National Marine Fisheries Service (2005); SAFMC (1998b); SAFMC (2009); Gilmore et al. (1981); SCDNR (2005); USGS (2010); Wenner and Sedberry (1989).

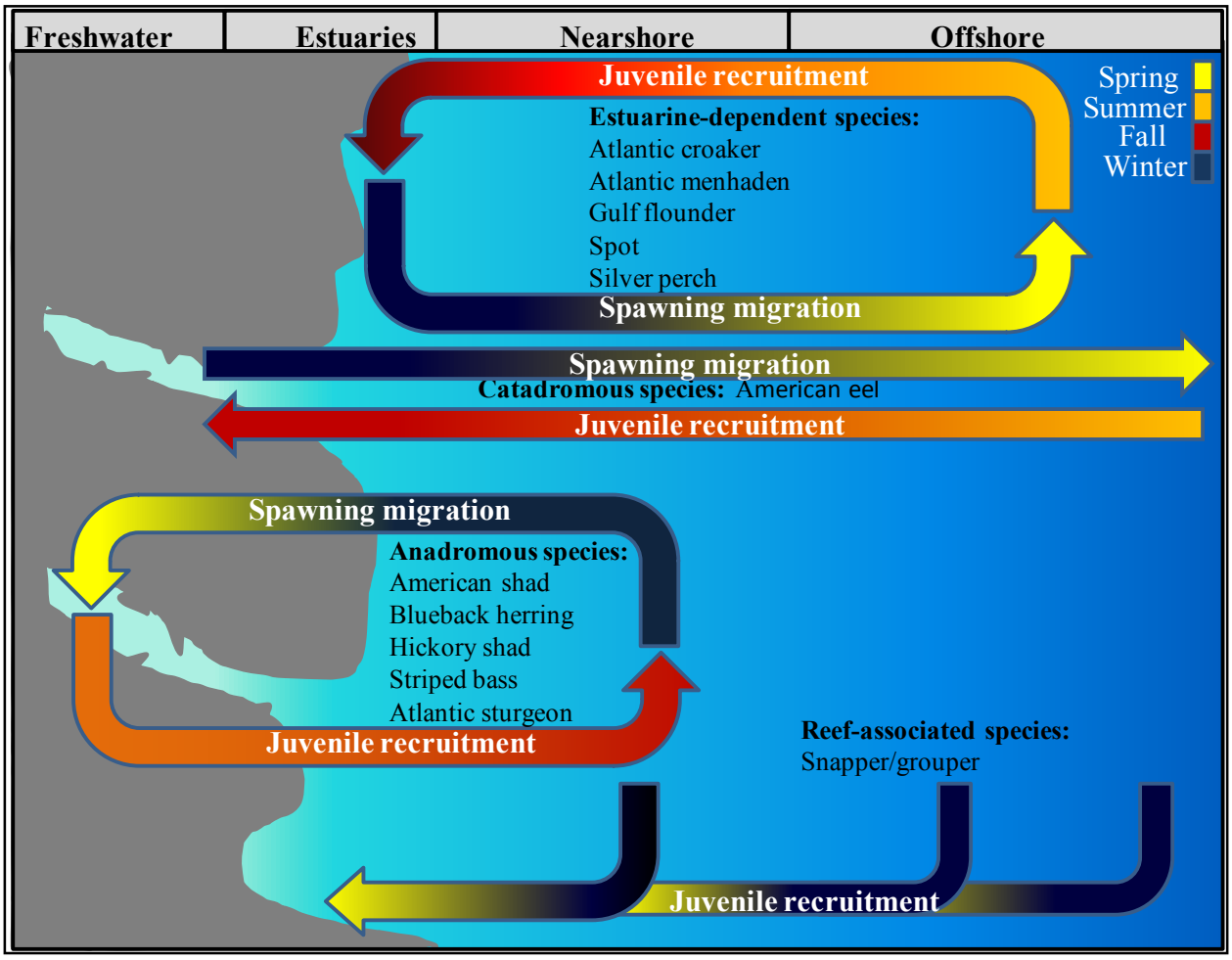

Figure 7.1 Schematic representation of the seasonal dynamics of the fish community in nearshore areas. Representative species are included as a reference. Not to scale.

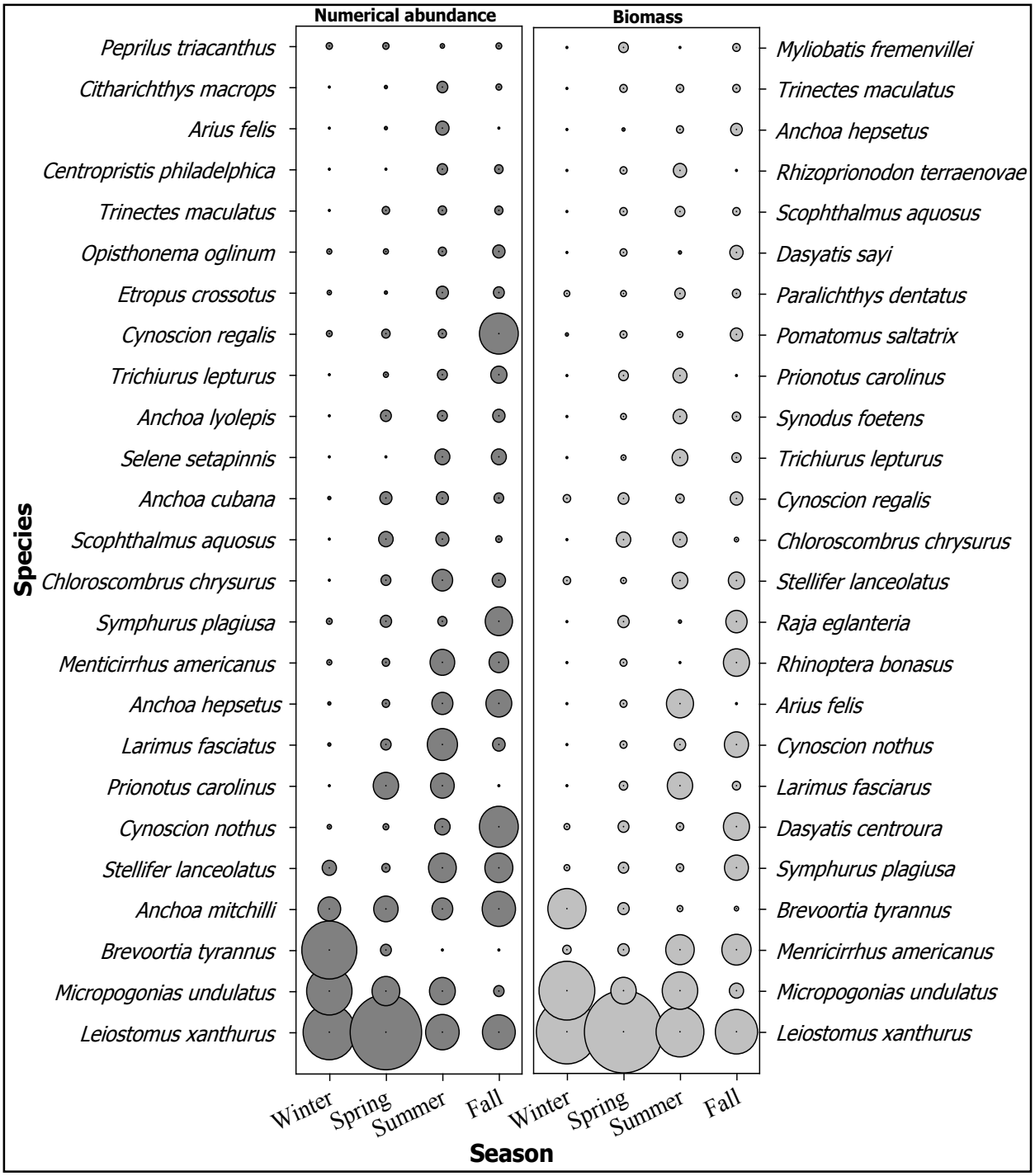

Figure 7.2 Example of the seasonal fish assemblage in coastal habitats of the South Atlantic Bight, by numerical abundance (left) and biomass (kg; right). Only the top 25 species are shown. Bubbles represent the percent seasonal contribution to the overall fish assemblage. Largest size shown: spring percent biomass of spot, *Leiostomus xanthurus* (65.4%); smallest size shown: 0.1%. Data modified from Wenner and Sedberry (1989). Note: This figure displays historical data and may not necessarily reflect current patterns.

Changes in the seasonal and spatial distribution of representative finfish species in coastal areas have been extensively documented through fishery-independent data collected by the Southeast Area Monitoring and Assessment Program-South Atlantic (SEAMAP-SA). SEAMAP-SA is a cooperative effort (state, federal, academic institutions) that annually monitors the distribution, abundance, and biomass of fish (accessible by high-rise trawls) along coastal habitats (primarily sandy bottoms at depths of 4–19 m) of the South Atlantic Bight (Cape Hatteras, North Carolina to Cape Canaveral, Florida). Results of the 1990–2008 surveys (summarized in Table 7.2; SEAMAP, 2000b; SEAMAP, 2001a; 2002-2008; Boylan, 2006) indicated that: 1) the fish assemblage was dominated by spot and Atlantic croaker; 2) the number of species in shallow waters (<9 m) was relatively constant throughout the seasons; 3) fish abundance was lower in deeper waters (10–19 m; spot = 30.8 individuals per hectare [ind/ha], Atlantic croaker = 47.2 ind/ha) than in shallower waters (<9 m; spot = 73.9 ind/ha, Atlantic croaker = 64.2 ind/ha); and 4) some species had clear spatial differences in abundance and biomass (e.g., higher abundance of black sea bass in South Carolina; higher abundance of Gulf flounder and Atlantic bumper in Florida), as well as temporal differences (e.g., higher abundance of Atlantic herring off Georgia during fall; higher spring biomass of bullnose ray in Long Bay, between North Carolina and South Carolina).

Nearshore waters are also important corridors for year-round residents, larval transport, travel of early life stages to and from nursery grounds (Atlantic croaker, Atlantic menhaden, summer flounder, southern flounder, silver seatrout and spot), and seasonal migrations (e.g., anadromous fishes, such as blueback herring; catadromous fish, such as American eel). One such corridor is the surf zone, a nutrient-rich and highly dynamic environment that supports large populations of benthic macro-invertebrates, zooplankton, diatoms, and detritus (DeLancey, 1989). Typical members of the fish assemblage in the surf zone are Atlantic menhaden, hardhead catfish, rough silverside, spot, flounders, Atlantic sharpnose shark, red drum, sea robin, and skates. However, a relatively small number of species (e.g., Florida pompano, Gulf kingfish, and silversides) tends to dominate the fish assemblage (Lindquist and Manning, 2001; Ross and Lancaster, 2002). Other species found in these areas include species that migrate seasonally between estuarine and ocean waters (e.g., southern flounder), species strongly associated with sand bottoms, and juveniles of many species. The fish assemblage during late spring and summer is characterized by juveniles of species that rely on the nearshore boundaries of ocean water masses as nursery grounds (dusky, bay and striped anchovy, bluefish, Gulf kingfish, mackerels, and Florida pompano) (DeLancey, 1989; Godcharles and Murphy, 1986; Hackney et al., 1996; Peters and Nelson, 1987; SAFMC, 1998b; Ross and Lancaster, 2002). Species richness and composition among surf zone areas along the South Atlantic Planning Area likely differs markedly, due to differences in geography, seasonal changes in salinity and temperature, subtidal habitat complexity such as proximity to reefs and jetties, and substrate composition (Peters and Nelson, 1987).

Additional information regarding nearshore coastal fishes is found in other sections of this report (see Sections 7.2.2 Open Shelf, 7.4.2 Water Column, 7.2.3.1.1 Nearshore Hard Bottom of Southeast Florida, Appendix 7-A1).

Table 7.2
Spatial and temporal distribution of representative coastal species in the South Atlantic Bight between 1990 and 2008 based on SEAMAP trawl surveys (primarily sandy bottom).

Common name	Scientific name	Abundance						
		South Atlantic Bight	Spatial			Seasonal		
			South Carolina	Georgia	Florida	Summer	Fall	Spring
Striped anchovy	*Anchoa hepsetus*	Very high	X	X	X	X	X	X
Sheepshead	*Archosargus probatocephalus*	Low	X	X			X	
Yellowfin menhaden	*Brevoortia smithi*	Low		X	X			X
Atlantic menhaden	*Brevoortia tyrannus*	High		X				X
Black sea bass	*Centropristis striata*	Low	X			X	X	X
Atlantic spadefish	*Chaetodipterus faber*	High		X		X		
Atlantic bumper	*Chloroscombrus chrysurus*	Very high	X	X	X	X	X	X
Spotted seatrout	*Cynoscion nebulosus*	Very low	X	X				
Silver seatrout	*Cynoscion nothus*	High	X	X	X	X	X	X
Weakfish	*Cynoscion regalis*	High	X	X	X	X	X	X
Pinfish	*Lagodon rhomboides*	High	X		X	X	X	X
Banded drum	*Larimus fasciatus*	Very high	X	X	X	X	X	X
Spot	*Leiostomus xanthurus*	Very high	X	X	X	X	X	X
Southern kingfish	*Menticirrhus americanus*	High	X	X	X	X	X	X
Gulf kingfish	*Menticirrhus littoralis*	Low			X		X	
Northern kingfish	*Menticirrhus saxatilis*	Low	X				X	X
Atlantic croaker	*Micropogonias undulatus*	Very high	X	X	X	X	X	X
Gag	*Mycteroperca microlepis*	Very low						
Atlantic herring	*Opisthonema oglinum*	Very high	X	X	X	X	X	X
Gulf flounder	*Paralichthys albigutta*	Low			X	X		
Summer flounder	*Paralichthys dentatus*	Moderate	X			X	X	
Southern flounder	*Paralichthys lethostigma*	Low	X				X	
Harvest fish	*Peprilus alepidotus*	High	X	X	X		X	
Butterfish	*Peprilus triacanthus*	High	X	X	X	X	X	X
Black drum	*Pogonias cromis*	Very low		X	X			
Bluefish	*Pomatomus saltatrix*	High	X					X
Red drum	*Sciaenops ocellatus*	Very low						
King mackerel	*Scomberomorus cavalla*	Moderate			X		X	
Spanish mackerel	*Scomberomorus maculatus*	High	X	X	X	X		X
Scup	*Stenotomus* sp.	High	X	X	X	X	X	X
Data modified from SEAMAP (2000-2001a, 2002-2008).								

7.2.2 Open Shelf

The open shelf (18–55 m) crosses the middle and outer shelf and is characterized by a smooth sandy bottom, interspersed with hard-bottom substrate (see Section 7.2.3 Live/Hard bottom). Many of the sub-tropical and tropical reef fish species that occupy these habitats have extended northward distributions from the Caribbean, benefiting from reef resources and the stable thermal regimes of the middle continental shelf (Sedberry et al., 2004b). Although open-shelf habitats sustain a variety of filefishes, hakes, grunts, and flatfish (eyed flounder *Bothus ocellatus*

and dusky flounder *Syacium papillosum*) (Chester et al., 1984), the fish assemblages are generally dominated by sea bass (*Centropristis* spp.) and porgies (pinfish, plus species of the genus *Calamus* and *Stenotomus*). In a study off Florida, Gilmore et al. (1981) identified 194 species associated with the open shelf, but dominated by pleuronectiforms (e.g., *Bothus ocellatus*, *B. robinsi*, *Citharichthys macrops*, *Etropus crossotus*, *Paralichthys albigutta*, *Syacium papillosum*, *Gymnachirus melas*), ophidids (e.g., *Ophidium holbrooki, O. marginatum*), triglids (e.g., *Bellator militaris, Prionotus roseus, P. scitulus, P. tribulus*), ogcocephalids, and rajiids. Other members of this assemblage include species that aggregate on the open shelf during the spawning season (e.g., sciaenids), as well as species characteristic of reef habitats (e.g., Labridae: *Hemipteronotus novacula*, Serranidae: *Diplectrum formosum*, *D. radiale, Centropristis ocyurus*) (Gilmore et al., 1981).

Species biomass, diversity, and richness on open-shelf habitats are generally lower than those of other areas within the continental shelf (Love and Chase, 2007; Rowe and Sedberry, 2006; Wenner, 1983). For example, Wenner (1983) found a much lower mean demersal fish density, estimated weight per hectare, and number of species at a 46 m depth open-shelf habitat (31 individuals, 3.2 kg, 26 species, respectively) than sponge-coral habitats at 18–44 m depths (384 individuals, 57 kg, 102 species, respectively) (Wenner, 1983). However, open-shelf habitats in the South Atlantic Bight have higher species diversity (30-100 m depth; 40 species) compared to similar areas on the Middle Atlantic (7 species), with differences in species composition driven by water depth and temperature (Love and Chase, 2007). In the South Atlantic Bight, the winter assemblages of shallow warm-waters (20–23ºC) were characterized by pelagic and reef-associated species (Chaetodontidae, Pomacanthidae, Balistidae, Sparidae, Monacanthidae, Carangidae), while deep-warm waters (17-22ºC) were comprised of demersal and reef-associated species (Paralichthyidae, Synodontidae, Serranidae) (Love and Chase, 2007).

Walsh et al. (2006) studied the spatial and temporal structure of the juvenile fish assemblage inhabiting soft bottoms on the continental shelf off Georgia and found that changes in species composition and distribution responded to seasonal fluctuations in environmental factors (depth, water stratification and temperature, and bottom salinity gradients; Table 7.3). From fall to spring, the juvenile fish formed distinct assemblages (inner-, middle-, and outer-shelf assemblages), while in the summer, the entire shelf was considered a single juvenile assemblage. The middle-shelf assemblage (20–40 m depth), particularly during the fall, consisted of a blend of estuarine, coastal, and open-shelf species. By contrast, the inner shelf (0–20 m) was typically characterized by resident shelf species and by species generally found as adults in estuarine environments. The outer-shelf assemblage (40–70 m depth) was typically comprised of open-shelf species and a few coastal species, except during winter, when a cross-shelf mixture of estuarine, coastal, and open-shelf species congregated in these areas. Walsh et al. (2006) and others (see SAFMC, 2009) indicated that the benthic communities (microalgae and invertebrates) associated with soft-bottoms are important in supporting the secondary productivity of the continental shelf (see Chapter 6: Benthic Communities).

Table 7.3
Seasonal and spatial distribution, denoted by X, of juvenile fish occupying soft-bottom sediments on the continental shelf off Georgia. Zones are based on depth.

Family	Species\Cross Shelf Areas	Juvenile Distribution												Adult Distribution				
		Spring			Summer			Fall			Winter							
		I	M	O	I	M	O	I	M	O	I	M	O	E	C	R	OP	SL
Antennariidae	*Antennarius radiosus*											x	x			x	x	x
Apogonidae	*Pristigenys alta*				x	x	x		x							x	x	
Apogonidae	*Apogon pseudomaculatus*				x	x	x									x	x	
Argentinidae	*Argentina striata*												x					x
Balistidae	*Aluterus schoepfii*				x	x	x		x						x	x	x	
Balistidae	*Monacanthus hispidus*	x	x		x	x	x		x				x		x		x	
Balistidae	*Monacanthus setifer*									x							x	
Batrachoididae	*Porichthys plectrodon*								x						x		x	
Blenniidae	*Parablennius marmoreus*				x	x	x							x	x	x		
Blenniidae	*Hypleurochilus geminatus*	x	x		x	x	x							x	x			
Bothidae	*Bothus lunatus*			x									x	x	x		x	
Bothidae	*Bothus robinsi*			x	x	x	x		x				x		x		x	
Bothidae	*Bothus ocellatus*				x	x	x		x				x		x		x	
Callionymidae	*Diplogrammus pauciradiatus*				x	x	x										x	
Carangidae	*Chloroscombrus chrysurus*				x	x	x		x						x	x	x	
Carangidae	*Decapterus punctatus*				x	x	x					x			x		x	
Carangidae	*Trachurus lathami*	x	x												x		x	
Carangidae	*Caranx bartholomaei*			x											x		x	
Carangidae	*Decapterus macarellus*			x								x					x	
Clupeidae	*Brevoortia tyrannus*											x		x	x		x	
Clupeidae	*Sardinella aurita*				x	x	x								x		x	
Clupeidae	*Etrumeus teres*											x			x		x	
Congridae	*Ariosoma balearicum*	x	x		x	x	x		x			x		x	x		x	
Cynoglossidae	*Symphurus plagiusa*				x	x	x							x	x		x	
Cynoglossidae	*Symphurus urospilus*	x	x		x	x	x		x			x					x	
Cynoglossidae	*Symphurus minor*			x	x	x	x			x			x				x	
Cynoglossidae	*Symphurus parvus*			x	x	x	x										x	
Cynoglossidae	*Symphurus diomedeanus*			x													x	
Dactyloscopidae	*Dactyloscopus moorei*	x	x		x	x	x		x			x					x	
Elopidae	*Elops saurus*				x	x	x					x		x	x			
Engraulididae	*Anchoa hepsetus*	x	x		x	x	x		x					x	x		x	
Engraulididae	*Anchoa lamprotaena*								x						x			
Exocoetidae	*Hirundichthys affinis*				x	x	x		x						x		x	
Exocoetidae	*Hemiramphus brasiliensis*				x	x	x								x		x	
Gadidae	*Urophycis regia*	x	x									x			x		x	
Gobiidae	*Ioglossus calliurus*			x	x	x	x								x		x	
Haemulidae	*Haemulon aurolineatum*				x	x	x			x					x	x	x	
Labridae	*Halichoeres bivittatus*				x	x	x									x	x	

I=inner shelf (0-20 m); M=middle-shelf (20-40 m depth); O=outer shelf (40-70 m depth). Habitats: R=reef associated; E=estuarine; C=coastal (0-20 m depth); OP=open shelf (20-70 m depth); SL=slope (>70 m depth). Yellow box, summer juvenile species; green box, adults strongly associated with reefs; blue font, most common juvenile species. Modified from Walsh et al. (2006).

Table 7.3 Seasonal and spatial distribution, denoted by X, of juvenile fish occupying soft-bottom sediments on the continental shelf off Georgia. Zones based on depth (continued).

Family	Species\Cross Shelf Areas	Juvenile Distribution												Adult Distribution				
		Spring			Summer			Fall			Winter			E	C	R	OP	SL
		I	M	O	I	M	O	I	M	O	I	M	O					
Labridae	*Xyrichtys novacula*				x	x	x										x	
Lutjanidae	*Lutjanus analis*				x	x	x								x	x	x	
Mugilidae	*Mugil curema*											x		x	x		x	
Mugilidae	*Mugil cephalus*												x	x	x		x	
Ogcocephalidae	*Ogcocephalus nasutus*	x	x		x	x	x				x				x		x	
Ogcocephalidae	*Halieutichthys aculeatus*			x	x	x	x								x		x	
Ophichthidae	*Ophichthus ocellatus*	x	x		x	x	x		x			x		x	x		x	
Ophichthidae	*Ophichthus gomesii*				x	x	x							x	x		x	
Ophidiidae	*Ophidion selenops*	x	x		x	x	x		x			x					x	
Ophidiidae	*Otophidium omostigmum*			x	x	x	x			x		x					x	
Ostraciidae	*Lactophrys quadricornis*				x	x	x									x	x	
Paralichthyidae	*Citharichthys macrops*	x	x		x	x	x		x			x			x		x	
Paralichthyidae	*Syacium papillosum*	x	x		x	x	x			x					x		x	
Paralichthyidae	*Ancylopsetta quadrocellata*											x			x		x	
Paralichthyidae	*Cyclopsetta fimbriata*			x	x	x	x		x								x	
Priacanthidae	*Priacanthus arenatus*				x	x	x									x	x	
Sciaenidae	*Leiostomus xanthurus*										x			x	x		x	
Sciaenidae	*Cynoscion nothus*								x					x	x			
Sciaenidae	*Cynoscion regalis*								x					x	x			
Sciaenidae	*Larimus fasciatus*							x						x	x			
Sciaenidae	*Menticirrhus americanus*							x						x	x			
Scorpaenidae	*Scorpaena plumieri*	x	x		x	x	x		x			x			x	x	x	
Scorpaenidae	*Scorpaena dispar*				x	x	x		x						x	x	x	
Serranidae	*Centropristis striata*	x	x		x	x	x							x	x	x	x	
Serranidae	*Diplectrum formosum*			x	x	x	x		x	x		x			x	x	x	
Serranidae	*Serraniculus pumilio*	x	x		x	x	x		x			x			x	x	x	
Serranidae	*Serranus phoebe*			x	x	x	x			x			x		x	x	x	
Serranidae	*Centropristis ocyurus*			x	x	x	x						x			x	x	
Soleidae	*Gymnachirus melas*			x	x	x	x										x	
Sparidae	*Lagodon rhomboides*											x		x	x	x	x	
Sparidae	*Stenotomus sp.*	x	x		x	x	x		x			x			x	x	x	
Stromateidae	*Peprilus triacanthus*	x	x									x			x		x	
Syngnathidae	*Hippocampus erectus*	x	x		x	x	x		x		x	x	x	x	x			
Syngnathidae	*Syngnathus scovelli*				x	x	x	x						x	x			
Syngnathidae	*Syngnathus springeri*	x	x		x	x	x					x			x		x	
Synodontidae	*Synodus foetens*	x	x	x	x	x	x		x			x		x	x		x	
Synodontidae	*Trachinocephalus myops*			x	x	x	x		x	x			x				x	
Synodontidae	*Synodus poeyi*			x													x	
Triglidae	*Prionotus carolinus*	x	x		x	x	x		x			x		x	x		x	

I=inner shelf (0-20 m); M=middle-shelf (20-40 m depth); O=outer shelf (40-70 m depth). Habitats: R=reef associated; E=estuarine; C=coastal (0-20 m depth); OP=open shelf (20-70 m depth); SL=slope (>70 m depth). Yellow box, summer juvenile species; green box, adults strongly associated with reefs; blue font, most common juvenile species. Modified from Walsh et al. (2006).

Table 7.3 Seasonal and spatial distribution, denoted by X, of juvenile fish occupying soft-bottom sediments on the continental shelf off Georgia. Zones are based on depth (continued).

Family	Species\Cross Shelf Areas	Juvenile Distribution												Adult Distribution				
		Spring			Summer			Fall			Winter			E	C	R	OP	SL
		I	M	O	I	M	O	I	M	O	I	M	O					
Triglidae	*Prionotus ophryas*				x	x	x								x		x	
Triglidae	*Prionotus scitulus*											x			x		x	
Triglidae	*Bellator militaris*			x	x	x	x										x	
Triglidae	*Bellator brachychir*				x	x	x			x							x	
Uranoscopidae	*Kathetostoma albigutta*											x					x	

I=inner shelf (0-20 m); M=middle-shelf (20-40 m depth); O=outer shelf (40-70 m depth). Habitats: R=reef associated; E=estuarine; C=coastal (0-20 m depth); OP=open shelf (20-70 m depth); SL=slope (>70 m depth). Yellow box, summer juvenile species; green box, adults strongly associated with reefs; blue font, most common juvenile species. Modified from Walsh et al. (2006).

7.2.3 Live/Hard Bottom

Hard-bottom habitats in the South Atlantic Planning Area (also called reefs and live bottom) are found from the nearshore (<18-55 m deep) to beyond the continental shelf break (>200 m deep; see Figure 6.8 in Chapter 6: Benthic Communities) (SEAMAP-SA, 2001b). This section, however, covers primarily hard-bottom habitats from the inner to the middle shelf, while deeper reefs on the continental shelf are covered separately (see Section 7.2.4 Shelf Edge and Lower Shelf). Hard bottoms are often encrusted with sessile invertebrates forming complex "live-bottom" habitats (see Section 6.3). Live-bottom habitats across the gradually sloping continental shelf vary in structural complexity from distinct interspersed hard-bottom substrates with or without significant vertical relief (~25% of the shelf) to ledges or rocky outcrops with vertical relief ranging from ~0.1–10 m (<5% of the shelf) (Struhsaker, 1969; Miller and Richards, 1980; Powles and Barans, 1980; Parker et al., 1983). A more recent mapping effort (SEAMAP-SA, 2001b) estimated that hard bottom and possible hard bottom covered ~33% and ~11%, respectively, of the continental shelf from North Carolina to the Florida Keys. Despite increased efforts to characterize the seafloor off the southeastern US, current estimates are only approximate, and likely lower than their actual extent, because most of the area has not been mapped.

Hard-bottom habitats provide refuge, foraging, nursery, and spawning areas to a variety of resident and migratory fishes, offshore reef fishes, warm-temperate and tropical species, and coastal pelagic species, including numerous commercially and recreationally important species. The number of reef-associated species between South Carolina and Florida, based on shelf-wide surveys and data compilations, includes over 350 species (Table 7.4). These numbers are in agreement with the list of live-bottom species (>400) found through annual fisheries-independent surveys since 1978 by the Marine Resources Monitoring, Assessment, and Prediction (MARMAP) program (Reichert, M. and Stephen, J., pers. comm.).

Table 7.4
Reef species of the South Atlantic Planning Area

FAMILY *species (probable synonym)*		
ACANTHURIDAE	*Parablennius marmoreus*	**CONGRIDAE**
Acanthurus bahianus	*Scartella cristata*	*Conger oceanicus**
Acanthurus chirurgus	**BOTHIDAE**	*Paraconger caudilimbatus*
Acanthurus coeruleus	*Ancylopsetta quadrocellata*	**DACTYLOPTERIDAE**
ANTENNARIIDAE	*Bothus ocellatus**	*Dactylopterus volitans*
*Antennarius ocellatus**	*Bothus robinsi**	**DACTYLOSCOPIDAE**
*Antennarius radiosus****	*Cyclopsetta fimbriata*	*Gillellus* sp.
Antennarius striatus	*Etropus rimosus**	**DIODONTIDAE**
(*A. scaber*)	*Syacium micrurum*	*Chilomycterus antennatus*
APOGONIDAE	*Syacium papillosum**	*Chilomycterus antillarum*
Apogon affinis	**BRANCHIOSTEGIDAE**	*Chilomycterus atinga*
Apogon aurolineatus	*Caulolatilus chrysops*	*Chilomycterus schoepfii*
Apogon binotatus	*Caulolatilus cyanops*	*Diodon holocanthus*
Apogon planifrons	*Caulolatilus microps*	*Diodon hystrix*
Apogon sp.	*Lopholatilus chamaeleonticeps*	**EMMELICHTHYIDAE**
Apogon maculatus	*Malacanthus plumieri*	*Erythrocles monodi*
*Apogon pseudomaculatus**	**CALLIONYMIDAE**	**EPHIPPIDAE**
Apogon quadrisquamatus	*Callionymus bairdi*	*Chaetodipterus faber**
Astrapogon alutus	*(Paradiplogrammus bairdi)*	**FISTULARIIDAE**
Astrapogon stellatus	**CARANGIDAE**	*Fistularia tabacaria*
Phaeoptyx conklini	*Caranx crysos*	*Fistularia villosa*
Phaeoptyx pigmentaria	*Caranx latus*	**GOBIESOCIDAE**
Phaeoptyx xenus	*Caranx ruber*	*Gobiesox strumosus**
AULOSTOMIDAE	*Decapterus punctatus**	**GOBIIDAE**
Aulostomus maculatus	*Selar crumenophthalmus**	*Coryphopterus punctipectophorus*
BALISTIDAE	*Seriola dumerili*	*Coryphopterus dicrus*
Aluterus heudelotii	*Seriola rivoliana*	*Coryphopterus personatus*
Aluterus monoceros	*Seriola zonala*	*Evermannichthys spongicola*
Aluterus scriptus	**CENTROPOMIDAE**	*Gnatholepis thompsoni*
*Aluterus schoepfii**	*Centropomus undecimalis*	*Gobiosoma ginsburgi**
*Balistes capriscus**	**CHAENOPSIDAE**	*Gobiosoma macrodon*

*inshore (<18 m depth), **intermediate (18-55 m depth), ***offshore reef (55-183 m depth) species. Modified from: Miller and Richards (1980), Van Dolah et al. (1994), and Perkins et al. (1997).

Table 7.4 Reef species of the South Atlantic Planning Area (continued).

FAMILY *species (probable synonym)*		
Balistes vetula	*Chaenopsis limbaughi*	*Gobiosoma oceanops*
BATRACHOIDIDAE	*Emblemaria atlantica*	*Gobiosoma xanthiprora*
Opsanus beta	*Emblemaria pandionis*	*Loglossus calliurus*
Opsanus pardus	*Stathmonotus hemphilli*	*Lythrypnus nesiotes*
Opsanus sp.	**CHAETODONTIDAE**	*Lythrypnus phorellus*
*Opsanus tau**	*Chaetodon aculeatus*	*Lythrypnus* sp.
BLENNIIDAE	*Chaetodon capistratus*	*Lythrypnus spilus*
*Blennius marmoreus**	*Chaetodon ocellatus***	*Risor ruber*
Chasmodes saburrae	*Chaetodon sedentarius***	**GRAMMISTIDAE**
Hypleurochilus aequipinnis	*Chaetodon* sp.	*Rypticus bistrispinus*
Hypleurochilus bermudensis	*Chaetodon striatus***	*Rypticus maculatus*
*Hypleurochilus geminatus**	*Paraclinus nigripinnis*	*Rypticus saponaceus*
Hypleurochilus springeri	*Prognathodes aya****	*Rypticus* sp.
Hypsoblennius hentz	**CLINIIDAE**	*Rypticus subbifrenatus*
Ophioblennius atlanticus	*Starksia ocellata*	
HOLOCENTRIDAE	**LABRISOMIDAE**	**OGCOCEPHALIDAE**
Adioryx bullisi	*Malacoctenus macropus*	*Ogcocephalus* spp.*
Adioryx vexillarius	*Malacoctenus triangulatus*	*Ogcocephalus vespertilio*
*Corniger spinosus****	**LUTJANIDAE**	**OPHICHTHIDAE**
*Holocentrus adscensionis****	*Lutjanus analis*	*Ahlia egmontis*
Holocentrus bullisi	*Lutjanus apodus*	*Letharchus velifer*
(Adioryx bullisi)	*Lutjanus buccanella****	*Myrichthys acuminatus*
Holocentrus marianus	*Lutjanus campechanus**	*Mystriophis interlinctus*
Holocentrus rufus	*Lutjanus cyanopterus*	*Ophichthus ocellatus**
Holocentrus sp.	*Lutjanus griseus*	**OPHIDIIDAE**
Holocentrus vexillarius	*Lutjanus jocu*	*Lepophidium jeannae*
Myripristis jacobus	*Lutjanus mahogoni*	*Ophidian holbrooki*
Ostichthys trachypoma	*Lutjanus purpureus*	*Ophidian selenops*
Ostichthys trachypomus	*Lutjanus synagris*	*Otophidium omostigmum*
Plectrypops retrospinis	*Lutjanus vivanus****	*Parophidion lagochila*
KYPHOSIDAE	*Ocyurus chrysurus***	**OPISTOGNATHIDAE**
Kyphosus incisor	*Pristipomoides aquilonaris****	*Opistognathus lonchurus*
Kyphosus sectatrix	*Rhomboplites aurorubens*	*Opistognathus maxillosus*
LABRIDAE	**MONACANTHIDAE**	**ORECTOLOBIDAE**
Bodianus pulchellus	*Stephanolepis ciliatus**	*Ginglymostoma cirratum*
Bodianus rufus	*Stephanolepis hispidus**	**OSTRACIIDAE**
Clepticus parrae (C. parrai)	**MULLIDAE**	*Acanthostracion polygonius*
*Decodon puellaris****	*Mulloidichthys martinicus*	*Acanthostracion quadricornis*
Doratonotus megalepis	*Mullus auratus**	*Lactophrys bicaudalis*
Halichoeres bathyphilus	*Pseudupeneus maculatus***	*Lactophrys polygonia*
Halichoeres bivittatus	*Upeneus parvus*	*Lactophrys trigonus*
(H. bivittata)	**MURAENIDAE**	*Lactophrys triqueter*
*Halichoeres caudalis**	*Anarchias similis (A. yoshiae)*	**PEMPHERIDAE**
Halichoeres cyanocephalus	*Enchelycore carychroa*	*Pempheris schomburgkii*
Halichoeres garnoti	*Enchelycore nigricans*	**POMACANTHIDAE**

*inshore (<18 m depth), **intermediate (18-55 m depth), ***offshore reef (55-183 m depth) species.
Modified from: Miller and Richards (1980), Van Dolah et al. (1994), and Perkins et al. (1997).

Table 7.4 Reef species of the South Atlantic Planning Area (continued).

FAMILY *species (probable synonym)*		
Halichoeres maculipinna	*Gymnothorax funebris*	*Centropyge argi*
Halichoeres pictus	*Gymnothorax hubbsi*	*Holacanthus bermudensis***
Halichoeres poeyi	*Gymnothorax kolpos*	*Holacanthus bermudensis***
Halichoeres radiatus	*Gymnothorax miliaris*	*(H. isabelita)*
Halichoeres sp.	*(Muraena miliaris)*	*Holacanthus ciliaris*
Hemipteronotus marlinicensis	*Gymnothorax moringa*	*Holacanthus* sp.
*Hemipteronotus novacula**	*Gymnothorax saxicola*	*Holacanthus tricolor***
Labrisomus gobio	*(G. nigromarginatus*;*	*Microspathodon chrysurus*
Labrisomus haitiensis	*G. ocellatus)*	*Pomacanthus arcuatus*
Labrisomus nuchipinnis	*Gymnothorax vicinus**	*Pomacanthus paru*
*Lachnolaimus maximus***	*Muraena retifera*	*Pomacanthus sp.*
Tautoga onitis	*Muraena robusta*	
Thalassoma bifasciatum		
POMACENTRIDAE	*Priacanthus* sp.	*Scorpaena isthmensis****
Abudefduf saxatilis	*Pristigenys alta*	*Scorpaena plumieri****
Abudefduf taurus	*(Pseudopriacanthus altus)*	*Scorpaenodes tredecimspinosus****
Chromis cyanea	*Pseudopriacanthus* sp.	***SERRANIDAE***
*Chromis enchrysurus**	**RACHYCENTRIDAE**	*Alphestes afer*
Chromis insolata (C. insolatus)	*Rachycentron canudum*	*Anthias nicholsi*
Chromis scotti	**SCARIDAE**	*Anthias sp.*
Chromis sp.	*Cryptolomus roseus*	*Anthias tenuis*
Eupomacentrus fuscus	*Nicholsina usta*	*Centropristis fuscula*
(Pomacentrus fuscus)	*Scarus coelestinus*	*Centropristis ocyurus**
Eupomacentrus leucostictus	*Scarus coeruleus*	*Centropristis philadelphica**
(Pomacentrus leucostictus;	*Scarus croicensis (S. iserti)*	*Centropristis striata**
Stegastes leucostictus)	*Scarus guacamaia*	*Dermatolepis inermis*
Eupomacentrus partitus	*Scarus taeniopterus*	*Diplectrum bivittatum*
(Pomacentrus partitus)	*Sparisoma atomarium*	*Diplectrum formosum**
Eupomacentrus planifrons	*Sparisoma chrysopterum*	*Epinephelus adscensionis*
(Pomacentrus planifrons;	*Sparisoma radians*	*Epinephelus afer*
Stegastes planifrons)	*Sparisoma viride*	*Epinephelus cruentatus*
Eupomacentrus sp.	***SCIAENIDAE***	*Epinephelus drummondhayi****
Eupomacentrus variabilis	*Equetus acuminatus*	*Epinephelus flavolimbatus****
(Pomacentrus variabilis;	*(E. pulcher)*	*Epinephelus fulvus*
Stegastes variabilis)	*Equetus iwamotoi*	*Epinephelus guttatus*
Pomacentrus diencaeus	*(Pareques iwamotoi)*	*Epinephelus inermis*
POMADASYIDAE	*Equetus lanceolatus***	*Epinephelus itajara*
Anisotremus surinamensis	*Equetus punctatus*	*Epinephelus morio*
Anisotremus virginicus	*Equetus* sp.	*Epinephelus mystacinus*
Haemulon album	*Equetus umbrosus*	*Epinephelus nigritus*
*Haemulon aurolineatum**	*(Pareques umbrosus)**	*Epinephelus niveatus*
Haemulon carbonarium	*Odontoscion dentex*	*Epinephelus* sp.
Haemulon chrysargyreum	*Pareques acuminatus*	*Epinephelus striatus*
Haemulon flavolineatum	*Pareques* sp.***	*Hemanthias aureorubens*

*inshore (<18 m depth), **intermediate (18-55 m depth), ***offshore reef (55-183 m depth) species.
Modified from: Miller and Richards (1980), Van Dolah et al. (1994), and Perkins et al. (1997).

Table 7.4 Reef species of the South Atlantic Planning Area (continued).

FAMILY *species (probable synonym)*		
Haemulon macrostomum	***SCORPAENIDAE****	*Hemanthias leptus*
Haemulon melanurum	*Helicolenus dactylopterus****	*Hemanthias sp.*
Haemulon parrai	*Pontinus helena****	*Hemanthias vivanus*
*Haemulon plumieri***	*Pontinus longispinis****	*Holanthias martinicensis*
Haemulon sciurus	*Pontinus nematophthalmus****	*Hypoplectrus indigo*
Haemulon striatum	*Scorpaena agassizi****	*Hypoplectrus aberrans*
*Orthopristis chrysoptera**	*Scorpaena albifimbria****	*Hypoplectrus nigricans*
PRIACANTHIDAE	*Scorpaena bergii*	*Hypoplectrus puella*
*Cookeolus boops****	*Scorpaena brasiliensis**	*Hypoplectrus unicolor*
Cookeolus japonicus	*Scorpaena calcarata**	*Liopropoma eukrines*
*Priacanthus arenatus**	*Scorpaena dispar****	*Mycteroperca bonaci*
Priacanthus cruentatus	*Scorpaena inermis*	*Mycteroperca interstitialis*
Mycteroperca microlepis	*Calamus nodosus*	***TETRAODONTIDAE***
Mycteroperca phenax	*Calamus penna*	*Canthigaster rostrata*
Mycteroperca sp.	*Calamus proridens*	*Sphoeroides dorsalis*
Mycteroperca venenosa	*Diplodus argenteus*	*Sphoeroides pachygaster*
Paranthias furcifer	*Diplodus holbrooki*	*Sphoeroides spengleri**
Plectranthias garrupellus	*Lagodon rhomboides*	***TRIGLIDAE***
Pronotogrammus aureorubens	*Pagrus pagrus (P. sedecim)**	*Bellator militaris**
*Serraniculus pumilio**	*Stenotomus aculeatus*	*Prionotus evolans*
Serranus annularis	***SPHYRAENIDAE***	*Prionotus ophryas**
Serranus baldwini	*Sphyraena barracuda*	*Prionotus roseus**
Serranus notospilus	*Sphyraena borealis*	*Prionotus salmonicolor**
Serranus phoebe	*Sphyraena guachancho*	***TRIPTERYGIIDAE***
*Serranus subligarius**	***SYNGNATHIDAE***	*Enneanectes altivelis*
Serranus tabacarius	*Hippocampus erectus**	*Enneanectes pectoralis*
Serranus tigrinus	*Syngnathus dunckeri*	
SPARIDAE	*Syngnathus elucens*	
Calamus bajonado	***SYNODONTIDAE***	
Calamus calamus	*Synodus intermedius*	
Calamus caprinus	*Synodus saurus*	
Calamus chrysops	*Synodus synodus*	
Calamus leucosteus	*Trachinocephalus myops**	

*inshore (<18 m depth), **intermediate (18-55 m depth), ***offshore reef (55-183 m depth) species.
Modified from: Miller and Richards (1980), Van Dolah et al. (1994), and Perkins et al. (1997).

Inshore live-bottom areas (<18 m deep), also known as "blackfish banks," are typically occupied by the conspicuous year-round resident, the black sea bass, as well as by associated warm-temperate species (snappers, groupers, porgies, grunts) (Mercer, 1989; Edwards et al., 2008b). On these reefs (<18 m depth, Miller and Richards, 1980; <40 m depth, Rowe and Sedberry, 2006; 16–25 m depth SCWMRD and GDNR, 1982) species diversity is generally low, and the assemblage is dominated by species that have broad distribution across the shelf, younger age classes of large-size species, and adults of small-size species. Fish abundance and number of species are higher during fall and lower during winter (Figure 7.3). In winter, when the bottom water reaches temperatures as low as 12º C, many tropical species move offshore or migrate south and are replaced by more temperate non-reef species (Sedberry and Van Dolah, 1984; Sedberry et al., 2005; Figure 7.4). On these reefs, studies have shown high abundance of tomtate and southern porgy during summer and winter, high abundance of black sea bass, northern

searobin, planehead filefish, and cubbyu (*Equetus umbrosus*) during summer, and high abundance of jackknife fish (*E. lanceolatus*) and spotted hake (*Urophycis regia*-not a reef species) during winter (Sedberry and Van Dolah, 1984; Sedberry et al., 2005; see Figure 7.3).

Middle-shelf reefs (~30 m deep), on the other hand, are known as "snapper banks," owing to the numerical dominance of red and vermilion snapper (*Lutjanus campechanus* and *Rhomboplites aurorubens*), gag, and other snapper and grouper species. On these reefs the fish assemblage is more stable (in abundance and number of species) than shallower reefs even during winter, and both fish density and biomass are much higher than in either inner- or outer-shelf habitats (see Figure 7.3). This stability is related to a higher persistence of warm water on the middle shelf (Miller and Richards, 1980; Sedberry and Van Dolah, 1984; Sedberry et al., 2005) (Figure 7.4). These more favorable environmental conditions support four distinct groups of fishes: 1) temperate species with cross-shelf distribution; 2) deep-water temperate species; 3) subtropical species with distributions limited to these habitats; and 4) species with seasonal movements between inshore and offshore reefs (18–55 m depth, Miller and Richards, 1980; 26–45 m depth, SCWMRD and GDNR, 1982). Reef species found on hard-bottom habitats off northeastern Florida and offshore areas of Georgia and South Carolina include rock sea bass (*Centropristis philadelphica*), tomtate, sand-bottom associates, such as sand perch (*Bairdiella chrysoura*), inshore lizard fish, and sand diver (*Trachinocephalus myops*), as well as species of damselfish, grunts, and porgies (Huntsman et al., 1983; Parker et al., 1983; Sedberry et al., 1998; 2004a). In addition to harboring a wide diversity of species, middle- and outer-shelf reefs are also critical spawning habitats for many species (Table 7.5; Sedberry et al., 2004a, 2006). Several of these species (black sea bass, sand perch, tomtate, red snapper, and vermilion snapper) have broad adult distributions, and they spawn across the continental shelf particularly in areas characterized by relatively shallow (<50 m depth) and warm waters (<29ºC). Peak spawning of many of these species occurs during spring and summer.

A detailed description of fish assemblages inhabiting deeper shelf reefs is provided further in the report (see Section 7.2.4 Shelf Edge and Lower Shelf). Descriptions of species-specific life histories and spawning strategies are provided in Appendix 7-A1.

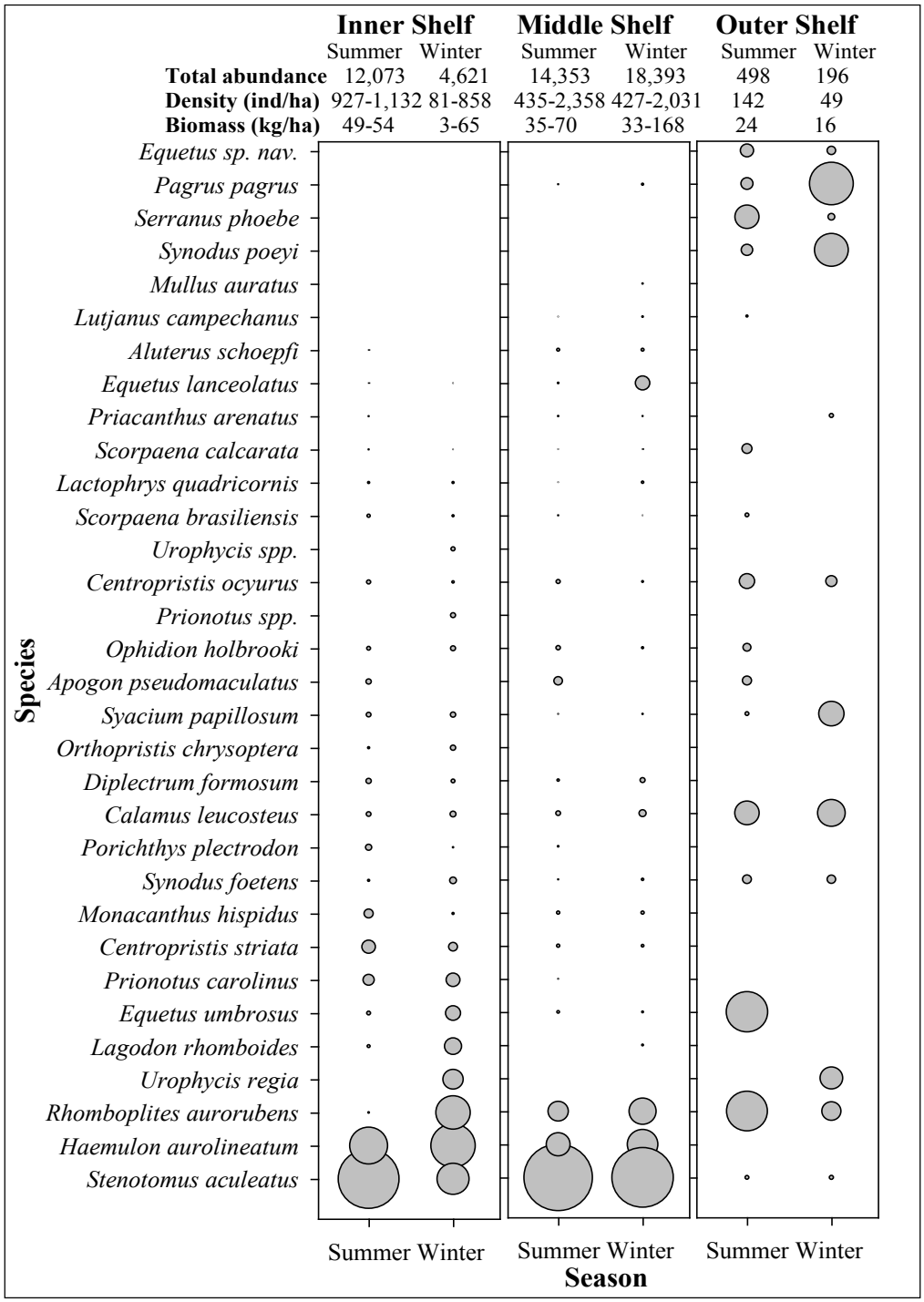

Figure 7.3 Demersal fish species on hard-bottom habitats. Only the most abundant species are shown. Bubbles represent the percent contribution to the overall fish assemblage. Largest size shown: summer percent abundance of *Stenotomus aculeatus* (77%) in middle-shelf reefs; smallest size shown: 0.1%. Data modified from Sedberry and Van Dolah (1984); Wenner and Sedberry (1989). *Note*: This figure displays historical data and may not necessarily reflect current patterns.

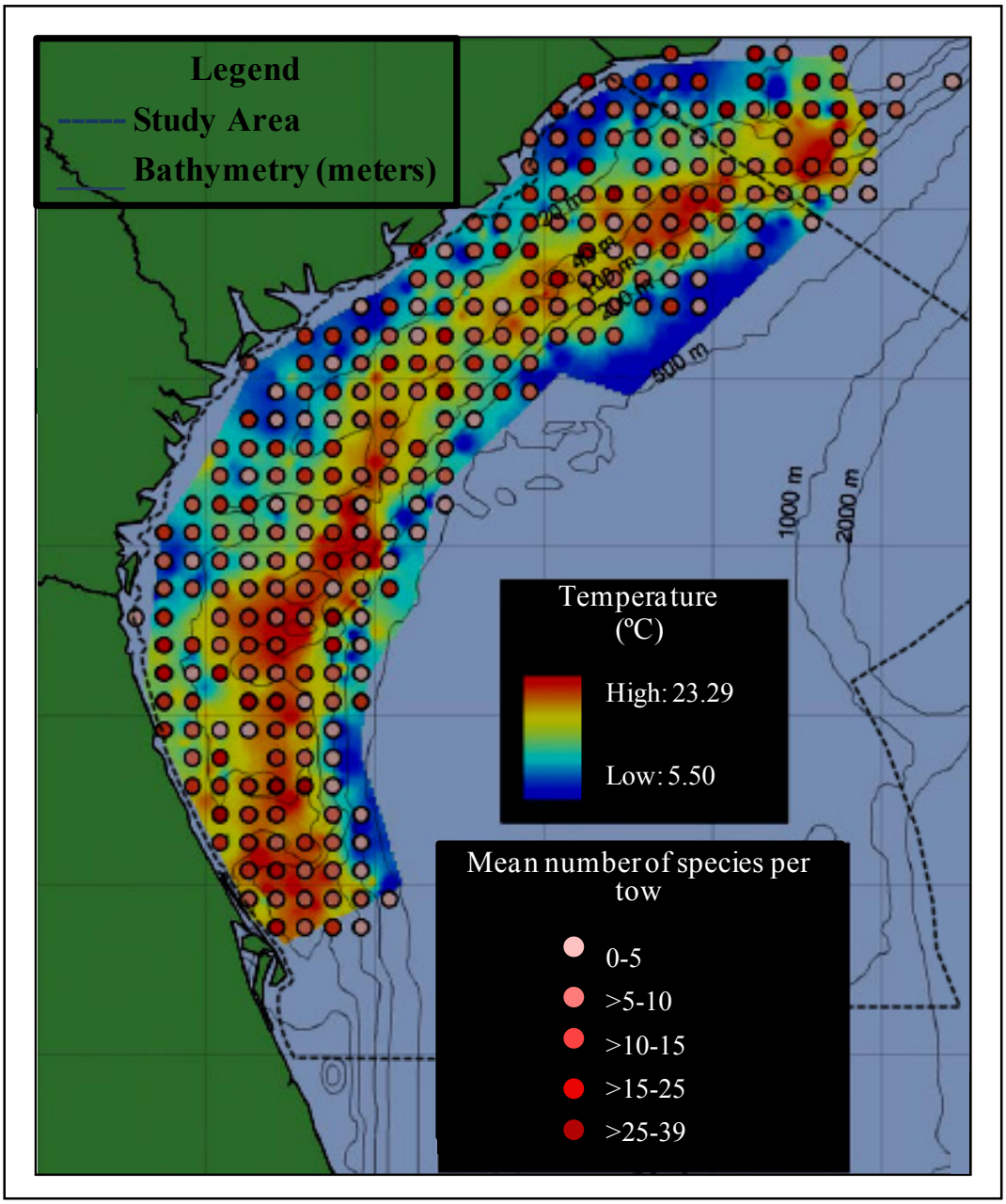

Figure 7.4 Mean number of fish species in relation to bottom water temperatures during winter (December–March; 1978-2004). Figure modified from Sedberry et al. (2005) and reproduced with permision from the author.

Table 7.5
Summary of reef species that spawn on middle- and outer-shelf areas. Modified from Sedberry et al. (2006).

Common name	Scientific name	Spawning depth (m)	Spawning temperature (ºC)	Females captured (% spawning)	Spawning peak
Gray triggerfish	*Balistes capriscus*	20–75	19–27	2259 (6)	Jun–Jul
Bank sea bass	*Centropristis ocyurus*	27–57	16–19	1267 (4)	Feb–Apr
Black sea bass	*Centropristis striata*	15–56	11–27	19740 (11)	Feb–Apr
Coney	*Cephalopholis fulva*	39	24	8 (13)	-
Sand perch	*Diplectrum formosum*	17–47	14–29	779 (81)	May–Sep
Rock hind	*Epinephelus adscensionis*	37–53	20–24	12 (42)	-
Tomtate	*Haemulon aurolineatum*	15–54	-	925 (26)	May–Jul
White grunt	*Haemulon plumieri*	22–51	-	1227 (12)	Apr–Jun
Red snapper	*Lutjanus campechanus*	24–67	18–28	402 (20)	Jun–Sep
Yellowmouth grouper	*Mycteroperca interstitialis*	49–51	-	12 (75)	-
Red porgy	*Pagrus pagrus*	26–57	16–19	10870 (4)	Nov–Apr
Vermilion snapper	*Rhomboplites aurorubens*	18–97	16–28	8666 (38)	May–Sep

7.2.3.1 Biologically Sensitive Areas

7.2.3.1.1 Nearshore Hard bottom off Southeast Florida

The northernmost portion of the relatively extensive nearshore hard-bottom habitats of southeast Florida (Brevard to Miami-Dade Counties) falls within the boundaries of this synthesis (~42.5 acres; Brevard County). These habitats occur in shallow waters (<6 m) and play roles comparable to those of coastal and shallow reef systems, particularly by providing resources to critical life stages of many fish species. An important feature of this nearshore hard-bottom habitat is the presence of sabellariid worm (*Phragmatopoma lapidosa*) reef builders in shallow subtidal areas (see Figure 6.11 in Chapter 6: Benthic Communities). These worm reefs rise 1–2.5 m above the bottom providing ample cover for many fish species and sustain a high biological diversity (Gilmore et al., 1981).

Although a few studies have documented the fish composition in nearshore hard-bottom habitats of Florida (e.g., Coral Cove, Broward County and Carlin Park, Palm Beach County) (see SAFMC, 2009; Lindeman and Snyder, 1999), information specific to the study area is limited. Gilmore et al. (1981) documented 107 species associated with worm reefs; of these, two demersal species (*Labrisomus nuchipinnis* and *Blennius cristatus*) and three semi-demersal species (*Diplodus holbrooki*, *Anisotremus virginicus*, and *Haemulon parrai*) numerically dominated the fish assemblage. Others have also documented that a handful of species (e.g., black margate, cocoa damselfish, hairy blenny, sailors choice, and silver porgy) consistently dominate the assemblage, and that most of the fishes are resident while a few are transient species (see Appendix 7-B1.1) (Lindeman and Snyder, 1999; Continental Shelf Associates, 2009; USACE, 2009).

Studies have also compared the diversity of these with nearby habitats. The fish assemblage in the nearshore hard-bottom habitat of Brevard County has a more diverse species assemblage (at least 19 species) and is strikingly different in abundance and composition than that of nearby soft bottom substrates (at least 13 species, but almost entirely dominated by false pilchard *Harengula jaguana*) (USACE, 2009). Furthermore, the ichthyofauna assemblage in these habitats resembles that of nearby shallow reefs and is dominated by tropical species. These observations agree with others who have reported a much higher fish abundance in these habitats (>30x) compared to nearby natural sand habitats, and often higher than that of hard-bottom habitats at similar depths (Lindeman and Snyder, 1999; Continental Shelf Associates, 2009). Though the number of fish species associated with worm reefs is not greater than that of the adjacent surf zone, the large number of associated species substantially enhances the fish diversity of the beach zone (Zale and Merrifield, 1989).

These habitats are important nursery grounds for species that ontogenetically migrate into deeper waters (i.e., newly settled larvae and juveniles) (see Appendix 7-B1.1) (Lindeman and Snyder, 1999; Continental Shelf Associates, 2009; USACE, 2009). These habitats are also important nursery, feeding grounds, and shelter for a variety of sharks (National Marine Fisheries Service, 1999). Sharks found in these habitats include neonate scalloped hammerhead, juvenile nurse shark (*Ginglymostoma cirratum*), juvenile blacktip shark (*Carcharhinus limbatus*), neonate, juvenile, and adult Atlantic sharpnose sharks, juvenile and adult bonnethead, and neonate and juvenile bull sharks (*Carcharhinus leucas*) (Adams and Paperno, 2007), blacknose shark (*Carcharhinus acronotus*), spinner shark (*Carcharhinus brevipinna*), dusky shark (*Carcharhinus obscures*), sandbar shark (*Carcharhinus plumbeus*), tiger shark (*Galeocerdo cuvier*), sand tiger shark (*Carcharias taurus*), and lemon shark (*Negaprion brevirostris*) (National Marine Fisheries Service, 1999; USACE, 2009) (see Appendix 7-A1). These nearshore, hard-bottom habitats represent important HAPCs for species managed under the Snapper/Grouper Fishery Management Plan and many other species that co-occur with the species in this management unit (SAFMC, 2009).

7.2.3.1.2 Gray's Reef National Marine Sanctuary

GRNMS (see Figure 6.8 in Chapter 6: Benthic Communities), located 32 km offshore of Sapelo Island, Georgia is one of the largest nearshore live reefs (58 km^2) on the US South Atlantic continental shelf (Sedberry et al., 1998). Benthic habitats are comprised primarily of rippled sand (~39 km^2 of unconsolidated coarse sediment and sand ridges; 67% of the sanctuary), sparsely colonized live-bottom (~14 km^2; 25% of the sanctuary), flat sandy bottom (~5 km^2 of thin sand layer overlying flat limestone; 8% of the sanctuary), and densely colonized live-bottom on ledges or high relief areas (~0.4 km^2 or <1% of the sanctuary) (Kendall et al., 2005). Live-bottom habitats are dominated by sessile benthic organisms, including corals, sponges, and tunicates, which support a rich ichthyofauna community (Figure 7.5). The reef is influenced by wind, the Gulf Stream, tidal flux, and by seasonal fluctuations in salinity and temperature (Atkinson et al., 1983; Gilligan, 1989).

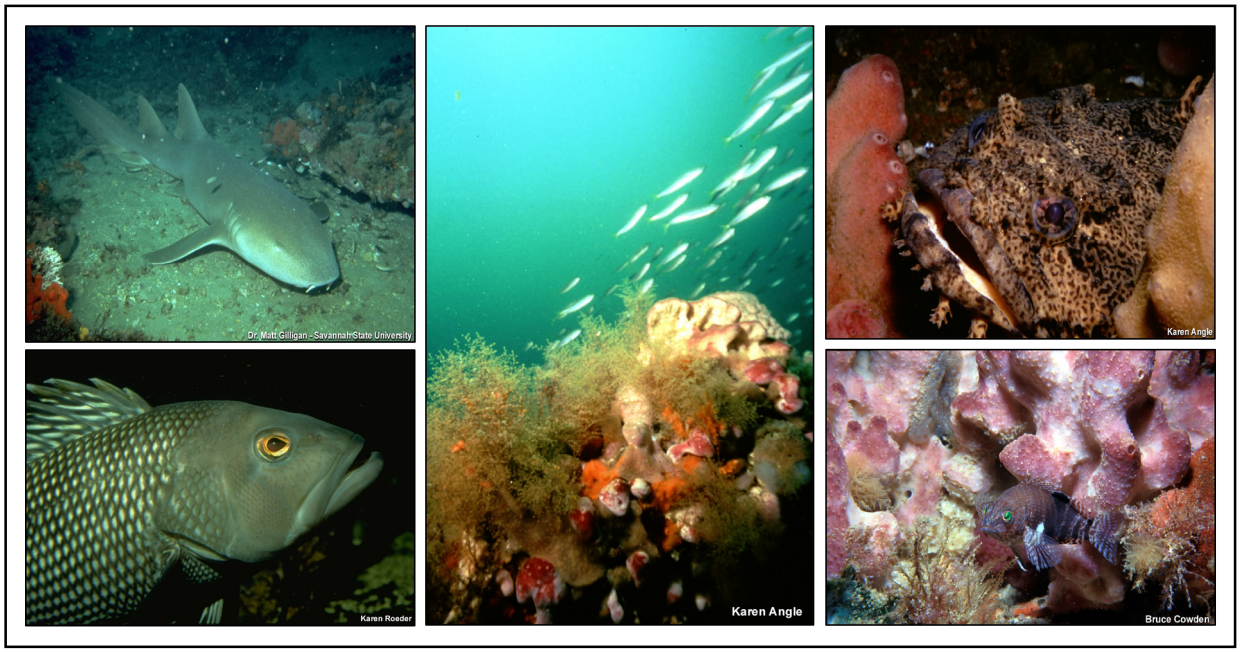

Figure 7.5 The ichthyofauna of GRNMS (top left: nurse shark; bottom-left: black sea bass; center: coral habitat; top right: oyster toadfish; bottom right: belted sand fish). Photos courtesy of NOAA National Marine Sanctuaries.

A compilation of the fish assemblage at GRNMS and its surrounding waters identified a partial list of 138 species (not including 11 species of sharks and several coastal migratory species) (Gilligan, 1989) known to occupy areas between the inner and outer shelf (Marancik et al., 2005; Walsh et al., 2006), including resident and seasonal migrant species (Table 7.6). The fish composition at the sanctuary is similar to that found on reefs at similar depths off South Carolina (Sedberry et al., 1998), where the black sea bass is the most abundant species. Other common species in the area include scup, tomtate, spottail pinfish, and a few individuals of blue runner, gray triggerfish, northern puffer, greater amberjack, pigfish, spottail pinfish, and planhead filefish (McGovern et al., 2002c; Sedberry et al., 1998).

Several studies (Parker et al., 1994; Kendall et al., 2008; Kracker et al., 2008; Kendall et al., 2009) discussed the role of bottom type on the distribution of fishes. Earlier work by Parker et al. (1994) reported differences in the number of species and fish density across several bottom types, with higher numbers on ledges (14–26 species, 4–20 ind/m), intermediate numbers on low relief and rock outcroppings (6–13 species, 1–6 ind/m), and lowest numbers on sandy substrates (3–5 species, 0.02–0.9 ind/m). Kendall et al. (2009) also evaluated the influence of bottom characteristics and physical attributes on bottom fish assemblages, finding that ledge habitats had much higher species richness (2x higher), diversity, abundance (2–10x higher), and fish biomass than flat live-bottom habitats. For instance, 95% of the 75 species identified in the study were found on ledge habitats (numerically dominated by juveniles of tomtate and jacks, as well as sciaenids, black sea bass, and scup), while only 45% were found on flat live-bottom habitats (numerically dominated by black sea bass and scup). It's likely that ledge habitats support a much more diverse species assemblage because of the habitat complexity and high cover of sessile invertebrates (Kendall et al., 2009). These findings are in agreement with the observations

by Kracker et al. (2008), who indicated that distance to the nearest rock ledge influenced fish biomass within 2 m of the seafloor, while a mix of habitats (sparsely colonized live-bottom and flat sand) influenced fish biomass in the 2–10 m portion of the water column. Kendall et al. (2009) also found that even within ledge sites, fishes could be separated into two clear assemblages: 1) fishes associated with relatively tall ledges (55±6.7 cm) heavily colonized with sessile invertebrates (72±4.7% cover), large in area (2,800±320 m^2), and with or without undercuts (e.g., sciaenids, sheepshead, and scamp); and 2) fishes associated with short ledges (14±1.4 cm), smaller in area (1280±130 m^2), and with or without heavy colonization by invertebrates (e.g., *Stenotomus* spp.). Another study (Kendall et al., 2008) analyzed the effect of benthic characteristics on the distribution of three bottom fish species commonly targeted in fisheries: black sea bass, gag, and scamp. The authors found that black sea bass were much more abundant (28±2.3 fish/100 m^2) on ledges within the sanctuary than either gag (1.0 ±0.2 fish/100 m^2) or scamp (2.0±0.5 fish/100 m^2), and that they had a much more even distribution than the other two species which tended to clump on ledges. The abundance of black sea bass was correlated with increased cover of sessile invertebrates, decreased ledge area, and absence of scamp and gag, while presence of gag and scamp was related to the presence of undercut height of ledges (Kendall et al., 2008).

Table 7.6
Fish assemblage at GRNMS and its surrounding areas

Common Name	Scientific Name	Habitat at GRNMS by Life Stage		
		Larvae	Juvenile	Adult
Ocean surgeon	*Acanthurus bahianus*●	P	R	R
Doctorfish	*Acanthurus chirurgus*●◊	P	R	R
Dotterel filefish	*Aluterus heudelotii*●	P	S	S R
Drange filefish	*Aluterus schoepfii*●◊	P	S	S R
Dtriped anchovy	*Anchoa hepsetus*▲▼	P	P	P
Digeye anchovy	*Anchoa lamprotenae*▲	P	P	P
Ocellated flounder	*Ancylopsetta quadrocellata*▲	P	S	S
Twospot cardinalfish	*Apogon pseudomaculatus*○◊	P	R	R
Sheepshead	*Archosargus probatocephalus*○◊	P	R	R
Bandtooth conger	*Ariosoma balearicum*▲	P		
Gray triggerfish	*Balistes capriscus*○◊	P		S R
Eyed/spottail flounder	*Bothus ocellatus*▲▼	P	S	S
Atlantic menhaden	*Brevoortia tyrannus*●▼◊	P	P	P
Whitebone porgy	*Calamus leucosteus*●◊	P		R
Yellow jack	*Caranx bartholomaei*○◊	P	S P	R P
Bar jack	*Caranx ruber*○◊	P	P	R P
Unidentified jack	*Caranx* sp.○			
Black sea bass	*Centropristis striata*○◊	P	S R	R
Bank sea bass	*Centropristis ocyurus*○▲	P	R	R
Rock sea bass	*Centropristis philadelphica*●◊	P		R
Atlantic spadefish	*Chaetodipterus faber*○◊	P		R P
Spotfin butterflyfish	*Chaetodon ocellatus*○◊	P	R	R
Reef butterflyfish	*Chaetodon sedentarius*●	P	R	R
Banded butterflyfish	*Chaetodon striatus*●			
Stripped burrfish	*Chilomycterus schoepfii*◊	P	R	R
Spotted whiff	*Citharichthys macrops*▲	P	S	S

Data combined from: ● Parker et al. (1994); ○ Kendall et al. (2009) and Parker et al. (1994); ▲Walsh et al. (2006); ▼ Marancik et al. (2005); ◊ Gilligan (1989). Habitats: sandy bottom (S), reef (R), pelagic (P).

Table 7.6 Fish assemblage at GRNMS and its surrounding areas (continued).

Common Name	Scientific Name	Habitat at GRNMS by Life Stage		
		Larvae	Juvenile	Adult
Bay whiff	*Citharichthys spilopterus*▼	P	S	S
Dolphin	*Coryphaena hippurus*▼◊	P	P	P
Spotted goby	*Coryphopterus punctipectophorus*◊	P	S R	S R
Flounder	*Cyclopsetta* spp.▼	P	S	S
Silver seatrout	*Cynoscion nothus*▼	P	S	S
Weakfish	*Cynoscion regalis*▼	P	S	S
Sand Stargazer	*Dactyloscopus moorei*▲	P	S	S
Southern stingray	*Dasyatis americana*●◊			
Round scad	*Decapterus punctatus*●◊	P	S P	R P
Porcupinefish	*Diodon hystrix*○			
Sand perch	*Diplectrum formosum*○▲▼◊	P	S R	S R
Spotfin pinfish	*Diplodus holbrooki*○◊	P		S R
Spotted dragonet	*Diplogrammus pauciradiatus*▼	P		
Sharksucker	*Echeneis naucrates*◊	P	P	P
High-hat	*Equetus acuminatus*●	P		R
Jackknife-fish	*Equetus lanceolatus*○	P		R
Cubbyu	*Equetus umbrosus*●	P		R
Fringed flounder	*Etropus crossotus*▼	P		
Little tunny	*Euthynnus alletteratus*●◊	P	P	P
Nurse shark	*Ginglymostoma cirratum*○			
Ocellated moray	*Gymnothorax saxicola*◊			
Moray	*Gymnothorax sp.*▼	P	R	R
Tomtate	*Haemulon aurolineatum*○◊	P	R	R
Slippery dick	*Halichoeres bivittatus*○◊	P	R	S R
Wrasse	*Halichoeres* spp.▼	P	R	R
Seahorse	*Hippocampus* spp.▼			
Lined seahorse	*Hippocampus erectus*●▲◊	P	S	R
American fourspot flounder	*Hippoglossina oblongata*▼	P		
Blue angelfish	*Holocanthus bermudensis*○◊	P	R	R
Squirrelfish	*Holocentrus ascensionis*●◊	P	R	R
Crested blenny	*Hypleurochilus geminatus*◊	P	R	R
Blue goby	*Ioglossus calliurus*●	P	R	R
Scrawled cowfish	*Lactophrys quadricornis*●▲◊	P	R	R
Smooth trunkfish	*Lactophrys triqueter*●	P		R
Pinfish	*Lagodon rhomboides*▼◊	P		
Banded drum	*Larimus fasciatus*▼	P		
Spot	*Leiostomus xanthurus*▲▼	P		
Red snapper	*Lutjanus campechanus*○◊	P	S R	R
Juvenile snapper	*Lutjanus* sp.○			
Southern kingfish	*Menticirrhus americanus*▼	P		
Banded pipefish	*Micrognathus crinitus*●			
Seminole goby	*Microgobius carri*○◊	P	S R	S R
Atlantic croaker	*Micropogonias undulatus*▼	P		
Unidentified	*Moray*○			
White mullet	*Mugil curema*▼	P		
Red goatfish	*Mullus auratus*●◊	P	S R	S R

Data combined from: ● Parker et al. (1994); ○ Kendall et al. (2009) and Parker et al. (1994); ▲Walsh et al. (2006); ▼ Marancik et al. (2005); ◊ Gilligan (1989). Habitats: sandy bottom (S), reef (R), pelagic (P).

Table 7.6 Fish assemblage at GRNMS and its surrounding areas (continued).

Common Name	Scientific Name	Habitat at GRNMS by Life Stage		
		Larvae	Juvenile	Adult
Gag	*Mycteroperca microlepis*○◊	P	R	R
Scamp	*Mycteroperca phenax*○◊	P	R	R
Speckled worm eel	*Myrophis punctatus*●▼	P	S R	S R
Shortnose batfish	*Ogcocephalus nasutus*▲◊	P	S	S
Roughback batfish	*Ogcocephalus parvus*◊	P	S	S
Palespotted eel	*Ophichthus ocellatus*◊			
Snake eel	*Ophichthus cruentifer*▼	P		
Bank cusk-eel	*Ophidion holbrooki-O. antipholus*▼	P		
	Ophidion josephi▼◊	P		
Striped cusk-eel	*Ophidion marginatum*▼	P		
Mooneye cusk-eel	*Ophidion selenops*▲▼	P	S	S
Redlip blenny	*Ophioblennius atlanticus*●	P	R	R
Atlantic thread herring	*Opisthonema oglinum*▼◊	P	P	P
Leopard/oyster toadfish	*Opsanus pardus* ◊	S R	R	S R
Toadfish	*Opsanus* sp.○			
Pigfish	*Orthopristis chrysoptera*●◊	P	S	S
Polka-dot cusk-eel	*Otophidium omostigmum*▼	P	S	S
Red porgy	*Pagrus pagrus*○◊	P	R	S R
Seaweed blenny	*Parablennius marmoreus*○◊	P	S R	R
Southern flounder	*Paralichthys lethostigma*▼	P	S	S
Butterfish	*Peprilus triacanthus*▲	P	S P	S P
Dusky cardinalfish	*Phaeoptyx pigmentaria*●			
Black drum	*Pogonias cromis*▼	P	S	S R
Bicolor damselfish	*Pomacentrus partitus*●◊	P	R	R
Cocoa damselfish	*Pomacentrus variabilis*●◊	P	R	R
Cluefish	*Pomatomus saltatrix*◊	P	P	P
Atlantic midshipman	*Porichthys plectrodon*◊	S R	S	S
Bigeye	*Priacanthus arenatus*●◊	P	S R	S R
Northern searobin	*Prionotus carolinus*▲◊	P	S	S
Leopard searobin	*Prionotus scitulus*▲	P	S	S
Unidentified searobin	*Prionotus* sp.○			
Short bigeye	*Pristigenys alta*●	P	S R	S R
Silver driftfish	*Psenes maculatus*●	P	P	P
Cobia	*Rachycentron canadum*◊	P	P	R P
Vermilion snapper	*Rhomboplites aurorubens*◊	P	R	S R
Whitespotted soapfish	*Rypticus maculatus*○◊	P	S R	R
Greater soapfish	*Rypticus saponaceus*	P	S R	R
Spanish sardine	*Sardinella aurita*●▲◊	P	P	P
Red drum	*Sciaenops ocellatus*▼	P	S R	S R
King mackerel	*Scomberomorus cavalla*◊	P	P	P
Spanish mackerel	*Scomberomorus maculatus*○▼◊	P	P	P
Barbfish	*Scorpaena brasiliensis*◊	P		S R
Spotted scorpionfish	*Scorpaena plumieri*▲	P	R	R
Greater amberjack	*Seriola dumerili*●◊	P	P	R P
Almaco jack	*Seriola rivoliana*●	P	P	R P

Data combined from: ● Parker et al. (1994); ○ Kendall et al. (2009) and Parker et al. (1994); ▲Walsh et al. (2006); ▼ Marancik et al. (2005); ◊ Gilligan (1989). Habitats: sandy bottom (S), reef (R), pelagic (P).

Table 7.6 Fish assemblage at GRNMS and its surrounding areas (continued).

Common Name	Scientific Name	Habitat at GRNMS by Life Stage		
		Larvae	Juvenile	Adult
Pygmy sea bass	*Serraniculus pumilio*▼	P		
Belted sandfish	*Serranus subligarius*○◊	P	R	R
Parrotfish	*Sparisoma* sp.○			
Northern puffer	*Sphoeroides maculatus*◊	P	S P	R
Great barracuda	*Sphyraena barracuda*○◊	P	S P	R P
Checkered blenny	*Starksia ocellata*◊	P		R
Longspine porgy	*Stenotomus caprinus*●◊			
Scup	*Stenotomus* sp.▲	P	R	S R
Planehead filefish	*Monocanthus hispidus*●	P	S	S R
Dusky flounder	*Syacium papillosum*◊			
Flounder	*Syacium* spp. ▼	P		
Blackcheek tonguefish	*Symphurus plagiusa*▲	P	S	S
Spottail tonguefish	*Symphurus urospilus*▲	P	S	S R
Chain pipefish	*Syngnathus louisianae*●▼	P		
Inshore lizardfish	*Synodus foetens*●▲◊	P	S	S
Tautog	*Tautoga onitis*●◊	P	R	R
Snakefish	*Trachinocephalus myops*●	P	S	S R
Hogchoker	*Trinectes maculatus*▼	P	S	S
	Unidentified flounder and jawfish ○			
Dwarf goatfish	*Upeneus parvus*▲	P		
Hake	*Urophycis earllii*▼◊	P		S R
Spotted hake	*Urophycis regia*▲	P		
Pearly razorfish	*Xyrichtys* spp.▼- *Hemipteronotus novacula*●◊	P	S	S

Data combined from: ● Parker et al. (1994); ○ Kendall et al. (2009) and Parker et al. (1994); ▲Walsh et al. (2006); ▼ Marancik et al. (2005); ◊ Gilligan (1989). Habitats: sandy bottom (S), reef (R), pelagic (P).

7.2.3.1.3 Artificial Reefs

Artificial reefs (see Figure 6.8 in Chapter 6: Benthic Communities) encompass all human-made structures of various materials intentionally or unintentionally deployed or constructed in nearshore habitats. These hard structures provide suitable habitat for the proliferation of live-bottom, thus enhancing opportunities for commercial and recreational fisheries. All federally designated artificial reefs are established as Special Management Zones (SMZs) under the SAFMC Snapper-Grouper Fishery Management Plan and are also considered HAPCs for managed species. For example, artificial reefs in deep water (50–70 nm off the Georgia coast) have been developed to address growing recreational needs for tunas, wahoo (*Acanthocybium solandri*), and other "bluewater" gamefish. These SMZs regulate fishing gear and harvesting, thereby promoting an even allocation of reef resources and opportunities (SAFMC, 2009).

The ichthyofauna composition of artificial reefs is similar to that of natural reef habitats within the same environmental (depth, temperature) and geographic conditions (i.e., low species diversity and large size fish in winter, high concentration of juveniles during spring and fall, and abundant young of the year in spring and early summer) (Arendt et al., 2009; Hay and Sutherland, 1988; Kellison and Sedberry, 1998; Mercer, 1989; Parker et al., 1979; Rountree, 1990). Reef species are generally grouped into:

- Species with low mobility (year round residents) that depend on the structural complexity of these reefs, including small cryptic species of the blenny (Blenniidae: crested blenny *Hypleurochi1s geminatus* and feather blenny *Hypsoblennius hentzi*), skilletfish (*Gobiesox strumosus*) and seaboard goby (*Gobiosoma ginsburgi*).
- Species numerically abundant during warmer periods but that migrate to deeper waters during winter (e.g., pinfish, spottail pinfish, black sea bass, and pigfish).
- Highly migratory species and pelagic predators attracted to these structures in search of food (e.g., bluefish, Spanish mackerel, sharks, little tunny, cobia, blue runner, amberjacks, and barracuda).
- Species attracted to these structures during their spring or fall migrations (e.g., smooth dogfish).
- Tropical species associated with these habitats during the warm months (e.g., butterfly fish-Chaetodontidae, and surgeon fishes-Acanthuridae).
- Small forage and juvenile fishes including those of offshore reef species that migrate to shallower estuarine nursery grounds (e.g., gag, pinfish, spottail pinfish, black sea bass, and spadefish).

An early study off South Carolina (Parker et al., 1979) found 63 species (33 families) at an estimated density of 0.025 fish per m^2, with a standing crop 1,814 times greater than pre-reef construction levels. However, the black sea bass appeared to be the only resident species. Rountree (1990) studied the fish assemblage associated with fish aggregation devices (FADs) and FAD anchors in shallow waters (14 m) off Charleston, South Carolina. This study found that fish aggregations attracted to FADs were characterized by round scad, blue runner, filefish (*Monacanthus hispidus*), and jacks (*Caranx bartholomaei*, *Seriola* spp., and *Seriola zonata*), while species attracted to FAD anchors were characterized by serranids (*Diplectrum formosum*, *Centropristis striata*, *C. ocyurus*) and a blenny (*Hypleurochilus geminatus*). A related study (Kellison and Sedberry, 1998) found that FADs not only attracted a large number of individuals (5,604 individuals including juveniles and/or adults of 33 species, including Atlantic spadefish, bank sea bass, black sea bass, filefish, gray triggerfish, greater amberjack, scup, and tomtate, but also enhanced vertical profiles and habitat complexity. These structures also provided substrate for fouling communities and pelagic fauna, thereby enhancing the benthic productivity of the surrounding area. Furthermore, Steimle and Ogren (1982) indicated that of the five common species in shallow artificial reefs off South Carolina (black sea bass, rock sea bass, scup, pinfish, and sheepshead), sheepshead was more dependent on the fauna associated with reef habitats (barnacles and tunicates).

Although the studies mentioned above indicate that artificial reefs facilitate habitat use by several species, the cumulative effects of these artificial structures are poorly understood. To date, it is unknown whether these habitats provide significant long-term biological benefits to the productivity of the continental shelf, and whether replacing natural habitats with artificial reefs disrupts natural processes (e.g., trophic interactions, fish behavior, and settlement patterns), and negatively impacts adjacent habitats (SAFMC, 2009) (see Section 7.7.1 Oil and Gas Exploration and Development).

7.2.4 Shelf Edge and Lower Shelf

The continental shelf edge occurs at depths between 55–110 m, while the lower shelf occurs at depths between 110–183 m. The substrate in these habitats is characterized by smooth muddy bottoms or rugged vertical relief heavily encrusted with corals and sponges. The proximity of the Gulf Stream creates stable and relatively warm bottom water temperatures (Struhsaker, 1969). Prominent shelf-edge reefs include St. Augustine Scarp, Jacksonville Scarp, Julians Ridge, Scamp Ridge, and Georgetown Hole (53–61 m), while prominent lower-shelf reefs include Charleston Lumps North and South (200–206 m). Although these reefs share similar oceanic salinities, lower-shelf reefs are characterized by cooler waters that range in bottom temperatures from 11 to 14°C, compared to shelf-edge reefs at 12–26°C (Struhsaker, 1969; Miller and Richards, 1980; Sedberry et al., 2004a).

Both the shelf edge and the lower shelf constitute EFH for deep-water reef fishes (SAFMC, 2009), are critical spawning ground for many reef fishes of the South Atlantic Planning Area (Sedberry et al., 2004a; Sedberry et al., 2005; Figure 7.6), and are important habitats for warm-water species and species found on the continental shelf. The fish assemblage in these habitats is comprised of a diverse group of wide-ranging species with distributions extended into shallower or deeper waters (Chester et al., 1984). Comparisons of species composition on reefs across the continental shelf have found that the offshore reef assemblage (64–183 m, Grimes et al., 1982; 55–183 m, Miller and Richards, 1980; 40–100 m, Rowe and Sedberry, 2006; 46–100 m, SCWMRD and GDNR, 1982 and Sedberry and Van Dolah, 1984) is markedly different from shallower habitats, being comprised of three distinct assemblages: 1) temperate species with cross-shelf distribution; 2) transient and subtropical species with seasonal movements offshore; and 3) deep-water temperate species (see Figure 7.3). High species diversity on the shelf break is consistent with the occurrence of hard-bottom substrates on the shelf edge and the proximity to the Gulf Stream (Rowe and Sedberry, 2006). Grimes et al. (1982), for example, found relatively distinct fish assemblages between open shelf (27–64 m) and shelf-edge/lower-shelf habitats (64–183 m). Open-shelf species were largely dominated (based on occurrence and abundance) by a few species (black and bank sea bass, sand perch, and white grunt), while shelf-edge/lower-shelf habitats were much more diverse (~19 species) and included a wide variety of tropical and subtropical species (Figure 7.7). Yet, there was substantial overlap in species composition between shallow waters and shelf-edge/lower-shelf habitats (~13 species). Most of these species appear to be residents of the continental shelf of the Carolinas. Chester et al. (1984) also found that the shelf-edge assemblage parallels the open shelf with increased abundance of tropical species (e.g., *Chaetodon ocellatus*, *Holocanthus bermudensis*, *Equetus lanceolatus*, *Fistularia tabacaria*, and *Apogon pseudomaculatus*) on and near live-bottom areas. Other species characteristic of shelf-edge reefs off South Carolina included red porgy, vermilion snapper, and gray triggerfish, and by communities of red hind-rock hind (*Epinephelus guttatus*), scamp, speckled hind (*Epinephelus drummondhayi*), and knobbed porgy (*Calamus nodosus*) (Chester et al., 1984). In contrast, the lower shelf fish assemblages was characterized by tilefish (Malacanthidae) found predominantly on muddy bottom and *Epinephelus* groupers (snowy grouper *E. niveatus*, Warsaw grouper *E. nigritus*, yellowedge grouper *E. flavolimbatus*), and blackbelly rosefish (*Helicolenus dactylopterus*) found on hard bottom (Chester et al., 1984; Parker and Mays, 1998).

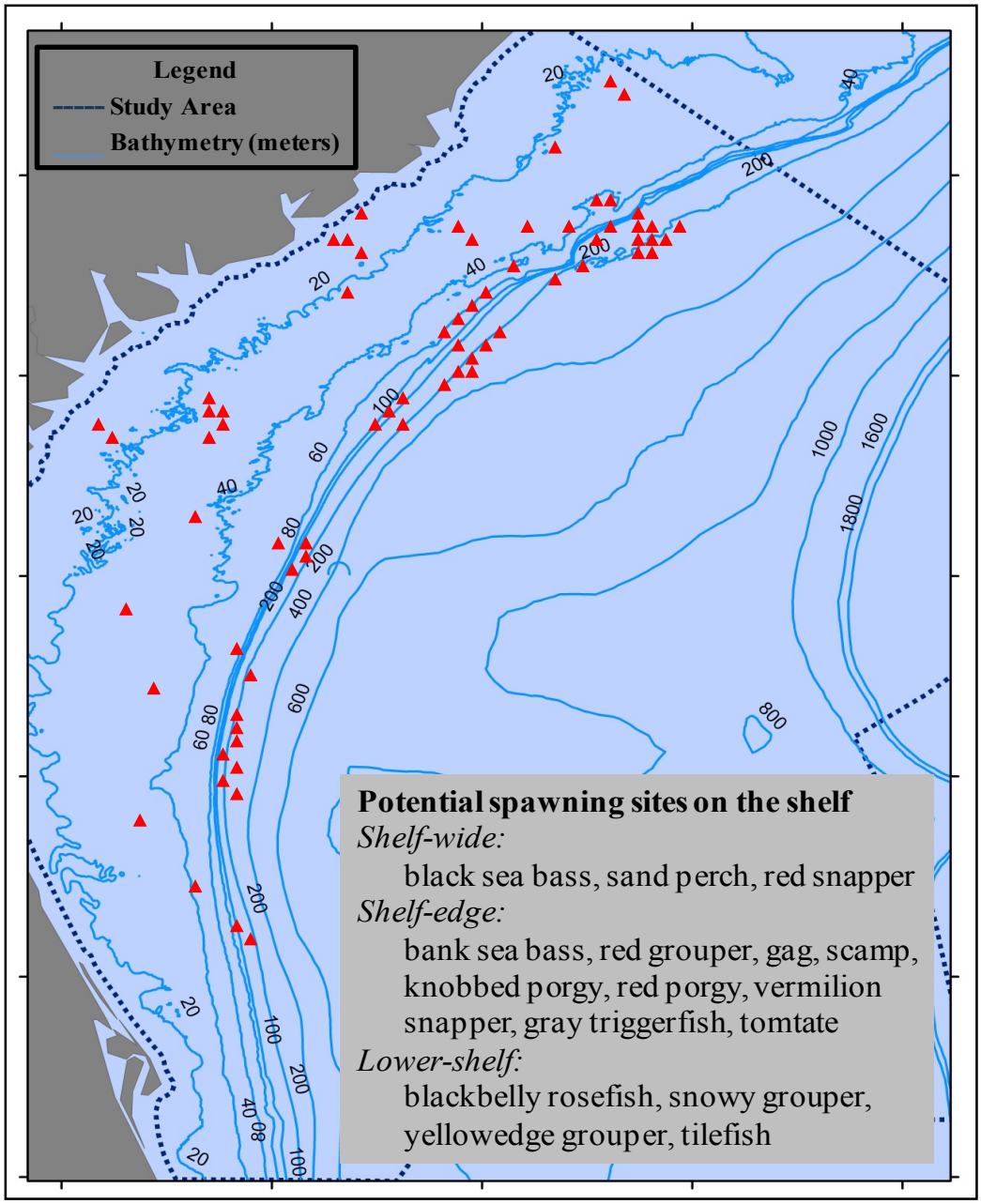

Figure 7.6 Potential spawning locations on the continental shelf (▲) of several reef fish species. Figure modified from Sedberry et al. (2005) and reproduced with permission from the author.

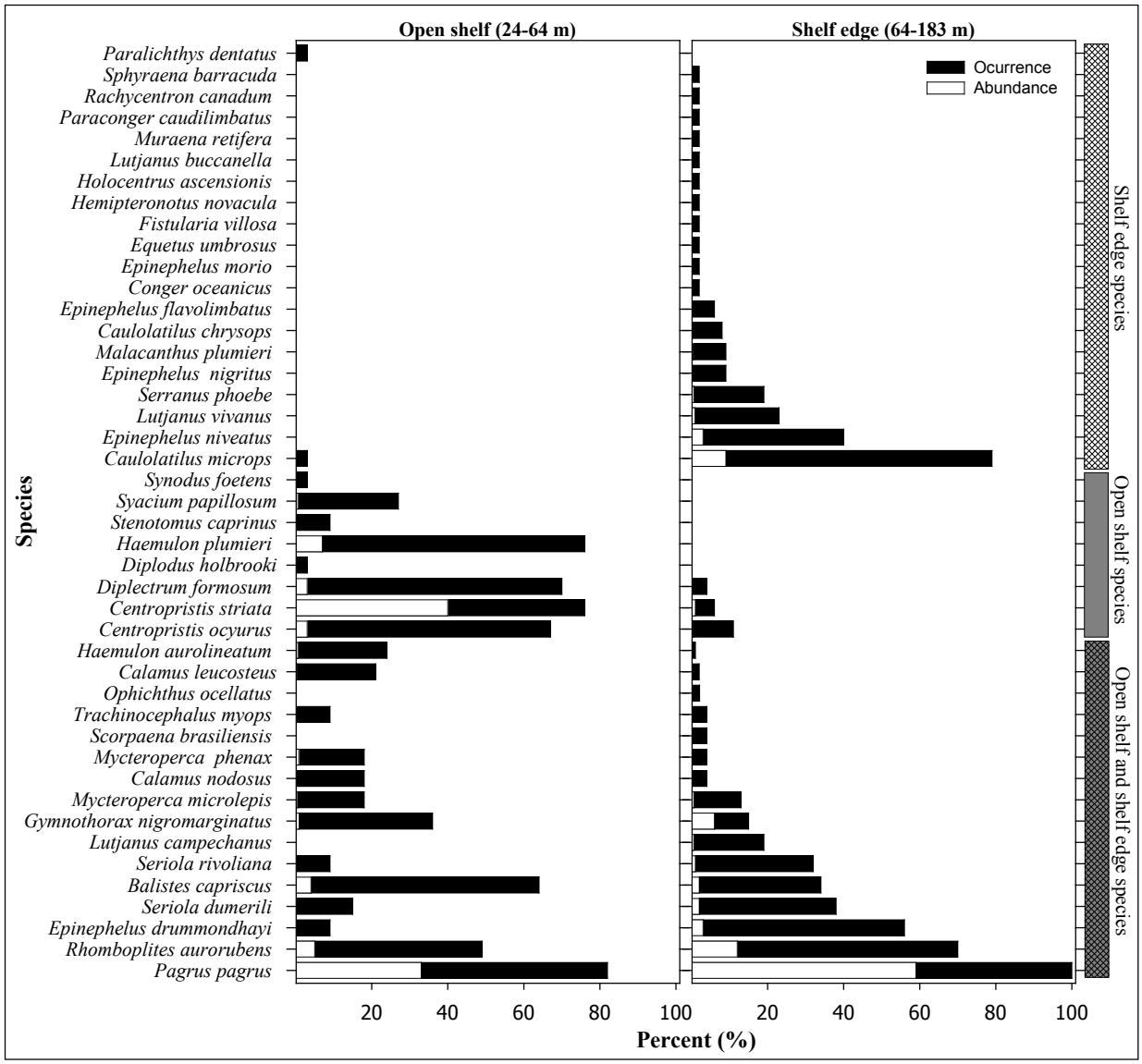

Figure 7.7 Species reported on surveys along the continental shelf of the Carolinas. The bars represent the percent occurrence (black bar) and abundance (white bar) of resident fish species among several cruises. The far-right column indicates species characteristic of the open shelf and/or shelf edge. Data modified from Grimes et al. (1982). *Note*: This figure displays historical data and may not necessarily reflect current patterns.

Relatively more recent surveys (1985 to 2000; with emphasis on commercial fish species) found unique, non-overlapping fish assemblages between shelf-edge and lower-shelf habitats, and a much higher diversity of shelf-edge reef assemblages (Sedberry et al., 2004a). Shelf-edge reef assemblages were dominated by tomtate, yellowtail reeffish (*Chromis enchrysura*), vermilion snapper, squirrelfish (*Holocentrus adscensionis*), and reef butterfly fish (*Chaetodon sedentarius*); whereas lower-shelf reefs were dominated by yellowfin bass (*Anthias nicholsi*) and blackbelly rosefish. Quattrini and Ross (2006) and Schobernd and Sedberry (2009) also compared shelf-edge and lower-shelf assemblages in the proximity of proposed marine protected areas (St. Augustine Scarp, Jacksonville Scarp, Charleston Lumps, Julians Ridge, and Charleston

Hole; see Section 7.2.4.1.2 Shelf-edge Marine Protected Areas). Shelf-edge surveys yielded 23,636 individuals (54 species), while lower-shelf surveys (Charleston Lumps) yielded 706 individuals (7 species) (Schobernd and Sedberry, 2009). Dominant species on shelf-edge and lower-shelf habitats were similar to those reported by Sedberry et al. (2004a). Tomtate, vermilion snapper, and yellowtail snapper comprised 70% of the total fish abundance on shelf-edge reefs, while yellowfin bass and blackbelly rosefish comprised 86% of the total abundance on lower-shelf reefs. On shelf-edge sites, the number of species ranged from 18 to 37, while mean fish density ranged from 300–950 ind./km^2. Reefs with moderate relief had higher fish diversity and abundance of certain species (tomtate, scamp, and vermilion snapper) than less morphologically complex reefs.

The shelf edge and lower shelf are not only important habitats for deep-water species; they are also critical spawning areas for many species found on the continental shelf (Table 7.7; Figure 7.6). Several widely distributed species (gag, gray triggerfish, greater amberjack, knobbed porgy, red porgy, and scamp) spawn at specific shelf-edge reef depths (50–100 m), requiring migrations to those sites during the spawning season, which is spring and summer for the large majority of reef species. Sedberry et al. (2006) also highlighted that spawning aggregations of reef species respond to spatial and temporal features, with hydrographic features such as upwellings and gyres playing an important role in ensuring the survival of early life-history stages. For instance, spawning in the proximity of gyres near the shelf edge allows the transport of pelagic eggs and larvae from the spawning areas to post-larval settlement habitat, reducing predation on early life stages in these highly productive waters. Description of species-specific life histories and spawning strategies are provided in Appendix 7-A1.

Table 7.7
Summary of reef species that spawn on the shelf edge and lower shelf. Modified from Sedberry et al. (2006).

Common Name	Scientific Name	Spawning Depth (m)	Spawning Temperature (ºC)	Females Captured (% spawning)	Spawning Peak
Gray triggerfish	*Balistes capriscus*	20–75	19–27	2,259 (6)	Jun–Jul
Knobbed porgy	*Calamus nodosus*	45–60	20–23	752 (12)	Apr–May
Blueline tilefish	*Caulolatilus microps*	48–234	9–16	619 (83)	Mar–Sep
Speckled hind	*Epinephelus drummondhayi*	-	-	169 (3)	-
Yellowedge grouper	*Epinephelus flavolimbatus*	160–194	15	52 (12)	-
Red grouper	*Epinephelus morio*	30–90	17–24	2,058 (2)	Apr
Warsaw grouper	*Epinephelus nigritus*	168	-	9 (11)	-
Gag	*Mycteroperca microlepis*	24–117	17	4,872 (28)	Feb–Apr
Scamp	*Mycteroperca phenax*	33–93	16–24	1,988 (18)	Mar–May
Vermilion snapper	*Rhomboplites aurorubens*	18–97	16–28	8,666 (38)	May–Sep
Greater amberjack	*Seriola dumerili*	45–122	24	1,363 (18)	Apr–May

7.2.4.1 Biologically Sensitive Areas

7.2.4.1.1 Oculina Bank, East-Central Florida

Deepwater *Oculina* coral reefs (see Figure 6.8 in Chapter 6: Benthic Communities) stretch over 167 km at depths of 70–100 m along the eastern Florida shelf (32-68 km offshore) of which 1,029 km^2 is considered as a HAPC (SAFMC, 1982; Reed, 2002a,b; Ross and Nizinski, 2007). This habitat consists of pinnacles and ridges ranging in heights of 3–35 m, and it is characterized by the presence of the branching scleractinian coral *Oculina varicosa* (Reed, 2002b). Only the northern-most portion of this area (Cape Canaveral reef) falls within the geographic boundaries of the South Atlantic Planning Area.

The fish community on the Florida shelf edge of the *Oculina* bank is typical of the southeastern shelf-edge reef fauna (Ross and Quattrini, 2007), characterized by 75–80 species numerically dominated by members of the Serranidae family (Gilmore et al., 1981). Some groupers, gag, and scamp use these reefs as spawning aggregation sites (Gilmore and Jones, 1992), while others (e.g., juvenile snowy grouper) use this habitat as nursery grounds (Reed, 2002b). Because of the high diversity of associated invertebrates, this habitat is also a feeding ground for groupers (red grouper, warsaw grouper), jacks (greater amberjack, almaco jack), sharks (tiger shark *Galeocerdo cuvieri*, scalloped hammerhead shark *Sphyrna lewini*), snappers (red snapper, gray snapper), and black sea bass (Gilmore and Jones, 1992; Reed, 2002b). The location of this habitat is also on the path of highly migratory species including king mackerel, Spanish mackerel, wahoo, and little tunny (Reed, 2002b) (also see Section 7.4.2.1 Important Areas for Migratory Pelagics). Other species associated with *Oculina* include red barbiers (*Hemanthias vivanus*), roughtongue bass (*Holanthias martinicensis*), small wrasse bass (*Liopropoma eukrines*), apricot bass (*Plectranthias garrupellus*), the bardrum (*Pareques* spp.), and bank butterflyfish (*Prognathodes aya*) (Gilmore et al., 1981). Shelf-edge *Oculina* reefs off central east Florida appear to have a much higher species richness (73 identified/unidentified fish species) than *Lophelia* reefs on the Blake Plateau (Appendix 7-B1.2; Ross and Quattrini 2007; 2009; see Section 7.3.1.1 Deep-Sea Coral and Deep Reef Habitats).

Studies in a nearby area within the *Oculina* Banks indicated that these highly biodiverse and spawning-critical habitats have been extensively degraded and reduced to rubble by destructive fishing practices (Koenig et al., 2000; Reed et al., 2007). Evidence of the threats posed by bottom trawling is unmistakable on the Cape Canaveral Pinnacle reef, which has been destroyed progressively over the past 25 years (Reed et al., 2005; Reed et al., 2007). In 1976 the Cape Canaveral Reef was colonized by live *Oculina* of ~1 m tall on the flanks covering 25% of the reef (17% coral rubble) and dominated by several fish species including snowy grouper, greater amberjack, butterflyfish, blue angelfish (*Holacanthus bermudensis*), damsels, and wrasses. By 2001, the same reef had been reduced to unconsolidated dead coral rubble, and the fish assemblage was reduced to amberjack and few small reef fish (Reed et al., 2007).

7.2.4.1.2 Shelf-edge Marine Protected Areas

Shelf-edge reefs along the edge of the Gulf Stream are areas of high species diversity. Protecting these critical areas may enhance the diversity along the shelf edge, while protecting valuable reef-spawning populations of commercially and non-commercially important species (McGovern et al., 1998a; Ross and Quattrini, 2006; Rowe and Sedberry, 2006; Sedberry et al., 2005; 2006).

MPAs are part of a comprehensive ecosystem-based management strategy of biological resources (NRC, 2001; SAFMC, 2007). Eight deep-water MPA areas (100–300 m deep) have been established in the South Atlantic (SAFMC, 2007; regulations effective in February 2009), and five of those are located within the study area (see Figure 6.8 in Chapter 6: Benthic Communities). These MPAs are designed to protect deep-water snapper-grouper species (e.g., speckled hind, snowy grouper, Warsaw grouper, yellowedge grouper, misty grouper, golden tilefish, and blueline tilefish; Table 7.8), where fishing for all snapper grouper species is prohibited. However, other fishing activities (trolling) are currently allowed. Protection of portions of snapper-grouper populations is warranted because many of these species share life-history traits (longevity, spawning aggregations, and protogynous hermaphroditism) that make them particularly vulnerable to overfishing (SAFMC, 2007). However, Quattrini and Ross (2006) noted that a large portion of the protected area off North Carolina is non-reef habitat and is not necessarily providing the level of reef fish population protection expected. This may also be true of other MPAs to the south, where it is not clear exactly how much reef habitat was protected within these new MPAs.

This network of shelf-edge MPAs is critical for the protection of larvae sources, settlement habitats, and nursery grounds for many species, as well as for ensuring the connectivity and persistence of reef fish populations (Rowe and Sedberry, 2006; Sedberry et al., 2005). Empirical evidence shows that MPAs are important sources of larvae, which can positively impact recruitment in unprotected areas through larvae export via long-distance planktonic transport or local planktonic retention (Hare and Walsh, 2007). Hare and Walsh (2007) identified the Georgia shelf (20–40 m depths) as an important retention area where drifters (a proxy for larvae) remained in the area for up to 60 days, which coincides with the time scales of most larval durations (e.g., Epinephelinae, Lutjanidae, Haemulidae, Sparidae, Labridae: 15–60 days). In contrast, the Gulf Stream provides an important mechanism for long-distance planktonic transport along the shelf of the southeast US (see Section 7.4.2 Water Column).

7.3 CONTINENTAL SLOPE AND BLAKE PLATEAU

The upper continental slope (200–450 m depth) is interrupted by a relatively flat area at depths between 450 and 1,200 m known as the Blake Plateau (see Chapter 2: Geological Oceanography). The southeastern edge of the Blake Plateau, known as the Blake Escarpment, is an area that marks the transition from intermediate (1,000–2,000 m) to oceanic depths (5,000 m). The western section of the Blake Plateau comprises important fish habitats including the Charleston Bump complex, and deep-sea corals occur throughout the Blake Plateau (Figure 7.8).

Except for a few studies on deep-sea reef habitats and the Charleston Bump, little is known about the fish assemblage on the Blake Plateau. A small number of studies have focused on areas deeper than the lower shelf (Low and Ulrich, 1983; Struhsaker, 1969). Low and Ulrich (1983) surveyed the demersal finfish species off South Carolina and northern Georgia at 180–800 m. Blackbelly rosefish were common near the 200 m isobath and over flat bottom; groupers (snowy grouper and yellowedge grouper) and blueline tilefish were dominant on ridges and rock outcrops (<210 m). In contrast, tilefish were more common among rubble substrate in deeper waters (>210–300 m). Rowe and Sedberry (2006), using trawl data from the late 1970s, also documented lower biomass of demersal fishes in deep shelf-edge/upper-slope areas (81–300 m)

Table 7.8
Shelf-edge Marine Protected Areas and site characteristics.

Marine Protected Area	Depth (m)	Distance from Shoreline (nm)	Area (nm)	Site Characteristics
Northern South Carolina	50–180	54	10 X 5	Low relief Snappers and groupers inhabit this site; Juvenile snowy grouper have been reported Abundant hard-bottom habitat
Edisto	45–80 and 80–140	45	10 X 5	Includes shallow and deep waters Relatively close to the Charleston Bump and Gyre Potential source of larvae to surrounding habitats, Potential key habitat to early life stages requiring nursery habitats offshore Snappers and groupers inhabit this site; Snowy grouper have been reported Juvenile snowy groupers and speckled hind have been reported High middle-shelf fish abundance has been reported Blueline tilefish in spawning condition have been reported Abundant hard-bottom habitat
Georgia	90–300	69	10 X 10	Mud-bottom habitat Snappers and groupers inhabit this site; Golden tilefish and gray triggerfish have been reported Spawning golden tilefish have been reported Mud habitat for golden tilefish
North Florida	60–200 and 380	60	10 X 10	Includes shallow and deep waters Includes a variety of habitats: unconsolidated bottoms and shelf-edge reefs Snappers and groupers inhabit this site; Snowy grouper and speckled hind have been reported Middle-shelf species have been reported Hard-bottom present
Charleston Deep Reef	100–150	50	3.5 X 6	Lacks hard-bottom habitats Placement of artificial structures may enhance fish attraction to the site Snowy grouper and golden tilefish have been reported. Snappers and groupers inhabit this site.
Modified from SAFMC (2007)				

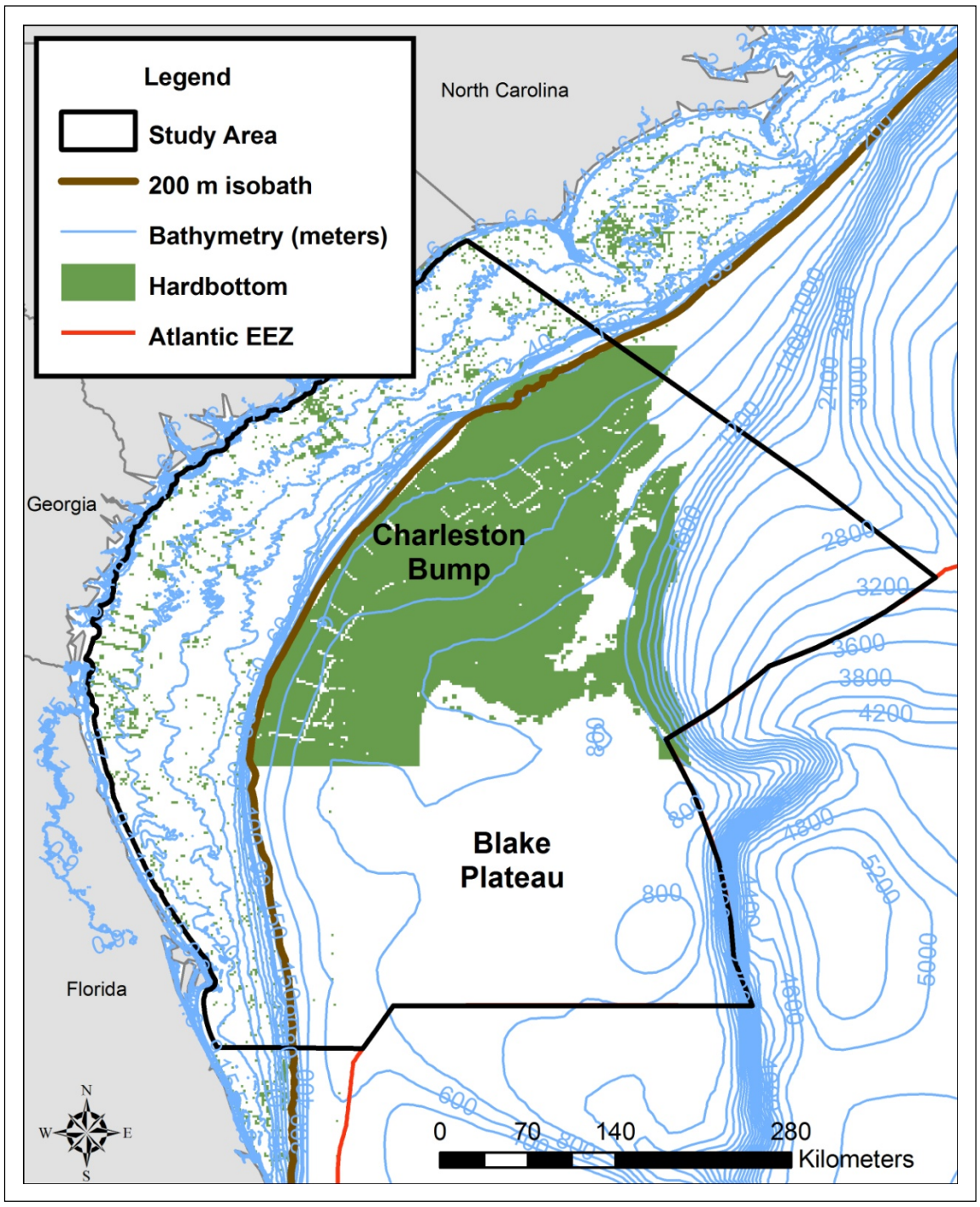

Figure 7.8 The Blake Plateau and other ecologically important fish areas. Data courtesy of SEAMAP-SA.

than in shallow/outer-shelf waters (11–80 m), as well as lower species abundance on the upper slope (141–340 m) than on the continental shelf (11–140 m).

A less robust fish assemblage in deeper waters, except for deep coral reef habitats, may be related to strong bottom currents and low water temperatures (7.5ºC) (Low and Ulrich, 1983). However, the continental slope and the Blake Plateau are important spawning grounds for deep-water species (Table 7.9) (Sedberry et al., 2006). Many of these species have specific habitat requirements (cooler <16ºC and deeper waters >200 m), and live and spawn on restricted deepwater areas (Charleston Bump; see Section 7.3.1.2 Charleston Bump complex). Most of these species are known to spawn between spring and late summer. Description of species-specific life histories and spawning strategies are provided in Appendix 7-A1.

Table 7.9
Summary of reef species that spawn on the continental slope and the Blake Plateau

Common name	Scientific name	Spawning depth (m)	Spawning temp. (ºC)	Females captured (% spawning)	Spawning peak
Red bream	*Beryx decadactylus*	433–595	-	11 (73)	-
Blueline tilefish	*Caulolatilus microps*	48–234	9-16	619 (83)	Mar–Sep
Yellowedge grouper	*Epinephelus flavolimbatus*	160–194	15	52 (12)	-
Snowy grouper	*Epinephelus niveatus*	187–302	-	533 (18)	May–Aug
Blackbelly rosefish	*Helicolenus dactylopterus*	229–238	-	548 (25)	Jan–Apr
Barrelfish	*Hyperoglyphe perciformis*	433–595	-	68 (18)	-
Tilefish	*Lopholatilus chamaeleonticeps*	190–300	10-15	1,161 (28)	Mar–Jul
Wreckfish	*Polyprion americanus*	433–595	-	793 (7)	Feb–Mar

In bold: Species that spawn on the Charleston Bump. Modified from Sedberry et al. (2006).

7.3.1 Biologically Sensitive Areas

7.3.1.1 Deep-Sea Coral and Deep Reef Habitats

Deepwater areas (>200 m) on the continental slope provide unique environments suitable for deep coral reefs and associated species. Ross (2006), Reed (2004), and Reed et al. (2006) reviewed available information on deep coral reef habitats off the southeastern US and described the location of several *Lophelia pertusa* and rocky reefs. These reviews were updated and expanded by Ross and Nizinski (2007), who also provided a checklist of the deep-sea corals known for the area. Deep coral and deep reef habitats in this region were further described by Partyka et al. (2007). Most deep coral reefs are found at depths of 370–800 m, temperatures of 5.4–12.3ºC, and fairly constant salinities (~35), and are dominated by a single species of a scleractinian coral *Lophelia pertusa* (Ross and Nizinski 2007; Ross and Quattrini, 2007; 2009). Isolated *Lophelia* reefs on the Blake Plateau off Florida are found at depths of 700-850 m and about 28–46 km east of the *Oculina* banks (Reed, 2002a; Ross and Nizinski, 2007). Other common species of deep-water corals include *Oculina varicose* (<200 m; discussed in Section 7.2.4.1.1 Oculina Bank, East-Central Florida), *Enallopsammia profunda*, *Madrepora oculata,*

and *Solenosmilia variabilis* (Reed, 2002a,b; Ross and Nizinski, 2007). *Lophelia* are found as small colonies or as complex bioherm structures rising more than 100 m from the bottom and share similar depths as *E. profunda* and *M. oculata* (Reed et al., 2006; Ross and Nizinski, 2007). Important coral formations along the southeastern US include Stetson Banks (~822 m depth), Savannah Banks (~550 m depth), Jacksonville Lithoherms (~700 m depth), and Cape Canaveral (*Lophelia* at 450-800 m depth) deep coral mound (Reed et al., 2006; Ross and Nizinski, 2007). Stetson Banks include several peaks of high relief (46–102 m), one of which contains one of the tallest known *Lophelia* coral bioherms (~153 m in relief) (Reed et al., 2006). Savannah lithoherms are characterized by high-relief *Lophelia* mounds of 61 m maximum relief consisting of several peaks. East Florida reefs include ~300 mounds that are 8–168 m in height and extend 222 km along the Florida coast. These reefs are dominated by *Lophelia pertusa*, towards the northern end, and by *L. pertusa, E. profunda*, and *M. oculata* towards the southern end of the region (Reed et al., 2006) (see Chapter 6: Benthic Communities for more detail).

Deep-sea corals and other deep rocky reefs provide habitat to a diverse number of fish species (Figure 7.9; see Appendix 7-B1.2) (Partyka et al. 2007; Ross and Quattrini, 2007; 2009). Fish surveys on deep coral reefs from Cape Canaveral, Florida to the northern banks off North Carolina identified 99 fish species that occur on or near these reefs (Ross and Quattrini, 2007; 2009), some of which appear to be closely associated with these deep-sea reef habitats (conger eel *Conger oceanicus*, reef codling *Laemonema melanurum*, roughy *Hoplostethus occidentalis* and red bream *Beryx decadactylus*). These surveys also found several species common on adjacent off-reef habitats (hagfish *Myxine glutinosa*, Pluto skate *Fenestraja plutonia*, shortbeard codling *Laemonema barbatulum*, offshore hake *Merluccius albidus*), and a group of species that characterized the deep-reef fish assemblages off the southeastern US (blackbelly rosefish, reef and shortbeard codling, conger eel, Pluto skate red bream, roughy, Kaup's arrowtooth eel *Synaphobranchus kaupii*, roughtip grenadier *Nezumia sclerorhynchus*, and Atlantic thornyhead *Trachyscorpia cristulata*). Of these species, reef codling, roughtip grenadier, red bream, and blackbelly rosefish comprised ~72% of the reef species, while Pluto skate, shortbeard codling, hagfish, and shortnose greeneye comprised ~52% of the off-reef species. Ross and Quattrini (2009) also compared the fish composition among *Lophelia* reefs and found that reefs on the Blake Plateau had a higher number of demersal species and higher abundance of fish (14-18 species and 228–447 fishes, respectively; dominated by roughtip grenadier and reef codling) than similar reefs off Cape Canaveral (7–8 species and 65–85 fishes, respectively; dominated by *Synaphobranchus* spp.). Plausible explanations for these differences include depth, structural differences across reefs, and site-specific environmental conditions. Of the species recorded only roughtip grenadier, reef codling, and Atlantic thornyhead were common to all *Lophelia* reefs (Ross and Quattrini, 2009). Interestingly, a fifth of the species reported by Ross and Quattrini (2007) have newly recorded distribution ranges (depth and/or geography), to which can be added a new species of hagfish (*Eptatretus lopheliae*) (Fernholm and Quattrini, 2008) and a new species of bythidid (*Bellottia obscura*) (Nielsen et al., 2009) found in *Lophelia* reefs. The challenges associated with accessing and studying deep-sea coral reefs are great and, consequently, the fish diversity in these habitats is likely higher than currently known.

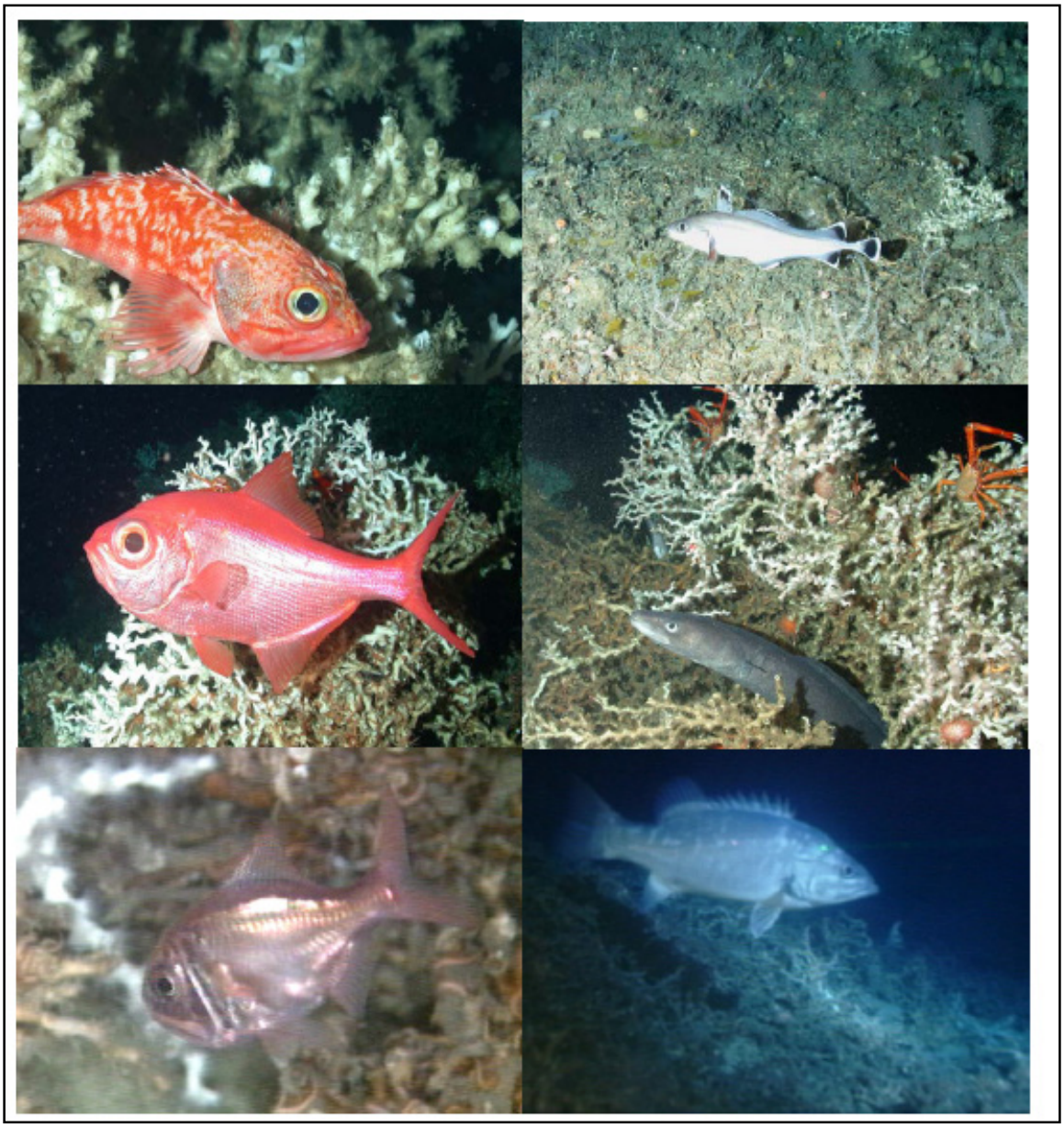

Figure 7.9 Ichthyofauna associated with deep-sea coral habitats. From left to right and top to bottom: Blackbelly rosefish, reef codling, red bream, conger eel, roughy, and wreckfish. Photos courtesy of S.W. Ross (see Ross and Quattrini, 2007).

7.3.1.2 Charleston Bump Complex

The Charleston Bump (130 km offshore) is a rugged-relief feature on the Blake Plateau (450–600 m depth) that deflects large water masses of the Gulf Stream. The side of the Charleston Bump that faces the Gulf Stream is heavily scoured by strong currents and characterized by steep rocky scarps (100–200 m high), overhangs, slopes, caves, depressions, carbonate outcrops, flat hard-bottom of manganese-phosphorite substrates, and coral pinnacles (Sedberry et al., 2001). The deflection of water masses off this large geological formation forms the cyclonic Charleston Gyre (Chapter 3: Physical Oceanography), which, within its core, contains nutrient-rich upwelled

water. This upwelling supports high plankton productivity, contributes to primary and secondary production in the South Atlantic Planning Area, and supports a wide variety and high abundance of fish species (Sedberry et al., 2004a,b; SAFMC, 2009).

The Charleston Gyre is an essential habitat for offshore fish species with pelagic stages (Govoni and Hare, 2001; Sedberry et al., 2001), and it is important in retaining and transporting larvae of species that spawn at the shelf edge (Sedberry et al., 2001; 2004a). This site, including the surrounding water column, is an important habitat and spawning ground for wreckfish, red bream, and barrelfish (*Hyperoglyphe perciformis*), nursery grounds for juvenile swordfish (*Xiphias gladius*), and feeding grounds for large migratory pelagics (swordfish, sailfish *Istiophorus platypterus*, blue marlin *Makaira nigricans*, white marlin *Tetrapterus albidus*, tunas *Thunnus albacares* and *Thunnus thynnus*, sharks, and dolphin *Coryphaena hippurus*) (Sedberry et al., 2004b; 2006). Other species inhabiting this and adjacent waters include sharks (black dogfish *Centroscyllium fabricii,* kitefin shark *Dalatias licha*, lantern sharks *Etmopterus* spp., chain dogfish *Scyliorhinus rotifer*, Cuban dogfish *Squalus cubensis*), skates, Darwin's slimehead (*Gephyroberyx darwinii*), barrelfish, blackbelly rosefish, and alfonsinos (*Beryx splendens*) (Weaver and Sedberry, 2001).

Wieber (2008) described the fish assemblage associated with six habitat types of the Charleston Bump and the Blake Plateau and, although there were no strong differences across habitats, a few species were dominant in each habitat type. Some of the dominant species, particularly on more complex habitats, included blackbelly rosefish, roughtip grenadier, and reef codling, whereas *Physiculus* spp. and longfin hake (*Phycis chesteri*) were the only species found on soft bottoms. Although hard-bottom and high-relief habitats had a much higher fish diversity than soft-sediment and coral-rubble habitats, fish assemblages appear to be more a function of depth (e.g., 300–650 m vs. 740–910 m deep) than habitat (Wieber, 2008). These observations are consistent with Ross and Quattrini (2009) who, in a wider treatment of deep reef fishes in the region, noted that both habitat type and depth were important in structuring deep reef assemblages. Habitat associations may also result from species-specific feeding requirements and need for shelter to avoid predation. Wieber (2008) documented the presence of rare species (e.g., frill shark *Chlamydoselachus anguineus*, unidentified ophidiids, and Shaefer's anglerfish *Sladenia shaefersi*) and noted the overall lack of juvenile fishes. Shaefer's anglerfish and other deep-sea lophiformes of this region were reviewed by Caruso et al. (2007).

Sedberry et al. (2001) stressed the role of the Charleston Bump and Gyre in the life history of several species. For instance, the wreckfish, a large and slow-growing demersal species, occurs on the Blake Plateau and throughout this region in waters deeper than 350 m (Sedberry et al., 2001; Sedberry et al., 2006; Ross and Quattrini, 2007). Because of the proximity of the Gulf Stream to its spawning grounds, deflection of this hydrographic feature is critical to the dispersal of juveniles and to their recruitment to locations farther offshore (Azores, Madeira, and Bermuda). Furthermore, strong upwellings in the Charleston Bump area are important in supporting the demersal adult population in the area, where squid and other vertically migrating organisms are the only reliable food source in deep-water habitats preferred by wreckfish (see Appendix 7-A1). Migratory pelagics also benefit from the available resources in the Charleston Bump and nearby waters (Sedberry et al., 2001). In fact, high occurrence of juvenile swordfish, sailfish, and blue marlin as bycatch in the proximity of the Charleston Bump (Sedberry et al.,

2001), and high densities of fish larvae at sites influenced by the Charleston Gyre (swordfish, pompano dolphin *Coryphaena equiselis*, wahoo, king mackerel, little tunny, and *Thunnus* spp., either blackfin or yellowfin tuna, and bullet mackerels *Auxis* spp.), provide ample evidence of the importance of the Charleston Bump and Gyre in supporting fish populations (Sedberry et al., 2004a,b). Additional information on some of these species is provided in Appendix 7-A1.

7.4 PELAGIC HABITAT

7.4.1 Sargassum

The pelagic brown algae *Sargassum natans* and *S. fluitans* float on the surface of warm waters of the western North Atlantic, forming a dynamic structural habitat that supports a wide variety of associated fauna. Pelagic *Sargassum*, comprised primarily of *S. natans* (90% of the drift algae), circulate in large amounts towards the western edge of the Florida Current/Gulf Stream, occurring frequently and for extended periods over the continental shelf (SAFMC, 2002; Gower and King, 2008). Many fish species, mostly of juvenile stages, take advantage of the resources (food, shelter, drifting transport, spawning, nursery) provided by *Sargassum*.

A number of studies have described the fish assemblage associated with *Sargassum* in the Western North Atlantic Ocean, including the Gulf of Mexico (Dooley, 1972; Bortone et al., 1977; Gorelova and Fedoryako, 1986; Moser et al., 1998; Casazza and Ross, 2008). SAFMC, 2002), in its management plan for *Sargassum*, reported at least 108 species along the North Atlantic, Caribbean, and Gulf of Mexico associated with this habitat, which has been augmented by the recent work by Casazza and Ross (2008) (Appendix 7-B1.3). While juveniles are the numerically dominant age class (at least 78 species), eggs, larvae, and adults of many species (at least 6, 53, 22 species, respectively), including large migratory pelagics (mackerels, tunas, swordfish), are also found in or near this habitat (SAFMC, 2002).

Although most of the above-mentioned studies were done outside the South Atlantic Planning Area, several observations are applicable to the study area. Species associated with *Sargassum* along the Florida Current can be generally divided into four groups (Dooley, 1972): 1) coincidentally associated or rarely associated species; 2) moderately associated fishes, including species with rare occurrence, but thought to be associated with *Sargassum* for food or shelter; 3) seasonally occurring fishes, including species found in high numbers during a short period of time; and 4) closely associated fishes, including common species with long temporal association with *Sargassum* (e.g., *Sargassum* anglerfish *Histrio histrio*, planehead filefish *Stephanolepis hispidus*, blue runner *Caranx crysos*, and round scad; see Appendix 7-B1.3 for details). These associations are in agreement with later studies in the South Atlantic Bight. For example, Settle (1993) found that filefish comprised 78% of the total larvae and juvenile fish abundance, while Casazza and Ross (2008) reported that planehead filefish, blue runner, Atlantic flyingfish (*Cheilopogon melanurus*), gray triggerfish, almaco jack, sailfin fiyingfish (*Parexocoetus brachypterus*), fringed filefish (*Monacanthus ciliatus*), round scad, and dolphin comprised 93% of the total catch.

Several studies (Casazza and Ross, 2008; Coston-Clements, 1991; Dooley, 1972; Settle, 1993) reported ample use of this habitat for refuge and food by young jacks (Carangidae) and filefishes

and triggerfishes (Balistidae), as well as spawning and nursery grounds for flyingfishes (e.g., *Cypselurus heterurus*), and as supplemental food source for many other species (e.g., Carangidae, Scombridae). Casazza and Ross (2008) also documented a higher species diversity and juvenile abundance in *Sargassum* habitats compared to the nearby open-water habitat. A recent workshop (Williams and Carmichael, 2009) also highlighted the importance of *Sargassum* as nursery habitat for several species of the snapper-grouper fishery management group: greater amberjack, lesser amberjack, bar jack, blue runner, almaco jack, banded rudderfish, gray triggerfish, ocean triggerfish, and queen triggerfish.

7.4.2 Water Column

A large diversity of pelagic fishes inhabits the water column of the South Atlantic Planning Area, often utilizing water fronts as feeding, nursery, or spawning habitats. Pelagic species include the families Carangidae (jacks), Clupeidae (herrings), Coryphaenidae (dolphin), Exocoetidae (flyingfish), Pomatomidae (bluefish), Rachycentridae (cobia), Sphyraenidae (barracudas), and the Scombridae (mackerels and tunas).

Fishes in the water column can be generally grouped into nearshore and offshore species. Shallow nearshore waters are important corridors for seasonal juvenile and adult fish migrations, offshore spawning migrations (estuarine-dependent species such as menhaden, spot, Atlantic croaker, pinfish, flounders and gag, and catadromous species), inshore spawning migrations of anadromous species, and larval transport to nursery areas (estuarine or offshore waters; see Section 7.2.1 Coastal Zone and Table 7.1). The nearshore is also an important feeding and nursery habitat for *Anchoa* spp. and *Scomberomorus* spp., and important spawning grounds for *Cynoscion* spp. and *Sciaenops* spp. The surf zone and nearshore ocean waters are also important nursery areas for bluefish, Florida pompano, and Gulf kingfish (Hackney et al., 1996; see Section 7.2.1 Coastal Zone). Small Florida pompano and Gulf kingfish remain in surf zone waters for 21–27 days during the summer, taking advantage of either ample resources or low predation pressures (Ross and Lancaster, 2002). Other species (e.g., anchovies and king mackerel) rely on the nearshore boundaries of ocean water masses as nursery habitats, which are also important foraging grounds for adults prior to and during their seasonal migrations. The offshore fronts are important habitats for a variety of species particularly for highly migratory pelagics (see Section 7.4.2.1 Important Areas for Migratory Pelagics). These offshore fronts may also be important feeding, spawning, and nursery grounds for *Coryphaena*, *Xiphias*, and important spawning grounds for middle-shelf species (*Micropogonias*, *Leiostomus*) (SAFMC, 2009). Because of the importance of the water column as a fish habitat, a large area of the study area (e.g., the Charleston Bump Complex) is designated by the SAFMC as a habitat area of particular concern.

Fish larvae are one component of the pelagic community. Their concentrations vary spatially across the continental shelf and temporally with seasons (Collins and Stender, 1987; Paffenhofer, 1985; Yoder, 1983; Weinstein et al., 1981). High abundances of larvae on the outer shelf during winter are linked to offshore spawning of estuarine dependent species (Atlantic menhaden, spot, Atlantic croaker, and paralichthid flounders) (Govoni and Spach, 1999; Marancik et al., 2005; Paffenhofer, 1985; Weinstein et al., 1981); high larvae densities during summer are associated with spawning events of reef and migratory species (Collins and Stender, 1987; Govoni et al., 2009; Parker and Mays, 1998; Yoder, 1983). Marancik et al. (2005) further described the larval fish assemblages on the inner- (<20 m depth), middle- (20–40 m depth), and outer- (40–50 m

depth) shelf off Georgia, finding distinct inner- and middle-shelf assemblages during spring, summer, and fall, but less distinct patterns during winter (i.e., owing to the high abundance of Atlantic menhaden and spot). Marancik et al. (2005) also found that the inner-shelf larval assemblage was the least diverse and was largely comprised of species that spawn in coastal and estuarine habitats (e.g., southern kingfish in spring, summer, and fall; Atlantic croaker and pinfish in winter), while the middle-shelf assemblage was the most diverse, containing species found on the inner and outer shelf. In these regions, seasonal changes in the larval assemblage appeared to respond to fluctuations in temperature and salinity. Although the outer-shelf assemblage was largely dominated by eyed flounder and twospot flounder (*Bothus robinsi*), this area also contained a mix of rare larvae (particularly during fall and winter), as well as species that spawn on the outer shelf (e.g., red barbiers), at the shelf break (e.g., lanternfish *Ceratoscopelus maderensis*), or south of the area (e.g., *Abudefduf* spp.). Marancik et al. (2005) indicated that increased water-column stratification (i.e., vertical change in density) of the outer shelf from intrusions of the Gulf Stream may have introduced rare taxa, and limited onshore exchange appears to occur between the outer- and middle-shelf regions.

Many studies have documented that larvae dispersal and distribution are largely controlled by physical processes, local circulation patterns, and prevailing winds (Weinstein et al., 1981; Yoder, 1983; Checkley et al., 1988; Govoni and Spach, 1999; Epifanio and Garvine, 2001; Govoni and Hare, 2001; Marancik et al., 2005; Edwards et al., 2006, 2008a,b; Govoni et al., 2009). Larvae transport along and across the continental shelf is heavily influenced by wind-driven and buoyancy-driven circulation (Epifanio and Garvine, 2001). The relative importance of these forces varies with season and with the location of spawning grounds. Species that occur on the inner shelf in the spring/summer are subjected to strong buoyancy-driven flow that influences the along-shelf larvae transport near the coast. By contrast, wind-driven, along-shelf flow plays an important role in transporting larvae of species (e.g., menhaden) that spawn on the middle and outer shelf of the northern South Atlantic Bight to estuarine nurseries further south (Checkley et al., 1988; Epifanio and Garvine, 2001). Strong seasonal patterns of larval dispersal from spawning grounds on the Georgia shelf (using dispersed particles as a proxy for larvae) are also influenced by seasonal patterns in wind and circulation, with along-shelf (inner- and middle-continental shelf) dispersal to the northeast occurring in summer (coinciding with upwelling-favorable winds) and along-shelf dispersal to the southwest occurring in winter (Edwards et al., 2008a). This work also showed that month and location of the particle release were the most important factors explaining dispersal patterns, suggesting that adult behavior (i.e., spawning time and location) may determine larval dispersal on the continental shelf. Consistently, high abundance of larvae in the outer shelf from fall to spring coincides with strong upwellings (Yoder, 1983; Marancik et al., 2005).

Studies have suggested that high larvae concentrations in the South Atlantic Planning Area are partially the result of entrapment in waters of the Gulf Stream, as it travels over spawning areas along its path. Govoni and Spach (1999) described the winter exchange of 75 families of fish larvae between the inshore and offshore sides of the Gulf Stream (see Appendix 7-B1.4), showing that this current supplies inshore and reef habitats with larvae of many fish species that spawn in oceanic or offshore waters, while species that spawn in shelf waters likely lose recruits when entrained into the Gulf Stream. Consistently, this current facilitates the dispersal of a substantial number of species of eel larvae along the southeast coast (Ross et al., 2007) and plays

an importance role in the life history of several species including those that spawn on the seaward margin of the outer continental shelf (e.g., bluefish) (Govoni and Spach, 1999; Govoni and Hare, 2001). Other studies have also highlighted the role of large oceanographic features in trapping, retaining, and transporting fish eggs and larvae in offshore waters (Govoni and Spach, 1999; Govoni and Hare, 2001; Govoni et al., 2009). Cyclonic eddies, which are common episodic events in regions of the shelf edge and lower shelf, bring nutrients from deep and off the shelf edge to the water surface supporting large phytoplankton and zooplankton communities (see Chapter 5: Plankton Communities). The turnover of zooplankton embedded within eddies supply pelagic larvae of many fishes with the constant food source that ensures their survival as they travel from their spawning areas (Govoni and Hare, 2001; Govoni et al., 2009).

7.4.2.1 Important Areas for Migratory Pelagics

Migratory pelagic species are generally classified into highly migratory fishes (e.g., Istiophoridae sailfishes, swordfish, tuna, and several sharks of the genus *Isurus* and *Carcharhinus*), and coastal migratory fishes (mackerels *Scomberomorus* and *Euthynnus*, cobia, and dolphin). Migratory species occupy the water column from coastal waters to offshore areas and undergo seasonal movements (north-south, inshore-offshore). Though not strongly associated with specific substrate types, their habitat use and movement are largely controlled by physiographic and hydrographic features, such as ocean fronts, current boundaries, the continental shelf margin, or sea mounts (National Marine Fisheries Service, 1999; 2009b). Essential fish habitats for coastal migratory pelagics shoreward from the Gulf Stream encompass sandy shoals, offshore bars, high-profile rocky bottom, and *Sargassum* (SAFMC, 2009). In South Carolina, areas considered critical for coastal migratory pelagics include the Charleston Bump, Hurl Rocks, and Broad River; in Florida, critical areas are found on *Phragmatopoma* (worm reefs) reefs (SAFMC, 2009). Estuarine and nearshore areas also provide critical habitat for early age classes and adults of migratory species. South Carolina's estuarine and nearshore waters provide nursery habitat for small and large coastal migratory shark species (Atlantic sharpnose, blacktip, finetooth, smooth hammerhead, and sandbar sharks), as well as extensive habitat for several adult small coastal shark species (Atlantic sharpnose, blacknose, and bonnethead sharks) (National Marine Fisheries Service, 2009b). Similarly, the St. Simon and St. Andrew sound systems in Georgia may serve as nursery habitat for both small and large coastal shark species (National Marine Fisheries Service, 2009b). Carcharhinid sharks, for instance, appear to migrate into estuaries during the warm months (June to September), except for the cold-water spiny dogfish, which enters estuaries during winter (Dahlberg, 1972).

7.5 TROPHIC ECOLOGY AND SPECIES INTERACTIONS

A great number of the fish species in the South Atlantic Planning Area are trophically interconnected, forming an extremely complex food web. Understanding this food web is an important step towards fishery ecosystem management, and it requires sufficient information on the diet and species interactions of functional groups, information which is lacking for most species. The trophic ecology of the species inhabiting the South Atlantic Planning Area is complex and cannot be described in simple terms. Factors influencing feeding ecology include species-specific energy demands, changes in feeding requirements with ontogenetic changes (Hales, 1987), and changes in prey availability and densities with seasonal changes. Although several publications exist on the feeding ecology single species (see Appendix 7-A2**),** only a few

have evaluated the ecological interaction of multiple prey-predator relationships in the South Atlantic Planning Area (Marancik and Hare, 2005; Marancik and Hare, 2007; SCWMRD and GDNR, 1984; Weaver and Sedberry, 2001; Casazza, 2009).

Marancik and Hare (2007), for instance, found that shelf predator species fall into a gradient of piscivory rather than into rigid piscivore and non-piscivore guilds. Their data compilation showed that predator species consumed a diverse number of non-fish prey (on average 15 prey taxa), and that the location of prey within the water column (pelagic or benthic) is important in defining food consumption gradients. This analysis categorized shelf predator species as (see Appendix 7-B1.5): 1) benthic and structure-browser species (e.g., spottail pinfish), which feed mostly on bryozoans, algae, poriferans, hydrozoans, and anthozoans; 2) piscivore species (e.g., all migratory pelagics) that feed mostly on fish (~80% of their diet) and can be differentiated based on the location of prey within the water column (demersal piscivores such as spiny searobin *Prionotus alatus*; pelagic piscivores such as bluefish, dolphin, king mackerel; and structure-associated piscivores such as vermilion snapper); and 3) carnivore species (e.g., Triglidae, Serranidae, and Haemulidae) that feed mostly on invertebrates (~80% of their diet) and can be further subdivided into benthic/demersal carnivores, such as banded drum, and structure-associated carnivores, such as black sea bass, tomtate, and red porgy. Species found in nearshore waters are generally carnivores that feed primarily on crustaceans (75% of their diet; e.g., Sciaenidae, Lutjanidae, and Paralichthyidae) and can be grouped into benthic/demersal carnivores (flounders), pelagic carnivores (great barracuda), and structure-associated carnivores (gag, cobia, gray snapper). The authors argue that a less-rigid scheme involving gradients rather than rigid trophic guilds may more accurately describe these complex trophic interactions.

Others have also shown that habitat-specific associations play an important role in defining a species' trophic ecology, which has facilitated the classification of species into feeding guilds (Freeman and Turner, 1977; Weaver and Sedberry, 2001; Marancik and Hare, 2007; Casazza, 2009; Continental Shelf Associates, 2009). A synthesis by Continental Shelf Associates (2009) on the nearshore hard-bottom habitats of central/southeast Florida indicated that half of the species associated with these habitats (124 species) were invertivores, one third were piscivore species (74 species), and a few were planktivores, herbivores, or detritivores (15, 13 and 2 species, respectively; see Appendix 7-A2). The feeding strategies of hard-bottom fishes are so diverse that there is relatively low diet overlap among species, allowing many species to coexist (SCWMRD and GDNR, 1984). The analysis by Weaver and Sedberry (2001) on the trophic interactions of reefs on the upper- and middle-continental slope (Charleston Lumps and Charleston Bump, respectively) found that predators inhabiting reefs in the Charleston Lumps (e.g., yellowfin bass, blackbelly rosefish, shortbeard codling, and longfin scorpionfish *Scorpaena agassizi*) consumed benthic invertebrates or small planktonic fauna, but those inhabiting deeper waters (Charleston Bump and nearby waters) exhibited pelagic and benthic feeding habits. For instance, the slender alfonsino, lantern sharks, and adult marlin-spike consumed mid-water fishes and invertebrates, whereas large sharks (sixgill sharks and bigeye thresher shark) used resources found in the entire water column from pelagic fishes (including dolphin *Coryphaena* spp. and billfishes) to benthos. Other predators (barrelfish, Darwin's slimehead, and blackbelly rosefish) specialized on other resources including plankton, micro nekton, and epibenthos. The relatively low food availability on these deep-water reefs, particularly in the Charleston Bump, suggests that species in these habitats (including the most abundant apex predator, the wreckfish) rely

heavily on pelagic food sources, including mid-water migrating organisms (fish, squid, shrimp) (Weaver and Sedberry, 2001).

Pelagic food web interactions were also studied by Casazza (2009) and Weaver and Sedberry (2001). As mentioned earlier, *Sargassum* not only provides habitat for early life stages and adults of many species, but also supplies food sources to a diverse fauna. The recent study by Casazza (2009) found that most species associated with pelagic *Sargassum* consumed prey items closely associated with this habitat (e.g., balistids, carangids, monacanthids, and endemic invertebrates), and that these species consumed a higher diversity and volume of prey than fishes in nearby open waters. Based on gut contents, Casazza (2009) categorized the fish assemblage associated with *Sargassum* into: 1) zooplanktivores (e.g., sailfin flyingfish, fringed filefish, round scad, Atlantic flyingfish, and sergeant major) which consumed invertebrates, fish eggs, or fish scales; 2) crustacean feeders (e.g., gray triggerfish and smallwing flyingfish *Oxyporhamphus micropterus*) which consumed crabs and shrimp; 3) piscivores (e.g., *Sargassum* anglerfish, dolphin, and sailfish); and 4) generalist feeders, (e.g., bluntnose flyingfish *Prognichthys occidentalis*, blue runner, pompano dolphinfish, and planehead filefish), which included most of the fishes associated with this habitat. This study demonstrated that *Sargassum* plays an important role in the pelagic food web as it enhances food resources in open waters.

The above studies show not only the complexity of trophic interactions within habitats and regions of the South Atlantic Planning Area, but also the plasticity in the diet of species inhabiting these areas. Species interactions are so important that disruption of these relationships can lead to cascade of effects along complex food webs. For example, in the mid-1990s the increased abundance of white grunt and gray triggerfish may have been the result, in part, of the selective removal of reef-dominant species: red porgy, vermilion snapper, black sea bass, and several groupers species (Harris and Machowski, 2004). Also, the large rise in natural mortality of weakfish from the mid-1990s to the early 2000s, which resulted in declines of biomass and size, may have been caused by inadequate forage (e.g., Atlantic menhaden) and increased predation (e.g., striped bass; SAFMC, 2009).

The fish community of the South Atlantic Planning Area displays complex relations with other biotic components of the habitats, which they occupy. Interactions that define fish assemblages include direct interactions (competition, predation) and indirect interactions (refuge). For instance, earlier observation by Manooch (1977) on the spatial distribution of red porgy suggested that its high abundance on the continental shelf relates to its successful feeding strategy, while its absence in shallower waters (<20 m) is likely the result of strong competition with the dominant black sea bass and white grunt. Likewise, adult bluefish−a common prey of sharks (mako, *Isurus* spp.), tuna, swordfish, and wahoo−exhibit competition for feeding resources with Spanish mackerel, king mackerel, striped bass, large weakfish, Atlantic bonito, and little tunny (Oliver et al., 1989). Fish larvae can also be potentially impacted by chaetognath predation (*Sagitta* spp., *Krohnitta* spp., and *Pterosagitta draco*), as their maximum abundance offshore coincides with fish spawning (Coston-Clements et al., 2009). These voracious members of the zooplankton community can consume between 4% and 21% of the daily total zooplankton production (Coston-Clements et al., 2009), and their substantial overlap with the diet of fish larvae may increase larvae mortality during periods of limited food availability (Baier and

Purcell, 1997). Additional information on the trophic ecology of selected species in the South Atlantic Bight is summarized in Appendix 7-A2.

7.6 CURRENT ISSUES AND THREATS

7.6.1 Overfishing and Destructive Fishing Practices

Many reef species inhabiting the South Atlantic Planning Area share similar life-history traits, including slow growth, late age at maturity (3–7 years), long life spans (15–50 years), high non-spawning and spawning site fidelity, clear developmental stages, seasonal and spawning migrations, nearshore nursery habitat requirements of early life stages, complex social structures (e.g., spawning aggregations), and sex reversal (i.e., protogynous hermaphrodites). Some of these traits (low growth rates and long life spans) may be linked to their evolutionary success in the reef environment (Huntsman, 1981). Furthermore, long life spans and large body size have likely maximized gamete and zygote production, enabling these species to overcome the low probability of encountering suitable habitat by their pelagic larvae (Matheson et al., 1986). However, life-history traits that have allowed them to succeed have also rendered them susceptible to overfishing (Coleman et al., 2000; Gilmore and Jones, 1992) and large-scale disturbances. Several studies (Harris and McGovern, 1997; Harris and Collins, 2000; Huntsman and Schaaf, 1994) have suggested that protogynous hermaphrodites (e.g., several groupers and snappers) are more sensitive to fishing pressures than gonochoristic species. Huntsman and Schaaf (1994) found that populations undergoing typical density-dependent responses (reduction in age at first maturity, increased size at age) are not able to compensate for the increased removal of males from the population, which ultimately leads to decreased reproductive output. Gilmore and Jones (1992) also indicated that the maintenance of social hierarchy is critical to the success of fish populations (e.g., gag, scamp). Specifically, the removal of dominant, larger males would encourage sex reversal within the spawning age class, possibly reducing the fecundity of older, reproductive females transitioning into males. The combination between life-history traits, specifically protogyny and spawning aggregation, appears to increase the vulnerability of reef species to overfishing particularly when fishing efforts concentrate on spawning grounds (Coleman et al., 2000).

Over half a century of sustained fishing pressure on commercial fish species, in addition to habitat degradation and destructive fishing practices, has lead to depletion of many fish resources of the South Atlantic Planning Area (see SEDAR stock assessments and amendments to fishery management practices). There is substantial evidence indicating that ecosystem overfishing is occurring on reefs of the study area (McGovern et al., 1998b), and that several species are at risk of experiencing unsustainable populations. Marine Resources Assessment Group-Americas (2009) conducted a Productivity and Susceptibility Analysis to assess the risk to a commercial species based on stock productivity and susceptibility. Productivity determines the rate at which a population can sustain fishing pressure and recover from it, and it is a function of species-specific, life-history attributes. Susceptibility refers to a species likelihood to encounter fishing activities, and it is a function of the fish behaviors that make them vulnerable to overfishing (i.e., site fidelity, spawning aggregations), as well as the selectivity of fishing gear (see Appendix 7-B1.6). Combined scores for productivity and susceptibility indicated that, of the 72 populations of commercial fish species used in this analysis, 44 were found to be at high risk (e.g., tilefish,

most groupers, snappers, and porgies), 24 at moderate risk, and 4 at low risk. These results are consistent with the analysis by Musick et al. (2000) who reported several populations at risk (e.g., groupers and other species such as white shark *Carcharodon carcharias* and thorny skate *Amblyraja radiata*), owing to their reproductive strategies and behavior, and age at maturity. To reduce overfishing and rebuild fisheries that are experiencing unsustainable fishing pressures, several state and federal regulations and restriction are in place, including size limits and quotas, as well as seasonally or permanently closed areas where most fishing activities are prohibited. However, the direct and indirect impacts of overfishing on non-commercial species are largely unknown, as are the impacts of overfishing of reef species on ecosystem-level trophic interactions. Additional information on fish population trends and status of several species is summarized in Appendix 7-A3.

To date, two fish species in the South Atlantic Planning Area have been listed as endangered under the Endangered Species Act (ESA), two are candidates for inclusion, and nine are species of concern not protected under the ESA (Table 7.10). Though some of these and other species have experienced declines from overfishing, other factors that contribute to their current unsustainable levels include degradation of their critical habitat by either destructive fishing practices or other anthropogenic activities. Fishing activities, such as trawling, have severely impacted and destroyed the complex physical structure of benthic habitats (Koenig et al., 2000; Reed et al., 2007) creating unsuitable foraging and refuge grounds (see Chapter 6: Benthic Communities).

Table 7.10
Status of fish species in the South Atlantic Planning Area.

Species	Status	Notes
Shortnose sturgeon (*Acipenser brevirostrum*)	E	Listed 03/11/67
Smalltooth sawfish (*Pristis pectinata*)	E	Listed 04/01/03
Atlantic sturgeon (*Acipenser oxyrhynchus oxyrhynchus*)	E	Listed 02/06/12
Largetooth sawfish (*Pristis pristis*)	CS	FL
Dusky shark (*Carcharhinus obscurus*)	SoC	FL, GA
Nassau grouper (*Epinephelus striatus*)	SoC	FL
Night shark (*Carcharhinus signatus*)	SoC	FL, GA, SC
Opossum pipefish (*Microphis brachyurus lineatus*)	SoC	FL
Salt marsh topminnow (*Fundulus jenkinsi*)	SoC	FL
Sand tiger shark (*Carcharias taurus*)	SoC	FL, GA, SC
Speckled hind (*Epinephelus drummondhayi*)	SoC	FL, GA, SC
Striped croaker (*Bairdiella sanctaeluciae*)	SoC	FL
Warsaw grouper (*Epinephelus nigritus*)	SoC	FL, GA, SC

E=Endangered; CS=Candidate species; SoC=Species of Concern. CS are species subject of a petition to list and for which NOAA NMFS has determined that listing may be warranted (69 FR 19975); SoC are species not protected under the ESA, but concerns about their status indicate that they may warrant listing in the future. From NMFS (2012).

7.6.2 Anthropogenic Activities

Coastal and nearshore fish habitats may be affected directly by habitat destruction, or indirectly through water-quality degradation and hydrologic modification (Table 7.11). Species that depend on coastal environments during critical life stages (spawning, nursery), as well as species that use these habitats as corridors, are particularly vulnerable to land-based threats. Major threats to coastal habitats include agriculture, coastal development, transportation, and navigation and climate change (Street et al., 2005; SAFMC, 2009). Coastal development and other anthropogenic activities are responsible for major large-scale modification of the coastal environment, alteration of its hydrology and sediment transport, and increased non-point source of pollution, which results in water quality and habitat degradation. Activities that cause habitat modifications and damages to shallow habitats (e.g., fishing gear, dredging, filling, and installation/maintenance of fiber optic cables) such as soft and hard bottoms, can disrupt natural processes (i.e., reduced recruitment and productivity, prey removal) and restrict re-colonization by reducing habitat use and suitability (e.g., reduced foraging and refuge conditions for fish larvae and juveniles, as well as fish diversity, spawning, and recruitment).

The SAFMC also listed current or potential marine and offshore human activities and natural events that can pose significant threats to fishes and fish habitats (Table 7.12). Many threats to offshore fish habitats are directly or indirectly linked to energy exploration. The SAFMC identified specific fish species (and their habitats) at risk from energy development activities (e.g., summer flounder, bluefish, red drum, many snapper and grouper species, black sea bass, coastal migratory pelagics), as well as habitats potentially affected by these activities (e.g., nearshore hard-bottom, reefs off central Florida, and essential fish habitat for highly migratory species) (SAFMC, 2005; 2008; 2009). Energy exploration and development activities could potentially threaten fish habitats through: 1) direct mortality and displacement of fishes; 2) bottom disturbance and habitat conversion and loss from installation and anchoring systems; 3) burial of habitat though increased deposition of sediments and drilling muds; 4) elevated turbidity; 5) direct mortality of larvae, post-larvae, juveniles, and adults of marine and estuarine organisms from spills; 6) entrainment of fish (primarily embryos and larvae); 7) alteration of shoreline migration patterns; and 8) alteration of community diversity, composition, food webs, and energy flow due to addition of artificial hard-bottom habitat and other structures. Current policies established to avoid, minimize, and offset damage caused by energy development activities include prohibited oil or gas drilling on or in the proximity of EFHs and HAPCs or other essential resources under SAFMC jurisdiction, as well as comprehensive measures and strategies to minimize impacts to these habitats.

Another threat that has received attention over the last few years is the introduction of exotic species. In particular, the widespread occurrence of lionfish (*Pterois volitans*) and potentially of a sympatric species (*P. miles*) on several reefs along the Atlantic and within the South Atlantic Planning Area indicates that this invasive species has become established in these critical habitats (Whitfield et al., 2002). The presence of juveniles indicates that adults are surviving in these non-native temperate water habitats (14–28ºC), and that this species has reproduced in shallow (~38 m deep) reefs of the continental shelf (Whitfield et al., 2002). Others (Meister et al., 2005) have documented a larger depth distribution of this species on live-bottoms extending from 40–90 m, and the presence large individuals (120–389 mm TL) and males with spermatocytes and spermatozoa in histological samples. Furthermore, thermal tolerance studies

suggest that this invasive species could overwinter along the continental shelf as far north as Cape Hatteras and between the 12°C isotherm and the shelf break (Kimball et al., 2004). The establishment of this lionfish species poses threats to reef habitats because of its voracious appetite and lack of known predators (Albins and Hixon, 2008; Whitfield et al., 2002). Lionfish can have negative effects on ecosystems (e.g., predator interactions) and ecosystem services (Hare and Whitfield, 2003).

Table 7.11
Current and potential coastal and land-based threats faced by fish and fish habitats.

Coastal Processes	Activity	Potential Effect
Direct Human-made		
Agriculture	Habitat conversion	Loss of habitat and habitat connectivity
		Hydrological modification
	Animal production and fertilizer use	Nutrient enrichment
		Water quality degradation (oxygen depletion; toxic algal blooms)
		Sediment pollution
	Use of pesticides	Sediment pollution
	Non-point source discharge	Water quality degradation (oxygen depletion; toxic algal blooms)
		Sediment pollution
Aquaculture	Animal production	Water quality degradation (fecal material)
		Undesirable interactions with wild populations (spread of diseases, interactions with genetically modified population)
		Habitat degradation
Urban/Suburban Development	Habitat conversion	Loss of habitat and habitat connectivity
		Hydrological modification
	Non-point source discharge	Water quality degradation (oxygen depletion; toxic algal blooms)
		Increase of organic/inorganic contamination
		Increased sedimentation rates and sediment pollution
		Nutrient enrichment
Transportation	Habitat conversion	Loss of habitat and habitat connectivity, and habitat fragmentation
	Non-point source discharge	Increased water runoff
Navigation	Creation/ maintenance of navigation channels	Habitat modification (i.e., subtidal and intertidal areas)
		Filling and conversion of wetlands
		Habitat degradation from dredging
	Vessel operations	Contaminant discharge and fuel spills
		Water quality degradation
		Vessel groundings Increased coastal erosion
		Introduction of exotic/harmful species through ballast water
Modified from SAFMC (2009)		

Table 7.12
Current and potential marine and offshore threats faced by fish and fish habitats.

Marine/Offshore Threats	Activity	Potential Effect
Direct Human-made		
Navigation	Maintenance of navigation channels	Habitat burial
		Increased turbidity
		Contaminant resuspension
		Interruption of sedimentary processes
	Vessel operations	Chemical spills
		Introduction of exotic/harmful species through ballast water
		Vessel groundings, noise, anchorings
Dredging	Sediment dumping	Habitat burial
		Increased turbidity
		Introduction of contaminants
Offshore Sand/Mineral Mining		Substrate removal
		Habitat conversion and burial
		Increased turbidity
		Alteration of hydrological processes
Oil/gas Exploration	Drilling	Bottom disturbance
		Habitat destruction and damage
		Toxic releases and drilling fluid discharges
		Accidental spills
		Habitat burial
Industrial Activities		Direct/non-point-source discharge
Artificial Reefs		Habitat conversion
		Introduction of species
Renewable Energy - Offshore Wind Turbines	Turbine anchoring	Usurpation of seafloor habitat
		Bottom disturbance
Non-native or Nuisance Species		Increased competition
		Physical overcrowding
		Increased behavioral aggression
Fishing Activities		Bycatch of non-target species
		Modification of fish communities
		Removal of large predators
		Habitat degradation Derelict nets and traps
Natural Events/Indirect Human-made		
Natural Events/Climate Change	Storms	Habitat erosion and burial
		Alteration of hydrological processes by strong currents
		Habitat damage
	Climate change	Change in weather patterns, ocean currents, water-column productivity
		Change in temporal and spatial distribution of species Disruptions of species relationships and community composition; Loss of important habitat (wetlands) from sea level rise
		Change in optimum water temperature for biological processes
Modified from SAFMC (2009).		

Climate change also has the potential to influence the spatial and temporal distribution of fish populations (e.g., expansion or contraction of spawning and feeding ground ranges), and may negatively or positively impact population densities (see Rose, 2000 and references herein). Although not discussed in detail in this synthesis, the impact of climate change on nearshore and offshore fish populations should be evaluated to establish new baselines and trends with respect to rising water temperatures.

7.7 Potential Impacts of OCS Development on Fish and Fish Habitats

Several reports submitted to the Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE) have evaluated the potential impacts of oil and gas exploration on live-bottom communities (SCWMRD and GDNR, 1982; 1984), the impacts of sand mining and dredging (Research Planning Inc., 2001; MMS, 2009), and the effects of renewable energy on fisheries (Michel et al., 2007).

7.7.1 Oil and Gas Exploration and Development

In 1982, SCWMRD and GDNR (1982) stated that predicting the impacts from oil and gas exploration on live-bottom communities of the South Atlantic Planning Area are uncertain given the lack of information on the resistance/resilience of these habitats to disturbance. Despite the paucity of documented effects of oil and gas exploration on fish, SCWMRD and GDNR (1982) noted some potential adverse effects, including: 1) interference with respiration and feeding; 2) altered community structure and negative ecological imbalances caused by habitat changes; 3) decreased primary productivity (from increased turbidity, reduced light transmission, and dissolved oxygen depletion); 4) increased vulnerability to species with narrow or restricted geographical distribution; 5) burial of formations that provide foraging and shelter; and 6) potential hydrocarbon contamination of the food web. The same report highlighted a potential beneficial effect: increased hard-bottom surface for colonization by sessile species, which in turn would support fish communities. A related report (SCWMRD and GDNR, 1984) further indicated that any damage to hard-bottom habitats could have negative effects on fish populations associated with these habitats. Physical destruction of the reef structure by drilling into hard bottom could severely compromise the food availability for fish species heavily relying on hard-bottom fauna and more so for hard-bottom dependent species (e.g., black sea bass). However, physical destruction of fish habitats, in particular reef and hard-bottom habitats, is highly unlikely given that current regulations are designed to prevent, mitigate, and restrict activities in these important fish habitats. Based on results from studies with artificial reefs, it is estimated that a hard bottom habitat would take over ten years to fully recover from a catastrophic oil spill, assuming no lingering toxicity or permanent alteration of the substratum (SCWMRD and GDNR, 1984).

Potential impact of oil and gas exploration on fish and fish habitat can also be derived from studies conducted on the continental shelf of the Gulf of Mexico. A two-year field study assessed the physical, chemical, and biological impacts of deep-water drilling at sites (1,000 m depth) in the Gulf of Mexico, documenting increased fish abundance in nearby areas (Continental Shelf Associates, 2006). Fish may have been attracted to the area by the disturbance at the site, increase in additional structures in an otherwise bare substrate, and possibly attracted by the elevated macroinfaunal density, which in turn may have increased food availability. This report

also identified other disturbances in soft-bottom areas within nearfield sites caused by drilling and production activities: 1) increased barium concentration several orders of magnitude above background and increased loading of synthetic-based fluids; 2) increased total organic carbon and oxygen depletion in deposition areas of synthetic-based drilling mud/cuttings; 3) disturbed benthic communities leading to low species diversity, evenness, and richness; and 4) increased sediment toxicity on indicator species. The duration and long-term consequences of these disturbances on the overall health of fish habitats are unknown.

Others (Neff et al., 2000 and references herein) have indicated that discharges of synthetic-based fluid cuttings, within the allowable range, did not adversely affect demersal fish abundance in the Gulf of Mexico, and there is little evidence of bioaccumulation of harmful components in tissues of benthic fauna and subsequent transfer through the food web to fish. Nevertheless, developing holistic monitoring/research strategies is essential to understanding the effects of these activities on fish, fish habitats, and entire ecosystems. Furthermore, although oil and gas structures augment habitat complexity, increase fish abundance, and provide added feeding and nursery opportunities for many fish species, these structures may not necessarily support a sustainable fishery or contribute to a healthy ecosystem−two basic principles of Essential Fish Habitats (as defined by Congress) (Helvey, 2002).

7.7.2 Sand and Gravel Extraction

The SAFMC and others (Diaz et al., 2004; Slacum et al., 2006 and 2010; Vasslides and Able, 2008) have identified sandy shoals and ridges as essential fish habitats and forage habitats for migratory pelagics (king mackerel, Spanish mackerel, cobia, and dolphin) and recreationally and commercially important species, as physical processes and benthic microhabitat features facilitate the concentration of a variety of invertebrates and other prey species. Slacum et al. (2006, 2010) indicated that sand shoals off the coast of the Middle Atlantic Bight (Maryland and Delaware) are used by a wide variety of fishes (57 species), and that species composition, distributions, and abundance experiencing seasonal fluctuations (i.e., high late summer-fall diversity, low winter diversity). A related study (Vasslides and Able, 2008) documents the highest fish species abundance and richness near sand ridges compared with other sampling stations along a transect extending from the nearshore to offshore. In its fishery ecosystem management plan, the SAFMC raised concerns about the excavation of offshore shoals (SAFMC, 2009; see also SAFMC, 2003). They were also concerned that these activities could cause adverse effects to the shoreline (e.g., increased erosion) and living marine resources, and could disrupt the ecological services (e.g., benthic nursery area, refuge, and feeding grounds) they provide to a variety of fishery resources. However, the potential offshore effects of sand mining must be balanced with the benefits from restoration of coastal habitats, which would likely have positive impact on nesting birds and sea turtle populations, and other coastal populations.

Conceptually, sand dredging and mining activities on the offshore continental shelf have the potential to affect directly or indirectly fish and fish habitats (Nairn et al., 2004). However, only a limited number of field studies have examined the impacts of sand mining on individual fish or fish populations. Potential direct impacts include: 1) loss or reduced suitability of habitat which would remove infauna and epifauna, reduce foraging, spawning, and overwintering habitat; and 2) increased turbidity and sedimentation causing gill clogging and burial. Potential indirect

impacts include recolonization by an altered benthic biological community, which would change foraging efficiency, potentially impacting size, weight, and fecundity. Previous environmental impact assessments of offshore sand mining projects indicated minimal effects on the fish community (see Nairn et al., 2004). This conclusion was based on the observation that most of the fish inhabiting the potential dredge areas are wide-foraging or migratory, spending only parts of their life cycle in the area. Therefore, habitat loss or habitat alteration would probably have minimal effects on the overall fish community. Furthermore, the available sand shoal habitat is often much larger than the borrow area, facilitating the relocation of resident fish populations to nearby unimpacted or less disturbed areas. The greatest potential effect to the fish populations using a sand borrow area is the alteration of energy flow (i.e., species interactions and trophic ecology) resulting from impacts on benthic communities. As described in Chapter 6 (Section 6.2.10.2), studies following dredging at borrow sites have documented changes in the abundance of representative invertebrate groups and shifts in diversity and richness patterns, with relatively fast recoveries varying from months to a few years. Since benthic invertebrate communities are dynamic in space and time, fish populations must exhibit flexible responses to fluctuations in food resources, flexibility that likely occurs following disturbances associated with sand mining. However, stil unanswered are key ecological questions about the energy-transfer efficiency of the post-dredging benthic community to higher trophic levels compared to the original community. Slacum et al. (2006, 2010) and Diaz et al. (2004) recommended that sand mining activities use a precautionary approach that minimizes impacts such as leaving refuge patches of the habitat intact to facilitate recolonization. These and other mitigations strategies that advocate a precautionary principle are currently in place during sand mining activities on the OCS. The current understanding of impacts to fish and fish habitat needs further attention, and also a more thoughtful conceptual model that fully integrates existing quantitative observations and definitive scientific evidences, and statements about impacts on populations and communities.

Aside from potential habitat loss, Greene (2002) also highlighted additional potential effects at borrow sites: 1) species present in the nearshore or offshore during spawning season may not be able to leave because their larvae are estuarine dependent; 2) permanent residents may be adversely impacted because they are unable to find an alternate habitat; and 3) fish that prey on slow-moving or non-motile organisms are at the greatest risk from effects. Furthermore, a recent assessment of Charleston's offshore Ocean Dredged Material Disposal Site (ODMDS) sand borrow project (MMS, 2009) indicated that the disturbance and increased benthic prey availability created by dredge operations can attract resident and non-resident fishes and expose them to adverse levels of turbidity, noise, and possibly resuspended pollutants. Turbidity can clog the gills and also impair feeding by reducing the ability of fish to visually locate prey. Noise, on the other hand, can alter their behavior, disrupt their swimming bladders, and cause hearing loss. However, these disturbances are short-lived and their effects are unlikely to cause long-term damage. The same assessment indicated that fishes, particularly eggs, larvae, demersal fish, and slow-moving species, can be entrained or entrapped in the dredge apparatus, but that adults are not likely to be adversely impacted by these activities. Biannual monitoring (2000–2005) of reef habitats in the proximity of the Charleston ODMDS did not find significant adverse changes in reef habitat characteristics (see Section 7.2.3 Live/Hard Bottom) and fish abundance compared to reference sites (Crowe et al., 2010). However, the authors noted the lack of baseline information and the highly dynamic nature of this environment may have hindered the detection of subtle changes in these reefs.

The effects of beach nourishment (not related to OCS dredging per se and outside BOEM's jurisdiction) on nearshore and surf zone fishes have also been evaluated (Hackney et al., 1996; Lindquist and Manning, 2001; Peterson and Manning, 2001). Experimental work (Lindquist and Manning, 2001; Peterson and Manning, 2001) showed that beach nourishment reduces the habitat value of the intertidal beach for fishes of the surf zone by reducing the production of prey (prey abundance and body size of benthic suspension feeders) and reducing trophic transfer. Furthermore, exposure of the benthos to turbidity can interfere with surf fishes' ability to visually locate food and, therefore, disrupt successful feeding. These impacts, however, appeared to be short lived and persist mostly during the equilibration period; recovery takes place over a few subsequent seasons. Whether beach nourishment impacts would translate into fish population effects is unknown (Lindquist and Manning, 2001). However, these activities can be detrimental to transitory and resident fish populations (e.g., Florida pompano, kingfishes, and spot), as well as to fish larvae requiring adequate settlement habitat (e.g., early spring–fall dredging related burial of hard bottom) (Hackney et al., 1996; Lindeman and Snyder, 1999). Large unknowns regarding the effects of site-specific beach nourishment projects on surf zone fishes include (Greene, 2002): 1) knowledge on the total available foraging and spawning habitat for each potentially impacted species; 2) species' seasonality and abundance; 3) species-specific life-history attributes (e.g., site fidelity, life-stage associations, and diel habitat use); 4) before and after species diversity comparisons; and 5) site-specific trophic interactions. The same issues apply to activities involving offshore mining activities.

7.7.3 Renewable Energy Development

A comprehensive review of the impacts of the construction and operation of renewable energy technologies for wave, ocean currents ,and wind on fisheries resources (Michel et al., 2007) stated the following with regard to wind technology: 1) sediment perturbations during installation can eliminate/enhance food sources, or alter the sedimentary environment leading to changes in spawning habitat or current flows; 2) the sound generated from pile driving during construction is within the audible range of most species and can cause short-term behavioral responses. In fishes with swim bladders, high-pressure waves from pile driving can be lethal at sufficiently close distances because of the potential rupture of the structure bladder. These high-pressure waves can also be detrimental to fishes' hearing apparatus 3) the addition of structures associated with renewable energy can be beneficial (enhanced fisheries) or negative (increased habitat for invasive species, harmful algae) to the fish community; and 4) electromagnetic fields introduced by cables may affect elasmobranches because these fishes have highly sensitive electrosensory organs, central pathways, and processors critical in behavior and biological functions. Disruption of electromagnetic fields can also be detrimental to the spatial orientation of migratory fish (e.g., eels), and could disrupting predatory behavior (e.g., sharks, skates, and rays) by hampering the detection of the subtle magnetic fields emitted by the prey. A recent BOEM-funded synthesis of information about electromagnetic fields from undersea power cables (Normandeau et al., 2011) indicated that although demersal species (e.g., sandbar shark) are more likely to be exposed to higher field strengths than pelagic species, the current state of knowledge about sensory systems (i.e., sensitivity thresholds and responses) and natural history (i.e., sensory biology, behavioral biology, sex and life stage sensory differences) is not sufficient to identify either beneficial or negative impacts on individuals, populations, or ecosystems. Given current data limitations, the impacts are largely unknown of electromagnetic fields on the feeding and reproductive behavior, migration, and habitat use of fish populations known to

detect these fields (elasmobranches and a few teleosts species of the Order Acipenseriformes , Anguilliformes, Chimaeriformes, Petromyzontiformes and Siluriformes); studies are needed to elucidate any potential effects.

There are very limited empirical data on the effects on fish behavior of underwater sound waves generated by pile driving during installation of turbine foundations, though some evidence suggests potential displacement from feeding and spawning areas, changes in communication and orientation signals, and increased mortality and injury (Hastings and Popper, 2005; Wahlberg and Westerberg, 2005; Kikuchi, 2010). Nevertheless, some of the reported effects of mortality, internal injuries, and abnormal behavior are equivocal and appear to be related to the distance from the sound source, as well as the intensity and duration of exposure to sound. Wahlberg and Westerberg (2005) found that the distance at which fish can detect sound generated by offshore wind farms depends on the size and number of turbines, the level of background noise, wind speed, water depth, and type of sea bottom. However, responses are likely species-specific (and even age-stage-specific), given differences in hearing capabilities and mechanisms among species. Furthermore, there is a substantial lack of studies on the long-term effects of exposure to underwater sound that may lead to delayed death or to behavioral changes that could negatively impact growth, reproduction, and survival. As pointed out by Hastings and Popper (2005), the body of scientific data on the effects of sound on fishes is inadequate (e.g., inadequate experimental designs, unrealistic exposure conditions, limited signal types and sound levels), and the available data are insufficient to develop scientifically supportable guidance protective of fish.

Although the long-term impacts to coastal ecosystems from offshore wind energy development are unclear, direct impacts would likely result from usurpation of seafloor habitat(s) by the foundations, distribution platforms, and cables that connect the turbines to the onshore power grid. Yet there is little doubt that offshore wind farms can serve as fish habitat, comparable to the habitat created by artificial reefs. One study in the Adriatic Sea suggested the beneficial link between offshore floating wind farms and several pelagic species (e.g., bluefin tuna, Atlantic mackerel, amberjack, dolphin, and swordfish) and recommended that considering the waters surrounding these structures as MPAs would be beneficial for the management of commercially sought and overfished populations, in particular bluefin tuna (Fayram and de Risi, 2007). Others have reported high abundance of demersal and semi-pelagic fish species on and near turbine monopiles compared to surrounding areas (Wilhelmsson et al., 2006), and rapid colonization by both epibenthic assemblages and fishes (particularly resident species) at the foundations of wave energy converters (Langhamer and Wilhelmsson, 2007). However, the role of wind farm foundations in supporting a sustainable fishery and a healthy ecosystem are largely unknown.

A 2007 workshop urged the need to understand how renewable energy activities may affect vertical diurnal movements, alongshore, and onshore-offshore migrations (Michel and Burkhard, 2007). Accurate assessment of the long-term effects of renewable energy on fishes is greatly limited by the lack of data. Furthermore, the impacts of renewable energy on fishes of the South Atlantic Planning Area are unknown and will require site-specific information on the fish community and its habitat coupled with site-specific monitoring.

7.8 SUMMARY AND DATA GAPS IN THE STATE OF FISH AND FISH HABITAT KNOWLEDGE WITH REGARD TO OCS DEVELOPMENT

The fish communities of the South Atlantic Planning Area vary in composition, abundance, and diversity in space and time, and many of their members are tightly associated with specific shelf and off-shelf zones and habitats. The nearshore coastal fish assemblage is comprised of many species, and it fluctuates seasonally, reflecting the migration patterns of the dominant species and the recruitment of juveniles to coastal nursery areas, as well as seasonal changes in water temperature, photoperiod, and productivity. These areas are also important corridors for year-round residents, larval transport, and travel of early life stages to and from nursery grounds. By contrast, middle-shelf waters are thought to be more thermally stable given the persistence of warm water, thus these areas support large numbers of temperate and subtropical species and are important spawning grounds for species with shelf-wide distributions. Similarly, the shelf edge and the lower shelf are essential fish habitat for deep-water reef fish species, critical spawning ground for many reef and deep-water species, and important habitats for warm-water species. However, these habitats have received less attention than shallower shelf areas. The same is true for deeper waters off the continental shelf (continental slope and Blake Plateau) where only a few studies exist on deep-sea reef habitats and the Charleston Bump. Although little is known about the fish assemblage on the Blake Plateau, this area is an important spawning habitat for deep-water species that have specific habitat requirements (cooler <16ºC and deeper waters >200 m). Furthermore, deep-sea corals and other deep rocky reefs provide habitat to a diverse number of fish species; in these areas species with newly recorded distribution ranges continue to be found as do species new to science (Ross and Quattrini, 2007; Fernholm and Quattrini, 2008; Nielsen et al., 2009). The challenges associated with accessing and studying deep-sea coral reefs and other remote areas are great and, consequently, the species richness and diversity in these habitats are likely higher than currently known.

From the extensive body of literature, it is clear that characterizing the location and extent of critical fish habitats is essential to better manage and protect fishery resources. A recent mapping effort (SEAMAP-SA, 2001b) estimated that hard-bottom and possible hard bottom covered ~33% and ~11%, respectively, of the continental shelf and upper slope (to 200 m depth) from North Carolina to the Florida Keys. Despite increased efforts to characterize the seafloor, current estimates are only approximate, and likely lower than their actual extent as most of the area has not been mapped. Ongoing efforts are also mapping the distribution of bottom types from the 200 m isobath out to the 2,000 m isobath. These efforts are important to identify and designate deep-water EFHs, to select and design shelf-edge MPA networks, and to aid in the rebuilding of deep-water fish populations such as the snapper-grouper complex. Although ongoing efforts have characterized the seafloor and mapped the location of some hard-bottom habitats and artificial reefs, these efforts must be extended to encompass all critical and vulnerable fish habitats. High-resolution mapping of all habitats on the shelf is critical to better understand the distribution (temporal and spatial) of fish and fish populations in the South Atlantic Planning Area. Such mapping is particularly essential to better protect habitats of species with specific habitat requirements and narrow depth distributions such as species on the shelf edge and upper slope. Managing protected areas and other important and vulnerable habitats within the South Atlantic Planning Area requires a continental shelf-wide understanding of the fish (abundance and spatial and temporal dynamics) and habitats to achieve multiple management goals.

The pelagic environment is also an important habitat for many species in the area of interest. Over the last three decades, published studies have reported the spatial and temporal distribution of eggs, larvae, and juveniles of tropical and temperate fish species over the continental shelf, highlighting the role of the Gulf Stream and large oceanographic features in trapping, transporting, and dispersing early life stages from spawning grounds to nursery areas. Because of the importance of the water column as a fish habitat, a large area of the study area (e.g., the Charleston Bump Complex) is designated by the SAFMC as a HAPC. Several studies have also documented ample use of *Sargassum* for foraging, refuge, spawning, and nursery grounds by a diverse group of fish species, showing that this habitat not only plays an important role in enhancing food resources in open waters, but also harbors a much higher species diversity and juvenile abundance than nearby open waters. However, literature specific to the region of interest on the fish assemblages associated with *Sargassum* and on the role of *Sargassum* as essential fish habitat is limited.

Over half a century of sustained fishing pressure on commercial fisheries, habitat degradation, and destructive fishing practices has lead to the depletion of many fish resources and to the increased number of fish populations at risk of attaining unsustainable levels. Although many studies have described the direct and indirect impacts of overfishing, there are substantial data gaps with regard to non-commercial species, and on the impacts of overfishing on ecosystem-level trophic interactions. Similarly, information on the life cycles (growth rates, reproductive cycles and seasonality, life-history parameters, mortality trends, and seasonal movements), trophic and ecological interactions, and habitat use of fishes (spawning and nursery grounds) is largely biased towards commercially important species and is lacking for most other species.

The extensive literature synthesis discussed here showed that over the last three decades, particularly since the mid 1990s, there have been significant gains in the knowledge and understanding of the fish assemblages and habitats in the South Atlantic Planning Area, particularly with regard to shallow water reefs (Figure 7.10). The increased understanding of habitat use throughout the life cycle of the species inhabiting these waters has been enhanced by continuous monitoring (e.g., SEAMAP, MARMAP). Although some literature exists on the life cycles (growth rates, reproductive cycles and seasonality, life-history parameters, and seasonal movements) and habitat use of many species of fishes (spawning and nursery grounds), the majority of information is biased toward commercially important species. However, significant data and knowledge gaps exist at all levels of biological organization. Data gaps range from basic knowledge about the life histories of commercial and non-commercial species to the spatial and temporal distribution of most species. Gaps also extend to knowledge in community structure, biotic and abiotic factors influencing such communities, trophic and ecological interactions, energy budgets, the location and environmental conditions of important spawning grounds, larval ecology (distribution, mortality, and transport), physical processes and topographic features that influence recruitment, and responses to environmental and anthropogenic changes. Specific habitat knowledge is lacking with respect to deep-water habitats (e.g., deep corals, fish diversity) and *Sargassum* (e.g., species composition, and spatial-temporal dynamics).

Other areas requiring additional information and site-specific assessments deal with energy exploration and development, particularly in the renewable energy arena. Currently, the body of

scientific data on the effects of offshore wind farms on fish and fish habitats is inadequate. Assessing these effects in the South Atlantic Planning Area would benefit from information on: 1) the sensitivities of species and life stages likely to be exposed to underwater sound waves and electromagnetic field emissions; and 2) how wind farms might affect migration processes and pathways.

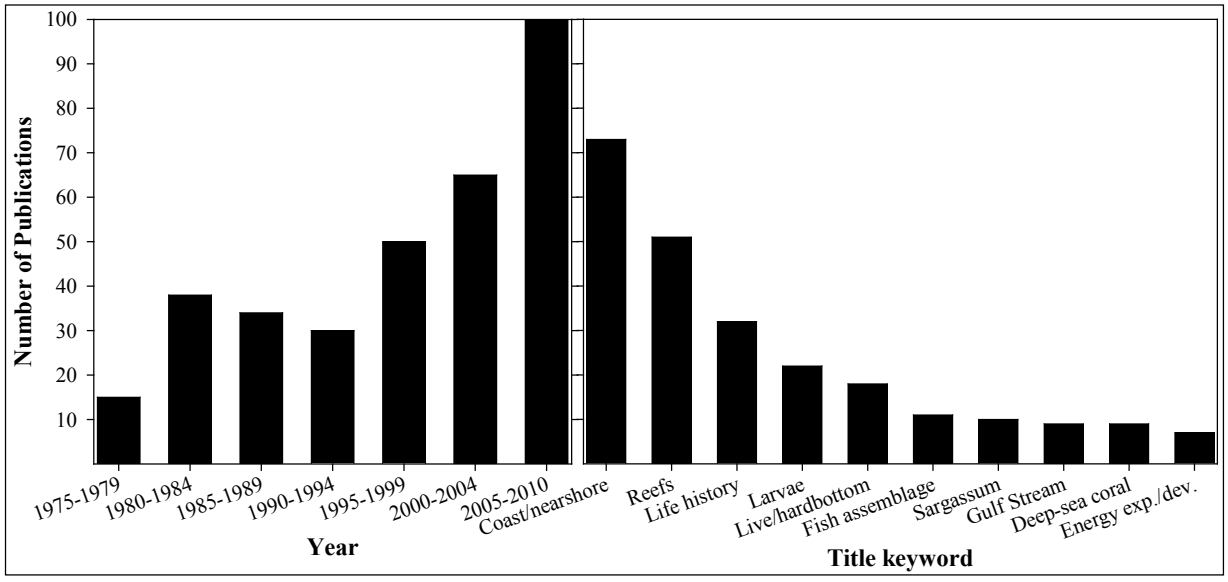

Figure 7.10 Annual and title keyword distribution of the citations included in this synthesis.

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CHAPTER 8: MARINE AND COASTAL BIRDS AND BATS

8.1 INTRODUCTION

This synthesis of information on the marine avifaunal communities of the South Atlantic Planning Area was prepared from a variety of sources, including but not limited to published literature, gray literature, agency reports, and other written documents. Spatial data were collected from a variety of sources, including state records, National Audubon Society online databases of Christmas Bird Count data and Important Bird Areas, The Conservation Biology Institute's database of protected areas, the BOEM Compendium of Avian Information and Comprehensive GIS Geodatabase, and the OBIS/SEAMAP marine mammals, birds, and turtles database.

It is clear from this synthesis that the marine bird community of the South Atlantic Planning Area has not received the level of research or conservation attention given to many other communities of marine birds throughout the US The most recent range-wide assessments were published in the early 1980s (Clapp et al., 1982a, 1982b; 1983; Clapp and Buckley, 1984). Other reviews, such as a recent 2007 overview of pelagic seabirds in the South Atlantic Bight (Wallace and Wigh, 2007), provide brief accounts of occurrence, but a synthesis of all relevant information is lacking. Given recent environmental events such as the *Deepwater Horizon* oil spill in the Gulf of Mexico, and what appears to be a growing national interest in the development of marine-based alternative energy facilities, a comprehensive synthesis of seabird information for the region is warranted.

8.2 STUDY AREA

The South Atlantic Planning Area extends from the North Carolina/South Carolina border to Palm Bay Florida and out to ~400 km from shore. The study area is generally characterized by a wide continental shelf (40–140 km) that is bordered to the east by the Gulf Stream. This is in contrast to adjacent areas to the north and south, such as Cape Hatteras and the central and southern peninsular regions of Florida, where the shelf is considerably narrower and where the Gulf Stream is much closer to the coast.

The coastal zone is characterized by a mix of sand beaches, salt marsh/estuarine habitats, and barrier and sea-islands. Ten major rivers terminate along the coast, introducing substantial freshwater discharge into the region. The coastal zone also is characterized by rapid population growth and land conversion and development. The nearshore region has yet to be subjected to substantial development (e.g., oil platforms, wind turbines). Commercial activities in the nearshore zone include primarily shrimp-trawl fisheries.

The composition of the avifaunal community of the study area is driven to a great extent by the pelagic, nearshore, and coastal characteristics of the region. The focus of this synthesis is predominantly on seabirds but wading birds, shorebirds, and wintering sea ducks and their associates are also addressed. For the purposes of this document, the goals are to define how each group is treated, provide examples of species included in the group from both within and outside of the South Atlantic Planning Area, and review basic life-history characteristics that are

most common within those groups, with specific emphases on characteristics that are relevant to the time each group spends in the study area.

The South Atlantic Planning Area includes a variety of Marine Protected Areas (MPAs); the location and characteristics of these appear in Chapter 6. Because the avifauna rely to a great extent on coastal areas, such as barrier islands and estuaries, it is important to consider protected areas on land which include but are not limited to national wildlife refuges (NWRs), state-managed wildlife management areas (WMAs), national parks, and Important Bird Areas (IBAs). This latter designation is used by the Audubon Society to identify and conserve areas that are vital to birds and other biodiversity. The distribution of coastal protected areas and IBAs that directly benefit or support nearshore seabirds or shorebirds is shown in Figure 8.1A-C; attributes of these areas are listed in Tables 8.1 and 8.2. Four of fifteen IBAs are on private land in South Carolina, two of eleven are on private land in Georgia, but none of the eight in Florida is on private land. While protected areas and IBAs do occur regularly along the entire coast, the two longest stretches of protected lands are at the north and south end of the Planning Area. In South Carolina, approximately 70 km of uninterrupted protected coastline extend from Winyah Bay to Bulls Bay (Figure 8.1A); in Florida there are approximately 80 km of uninterrupted protected coastline in the Cape Canaveral area (Figure 8.1C).

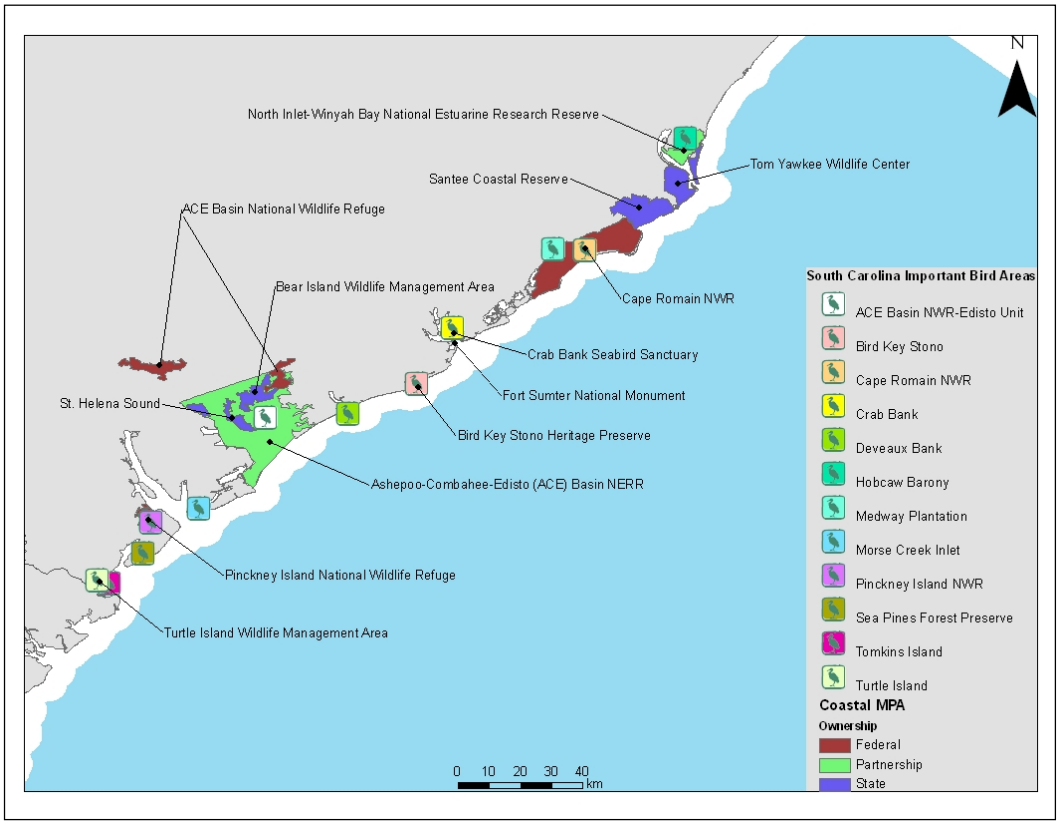


Figure 8.1A National Audubon Society Important Bird Areas and coastal marine protected areas (MPA) on the South Carolina coast.

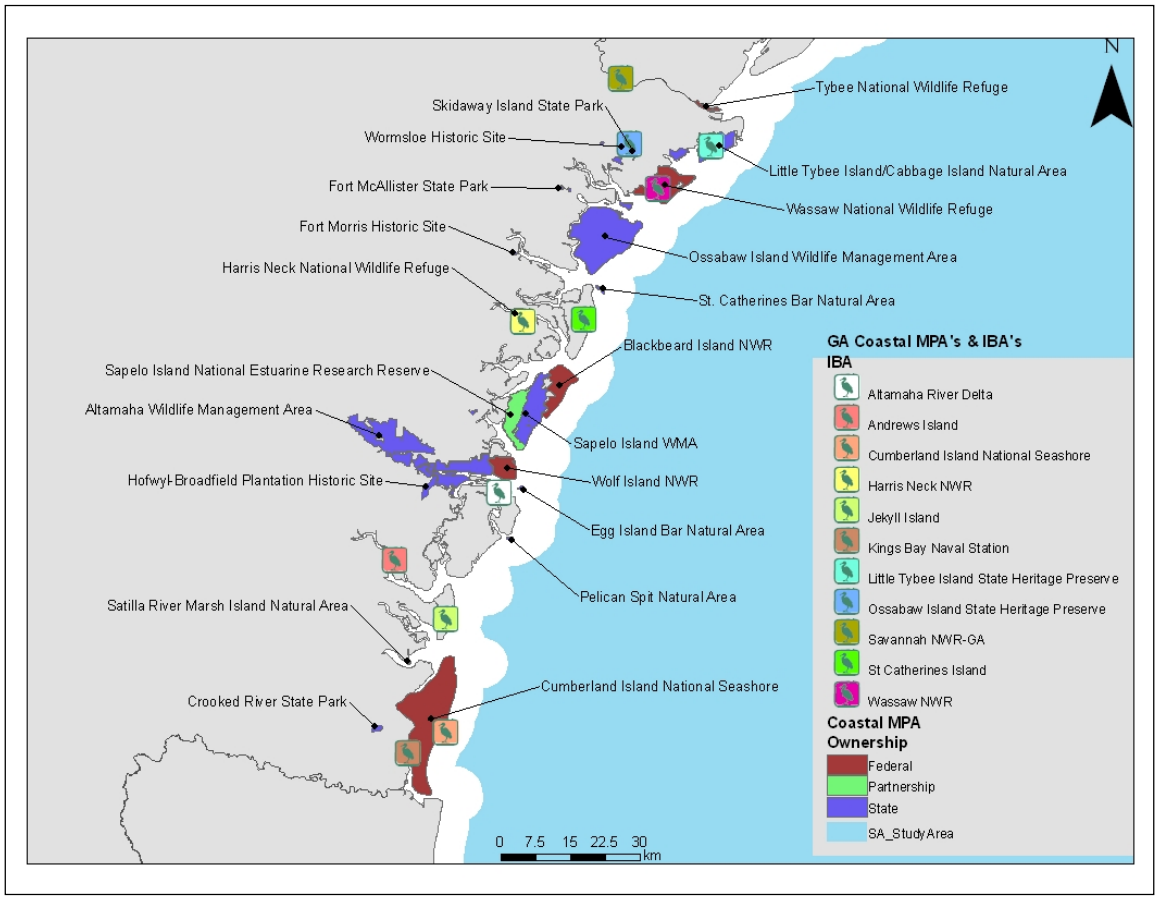


Figure 8.1B National Audubon Society Important Bird Areas (IBA) and coastal marine protected areas (MPA) on the Georgia coast.

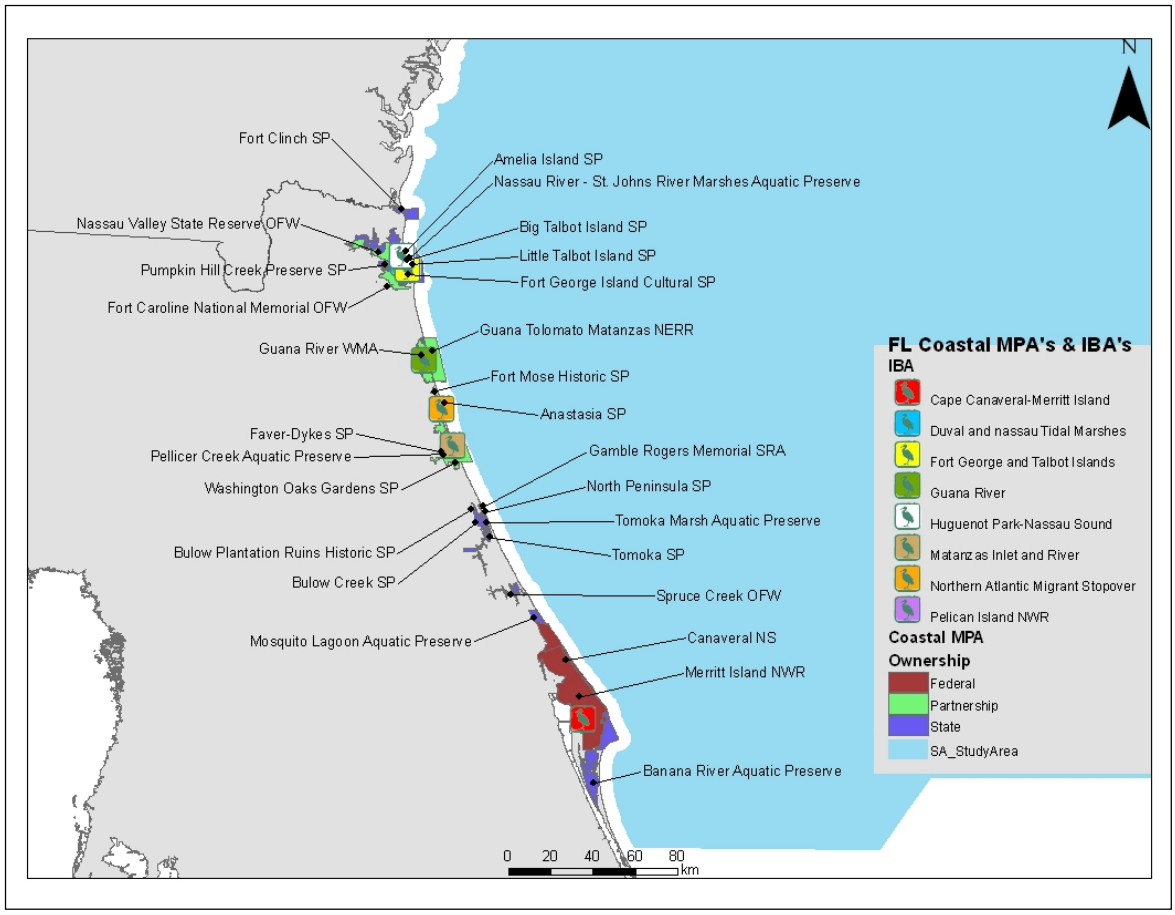


Figure 8.1C National Audubon Society Important Bird Areas (IBA) and coastal marine protected areas (MPA) within the study area on the Florida coast.

Table 8.1
Coastal locations within the South Atlantic Planning Area afforded some level of federal, state, county, or other designation/protection that provide some habitat for coastal birds.

Protected Area	Ownership	Habitat Type
South Carolina		
North Inlet-Winyah Bay National Estuarine Research Reserve (NERR)	Partnership	Tidal marsh/estuary
Tom Yawkey Wildlife Center	State	Habitat complex
Santee Coastal Reserve	State	Habitat complex
Cape Romain NWR	Federal	Habitat complex
Crab Bank Seabird Sanctuary	State	Sand island
Fort Sumter National Monument	Federal	Beach
Bird Key Stono Heritage Preserve	State	Barrier island
Bear Island Wildlife Management Area	State	Tidal/non-tidal wetlands
St Helena Sound	State	Barrier islands
ACE Basin NERR	Partnership	Habitat complex
Pinkney Island NWR	Federal	Salt marsh
Turtle Island Wildlife Management Area	State	Barrier island
Georgia		
Tybee NWR	Federal	Dredge spoil
Little Tybee Island/Cabbage Island Natural Area	State	Barrier island
Skidaway Island State Park	State	Barrier island/Salt marsh
Wassaw NWR	Federal	Salt marsh/estuary
Fort McAllister State Park	State	Salt marsh
Ossabaw Island Wildlife Management Area	State	Barrier island
Fort Morris Historic Site	State	
St. Catherines Bar Natural Area	State	Barrier island
Harris Neck NWR	Federal	Wetland
Sapelo Island NERR	Partnership	Barrier island/ Habitat complex
Altamaha Wildlife Management Area	State	Wetland
Egg Island Bar Natural Area	State	

Sites listed were derived from expert knowledge and web searches where coastal birds were noted as being present.

Table 8.1 Coastal locations within the South Atlantic Planning Area afforded some level of federal, state, county, or other designation/protection that provide some habitat for coastal birds (continued).

Protected Area	Ownership	Habitat Type
Wolf Island NWR	Federal	Barrier island/salt marsh
Blackbeard Island NWR	Federal	Barrier Island/complex
Pelican Spit Natural Area	State	Sand island
Hofwyl-Broadfield Plantation Historic Site	State	Salt marsh
Satilla River Marsh Island Natural Area	State	Salt marsh
Crooked River State Park	State	Salt marsh
Cumberland Island National Seashore	Federal	Barrier island/complex
Florida		
Amelia Island State Recreation Area Outstanding Florida Water	State	Open water
Anastasia State Park Outstanding Florida Water	State	Open water
Banana River Aquatic Preserve Outstanding Florida Water	State	Open water
Big Talbot Island State Park Outstanding Florida Water	State	Open water
Bulow Creek State Park Outstanding Florida Water	State	Open water
Canaveral National Seashore Outstanding Florida Water	State	Open water
Faver-Dykes State Park Outstanding Florida Water	State	Open water
Fort Caroline National Memorial Outstanding Florida Water	State	Open water
Fort Clinch State Park Aquatic Preserve Outstanding Florida Water	State	Open water
Fort Clinch State Park Outstanding Florida Water	State	Open water
Fort George Island Outstanding Florida Water	State	Open water
Gamble Rogers Memorial State Recreation Area at Flagler Beach Outstanding Florida Water	State	Open water
Guana River Outstanding Florida Water	State	Open water
Guana River Marsh Aquatic Preserve Outstanding Florida Water	State	Open water
Little Talbot Island State Park Outstanding Florida Water	State	Open water

Sites listed were derived from expert knowledge and web searches where coastal birds were noted as being present.

Table 8.1 Coastal locations within the South Atlantic Planning Area afforded some level of federal, state, county, or other designation/protection that provide some habitat for coastal birds (continued).

Protected Area	Ownership	Habitat Type
Merritt Island National Wildlife Refuge Outstanding Florida Water	State	Open water
Mosquito Lagoon Aquatic Preserve Outstanding Florida Water	State	Open water
Nassau River-St. Johns River Marshes Aquatic Preserve Outstanding Florida Water	State	Open water
Nassau Valley State Reserve Outstanding Florida Water	State	Open water
North Peninsula State Recreation Area Outstanding Florida Water	State	Open water
Pellicer Creek Aquatic Preserve Outstanding Florida Water	State	Open water
Spruce Creek Outstanding Florida Water	State	Open water
Spruce Creek Special Water Outstanding Florida Water	State	Open water
Timucuan Ecological and Historic Preserve Outstanding Florida Water	State	Open water
Tomoka Marsh Aquatic Preserve Outstanding Florida Water	State	Open water
Tomoka River Outstanding Florida Water	State	Open water
Tomoka State Park Outstanding Florida Water	State	Open water
Washington Oaks State Gardens Outstanding Florida Water	State	Open water
Fort Mose Historic State Park	State	Salt marsh
North Peninsula State Park	State	Beach
Washington Oaks Gardens State Park	State	Salt marsh
Fort Mose Historic State Park Outstanding Florida Water	State	Open water
Guana River Wildlife Management Area	State	Salt marsh
Banana River Aquatic Preserve	State	Estuary
Guana River Marsh Aquatic Preserve	State	Barrier Island/salt marsh
Indian River Lagoon Preserve State Park	State	Estuary/Barrier Island
Mosquito Lagoon Aquatic Preserve	State	Estuary
Sites listed were derived from expert knowledge and web searches where coastal birds were noted as being present.		

Table 8.1 Coastal locations within the South Atlantic Planning Area afforded some level of federal, state, county, or other designation/protection that provide some habitat for coastal birds (continued).

Protected Area	Ownership	Habitat Type
Nassau River – St. Johns River Marshes Aquatic Preserve	State	Salt marsh
Pellicer Creek Aquatic Preserve	State	Salt marsh
Pumpkin Hill Creek Preserve State Park	State	Tidal creek
Tomoka Marsh Aquatic Preserve	State	Estuary
Amelia Island State Park	State	Barrier Island/salt marsh maritime forest
Anastasia State Park	State	Barrier Island/Salt Marsh Maritime Forest
Big Talbot Island State Park	State	Sea island
Bulow Creek State Park	State	
Bulow Plantation Ruins Historic State Park	State	
Faver-Dykes State Park	State	Tidal marsh
Fort Clinch State Park	State	Barrier island/beach
Fort George Island Cultural State Park	State	Maritime forest/salt marsh
Gamble Rogers Memorial State Recreation Area at Flagler Beach	State	Beach/tidal creek
Little Talbot Island State Park	State	Barrier island
Tomoka State Park	State	Tidal river
Indian River, Reliant Corporation Delespine Power Plant No Entry Zone	State	Open water
Indian River, FPL Frontenac Power Plant No Entry Zone	State	Open water
Indian River, Reliant Corporation Delespine Power Plant Motorboats Prohibited Zone	State	Open water
Guana Tolomato Matanzas National Estuarine Research Reserve	Partnership	Habitat complex
Timucuan Ecological and Historic Preserve	Partnership	Salt marsh/coastal dune
Canaveral National Seashore	Federal	Barrier island
Merritt Island National Wildlife Refuge	Federal	Barrier island

Sites listed were derived from expert knowledge and web searches where coastal birds were noted as being present.

Table 8.2
National Audubon Society Important Bird Areas (IBAs) on the South Atlantic Planning Area.

Site Name	Ownership	Habitat Type
South Carolina		
Woodbury Wildlife Management Area	State/Federal	Forested upland/wetland
Hobcaw Barony	Private/Non-profit	Salt marsh
Santee Coastal Reserve	State	Habitat Complex
Cape Romain NWR	Federal	Habitat Complex
Medway Plantation	Private/Individual	Forest/Wetland
Crab Bank	State	Small Sand Island
Bird Key Stono	State	Small Barrier Island
Deveaux Bank	State	Small Barrier Island
ACE Basin NWR- Edisto Unit	Federal	Habitat Complex
Bear Island Wildlife Management Area	State	Tidal/Non-Tidal Wetlands
Morse Creek Inlet/Bay Point Island	Private	Beach/Intertidal Mudflat
Pinckney Island NWR	Federal	Salt marsh
Sea Pines Forest Preserve	Private/For Profit	Maritime Forest/Wetland
Tomkins Island	Federal/ACOE	Dredge Spoil Island
Turtle Island	State	Barrier Island
Georgia		
Savannah NWR	Federal	Habitat Complex
Little Tybee Island State Heritage Preserve	State	Barrier Island
Ossabaw Island State Heritage Preserve	State/Private	Large Barrier Island
Wassaw NWR	Federal	Salt marsh/Estuary
St. Catherines Island	Private/Non-Profit	Barrier Island
Harris Neck NWR	Federal	Wetland
Altamaha River Delta (Blackbeard, Sapelo, Wolf, Egg, Little Egg, Little St. Simon's Islands)	Federal/State/ Municipal	Barrier Islands/Salt marsh
Andrews Island	Federal/State/ Municipal	Dredge Spoil
Jekyll Island	State	Barrier Island
Cumberland Island National Seashore	Federal	Barrier Island
Kings Bay Naval Station	Federal/DOD	

Table 8.2 National Audubon Society Important Bird Areas (IBAs) on the South Atlantic Planning Area (continued).

Site Name	Ownership	Habitat Type
Florida		
Huguenot Park-Nassau Sound	State/ACOE	Coastal Beach
Duval and Nassau Tidal Marshes		Salt marsh
Fort George and Talbot Islands (State Parks)	State	Barrier Island
Guana River	State	Barrier Island
North Atlantic Migrant Stopover (Anastasia State Park, Faver-Dykes State Park, Smyrna Dunes Park, Tomoka Basin GEOPark, Tomoka Aquatic Preserve, Washington Oaks Gardens State Park)	State	Habitat Complex
Matanzas Inlet and River (Fort Matanzas National Monument, Northeast Florida Blueway Phase II Tolomata and Matanzas River FF Project, State sovereign lands)	State/Federal	Coastal/Tidal Marsh/Estuary
Volusia County Colony Islands (New Smyrna Beach Colony, Port Orange Colony)		Small Islands
St John's NWR	Federal	Inland Salt marsh
Cape Canaveral-Merritt Island	Federal	Barrier Island Complex

8.3 OVERVIEW OF MARINE AND COASTAL AVIFAUNA

The following categories are used for coastal and marine birds of interest: seabirds (nearshore or pelagic), shorebirds, wading birds, and sea ducks and allies.

8.3.1 Seabirds

The term "seabird" is generally applied to species that forage in the marine environment over open water. Globally, this includes all species from the orders Sphenisciformes (penguins) and Procellariiformes (albatrosses, petrels, storm-petrels, fulmars, and shearwaters), most species from the order Pelecaniformes (tropicbirds, pelicans, boobies, frigatebirds, and cormorants), and some species from the order Charadriiformes (alcids, gulls, terns, skuas, and skimmers) (Schreiber and Burger, 2002). Seabirds can also be categorized by the marine zones in which they tend to forage. For example, pelagic seabirds (e.g., many shearwaters) forage away from the coastal zone and over open oceans during both the breeding and non-breeding seasons. In contrast, nearshore seabirds (e.g., most gulls and terns) forage in coastal waters and winter in coastal zones where they may often be found loafing on beaches. Some seabirds use both nearshore and pelagic zones. For example, many alcids forage in both nearshore and pelagic zones during the breeding and non-breeding seasons but only rarely use terrestrial habitat outside of the breeding season. In the South Atlantic it may be best to consider species like alcids as pelagic seabirds because they do not use coastal lands outside of the breeding season. Although these categories present some ambiguities and are not strictly defined, they do provide an immediate and clear reference in terms of spatial scale (Jodice and Suryan, 2010).

Globally, about 96% of seabirds nest in colonies that vary from tens of pairs to over one million (Wittenberger and Hunt, 1985). Seabirds tend to be long lived and relatively slowly reproducing. While gulls and terns may breed at 2–4 years of age, other more pelagic species may delay breeding until ten or more years. Seabird clutches tend to be small ($\leq$5 eggs) and nearshore species typically have larger clutches compared to pelagic species, most of which lay only one egg. The incubation period of seabirds ranges from a fairly typical 28–30 days in many nearshore species to about 80 days in larger seabirds. Nestling or chick-rearing periods are variable among seabirds and can be extensive. Gulls and terns may fledge in 30 days or less, brown pelicans (*Pelecanus occidentalis*) require approximately 75 days, and magnificent frigatebirds (*Fregata magnificens*) up to 185 days. Seabirds forage primarily by surface feeding (e.g., gulls, terns, albatrosses), plunge diving into the top few meters of the water column (e.g., pelicans), pursuit diving (e.g., alcids, penguins, shearwaters, diving-petrels, and cormorants, some of which can access waters as deep as 100–500 m during their pursuit dives), and kleptoparasitism (skuas, jaegers, and frigatebirds). The dominant diet item among seabirds is fish, and the type and size taken depends, in part, on the foraging technique, geographic distribution, size of the bird, and marine habitat. Foraging locations are dictated by a combination of habitat features that affect prey availability, including attributes such as ocean and wind circulation patterns, the extent of upwelling and productivity, turbidity, and distance from the breeding site.

The South Atlantic Planning Area supports nearshore seabirds that breed and often winter within the region (e.g., brown pelican, various terns, black skimmer [*Rynchops niger*]), nearshore species that breed entirely or primarily outside of the region but migrate through or winter in the region (e.g., ring-billed gull [*Larus delawarensis*], Forster's tern [*Sterna forsteri*]), and pelagic

species that do not breed within the region but do occur in offshore habitats during various phases of the annual cycle (e.g., Audubon's shearwater [*Puffinus lherminieri*], Wilson's storm-petrel [*Oceanites oceanicus*], greater shearwater [*Puffinus gravis*]). Nearshore breeding species and pelagic species are discussed in detail below, and migratory nearshore species are briefly mentioned.

8.3.2 Shorebirds

The order Charadriiformes includes most species considered to be shorebirds. Three families typically associated with coastal and marine environments and common in the South Atlantic Planning Area include the Scolopacidae (sandpipers, phalaropes), Charadriidae (plovers), and Haemotopodidae (oystercatchers). Globally, about 60% of species classified as shorebirds regularly use marine habitats for nesting or wintering, or cross marine areas during migration (Warnock et al., 2002). Shorebirds are often found on coastal beaches and barrier islands throughout the year and so often occur over nearshore waters.

8.3.3 Wading Birds

For the purposes of this synthesis, wading birds include the long-legged waders in the order Ciconiiformes, such as egrets, herons, and ibises. These species often nest on barrier islands, in coastal wetlands, in salt marshes, and frequently with or adjacent to some seabirds. In fact, waders and seabirds are often grouped together in management plans or documents as "colonial waterbirds." While this designation is handy when referring only to breeding habitats, it tends to obscure the broader ecological role that each group fills. Within the marine environment wading birds occur as commuters, often flying along shorelines, and as foragers, often feeding or loafing along beach edges.

8.3.4 Sea Ducks and Their Allies

The Anseriiformes is a large order that includes a diverse array of waterfowl. For the purposes of this synthesis, however, sea ducks or species that winter in the marine environment are of main concern. This includes eiders, scoters, mergansers, goldeneyes, buffleheads, long-tailed ducks, and harlequin ducks. This group also includes loons and grebes which, although occurring each in their own order, are discussed alongside of sea ducks due to similarities in certain behaviors.

8.3.5 Other Avian and Flighted Animals in the Marine Zone

While the above guilds represent most of the avifauna that use the marine zone of the South Atlantic Planning Area, other species may use this zone periodically or during specific times of year. Thus, a brief review is provided of the known use of the marine zone by perching birds, raptors, and bats, three groups of flighted animals that occur in the marine zone.

8.4 SPECIES PROFILES: ECOLOGY, STATUS AND TRENDS, AND CONSERVATION ISSUES

For nearshore and pelagic seabirds, each account begins with a ranking of the state of knowledge including the red-list categorization of the species, which precedes the species name (n/a when guilds or suites of species are discussed). These categories are:

Least Concern – LC
Vulnerable – V
Near Threatened – NT
Endangered – E
Critically Endangered – CR
Extinct – EX

An ordinal ranking is used to indicate the state of knowledge in four categories: Breeding sites (Breeding), Foraging Ecology and Diet (Foraging), Distribution and Habitat Use at Sea (Distribution), and Status and Population Trends (Status). For nearshore seabirds, these are followed by the estimated number of breeding pairs in the South Atlantic Planning Area and for pelagic seabirds for the global population. Estimates of the population size for nearshore seabirds are taken from agency reports, unpublished agency data, and BNA accounts. Estimates for pelagic seabirds are taken from BirdLife International. We provide ranges when appropriate (i.e., when the available data allow). Rankings for the state of knowledge are:

1) Limited or no data throughout the range
2) Incomplete data throughout the range, no data near or within the study area
3) Sufficient data, well studied, or well documented somewhere in range but incomplete data, effort, or documentation near or within the study area
4) Sufficient data, well studied, or well documented outside but nearby the South Atlantic Planning Area but incomplete data, effort, or documentation within the study area
5) Sufficient data, well studied, or well documented in the study area.

8.4.1 Seabirds

The following topics on seabirds that breed in the South Atlantic Planning Area are covered in this section:

- A brief species synopsis;
- Nesting habitat information which provides insight for coastal use and specific terrestrial habitat requirements for the breeding season;
- What is known about breeding and wintering ranges and migration routes, which ecologically links the South Atlantic Planning Area to other regions in terms of potential impacts to bird populations;
- Foraging ecology and diet which often is not known in detail for the region due to a lack of data, but which provides information about at-sea habitat use and is often an important metric when assessing impacts to seabirds or comparing populations across space or time;

- Data on reproductive ecology such as chick growth rates, feeding rates, and reproductive success (as well as factors that affect these metrics), which also are a commonly used metric when comparing the health or status of populations spatially or temporally, or in reference to any issues/events which are also reviewed; and
- Any data available on the status or population trends of the species in the South Atlantic Planning Area, as well as current conservation and management issues. The focus is on data and information relevant to the study area but the discussion often draws upon broader knowledge from throughout the range where location-specific information is lacking.

Accounts for pelagic seabirds are less detailed due, in part, to this guild not breeding within the South Atlantic Planning Area and also to a general lack of data on pelagic seabirds in the northwest Atlantic.

8.4.1.1 Nearshore Seabirds in the South Atlantic Planning Area

Nearshore seabirds that breed in the study area and are discussed include brown pelican, laughing gull (*Larus atricilla*), royal tern (*Thalasseus maximus*), sandwich tern (*Thalasseus sandvicensis*), gull-billed tern (*Gelochelidon nilotica*), least tern (*Sternula antillarum*), and black skimmer. Information is also provided for nearshore species that either breed in the study area but less commonly than the aforementioned species (e.g. Forster's tern, sooty tern (*Sterna fuscata*), and roseate tern (*Sterna dougallii*)), and that winter here (e.g., ring-billed gull).

Ten species that can be classified as nearshore seabirds from two orders (Pelecaniformes, Charadriiformes) and three families (Pelecanidae, Laridae, Rynchopidae) nest in the South Atlantic Planning Area: one gull, seven terns, one pelican, and one skimmer (Table 8.3). Although some of these species are at population levels that have warranted some level of listing, none are considered to be of global importance nor does the region support, for example, the entire US population of any of these species (Appendix 8.1). The species that breed in each state (and only within the South Atlantic Planning Area within Florida) at levels beyond occasional breeding are brown pelican, laughing gull, gull-billed tern, royal tern, least tern, and black skimmer. Sandwich terns also breed in South Carolina and Georgia, as well as in Florida outside of the South Atlantic Planning Area.

Table 8.3
Breeding status of nearshore seabirds in the South Atlantic Planning Area by state.

Scientific Name	Common Name	SC	GA	FL
Order PELECANIFORMES				
Family PELECANIDAE				
Pelecanus occidentalis	Brown Pelican	B	B	B
Order CHARADRIIFORMES				
Family LARIDAE				
Larus atricilla	Laughing Gull	B	B	B
Gelochelidon nilotica	Gull-billed Tern	B	B	B
Thalasseus maxima	Royal Tern	B	B	B
Thalasseus sandvicensis	Sandwich Tern	B	B	
Sterna hirundo	Common Tern	B		
Sterna forsteri	Forster's Tern	B		
Sternula antillarum	Least Tern	B	B	B
Onychoprion fuscata	Sooty Tern	B		
Family RYNCHOPIDAE				
Rynchops niger	Black Skimmer	B	B	B

B = breeding species within that state (for Florida, within the South Atlantic Planning Area portion of the state).

These nearshore species all nest colonially on the ground (or in the case of pelicans low vegetation also is used in Florida), although the size and density of colonies vary among species. The primary colony sites for nearshore seabirds are presented in Figure 8.2. Along the South Atlantic Planning Area, the major colonies are clustered along the central coast of South Carolina from Cape Romain south to the North Edisto River, are distributed somewhat regularly from the Savannah River south to the St. John's River, and then are clustered in the Cape Canaveral area. Accompanying data on colony attributes appear in Table 8.4. Colony sites in South Carolina appear to be used more consistently among years compared to those in Florida (with the exception of pelican colonies in Florida which are spatially consistent). Colony sites in South Carolina also tend to have higher species richness in most years compared to most sites in Georgia and Florida. For example, three colonies in South Carolina support five of the six breeding nearshore species in most years. In South Carolina and Georgia, brown pelicans often nest at the same sites as royal and sandwich terns, although not in mixed species colonies. Brown pelicans do, however, often nest in mixed species colonies with wading birds (e.g., snowy egrets [*Egretta thula*]) and this has led to the common practice of grouping these species together as colonial waterbirds. Royal and sandwich terns often nest in densely packed mixed species colonies. Black skimmers may nest alone or gull-billed terns may nest amongst them. Least terns nest in dispersed colonies, and many of the nesting sites in the South Atlantic Planning Area now

occur on roof tops of buildings (not listed in Table 8.4). Laughing gulls nest adjacent to many of the aforementioned species at many of the colonies listed in Table 8.4, although they are not commonly surveyed or censused.

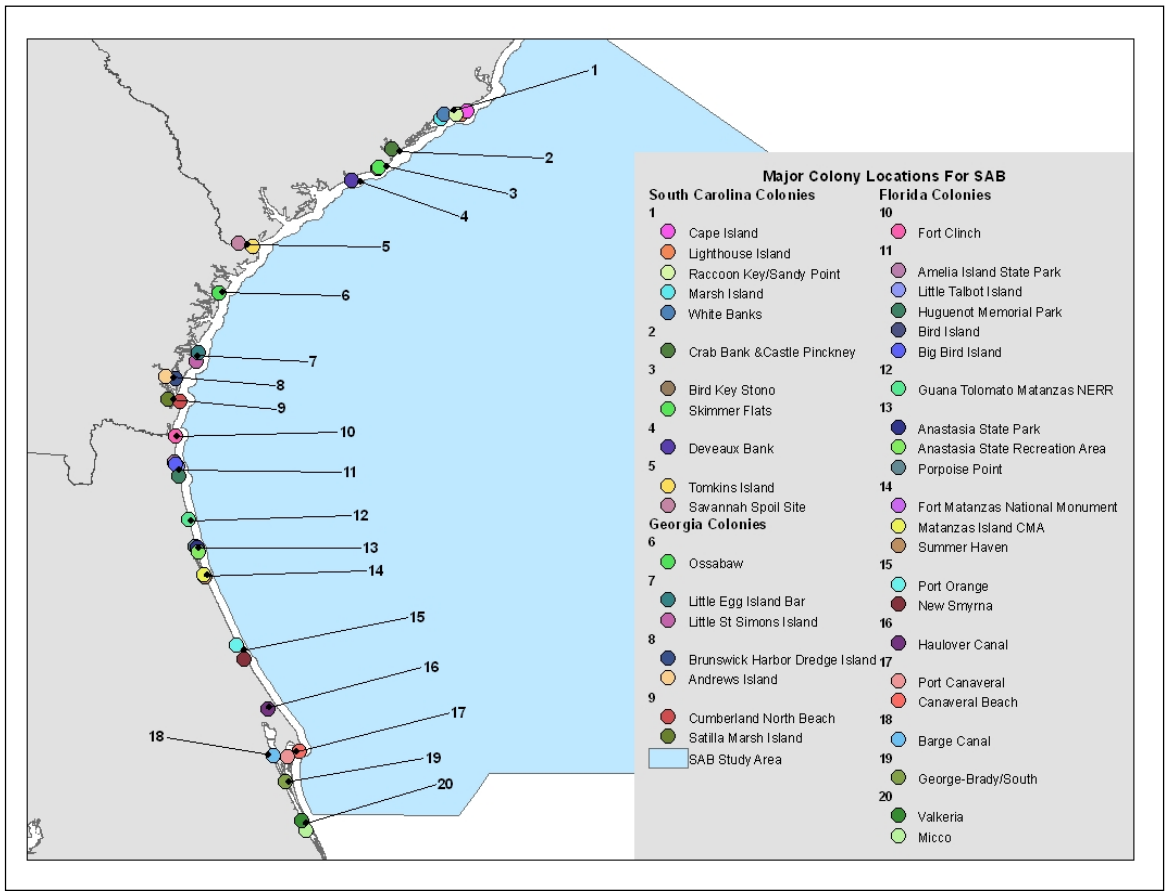


Figure 8.2 Colony locations for nearshore seabirds in the South Atlantic Planning Area.

Table 8.4
Major colony sites for nearshore seabirds along the South Atlantic Planning Area. Colony locations appear in Figure 8.2. Colonies are listed from north to south.

Name	Coordinates	Brown Pelican	Royal Tern	Sandwich Tern	Least Tern	Gull-billed Tern	Black Skimmer
South Carolina							
Cape Island	33.04, -79.35	0/6	0/6	0/6	4/6	1/6	3/6
Lighthouse Island	33.02, -79.39	0/6	0/6	0/6	5/6	2/6	4/6
Raccoon Key/Sandy Point	33.02, -79.42	0/6	0/6	0/6	3/6	2/6	1/6
White Banks Islands	33.02, -79.51	0/6	1/6	0/6	2/6	6/6	4/6
Marsh Island	32.98, -79.53	6/6	6/6	6/6	0/6	4/6	3/6
Crab Bank and Castle Pinckney	32.77, -79.88	6/6	6/6	3/6	0/6	4/6	6/6
Bird Key Stono River	32.63, -79.99	H	H	H	H	H	H
Deveaux Bank	32.55, -80.17	6/6	6/6	6/6	1/6	6/6	6/6
Skimmer Flats	32.63, -79.98	0/6	0/6	0/6	1/6	3/6	5/6
Tomkins Island	32.06, -80.88	5/6	6/6	6/6	0/6	4/6	4/6
Savannah Spoil Sites	32.09, -80.98	0/6	0/6	0/6	6/6	4/6	4/6
Georgia							
Ossabaw	31.73, -81.12	A	A	A	P	A	A
Little St. Simons Island	31.24, -81.29	A	A	A	P	P	P
Little Egg Island Bar	31.31, -81.27	P	A	A	A	A	A
Andrews Island	31.13, -81.51	A	A	A	P	P	A
Brunswick Harbor Dredge	31.11, -81.44	P	P	A	P	P	P
Satilla Marsh	30.97, -81.49	P	A	A	A	A	A
Cumberland N. Beach	30.95, -81.40	A	A	A	P	A	A

Breeding status for all species in South Carolina is scored as number of years between 2005 and 2010 that nesting occurred (n/6), in Georgia as Present or Absent during 2010, in Florida for terns and black skimmer as number of years between 2005 and 2010 that nesting occurred (n/6), and in Florida for brown pelicans as number of years between 2001 and 2007 that nesting occurred (n/7). 'H' = Historically used but not used currently. Laughing gulls are not included because they are rarely counted. Sites that were used in 1 year and where very few nests were counted are not included. Only ground colonies are included. SP = State Park, NM = National Monument, CWA = Critical Wildlife Area.

Table 8.4 Major colony sites for nearshore seabirds along the South Atlantic Planning Area. Colony locations appear in Figure 8.2. Colonies are listed from north to south (continued).

Name	Coordinates	Brown Pelican	Royal Tern	Sandwich Tern	Least Tern	Gull-billed Tern	Black Skimmer
Florida							
Ft. Clinch SP	30.70, -81.45	0/6	0/6	0/6	5/6	0/6	0/6
Amelia Island SP	30.33, -81.31	0/6	0/6	0/6	5/6	0/6	1/6
Big Bird Island	30.50, -81.43	0/6	0/6	0/6	1/6	2/6	3/6
Huguenot Mem. Park	30.42, -81.41	0/6	3/6	0/6	0/6	1/6	1/6
Little Talbot Isl. SP	30.49, -81.42	0/6	0/6	0/6	3/6	3/6	3/6
Bird Island	30.50, -81.44	0/6	0/6	0/6	1/6	0/6	1/6
Anastasia State Park	29.91, -81.28	0/6	0/6	0/6	3/6	0/6	0/6
Anastasia State Rec.	29.87, -81.27	0/6	0/6	0/6	6/6	0/6	0/6
Canaveral Beach	28.44, -80.55	0/6	0/6	0/6	2/6	0/6	0/6
Ft. Matanzas NM	29.71, -81.23	0/6	0/6	0/6	1/6	0/6	0/6
Guana Tolomato	30.10, -81.34	0/6	0/6	0/6	5/6	0/6	0/6
Matanzas Island CWA	29.71, -81.23	0/6	0/6	0/6	4/6	0/6	0/6
Porpoise Point	29.91, -81.29	0/6	0/6	0/6	5/6	0/6	0/6
Port Canaveral	28.40, -80.63	0/6	0/6	0/6	1/6	0/6	0/6
Summer Haven	29.70, -81.22	0/6	0/6	0/6	1/6	0/6	0/6
Barge Canal	28.41, -80.74	4/7	0/7	0/7	0/7	0/7	0/7
George-Brady	28.22, -80.65	1/7	0/7	0/7	0/7	0/7	0/7
Haulover Canal	28.64, -80.44	7/7	0/7	0/7	0/7	0/7	0/7
Micco	27.81, -80.39	7/7	0/7	0/7	0/7	0/7	0/7
Valkeria	27.94, -80.53	7/7	0/7	0/7	0/7	0/7	0/7
New Smyrna	29.10, -80.94	3/7	0/7	0/7	0/7	0/7	0/7
Port Orange Islands	29.20, -81.00	7/7	0/7	0/7	0/7	0/7	0/7

Breeding status for all species in South Carolina is scored as number of years between 2005 and 2010 that nesting occurred (n/6), in Georgia as Present or Absent during 2010, in Florida for terns and black skimmer as number of years between 2005 and 2010 that nesting occurred (n/6), and in Florida for brown pelicans as number of years between 2001 and 2007 that nesting occurred (n/7). 'H' = Historically used but not used currently. Laughing gulls are not included because they are rarely counted. Sites that were used in 1 year and where very few nests were counted are not included. Only ground colonies are included. SP = State Park, NM = National Monument, CWA = Critical Wildlife Area.

In comparison to the mid-Atlantic area (i.e., North Carolina, Virginia, and Maryland) the South Atlantic Planning Area nearshore seabird community supports somewhat larger and historically older pelican colonies, larger skimmer colonies, and a less-diverse gull community. For example, both herring (*Larus argentatus*) and black-backed (*Larus marinus*) gulls now nest in the mid-Atlantic area although these species have yet to nest in the South Atlantic at a level beyond scattered individuals. This is an important difference in community structure because, compared with the laughing gull, herring and black-backed gulls are both larger in size and more aggressive in terms of predation pressure on other colonial nesting species. For example, although laughing gulls will predate eggs and chicks of terns and skimmers, their impact on pelicans appears to be minimal. In contrast, the larger herring and black-backed gulls readily predate smaller seabirds and pelican eggs and chicks.

The nonbreeding season in the South Atlantic Planning Area includes a migratory period when nearshore seabirds move through the area and an overwinter period during which birds remain in the region. Due to the latitudinal extent of the region, the community of nearshore species present during either time period can vary substantially from the northern to the southern end of the region. For example, black skimmers may be relatively common along beaches in the southern end of the study area during winter compared to more northern beaches. Migratory nearshore seabirds may appear in the northern end of the study area as early as August (e.g., black terns [*Chlidonias niger*] are early arrivals in August). Common migratory species in this guild include black terns, common (*Sterna hirundo*) and Forster's terns, and ring-billed and herring gulls. The extent to which a species migrates through a location and overwinters in a location varies across the South Atlantic Planning Area; more northerly areas have more of a migratory role and more southerly areas have more of a wintering role.

In South Carolina, important migratory/wintering sites for seabirds include but are not limited to Santee WMA, Cape Romain NWR, Charleston Harbor area (Crab Bank, Morris Island), Bird Key Stono, Deveaux Bank, St. Helena Sound area, and Tomkins Island, a dredge spoil island created in 2005 and located in Savannah Harbor but managed in part by SC DNR (Bailey and Hatcher, 2005). In Georgia, important migratory/wintering sites for nearshore seabirds include Tybee and Little Tybee, St. Catherine's, Sapelo, St. Simon's, Jekyll, and Cumberland islands. In Florida (specifically the region within the South Atlantic Planning Area), important migratory/wintering sites for seabirds and shorebirds include Huguenot Memorial Park and the Cape Canaveral area. Many, but not all, of these sites also support breeding colonies.

Survey efforts for nearshore seabirds are not coordinated among the states. South Carolina conducts an annual nesting survey for all nearshore seabirds and censuses of all of the breeding nearshore species except laughing gulls. South Carolina has been conducting these surveys since 1969 for brown pelicans and since 1975 for other nearshore seabirds. Wilkinson (1997) and Jodice et al. (2007) reviewed many of these data. South Carolina does not conduct wintering surveys. Georgia conducts censuses at critical colonies in most years but since 1999 has conducted annual Midwinter Waterbird Surveys. Florida has breeding data for each species except pelicans available on the internet since 2005, called the Florida Shorebird Database. Nesting effort for brown pelicans has been collected since the late 1960s but the most recent summary covers the 2001–2007 period (although a status assessment is in preparation and due in 2011) and is available in report form (Brush, 2007). The Audubon Christmas Bird Counts also

offer some level of information on wintering bird occurrence and historical data can be gleaned from those records.

8.4.1.1.1 LC Brown Pelican (*Pelecanus occidentalis*)

State of Knowledge - Breeding: 4; Foraging: 3; Distribution: 3; Status: 4; Population: 6,000-7,000 pairs

Brown pelicans are the only truly marine pelican in the Pelecanidae. Despite their year-round occurrence and abundance throughout the South Atlantic Planning Area, research in the region has been limited predominantly to early studies of contaminant effects and more recently a suite of studies on reproductive ecology in South Carolina. Pelicans nest primarily on small estuarine and offshore islands and forage in estuarine and nearshore zones on forage fish, such as Atlantic menhaden and mullet. Current conservation concerns include human disturbance at nesting colonies, loss and disturbance to colony sites, exposure to contaminants, and entanglement in fishing gear.

Six subspecies of brown pelican are recognized; the eastern brown pelican (*P. o. carolinensis*) resides in the South Atlantic Planning Area. Within the US, the Eastern brown pelican breeds from Maryland (first successful record in 1987; Wilkinson et al., 1994) south around Florida to the southern tip of Texas. This subspecies also breeds outside of the US along the Gulf of Mexico to Venezuela. The wintering range for this subspecies includes the entire South Atlantic as well as areas along the mid-Atlantic coast. The extent to which this subspecies winters in the Bahamas or Cuba is unclear, although band recoveries have been returned for those regions (Stefan, 2008).

Pelicans nest on islands that range widely in size and are located in estuaries, river mouths, and bays. Colony sites are typically free of consistent pressure from mammalian predation. Pelicans are primarily ground-nesters in South Carolina and Georgia but shrub-nesters in Florida. Pelican nests may occur with laughing gulls, wading birds, or independent of other species. Habitat analyses of nest sites or colony sites have not been conducted in the study area or throughout the range.

Brown pelicans can be found year-round along the entire north-south gradient of the study area, primarily in the nearshore and estuarine zones. No single source currently exists that lists all current or historic breeding locations in the study area. Breeding extends from colonies in Cape Romain NWR in central South Carolina to the southern edge of Brevard County, Florida (Figure 8.2; Table 8.5). In South Carolina pelicans nest on islands in Cape Romain NWR, in Charleston Harbor, and at the mouth of the Stono River on Bird Key (not currently but every year from 1980–1994), and the mouth of the North Edisto River on Deveaux Bank. Tomkins Island, a dredge spoil island created in 2005 and located in Savannah Harbor (Bailey and Hatcher, 2005), also supports pelican nesting. The first record of brown pelicans nesting in Georgia is from 1988 along the north end of St. Catherine's Island, and a second nesting site was located in 1990 in the mouth of the Satilla River (Wilkinson et al., 1994). Nests also occur on Little Egg Island Bar and the Brunswick Harbor Dredge Island. Within the Florida portion of the study area, pelicans nest at 1–2 colonies in Volusia County and 5 colonies in Brevard County. An additional four colonies on the Florida Atlantic coast that support <300 nests occur south of the study area, in Indian

River and Martin counties (Brush, 2007). Wilkinson et al. (1994) report that most sites in Florida were used intermittently between 1970 and 1991. The largest spatial gaps between pelican colonies occur at the north end of the study area (~170 km from the Marsh Island colony in Cape Romain NWR to colonies in southern North Carolina) and also at the south end (~210 km from the Satilla Marsh colony in Georgia to colonies in Volusia County, Florida). In each area this gap is likely due to a combination of human disturbance and a lack of undeveloped islands that provide appropriate nesting habitat.

Table 8.5
Attributes of brown pelican colonies in the South Atlantic Planning Area. Nest counts are provided for the most recent year for which data were readily available.

Colony Name	Ownership	Nest Count (year)	Habitat Type	Comments
South Carolina				
Marsh Island	NWR	854 (2010)	Coastal island	Used annually since ~1960
Crab Bank and Castle Pinckney	State	648 (2010)	Harbor island	First used 1990s after Bird Key Stono eroded
Deveaux Bank	State	3,202 (2010)	Barrier island	Largest colony in the South Atlantic Planning Area
Tomkins Island	USACE	280 (2010)	Dredge island	Created in 2005
Georgia				
Little Egg Island Bar	State	150 (2010)	Vegetated bar	
Brunswick Hbr. Dredge Island	State	37 (2010)	Dredge island	Created in 2008
Satilla Marsh	State	441 (2010)	Marsh island	
Florida				
Port Orange Island	Port Authority	110 (2007)	Dredge island	>500 nests/yr 2001-2006
New Smyrna	County	80 (2006)	Dredge island	0 nests in 2007
Haulover Canal	County	405 (2007)	Dredge island	
Barge Canal	County	65 (2007)	Dredge island	
George-Brady	County	360 (2007)	Dredge island	Not used 2001-2006
Valkeria	County	128 (2007)	Dredge island	
Micco	County	125 (2007)	Dredge island	

During the breeding season (April–September), nonbreeding birds (subadults, nonbreeding adults) also may occur in areas devoid of colonies where there is ample prey or in areas that may support future colonies. For example, in South Carolina pelicans frequently loafed at Bird Key

Stono during the breeding season during the late 2000s. Though this island did not support a pelican colony during these years, it had been the site of a colony in previous years (1980–1994) and appears to provide many essential habitat components, such as prey (pelicans often observed foraging nearby) and potential nesting habitat. Therefore, while colony location will indicate areas of expected concentrations during the breeding season, other coastal areas that do not support colonies may support significant concentrations of nonbreeding birds during the breeding season. Dedicated surveys may be needed to identify these roosting or loafing areas.

Data from Christmas Bird Counts show that pelicans occur throughout much of the coastal South Atlantic Planning Area during winter and that little change occurred in the distribution of those observations between 1992–93 and 2002–03 (Figure 8.3). In Georgia, pelicans occur on most of the barrier islands during winter although counts vary by island among years.

Migratory routes are not well known and have been inferred from casual observations and band return data. Schreiber and Mock (1988) and Stefan (2008) both report that birds banded in South Carolina were recovered or observed during winter most frequently along the east coast of Florida. Stefan (2008) identified dense clusters of band returns from Volusia, Brevard, and Indian River counties, Florida, and found moderately dense clusters of winter recoveries in South Carolina, North Carolina, and Georgia. Pelicans banded along the east coast of Florida also tend to be recovered on the Florida east coast (Schreiber and Mock, 1988). Given that individual condition, survival, and reproductive success in seabirds can all be affected by events or conditions during the wintering period, and that these factors in turn affect population dynamics, the aforementioned banding data suggest that areas outside of the South Atlantic Planning Area likely play a critical role in population dynamics within this area.

Brown pelicans plunge-dive for prey and also can surface-seize prey. Detailed studies of diet or foraging ecology are very limited for the South Atlantic Planning Area or even for adjacent regions, and it is assumed that adult diets are similar to chick diets. Sprunt (1925) reported that Atlantic menhaden were found in 95% of nests (n=unknown) in Cape Romain NWR, South Carolina, and Shields (2002) reports menhaden occurred in 86% (n=267) of boluses collected from a colony along the southern coast of North Carolina. Menhaden occur regularly in nearshore and estuarine waters throughout the South Atlantic Planning Area (see Chapter 7). Mullet, anchovies, and sardines also appear in diets where these items are common in nearshore and estuarine waters (Blus et al., 1979; Fogarty et al., 1981; Collazo, 1985; Shields, 2002).

Despite what appears to be a preference for pelagic schooling prey, such as menhaden, pelicans also display diet plasticity. A recent study in South Carolina demonstrated that pelicans readily consumed discarded bycatch from shrimp trawlers (Wickliffe, 2008). The most common bycatch items were benthic fish (e.g., Atlantic croaker, spot, and star drum) although demersal species, such as broad-striped anchovy and Atlantic threadfin herring, also occurred but in far fewer numbers. Benthic prey would not normally be available to a plunge-diving species like pelicans and hence not typically found in their diet. Nonetheless, pelicans readily consumed benthic species during the study. Many nearshore and pelagic seabirds scavenge for discarded bycatch at commercial fishing vessels, apparently because of the relative efficiency they afford

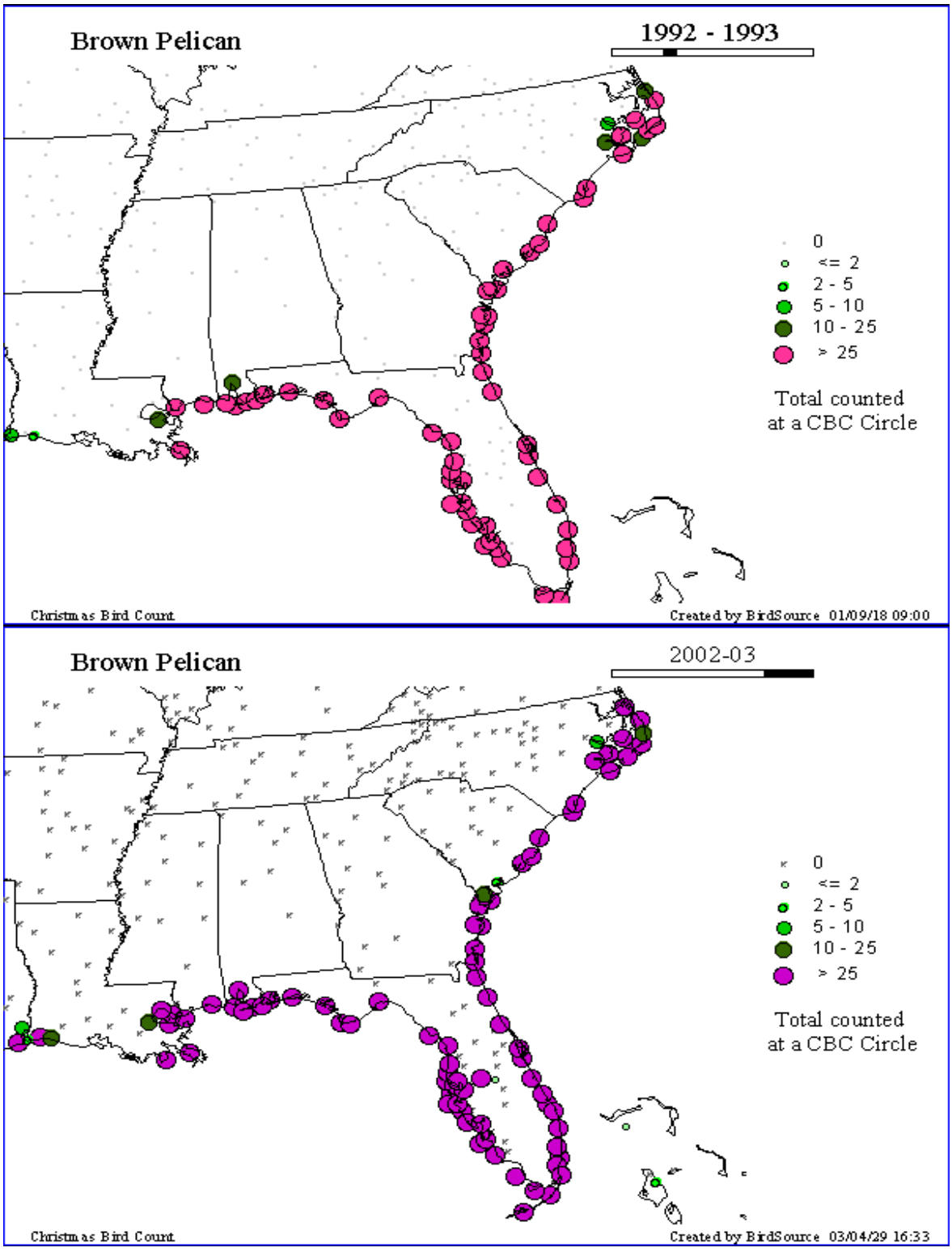


Figure 8.3 National Audubon Society Christmas Bird Count data for brown pelicans in the Southeast US, 1992–1993 and 2002–2003.

in terms of energy gained compared to energy expended searching for and capturing prey. In this manner, commercial vessels can function as supplemental food sources; studies from the North and Mediterannean seas have shown that seabird population size can positively track the amount of discarded bycatch in the fishery. It is unclear if the commercial shrimp fleet has such an effect on the population size of nearshore seabirds, although many colonies in the South Atlantic Planning Area are located nearby ports that support commercial shrimp fleets.

Foraging ranges have not been studied directly either within the study area or range-wide, although current efforts to track adult pelicans with satellite tags in Louisiana and South Carolina may provide some future data. Wickliffe and Jodice (2010) examined the relationship between nearshore seabirds, including brown pelicans, and shrimp trawlers during the breeding season in South Carolina. Pelicans were observed at trawlers during approximately 60% of surveys during two breeding seasons; birds were most commonly in attendance during the discarding phase of trawler operations suggesting attendance was driven by the availability of discarded fish bycatch. Pelicans were observed foraging at trawlers as far as 10 km from shore and as far as 30 km from the nearest colony, and there were few locations visited by trawlers where pelicans were not observed (Figure 8.4). The shrimp season extends into early winter throughout the South Atlantic but the extent to which juvenile or adult pelicans attend shrimp trawlers during this time period is unknown. Given that first year survival is low in long-lived seabirds, particularly those with specialized foraging techniques like pelicans, and that mortality of adults also tends to increase during winter, it is feasible that the shrimp fleet could be an important food source during this period.

Shields (2002) provides a review of the annual cycle; no apparent deviations occur within the South Atlantic Planning Area. Egg-laying begins in early to mid-April and within a colony initiation of laying may be staggered over the course of weeks. Peak chick hatching occurs May–July. Chicks are altricial and remain in the nestling stage for 10–12 weeks. Rates of chick growth within the study area are reported only for birds from two colonies in South Carolina and predominantly during the period of 1–50 day post-hatching when ground-nesting chicks can be accessed most readily and with the least level of colony disturbance (Eggert and Jodice, 2008; Eggert et al., 2010). Linear rates of growth for body mass ranged from approximately 55 g/day in gamma chicks to 90 g/day in alpha chicks. Linear rates of growth for culmen length ranged from approximately 2.9 mm/day in gamma chicks to 4.0 mm/day in alpha chicks. Each of these measures appears to be similar to measures obtained for the species in Florida (Schreiber, 1976) and Mexico (Pinson and Drummond, 1993). There have been no studies to determine what environmental factors most strongly affect growth rates in pelican chicks in the South Atlantic Planning Area or throughout their range. Such data would be valuable as a means to assess potential limiting factors to reproductive success.

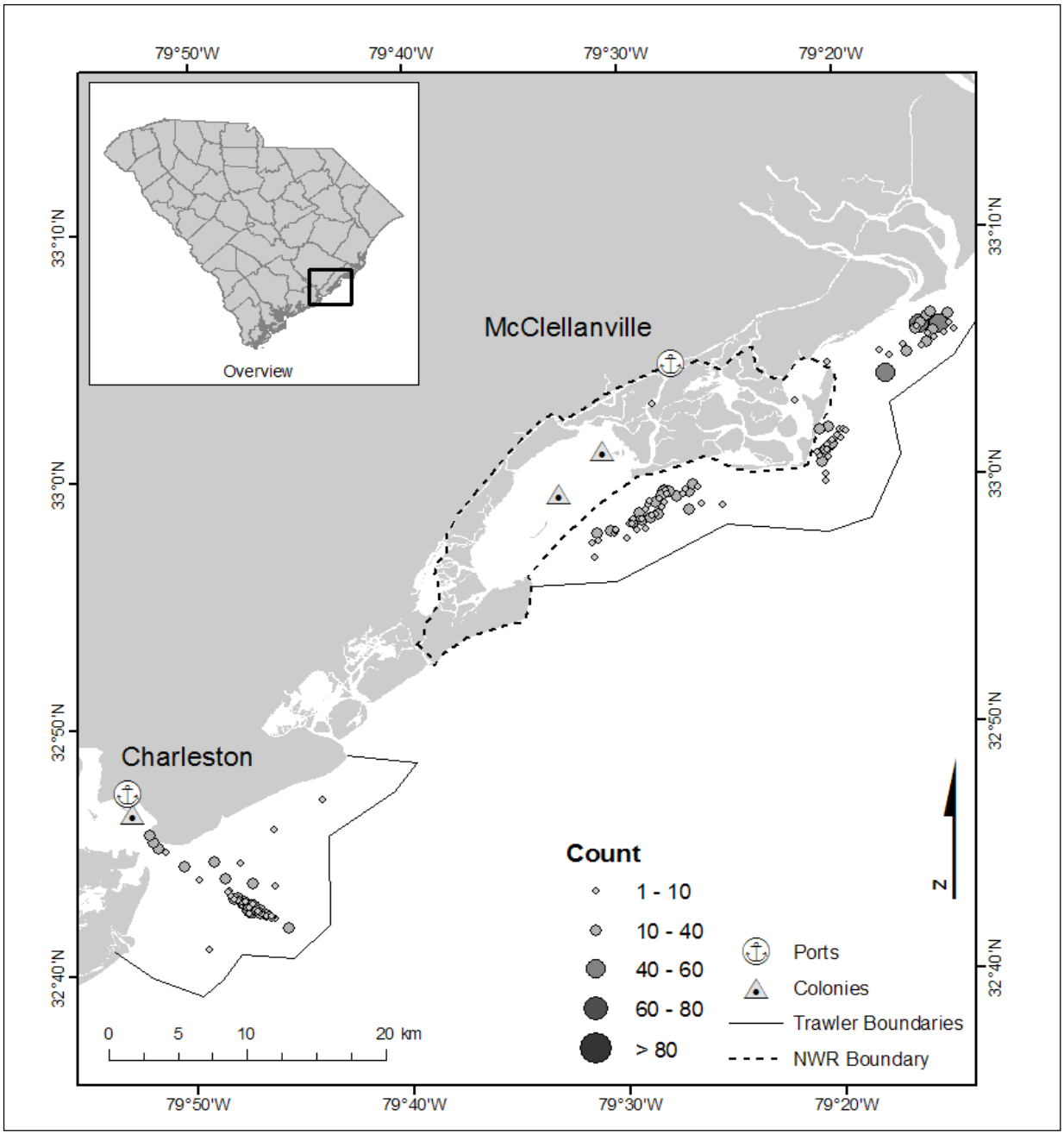


Figure 8.4 Distribution and abundance of brown pelicans observed during surveys conducted from active shrimp trawlers along the central coast of South Carolina in 2006 and 2007. Circles represent single counts; size increases in proportion to the number of birds counted (refer to legend at bottom right). All trawler cruises from which data were collected occurred within the indicated trawler boundary. Surveys were not conducted in areas without trawls. From Wickliffe and Jodice (2010).

Data on attendance and chick-feeding rates are also rare for pelicans. Sachs and Jodice (2009) examined these data at a colony in South Carolina and found that the relationship between parental attendance and chick age was nonlinear, with a peak occurring approximately 20 days post-hatch. Feeding rates ranged from nearly 3 feeds/3 hour observation period to <1, and there

was a linear decline with chick age. Feeds were exclusively indirect (i.e., chicks feed from prey regurgitated on to nest substrate) when chicks were <11 days and exclusively direct (i.e., chicks feed directly from parents) when chicks were >20 days. Nest-based behavioral data are relatively easy to measure in pelicans and, as in many seabirds, these data are sensitive to both natural and anthropogenic system perturbations. As such, an assessment of these behavioral data can provide a means by which to determine if colony dynamics may change in response to an event of interest (e.g., human disturbance, oil spill, climate change).

Annual data on reproductive success is poorly known for the study area. In South Carolina, annual productivity ranged from 0.7–1.7 chicks per nest structure during a phase of population growth from 1969–1984 (Mendenhall and Prouty, 1978; Blus, 1982; Wilkinson, 1982). Productivity estimates averaged 1.0 chick per nest structure from Marsh Island, South Carolina in 2004 and 2005 (Jodice et al., 2007), 1.4 chicks per nest structure from Crab Bank, South Carolina in 2006–2008, and 1.6 chicks per nest structure from Deveaux Bank, South Carolina in 2006–2008 (Jodice and Eggert, 2010). All of these values appear to be similar to those reported from other portions of the breeding range (Shields, 2002; Holm et al., 2003). Reproductive success is a basic measure of colony health and population dynamics and, in most seabirds, responds relatively strongly to factors such as prey availability, disturbance (human or predator), or environmental stress. As such these data would be valuable as a means to assess potential limiting factors to population growth in the South Atlantic Planning Area.

Ticks are known to infest pelican colonies throughout their range (Duffy, 1983; Norcross and Bolen, 2002) including the South Atlantic Planning Area. The soft tick (*Ornithodoros capensis*) was first identified in pelican colonies in South Carolina at Bird Key Stono and Marsh Island in 1987 (Keirans et al., 1992) and now occurs at all pelican colonies in South Carolina (Eggert and Jodice, unpubl. data). Ticks may contribute to localized abandonment of pelican nests and to chick mortality (Keirans et al., 1992; Ferguson, 2006). Under low to moderate tick infestation levels, however, tick presence does not appear to have a significant negative effect on growth rates or physiological condition of pelican chicks (Eggert and Jodice, 2008; Eggert et al., 2010). Predation of chicks and eggs from avian predators, such as laughing gulls, does occur, although pelican colonies in more northern states appear to experience higher predation pressure from the larger-bodied and more aggressive herring gull and greater black-backed gull.

In 1970, brown pelicans were listed as endangered in the US (the primary causes were listed as exposure to contaminants such as DDT, DDE, and endrin) and in 1985 delisted throughout the Atlantic Coast, based on apparent recovery of breeding populations in the region (Wilkinson et al., 1994). The species is currently listed within the South Atlantic Planning Area as a species of special concern by the states of South Carolina and Florida (Appendix 8.1). Population estimates by state appear in earlier species reviews (e.g., Wilkinson et al., 1994; Shields, 2002) and for South Carolina in Jodice et al. (2007). The most recent estimates for the study area appear in Table 8.5. Currently each state maintains its own records of nesting effort, and these are currently gathered at varying levels of frequency, intensity, and standardization within and among states. Availability of long-term data varies by state.

Within South Carolina, breeding populations increased from approximately 1,200 nests in the late 1960s (first complete statewide surveys) to a maximum of 6,600 nests in 1982; subsequently

nest counts declined to a low of <2,500 in 2003 and in 2010 the nest count approached 5,000 (Jodice et al., 2007; F. Sanders, pers. comm.). Within Georgia, breeding populations were estimated at approximately 200 pairs in 1988 and 600 pairs in 1991 (Wilkinson et al., 1994). The nesting effort increased to 3,600 pairs by 1999 (Shields, 2002) but in the past few years has declined to <1,000 (GA DNR, unpubl. data). Within Florida, the statewide nesting effort between 2001 and 2007 ranged from 4,700 to 8,100 (Brush, 2007). Along the entire Atlantic coast, pelican-nesting effort was estimated at approximately 1,600 in 1970, approximately 3,000 in 1980 and 1990, and approximately 2,600 in 1999 (Shields, 2002). Within the study area of the Florida coast, the nesting effort for pelicans has ranged between 900 and 1,400 from 2001–2007 (Brush, 2007). There is no systematic review of breeding effort across the study area, and potential causes of population fluctuations are, for the most part, unknown, although a northward expansion in breeding range, reductions in use of pesticides, and the closure of the menhaden fishery in North Carolina all may have affected regional population sizes. It is suspected that some level of inter-colony movement may have contributed to declines observed in South Carolina and increases observed in Georgia during the late 1980s, although the causes underlying these possible movements are unknown (Jodice et al., 2007). In Georgia, recent declines appear to be due, at least in part, to predation at colonies (raccoons, vultures). Florida is currently developing a status assessment for pelicans within the state and that document, due in 2011, will likely enhance the available data on trends in that region.

Current conservation and management efforts for pelicans in the South Atlantic Planning Area focus primarily on limiting disturbance at breeding colonies and loss of nesting habitat. All three states prohibit access to colonies and limit access to islands supporting colonies to varying extents. The extent to which breeding pelicans are disturbed by approaching humans appears to vary considerably among populations and sites. Evidence suggests that breeding adults may habituate to human activity to some extent, although nonbreeding birds appear to flush more readily (Schreiber, 1979; Rodgers and Smith, 1997; Shields, 2002, pers. obs.). It should be noted that breeding pelicans along the Pacific and in the Gulf of California appear to flush much more readily compared to Atlantic birds, although this has not been quantified (Shields, 2002).

Nevertheless, because disturbance can result in egg loss (predation, heat stress) and chick loss (predation, trampling by adult, heat stress), protection of colonies is warranted. In ground-nesting colonies in South Carolina, the intensity of research efforts is reduced as a means to minimize disturbance once chicks begin to crèche and mobilize within colonies. Pelicans (adults, subadults, pre-fledged young) regularly loaf and roost in the intertidal zone away from colonies throughout the breeding season; disturbance here, where human recreation is often focused, can be of equal importance to disturbance at nest sites (Jodice and Eggert, 2010). Currently, loss of nesting habitat primarily occurs as a result of erosion to beaches, although, historically, development of beaches and islands likely was a contributing factor. There is a great potential for sea-level rise to contribute to loss of nesting habitat (Daniels et al., 1993). Predation at colonies also is a concern; recent declines in Georgia appear to have been due at least in part to raccoons establishing on Little Egg Island Bar.

Other current conservation and management concerns include entanglement in fishing gear and contaminants. Entanglement in fishing gear appears to be more common for recreational than commercial fisheries. Bycatch mortality is not commonly reported from commercial fisheries;

during two years of surveys during the breeding season in South Carolina no mortalities or collisions were observed at shrimp trawlers (pers. obs.). Not enough is known about detailed habitat use at sea to completely ascertain conservation concerns there; in other regions within the species range competition with fisheries has had negative effects on pelicans (Anderson et al., 1982).

Pelicans appear to be one of the most sensitive avian species with respect to organochlorines (Blus, 1982). While population declines in the 1960s were attributed primarily to contamination issues, this threat has likely subsided. Van der Pol et al. (in prep.) found a substantial decrease in levels of organochlorine contamination in pelican eggs collected in South Carolina in 2005 compared to historic values. An emerging contaminant that has gained recent attention in the nearshore system is polybrominated diphenyl ethers (PBDEs). These brominated flame retardants appear to biomagnify in higher trophic levels. An analysis of PBDEs in eggs of pelicans collected from South Carolina in 2005 found that 18 of the 28 targeted PBDE congeners were present, that a brominated compound previously not seen in environmental samples and suspected to be BDE205 was detected, and that concentrations were approximately in the middle of the range of concentrations measured for total PBDEs in other seabirds (Stuckey, 2007).

8.4.1.1.2 LC Laughing Gull (*Larus atricilla*)

State of Knowledge - Breeding: 4; Foraging: 3; Distribution: 3; Status: 4; Population: n/a

Laughing gulls are a medium-sized gull that, like many of its congeners, has adapted well to human presence. It is "the" typical gull observed throughout the South Atlantic Planning Area and the only gull in the region that breeds in substantial numbers. Despite their year-round occurrence and abundance throughout the study area and their apparent role as nest predators of other nearshore seabirds and coastal birds, laughing gull research has been limited in the region. Laughing gulls nest primarily on estuarine and offshore islands. Current conservation and management concerns include human disturbance at nesting colonies, loss/degradation of nesting habitat, and their role as nest/chick predators particularly as their populations appear to be increasing in size. Two subspecies of laughing gull are recognized but only one (*L. a. megalopeterusr*) resides in the study area. Within the US, laughing gulls breed from Maine south around Florida to the southern tip of Texas. Laughing gulls also breed along the Gulf coast of Mexico east to the Yucatan Peninsula. *L. a. atricilla* breeds in West Indies, including the Bahamas.

Throughout the study area, laughing gulls frequently nest on islands that support other nearshore seabirds. Nest sites are often located in vegetation (e.g., clumps of dune grasses) on the periphery of other seabird colonies. Colony sites are typically free of consistent pressure from mammalian predators. Habitat analyses of nest sites or colony sites have not been conducted in the study area. An analysis of colony site locations in North Carolina showed that this species used dredged and unmodified estuarine islands in proportion to their availability, i.e., there was neither positive or negative selection for these habitat types (McCrimmon and Parnell, 1983).

Laughing gulls can be found year-round along the entire north-south gradient of the study area in the nearshore and estuarine zones, and also inland. Laughing gulls breed in colonies from Cape Romain NWR to Huguenot Memorial Park in Duval County, Florida. No single source currently

exists that lists all current or historic breeding locations in the study area, but laughing gulls appear to nest in most/all locations that support other nearshore seabirds and for these reasons details about colony locations and sizes are not readily available.

Data from Christmas Bird Counts show that laughing gulls occur throughout the coastal zone during winter (Figure 8.5) and are common on most barrier islands in Georgia. Migratory routes are not well known and inferred from casual observations as well as band return data. Florida birds appear to be residential, and more northern breeders may leap-frog southern breeders, with the former wintering more frequently in Central and South America and the latter more frequently in Florida and the South Atlantic Bight (Burger, 1996).

Laughing gulls dive for prey at the surface, seize prey from the surface of the land or water, and pirate food. They are opportunistic predators with a broad and varied diet that includes fish, mollusks, insects, crustaceans, and anthropogenic foods. Direct studies of diet or foraging ecology do not exist in the South Atlantic Planning Area and are rare elsewhere. In New Jersey, adults nesting on salt marsh islands provided primarily inland foods (anthropogenic items, fruit, insects, freshwater fish; Dosch, 1997) to chicks. An assessment of isotope ratios in chicks of laughing gulls from New York and Virginia determined that the diet was more terrestrial-based at a New York colony and more marine based at a Virginia colony (Knoff et al., 2002). Although Burger (1996) suggests that egg predation is unusual in the species, observations at colonies of skimmers and terns in South Carolina suggest this may not be the case, and that skimmer and tern chicks may be predated as well. Data on the extent to which tern and skimmer eggs and chicks are predated by laughing gulls are a critical need for understanding their potential role as predators of other seabirds. Laughing gulls readily consumed discarded bycatch from shrimp trawlers in South Carolina. Bycatch was primarily benthic fish (e.g., Atlantic croaker, spot, and star drum) not normally attainable by this surface feeding species (Wickliffe, 2008). Laughing gulls also regularly attempted to pirate food from pelicans and terns, though this has not been quantified.

Foraging ranges in the South Atlantic Planning Area have not been studied directly, although laughing gulls in a New Jersey salt marsh colony were reported to forage up to 40 km inland and were active during both nocturnal and diurnal periods (Dosch, 2003). Within the study area, Wickliffe and Jodice (2010) examined the relationship between nearshore seabirds, including laughing gulls, and shrimp trawlers during the breeding season in South Carolina. Laughing gulls were observed at trawlers during approximately 95% of surveys during two breeding seasons. Laughing gulls were most commonly in attendance during the discarding phase of trawler operations and were commonly observed as far as 10 km from shore and 20–30 km from the nearest large colony. There were few locations visited by trawlers where pelicans were not observed (Figure 8.6).

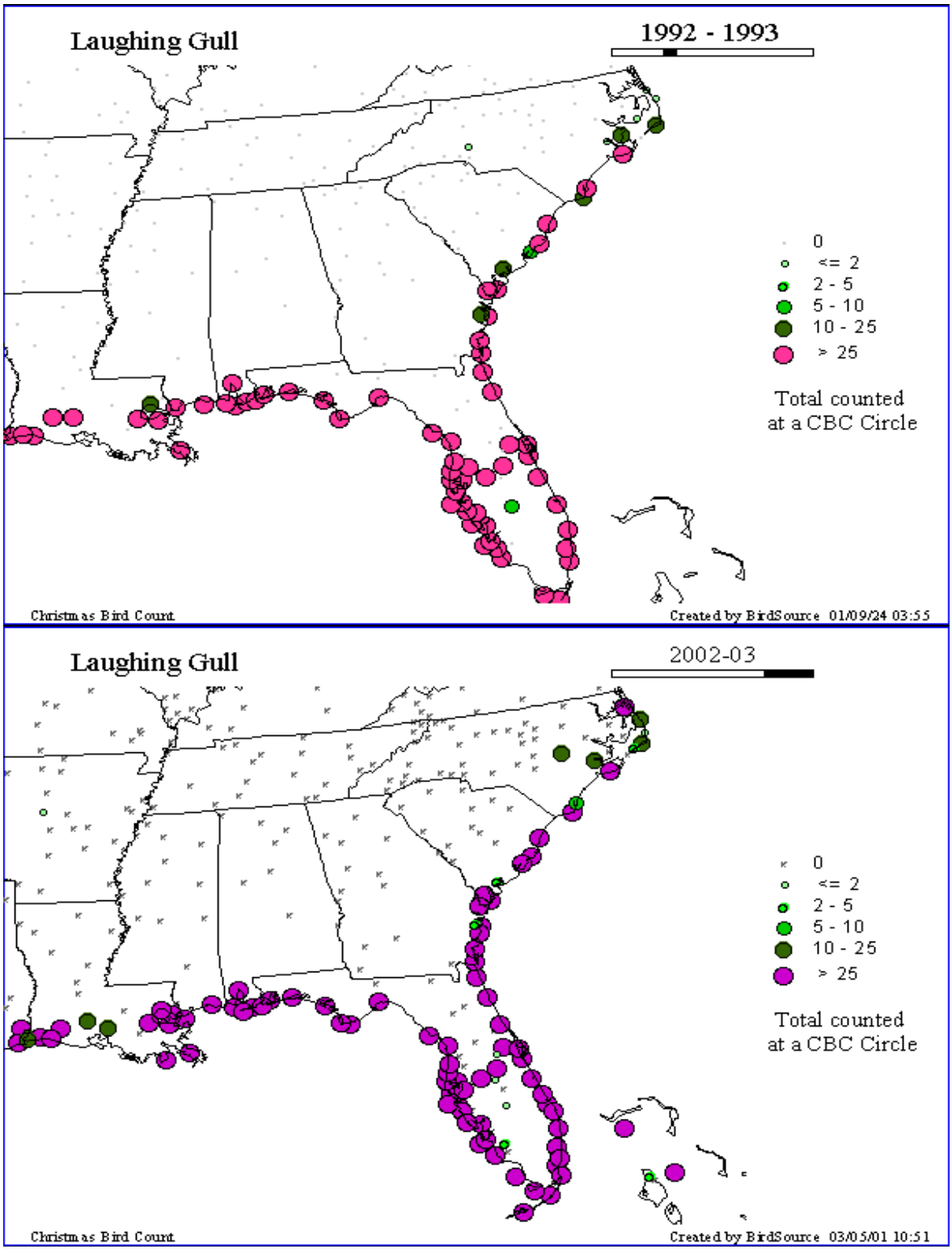


Figure 8.5 National Audubon Society Christmas Bird Count data for laughing gulls in the Southeast US, 1992–1993 and 2002–2003.

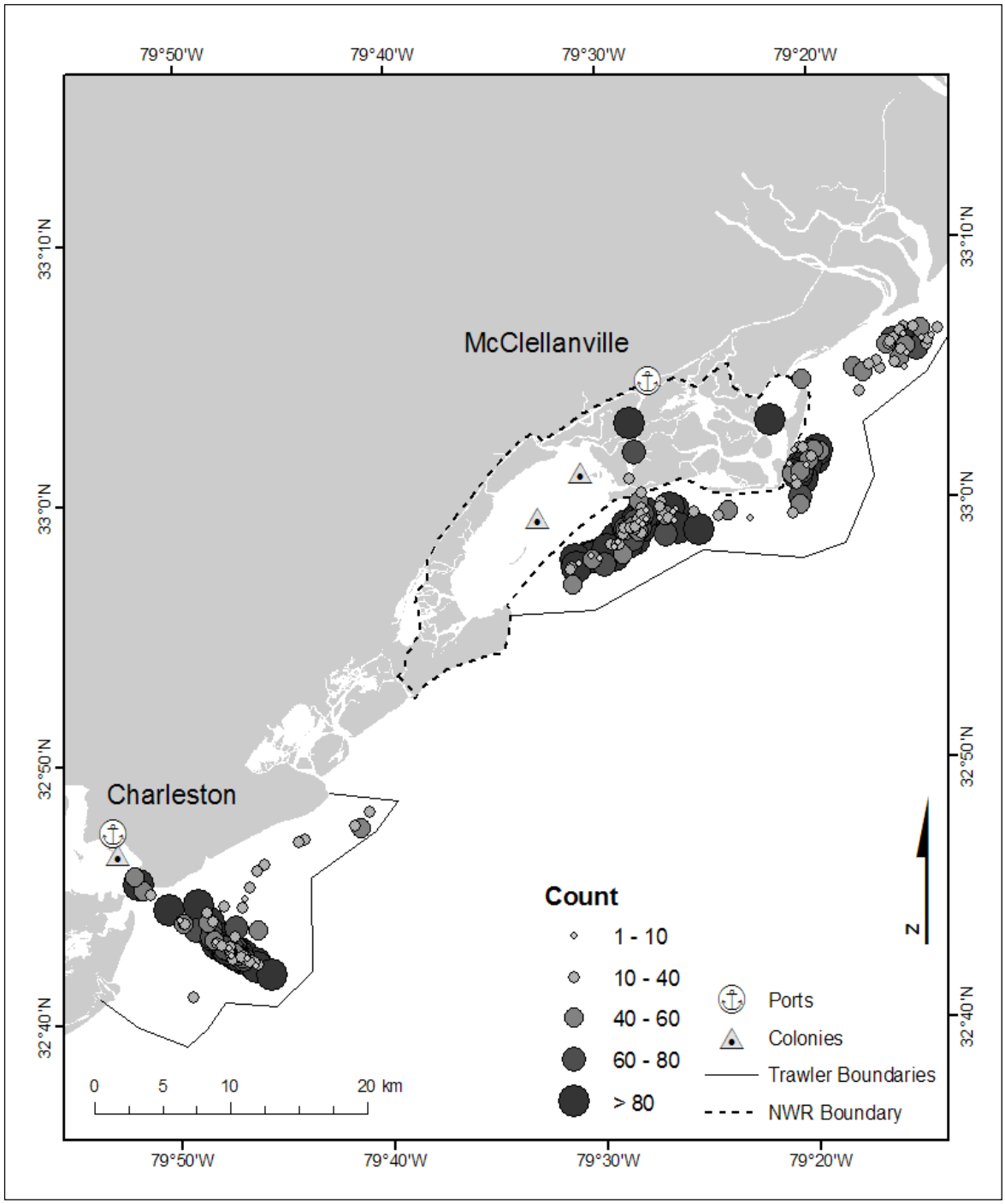


Figure 8.6 Distribution and abundance of laughing gulls observed during surveys conducted from active shrimp trawlers along the central coast of South Carolina in 2006 and 2007. Circles represent single counts; size increases in proportion to the number of birds counted (refer to legend at bottom right). All trawler cruises from which data were collected occurred within the indicated trawler boundary. Surveys were not conducted in areas without trawls. From Wickliffe and Jodice (2010).

Dinsmore and Schreiber (1974) and Burger (1996) provide reviews of the annual cycle for laughing gulls; no apparent deviations occur within the South Atlantic Planning Area. Laughing gulls typically lay up to three eggs; egg-laying appears to peak in mid to late-May, although this has yet to be quantified in the region. Re-laying can occur if a clutch is lost. Peak chick hatching appears to occur in early to mid-June, although this also has not been quantified. Chicks are semiprecocial but appear to remain in the nest until >5 days of age. Adults will behave aggressively towards other chicks. Rates of chick growth have not been reported within the study area and the only available rate found in the breeding range came from a study along the Gulf coast of Florida (Schreiber and Schreiber, 1980). During the linear phase of growth, mass increased approximately 10 g/day and culmen length increased approximately 0.4 mm/d. Rates of chick feeding have not been reported within the South Atlantic Planning Area. Laughing gulls nesting in a New Jersey salt marsh, however, made up to eleven trips to and from the colony per day (Dosch, 2003).

Annual data on reproductive success are poorly known throughout the range. Burger (1996) reports that 55–70% of nests examined in New Jersey fledge at least one young in most years. Schreiber et al. (1979) report similarly high rates of brood success at colonies in the Tampa Bay region of Florida (65–88%).

Predation of eggs and chicks does occur. Within the South Atlantic, likely predators include raccoons, mink, great-horned owls, other laughing gulls, and ghost crabs. Eggs are also susceptible to heat exposure when unattended and, depending upon exact locations with respect to the high tide line and the beach profile, to tidal flooding and storm surges.

Laughing gulls are not currently listed as threatened or endangered within the US. Within the South Atlantic Planning Area, the species does not merit any listing classifications. Currently, each state maintains its own records of nesting effort; within each state, these are gathered irregularly and incompletely due to the difficulty of locating and counting gull nests. Rough estimates for nest counts for each state suggest about 5,000–7,500 in South Carolina (Burger, 1996; Wilkinson, 1997), 750 in Georgia (Brad Winn, GA DNR, 11 March 2008), and >20,000 throughout all of Florida with ~4,000-5,000 at Huguenot Memorial Park in Duval County. However, these data are very rough estimates at best. In general, laughing gulls appear to be increasing in population size and range (Burger, 1996).

Current conservation and management efforts for laughing gulls in the South Atlantic Planning Area take place primarily because of efforts aimed at co-nesting species (e.g., terns, skimmers, pelicans) that focus on limiting human disturbance at breeding colonies. All three states prohibit access to colonies (i.e., actual nesting areas). However, access to islands that support colonies is limited to varying extents. Laughing gulls also may play a critical role as a nest and chick predator of other seabirds and coastal nesting species (e.g., American oystercatcher [*Haematopus palliatus*]). The extent to which this species is responsible for nest or chick failure of other nearshore seabirds and shorebirds is unknown; observations suggest that, at a minimum, laughing gulls are opportunistic predators on these species when they are flushed from nests. This behavior appears to be more common at skimmer and tern nests compared to pelican nests, and overall the effect of laughing gulls on these species may not be as great as the potential

predator effect of larger gulls (e.g., herring gulls, greater black-backed gulls) should their numbers increase in the South Atlantic Planning Area.

8.4.1.1.3 LC Royal Tern (*Thalasseus maximus*) and Sandwich Tern (*Thalasseus sandvicensis*)

State of Knowledge - Breeding: 4; Foraging: 3; Distribution: 3; Status: 4; Population: Royal Tern 16,000–17,000, Sandwich Tern 2,500–3,000 pairs

Royal tern and sandwich tern are treated together because the two species share many ecological similarities. These are the only two "crested" terns that breed regularly throughout the South Atlantic Planning Area. Despite their year-round occurrence and abundance throughout the area, royal and sandwich tern research has been very limited in the region, due in large part to the challenging nature of working in dense tern colonies. Each species nests primarily on estuarine and offshore islands, and often in mixed-species colonies. Each tern forages in estuarine, nearshore, and offshore zones on forage fish, such as anchovy and herring, although the extent to which each species forages in each zone is still in question. Current conservation concerns include human disturbance at nesting colonies and loss/degradation of nesting habitat.

Two subspecies of royal tern and three subspecies of sandwich tern are recognized but only one of each (*T. m. maximus* and *T. s. acuflavida*, respectively) resides in the South Atlantic Planning Area (introgression of two subspecies of sandwich tern does occur within the West Indies). Within the US, royal terns breed from Virginia south around Florida to the southern tip of Texas. Sandwich terns breed from Virginia to South Carolina along the Atlantic, and from central Florida to south Texas along the Gulf Coast (the core of their breeding range). *T. m. maximus* and *T. s. acuflavida* also breed along the Gulf coast of Mexico, in the West Indies, and along portions of the east coast of South America.

Throughout the study area, both terns nest on islands that range widely in size and are located in estuaries, river mouths, and bays. Colony sites are typically free of consistent mammalian predators. Nest sites consist of scrapes on bare sand or sand-shell substrate. In South Carolina, sandwich terns only nest in mixed colonies with royal terns, although royal terns may nest without sandwich terns. Brown pelicans nest on the same colony islands as royal and sandwich terns throughout South Carolina, at one colony in Georgia (Brunswick Dredge Island), and not at all in the South Atlantic Planning Area portion of Florida. Laughing gulls often nest adjacent to tern colonies. Habitat analyses of nest sites or colony sites have not been conducted in the study area.

Royal terns can be found year-round along the entire north-south gradient of the study area, primarily in the nearshore and estuarine zones; sandwich terns are more restricted to the South Carolina coast and the southern end of the study area within Florida (and also common along the southern Atlantic coast of Florida outside of the study area). Breeding for royal terns extends from Cape Romain NWR in central South Carolina to Huguenot Memorial Park in north Florida, while breeding for sandwich terns in South Carolina extends from Cape Romain NWR to Tomkins Island on the Georgia border (Figure 8.2; Table 8.6).

Table 8.6
Attributes of royal and sandwich tern colonies in the South Atlantic Planning Area. Nest counts are provided for the most recent year for which data were readily available.

Colony Name	Ownership	Nest Count Royal/Sandwich (year)	Habitat Type	Comments
South Carolina				
Marsh Island	NWR	1205/384 (2010)	Coastal island	Royals peaked at 10,000 in early 1980s
Crab Bank and Castle Pinckney	State	1032/0 (2010)	Harbor island	Royals every year, Sandwichs intermittent <35/yr
Deveaux Bank	State	905/425 (2010)	Barrier island	Royal peaked at 11,000 in 1991
Tomkins Island	USACE	7057/1934 (2010)	Dredge island	Created in 2005
Georgia				
Brunswick Hbr. Dredge Isl.	State	6650/0 (2010)	Dredge island	Royal only; created in 2008
Florida				
Huguenot Memorial Park	Dept. of Defense	110 (2007)	Coastal beach	Sandwich 1 year, <5 nests

No single source currently exists that lists all current or historic breeding locations in the study area (but see status and trends below). South Carolina supports the greatest number of sites that have supported colonies of royal and sandwich terns. Nests regularly occur or have occurred on islands in Cape Romain NWR, in Charleston Harbor (since mid-1990s; Jodice et al., 2007), and at the mouth of the Stono River on Bird Key and the North Edisto River on Deveaux Bank (since at least the mid-1960s; Beckett, 1966). Both terns also nest at Tomkins Island, a dredge spoil island created in 2005 and located in Savannah Harbor (Bailey and Hatcher, 2005). In Georgia, royal terns nest on the Brunswick Harbor Dredge Island. Within the Florida portion of the study area, royal terns nest only at Huguenot Memorial Park (the majority of tern nests in Florida occur on the Gulf coast). During the breeding season (April-September), nonbreeding birds (subadults, nonbreeding adults) also may occur in areas devoid of colonies where there is ample prey or in areas that may support future colonies. Therefore, while colony location will indicate areas of expected concentrations during the breeding season, other coastal areas that do not support colonies may support significant concentrations of nonbreeding birds during the breeding season. Planning efforts must therefore consider the potential importance of colony-free zones, most likely through dedicated survey efforts. The largest spatial gap between royal and sandwich tern colonies is at the north end of the study area (~170 km from the Marsh Island colony in Cape Romain NWR to colonies in southern North Carolina) and between Deveaux Bank and Savannah Harbor (85 km). In each area, this gap is likely because of a lack of undeveloped islands that provide appropriate nesting habitat as well as human disturbance.

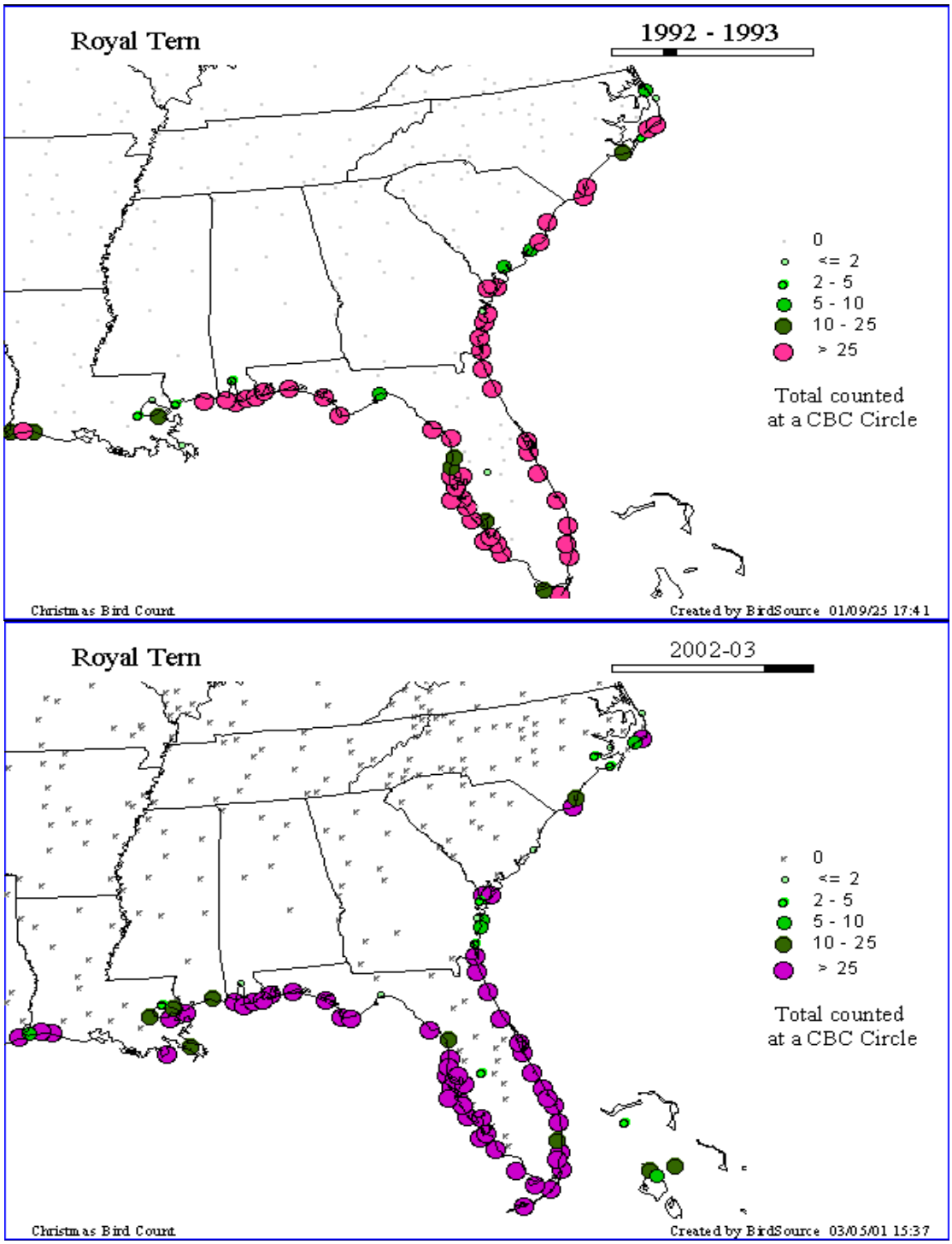
Data from Christmas Bird Counts show that royal terns occur throughout much of the coastal zone during winter (Figure 8.7). Royal terns also are observed on most of the Georgia barrier

islands during midwinter surveys. In contrast, sandwich terns are not observed during the Georgia midwinter counts and are lacking from most of the northern South Atlantic Planning Area during Christmas Bird Counts (Figure 8.8).

Migratory routes are not well known and are inferred from casual observations and band return data. Stefan (2008) reports that royal terns banded in South Carolina (sandwich tern returns not analyzed) are reported during winter throughout the coastal South Atlantic Planning Area with high density clustering at the southern edge of the region. Band returns also occur along the south Florida Atlantic and Gulf coasts (with high density clusters in Dade and Pinellas counties), South and North Carolina coasts, in the West Indies, along the northern coast of South America, and in Central America. Given that individual condition, survival, and reproductive success in seabirds can all be affected by events or conditions during the wintering period, and that these factors, in turn, affect population dynamics, the aforementioned banding data suggest that areas outside of the South Atlantic Planning Area and outside of the US likely play a critical role in population dynamics within the region.

Both terns dive for prey at the surface and also can surface seize prey. Direct studies of diet or foraging ecology in the South Atlantic Planning Area do not exist, although Blus et al. (1979) reported shrimp, insects, and fish in adult diets of sandwich terns in South Carolina. Chick diet has not been measured in the study for either species; however, data are available from other regions. In southern North Carolina, anchovies, herring, and drum comprised 36–57% of items observed being carried by adult royal terns to colonies during two breeding seasons. At Fisherman Island NWR, Virginia, anchovies and herring comprised 80–85% of items observed being carried by adult royal terns to colonies during two breeding seasons. Shealer (1999) reported mainly sardines and dwarf herring in chick diets of sandwich terns in Puerto Rico. Anchoa spp., clupeidae, and sciaenidae are all common fish of estuarine and nearshore waters of the South Atlantic Planning Area (see Chapter 7: Fish and Essential Fish Habitat).

A recent study in South Carolina demonstrated that royal and sandwich terns readily consumed discarded bycatch from shrimp trawlers (Wickliffe, 2008). Terns readily consumed discarded bycatch that was primarily benthic fish (e.g., Atlantic croaker, spot, and star drum) not normally attainable by either species, although demersal species, such as broad-striped anchovy and Atlantic threadfin herring, also occurred but in far fewer numbers. Benthic prey would not normally be available to a surface-feeder like terns and hence not typically found in their diet. Nonetheless, terns readily consumed benthic species during the study. Many nearshore and pelagic seabirds scavenge for discarded bycatch at commercial fishing vessels apparently because of the relative efficiency they afford in terms of energy gained compared to energy expended searching for and capturing prey. In this manner, commercial vessels can function as supplemental food sources, and studies in Europe have shown that seabird population size can positively track the amount of discarded bycatch in the fishery. It is unclear if the commercial shrimp fleet has such an effect on the population size of nearshore seabirds, although many colonies in the South Atlantic Planning Area are located near ports that support commercial shrimp fleets.



Figures 8.7 National Audubon Society Christmas Bird Count data for royal terns in the Southeast US, 1992–1993 and 2002–2003.

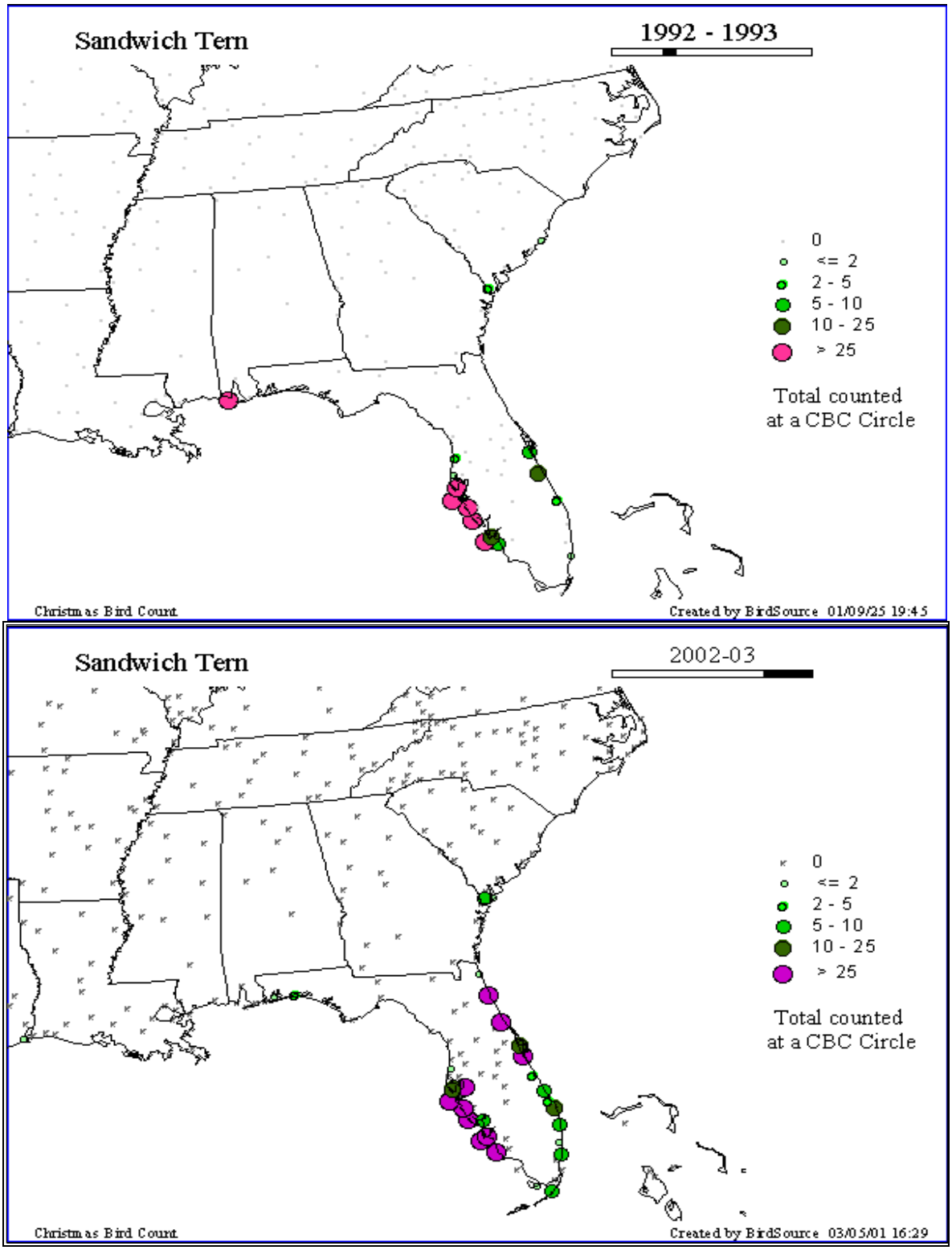


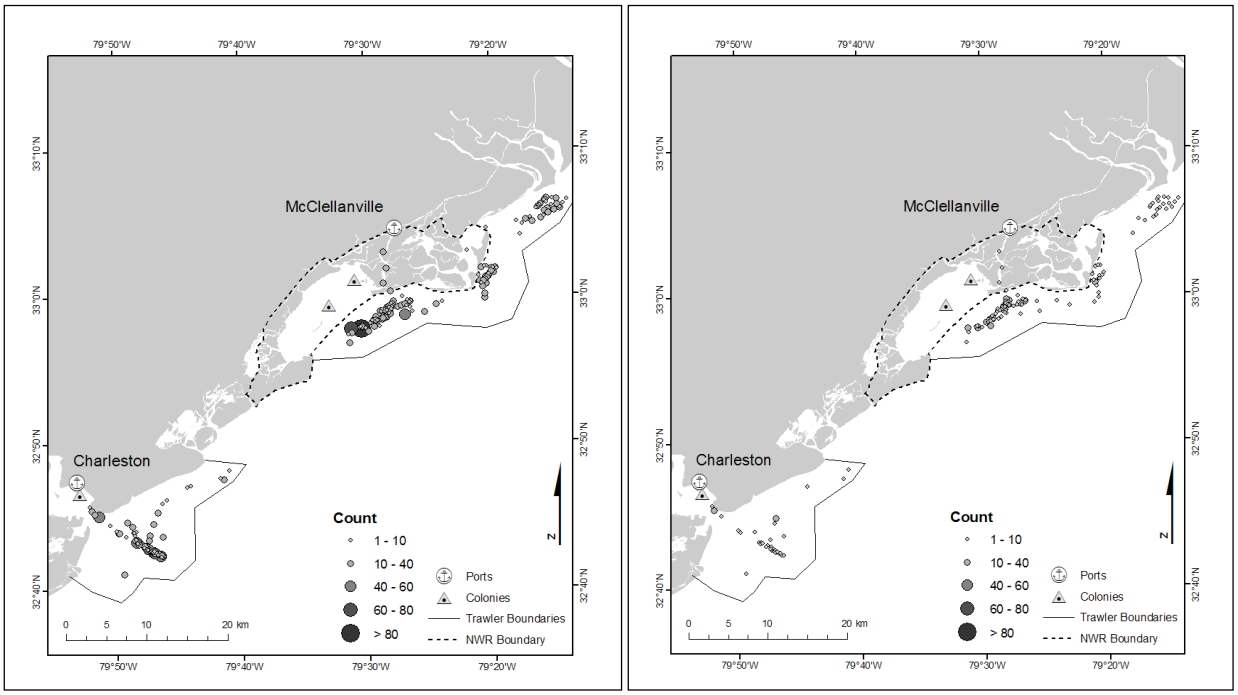
Figure 8.8 National Audubon Society Christmas Bird Count data for sandwich terns in the Southeast US, 1992–1993 and 2002–2003.

Foraging ranges have not been studied directly in the study area, but foraging range and habitat were studied in southern North Carolina. There, McGinnis and Emslie (2001) found that both royal and sandwich terns primarily fed close to shore with royal terns frequenting estuaries and sandwich terns frequenting marine coastal waters. In areas where *Sargassum* patches are found near the Gulf Stream edge and also closer to shore (e.g., Cape Hatteras region), royal terns have been observed carrying fish towards colonies as far as 50 km from shore (Lee, 1995). Given the distance to the edge of the Gulf Stream throughout much of the South Atlantic Planning Area, such behavior seems less likely.

Wickliffe and Jodice (2010) examined the relationship between nearshore seabirds, including royal and sandwich terns, and shrimp trawlers during the breeding season in South Carolina. Royal terns were observed at trawlers during approximately 90% of surveys and sandwich terns during approximately 65% of surveys during two breeding seasons. Terns were most commonly in attendance during the discarding phase of trawler operations. Royal terns appeared to forage at trawlers at a greater distance from colonies than did sandwich terns but each species was commonly observed as far as 10 km from shore and 20–30 km from the nearest colony (Figure 8.9). The shrimp season extends into early winter throughout the South Atlantic Planning Area; however, the extent to which juvenile or adult terns attend shrimp trawlers during this time period is unknown. Given that first year survival is low in long-lived seabirds and that mortality of adults also tends to increase during winter, it is feasible that the shrimp fleet could be an important food source during this period.

Buckley and Buckley (2002) and Shealer (1999) provide reviews of the annual cycle for royal and sandwich terns, respectively, and no apparent deviations occur within the South Atlantic Planning Area. Both species typically lay a single egg and egg-laying peaks late May-mid June for both species. Relaying can occur if the clutch is lost. Egg-laying is fairly synchronous within subsections of colonies for both species. Peak chick hatching occurs mid to late June. Chicks are semiprecocial and can leave the nest scrape and move into crèches shortly after hatching (as soon as 1–3 days). In locations where species nest within the same colony, crèches also include chicks of both species. Habitat use of creches includes intertidal zones of beaches and areas above the high tide line. Rates of chick growth have not been reported within the study area or within the North American range for either species. Such data would be valuable as a means to assess potential limiting factors to reproductive success.

Rates of chick feeding have not been reported for either species within the South Atlantic Planning Area. For royal terns, Erwin (1977) reported that food was delivered to chicks at a Virginia colony on average every 147 minutes. Because chicks from both species form large creches it is difficult to measure parent/chick interactions and therefore the expectation that such data could be used to assess ecological relationships between these terns and the local environment is low. Similarly, annual data on reproductive success is poorly known throughout the range for each species and is one of the major knowledge gaps (Shealer, 1999). For sandwich terns, Blus et al. (1979) estimated reproductive success in 1974 and 1975 in South Carolina colonies at 0–0.5 chicks/pair. Reproductive success is difficult to obtain for royal and sandwich terns because of their creching behavior, and likely the best mechanism to do so is through the development of nest:chick ratios.



(a) Royal Terns (b) Sandwich Terns

Figure 8.9 Distribution and abundance of (a) royal terns and (b) sandwich terns observed during surveys conducted from active shrimp trawlers along the central coast of South Carolina in 2006 and 2007. Circles represent single counts; size increases in proportion to the number of birds counted (refer to legend at bottom right). All trawler cruises from which data were collected occurred within the indicated trawler boundary. Surveys were not conducted in areas without trawls. From Wickliffe and Jodice (2010).

Predation of eggs from avian predators such as laughing gulls does occur, although tern colonies in more northern states appear to experience higher predation pressure from the larger-bodied and more aggressive herring gull and greater black-backed gull. Nevertheless, laughing gulls often predate and attempt to predate eggs in colonies, particularly when adults are disturbed and flush from colony en masse. Eggs are also susceptible to heat exposure when unattended and, depending upon exact locations with respect to the high tide line and the beach profile, to tidal flooding and storm surges.

Neither species is currently listed as threatened or endangered within the U.S or within any of the states in the South Atlantic Planning Area (Appendix 8.1). Currently each state maintains its own records of nesting effort; these are currently gathered annually in each state but at varying levels of standardization within and among states. Availability of long-term data varies by state.

Recent nesting effort for each species is presented in Table 8.6. Jodice et al. (2007) reviewed annual nest counts for both species between 1975 and 2005 in South Carolina. Nest counts of royal terns declined from the late 1970s, when approximately 10,000–20,000 nests occurred each year, to the mid-2000s when approximately 5,000 nests occurred each year. Since 2005, nest counts for royal terns in South Carolina have varied between 3,000 and 4000. Within Georgia, breeding populations for royal terns were estimated at 5,000–9,000 pairs in recent years and most birds nest at Tomkin's Island (B. Winn, pers. comm.). Since its creation in 2005, the nest count

for royal terns there has increased from approximately 1,700 during that first year to 7,000–10,000 in 2009 and 2010 (F. Sanders, pers. comm.). Within Florida, the state-wide nesting effort for royal terns was recently estimated at approximately 5,000 at nine colonies. Within the South Atlantic Planning Area, however, nesting is restricted to Huguenot Memorial Park in Duval County which supported approximately 500 nests per year during the past five years.

Within South Carolina, nest counts of sandwich terns follow a different trend compared to royal terns. Sandwich tern nests increased from <1,000 nests before 1988 to 2,000–2,500 nests from 1988–2005 (Jodice et al., 2007). In recent years the counts have decreased to <1000 nests in the state. However, like royal terns, sandwich tern nests are now abundant on Tomkin's Island. Since its creation in 2005, the nest count for sandwich terns there has increased from approximately 75 during that first year to 2,000–2,700 in recent years (F. Sanders, pers. comm.). Sandwich terns have not been recorded nesting elsewhere in Georgia and in Florida have been recorded rarely in the South Atlantic Planning Area (Huguenot Memorial Park, Duval County). About 600 nests do occur in five colonies along the Florida Gulf coast.

There is no systematic review of breeding effort across the study area, and potential causes of population fluctuations are for the most part unknown. It is suspected that inter-colony movement may be substantial and may contribute to fluctuations observed within regions (Jodice et al., 2007). Emslie et al. (2009) reported that statewide nest counts of royal and sandwich terns ranged from 9,700–7,000 and 1,200–2,900, respectively, in North Carolina between 1977 and 2003. Royal terns appeared to decrease and then rebound during the study period, but sandwich terns appeared to remain relatively stable.

Current conservation and management efforts for royal and sandwich terns in the South Atlantic Planning Area focus primarily on limiting human disturbance at breeding colonies and loss of nesting habitat because of erosion, habitat conversion, and succession of vegetation. All three states prohibit access to colonies and limit access, to varying extents, to islands supporting colonies. Breeding terns appear to flush much more readily in comparison to brown pelicans, for example, and during incubation this can result in nest loss due to egg predation or egg exposure. During chick-rearing both adults and chick crèches frequently use the intertidal zone for loafing and feeding (i.e., adults provisioning chicks) and disturbance here, where human recreation is often focused, can be of equal importance to disturbance at nest sites (Jodice and Eggert, 2010). Currently, loss of nesting habitat occurs primarily as a result of erosion to beaches although historically development of beaches and islands likely was a contributing factor. There is a great potential for sea-level rise to contribute to loss of nesting habitat (Daniels et al., 1993).

Other current conservation and management concerns include entanglement in fishing gear and contaminants. Entanglement in fishing gear appears to be more common for recreational than commercial fisheries. Bycatch mortality is not commonly reported from commercial fisheries and during two years of surveys during the breeding season in South Carolina no mortalities or collisions were observed at shrimp trawlers. Contaminants were examined in South Carolina colonies during late 1960s but, unlike in brown pelicans, little evidence was found for either high levels of contaminants or negative effects on reproductive success (Blus et al., 1979). Not enough is known about detailed habitat use at sea to completely ascertain conservation concerns there.

8.4.1.1.4 LC Gull-billed Tern (*Gelochelidon nilotica*)

State of Knowledge - Breeding: 3; Foraging: 3; Distribution: 3; Status: 3; Population: 500–750 pairs

A comprehensive status assessment of the gull-billed tern was recently completed by the US Fish and Wildlife Service (USFWS) (Molina et al., 2010) and, therefore, precludes the need for a detailed treatment of the species here. Instead, a brief summary of their findings including details on population status by state is provided.

The gull-billed tern is widely distributed but rarely abundant throughout its range. It breeds from southern New Jersey south to Florida and around the Gulf coast to south Texas. These terns nest primarily on estuarine and offshore islands and often nest with or near other species, particularly black skimmers. Compared to most terns, gull-billed terns are opportunistic foragers with a very broad diet. They forage over inshore and estuarine waters and over land (e.g., beaches and salt marshes). Primary diet items include insects, fiddler crabs, and small fish. Their use of insects as a food source may make gull-billed terns a relatively good indicator for hydrocarbon contamination because the calcified shell of their prey tends to store hydrocarbons. Gull-billed terns were not observed attending shrimp trawlers during two years of observations in nearshore waters of the South Carolina coast (Wickliffe and Jodice, 2010).

Research has been limited on this species throughout its range and its status is currently under review in the US. Gull-billed terns are not abundant in any portion of their North American range. Historical estimates are lacking, as are current coordinated surveys during the breeding season. Population trends are therefore difficult to ascertain; however, Molina et al. (2010) suggest that the numbers are declining in Florida, possibly in Georgia, and throughout the mid-Atlantic region. They attribute declines primarily to loss of and disturbance to nesting habitat.

Gull-billed terns nest from Cape Romain in the northern end of the South Atlantic Planning Area to Little Talbot Island State Park in north Florida (Figure 8.2, Table 8.7). In South Carolina, gull-billed terns have nested at approximately 18 locations between 1975 and 2010 (although 6–8 sites have supported most of the nesting effort); during this time annual nest counts have ranged from approximately 50–450. The number of nests in the state can vary substantially among years. Since the early 1990s, nest counts have fluctuated between 90 and 250.

In Georgia, gull-billed terns nest at 2–3 sites only and annual nest counts total <100. In northern Florida, gull-billed terns nest or have nested at 6 sites. Since 1985 annual nest counts in the South Atlantic Planning Area have totaled <25 nests/year, although before 1980, 100–400 nests/year were counted in this region. The largest spatial gap between colonies is at the north end of the study area (~170 km from the Marsh Island colony in Cape Romain NWR to colonies in southern North Carolina) and between Deveaux Bank and Savannah Harbor (85 km). Gull-billed terns are not recorded during Christmas Bird Counts in the South Atlantic Planning Area nor are they counted during Georgia midwinter waterbird surveys.

Table 8.7
Attributes of gull-billed tern colonies in the South Atlantic Planning Area. Nest counts are provided for the most recent year for which data were readily available.

Colony Name	Ownership	Nest Count (year)	Habitat Type
South Carolina			
Raccoon Key	NWR	15 (2008)	Coastal island
White Banks Islands	State	43 (2009)	Coastal islands
Marsh Island	NWR	42 (2010)	Coastal island
Crab Bank/Castle Pinckney	State	44 (2010)	Harbor islands
Skimmer Flats		8 (2010)	
Deveaux Bank	State	55 (2010)	Barrier island
Tomkins Island	USACE	42 (2008)	Dredge island
Savannah Spoil Site	USACE	232 (2010)	Dredge island
Georgia			
Little St. Simons	Pvt.	12 ch (2010)	Barrier island
Andrews Island	State/Fed	30 (2010)	Dredge island
Brunswick Harbor Dredge Island	State	15 (2010)	Dredge island
Florida			
Bird/Big Bird Island	State	24 (2010)	
Little Talbot Island SP	State	4 (2010)	

Current conservation concerns include human disturbance at nesting colonies and loss or degradation of nesting habitat. Gull-billed terns are not currently listed as threatened or endangered within the US. Within the South Atlantic Planning Area, the species is listed as threatened in Georgia (Appendix 8.1). Currently, each state maintains its own records of nesting effort; these are currently gathered annually in each state but at varying levels of standardization within and among states. Availability of long-term data varies by state.

8.4.1.1.5 LC Least Tern (*Sternula antillarum*)

State of Knowledge-- Breeding: 4; Foraging: 3; Distribution: 3; Status: 4; Population: 1,800–2,200 pairs ground nesting

The least tern is the smallest member of the Laridae family. A significant amount of research has been conducted throughout most of its breeding distribution within the US. Three subspecies of the least tern occur in the US. The California (*S. a. browni*) and interior least tern (*S. a. athalassos*) subspecies are federally listed as Endangered. The eastern least tern (*S. a. antillarum*) is the only one of the three found in the study area. Its breeding range extends along the Atlantic and Gulf coast regions, from southern Maine to Texas. The eastern subspecies is state listed as species of special concern in North Carolina, as threatened in South Carolina and

Florida, and as rare in Georgia (Appendix 8.1). Current conservation concerns along the South Atlantic Planning Area are associated with recreational, commercial, and residential development of nesting habitat (i.e., beaches).

Least terns nest primarily on estuarine and offshore sandy or shell mound islands but also on rooftops. Ground colonies within the South Atlantic Planning Area extend from Cape Romain NWR in South Carolina to the Cape Canaveral area, Florida (Figure 8.2, Table 8.8), while rooftop colonies extend from the northernmost coastal county in South Carolina to Brevard County in Florida. Historically, the least tern nested in natural habitats within all six coastal counties within South Carolina (Savereno and Murphy, 1995), although active colonies are now only found in three of six counties (Charleston, Colleton, and Jasper). Natural colony sites usually consist of open beaches or islands with sparse vegetation. Colony sites may be monospecific or include other breeding nearshore seabirds such as the black skimmer, gull-billed tern, common tern and laughing gull. Typically, at multispecies sites, the least tern is the first species to arrive and establish an active colony. Nest sites consist of scrapes in sand or shells and are generally located in areas where there is 0–20% vegetative cover (Carreker, 1985). Both male and female build multiple scrapes, then the female selects the final nest scrape (Thompson et al., 1997).

Within the study area, the least tern has experienced a documented shift from natural nesting sites to rooftops (Savereno and Murphy, 1995). The proportion of rooftop colonies increased from 14 to 61% from 1989–1995 (Murphy and Dodd, 1995). This shift is believed to be a result of an increase in human development, other forms of human disturbance, and associated low reproductive success on beaches. Little research has been conducted to determine if rooftop colonies are successful. Krogh and Schweitzer (1999) observed rooftop colonies within Chatham and Glynn County, Georgia to be poor to moderately successful compared with natural least tern colony sites. Others have found hatching success to be higher on rooftops compared to natural sites (Gore and Kinnison, 1991; Roche, 1977; Savereno and Murphy, 1995), although little data exist about fledge success of these rooftop colonies. Because the link between rooftop colonies and foraging locations (e.g., estuarine or nearshore waters) has not been examined, it is unclear if this species would be commonly found foraging in the marine zone in areas devoid of ground colonies but supporting rooftop colonies. Least terns also forage at anthropogenic sources (e.g., golf course ponds).

Table 8.8
Attributes of least tern ground colonies in the South Atlantic Planning Area. Colonies are listed only if they have been used in at least two of six years since 2005. Nest counts are provided for the most recent year for which data were readily available.

Colony Name	Ownership	Nest Count (year)	Habitat Type	Comments
South Carolina				
Cape Island	NWR	48 (2010)	Barrier island	
Lighthouse Island	NWR	15 (2010)	Barrier island	
Raccoon Key	NWR	5 (2010)	Coastal island	
White Banks Islands	State	126 (2010)	Coastal islands	
Kiawah Island	Pvt.	26 (2010)	Barrier island	
Botany Plantation		18 (2010)		
Deveaux Bank	State	6 (2010)	Barrier island	
Savannah Spoil Site	USACE	220 (2010)	Dredge island	
Georgia				
Ossabaw	State WMA	12 (2010)	Barrier island	All overwashed
Little St. Simons Island	Pvt.	12 ch (2010)	Barrier island	
Andrews Isl.	GADNR/USACE	150 ch (2010)	Dredge island	
Brunswick Harbor Dredge Island	State	200 (2010)	Dredge island	All abandoned
Cumberland N Beach	NPS	100+ (2010)	Sand spit	All overwashed
Florida				
Amelia Island SP	State	150 (2010)	Barrier island	
Bird Island Group	State	100 (2010)	Coastal island	
Huguenot Memorial Park	Dept. Defense		Coastal island	125 nests in 2006
Little Talbot Island SP	State	150 (2010)	Barrier island	75 in 2008, 2 in 2010
Porpoise Point	County	51 (2010)	Barrier spit	
Matanzas Inlet CWA	NPS	256 (2010)	Barrier spit	
Summer Haven	na	102 (2010)	Barrier island	

Least terns arrive to colony sites along the South Atlantic Planning Area at the end of April, with peak nesting occurring mid-May. Clutch size ranges from 1–3 eggs; 2-egg nests are most common. Re-nesting within the same or new scrape can occur if an entire clutch is lost. Typically, semi-precocial chicks remain close to the natal scrape for the first 1–3 days. Older chicks are found away from their natal scrape, although in close proximity to parents. Chicks seek refuge from heat and predators under vegetation and debris. Least tern chicks have been seen flying at 14 days, although most literature suggests chick fledge at 17–21 days (Dugger et al., 2000; Bailey and Servello, 2008; Thompson et al., 1997). Fledged young are typically found along the water's edge awaiting return of a parent with prey. Dispersal from natal nesting sites usually occurs 3 weeks after fledge (Thompson et al., 1997).

Least terns forage primarily in bays, estuaries, river and creek mouths, tidal marshes, and, occasionally, offshore. Detailed data on foraging habitats do not exist for the South Atlantic Planning Area, however. To search for prey (primarily small fish), least terns fly and hover 1–10 m above water and then dive to capture prey with their mandible. Birds may forage solo or in flocks. Direct studies of diet do not exist for least terns in the study area. The majority of diet studies have focused on the California and interior least tern subspecies. Atwood and Kelly (1984) identified a total of 49 fish species comprising the diets of the California least tern. Northern anchovy and silverside were the primary food source collected at ten California least tern colonies. A significant inter-colony difference of the relative abundance of prey items was detected, reflecting a difference in foraging habitats between colonies.

Little research has been done in the study area regarding least tern chick provisioning. Male and female share duties in chick feeding, bringing smaller fish to chicks than those brought to mates. Studies outside of the study area found adults fed chicks an average of 2 fish/hour on the Gulf coast (Brubeck et al., 1981), 2 fish/hour on the Platte River, Nebraska (Wilson et al., 1993), and 2–4 fish/hour along the Mississippi River (Thompson et al., 1997). Parents continue to feed chicks post-fledge. Fledglings will fly alongside foraging adults and return to shoreline to receive prey.

Annual data on the reproductive success of the least tern does exist within the South Atlantic Planning Area. Nest success appears to be extremely variable among years and sites for the majority of studies conducted. Annual hatch success (i.e., percent of nests where one or more eggs hatch) ranges from 0–98% (Roman, 2008; Krogh and Schweitzer, 1999, Harris and Goodloe, 1995; Corbat, 1990). Apparent hatch success pooled among three colonies in Cape Romain NWR was 41% in 2009 and 59% in 2010 (Jodice and Brooks, unpubl. data). High variability may relate to the unpredictable occurrence of predators, and high tides or storms. Little data exist on the annual productivity (number of chicks fledged per pair) of the least tern within this study area. Elsewhere, annual productivity has been estimated at 0.06 fledgling/ breeding pair in the US Virgin Islands (Lombard et al., 2010), 0.72 and 1.0 fledgling/breeding pair on the lower Mississippi River (Dugger et al., 2000), 0.59 fledgling/ breeding pair on Gulf Coast (Thompson, 1982), and 0.47 on the lower Platte River (Kirsch, 1996).

For most studies, the primary causes of nest failure have been attributed to predation or flooding. Predation of eggs and chicks from black vultures and great-horned owls has been documented in the South Atlantic Planning Area (Jodice and Brooks, unpubl. data; Krogh and Schweitzer,

1999). Mammalian predation by raccoons and American mink also occurs within the South Atlantic Planning Area (Jodice and Brooks, unpubl. data). Nocturnal predation events have direct and indirect effects on nest success. In many cases, night-time abandonment of the entire colony will occur multiple nights after a predation event, allowing for eggs and chicks to be exposed to inclement weather. Colony sites are also often threatened by inundation.

There is no systematic review of breeding effort across the study area. In South Carolina, counts at ground colonies between 1971 and 2010 ranged from 25 to approximately 1,400. Counts were highly variable among years but appeared to generally increase from the mid-1970s to the mid-1990s. Since that time counts of ground nests have varied from about 350 to 850 per year. The most consistent locations have included Cape Romain NWR (Cape Island, Lighthouse Island, and Raccoon Key), Botany Bay, Kiawah Island, and the Savannah Spoil sites. Detailed data are not readily available for Georgia. In Florida, between 2005 and 2010, nest counts at ground colonies within the South Atlantic Planning Area have ranged from approximately 300–800. There has not been a simple trend during that time, although the maximum count did occur in 2010. Rooftop counts appear less reliable due to the difficulty in consistently accessing so many private properties.

Current conservation and management efforts for the least tern in the study area focus mainly on habitat loss and disturbance. The presence of humans close to colonies can cause adults to abandon colony sites for an extended period. In extreme temperatures, eggs and chicks can perish within 15 minutes of exposure. Across the entire study area, many colonies are located on property where public access is allowed. In these cases, active colonies are posted and protected from the public. In some cases, entire islands are closed to the public during the breeding season. There is also an effort to decrease predator disturbance to colonies by the use of predator control.

8.4.1.1.6 LC Black Skimmer (*Rynchops niger*)

State of Knowledge - Breeding: 4; Foraging: 3; Distribution: 3; Status: 3; Population: 1,500–1,700 pairs

Black skimmers are a distinctive coastal species that uses tactile feeding to capture prey from inshore and estuarine waters. Despite their year-round occurrence and abundance throughout the South Atlantic Planning Area and their relative high-profile nature, black skimmer research has been limited in the region predominantly due to challenges associated with working in skimmer colonies. Skimmers nest primarily on estuarine and offshore islands. Current conservation concerns include human disturbance at nesting colonies and loss/degradation of nesting habitat.

Three subspecies of black skimmer are recognized but only one (*R. n. niger*) resides in North America. Within the US, black skimmers breed from New York (occasional breeder in Massachusetts, Connecticut) south around Florida to the southern tip of Texas. Black skimmers also breed along the Gulf coast of Mexico east to the Yucatan Peninsula.

Throughout the study area, skimmers nest on islands that range widely in size and are located in estuaries, river mouths, and bays. In Florida, skimmers also nest on rooftops, although this occurs predominantly on the Gulf coast (Gore, 1991). In northern areas of the breeding range they also may nest in salt marshes and mainland beaches. Colony sites are typically free of

consistent pressure from mammalian predators. Nest sites consist of scrapes on bare sand or sand-shell substrate. Colony sites may occur on the same islands or in the same area of an island, as is the case with other nearshore seabirds, but also may occur separately. The extent to which skimmers co-nest with other species, and the species they co-nest with, appears to vary across the entire range. In the South Atlantic Planning Area, skimmer colonies occur as monospecific or also may include least terns or gull-billed terns. In the Gulf of Mexico laughing gulls also may co-nest with skimmers. Habitat analyses of nest sites or colony sites have not been conducted in the study area except for a very recent analysis in South Carolina for which analysis is not yet complete. Outside of the study area, habitat analysis has been conducted in New York and New Jersey; skimmers chose beaches with <20% vegetation and often nested on beaches with no vegetation at all (Burger and Gochfeld, 1990). This does not appear to be the case in the South Atlantic Planning Area. In South Carolina, for example, all major skimmer colonies in recent years have occurred on vegetated islands and the vegetation often has provided cover for skimmer chicks (pers. obs.).

Black skimmers can be found year-round along the entire north-south gradient of the study area, primarily in the nearshore and estuarine zones. Breeding for black skimmers extends from colonies in Cape Romain NWR, South Carolina to Little Talbot Island and occasionally Bird Island in Florida (Figure 8.2, Table 8.9). The largest spatial gap between colonies is at the north end of the study area (~170 km from the Marsh Island colony in Cape Romain NWR to colonies in southern North Carolina) and between Deveaux Bank and Savannah Harbor (85 km).

Table 8.9
Attributes of black skimmer ground colonies in the South Atlantic Planning Area. Colonies are listed only if they have been used in at least 2 of 6 years since 2005. Nest counts are provided for the most recent year for which data were readily available.

Colony Name	Ownership	Nest Count (year)	Habitat Type	Comments
South Carolina				
Cape Island	NWR	227 (2010)	Barrier island	
Lighthouse Island	NWR	122 (2010)	Barrier island	
White Banks Islands	State	117 (2010)	Coastal islands	
Marsh Island	NWR	18 (2010)	Coastal island	
Crab Bank / Castle Pinckney	State	213 (2010)	Harbor islands	
Skimmer Flats	State	29 (2010)	River mouth island	
Deveaux Bank	State	190 (2010)	Barrier island	
Tomkins Island	USACE	100 (2008)	Dredge island	
Savannah Spoil Site	USACE	124 (2010)	Dredge island	

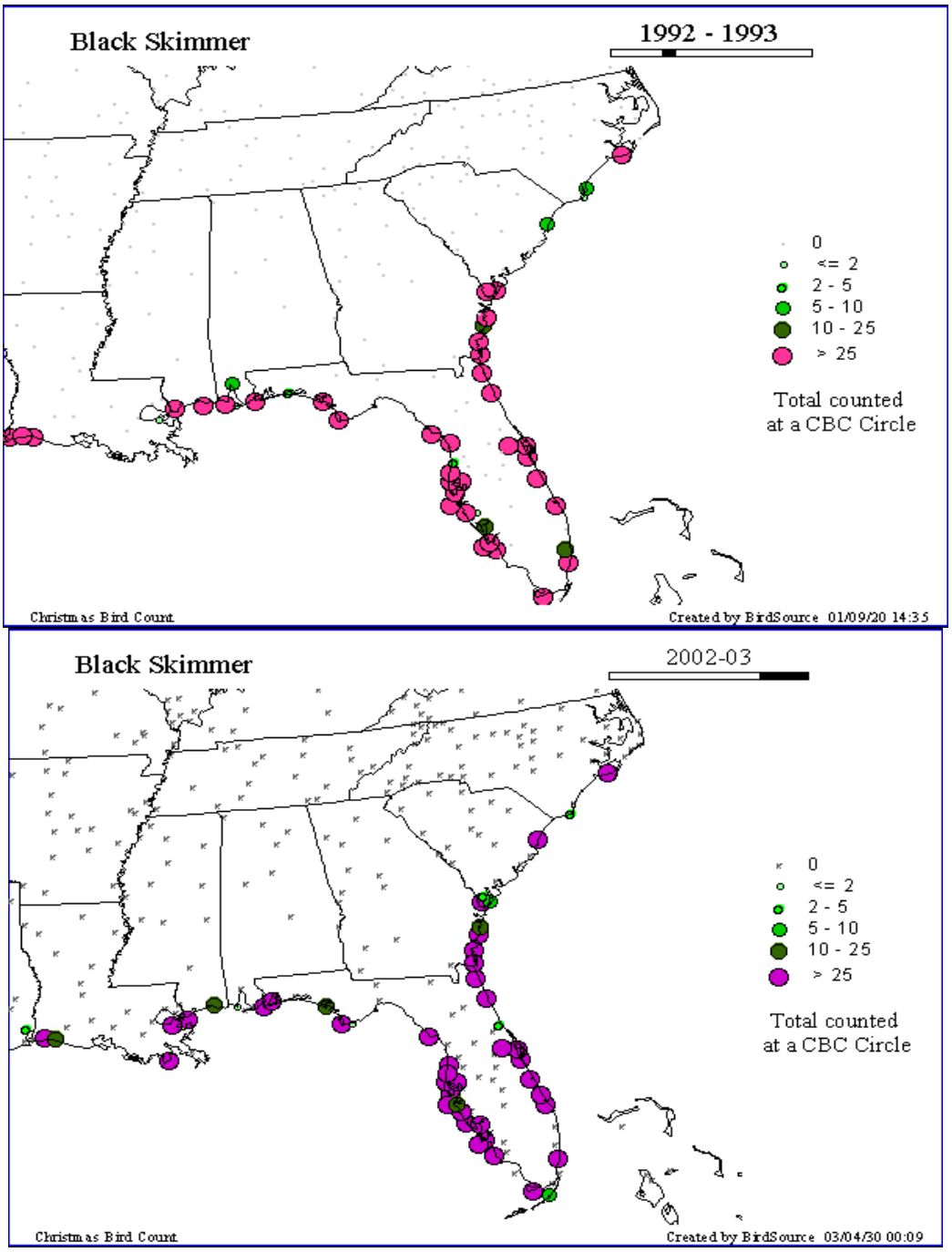
Table 8.9 Attributes of black skimmer ground colonies in the South Atlantic Planning Area. Colonies are listed only if they have been used in at least 2 of 6 years since 2005. Nest counts are provided for the most recent year for which data were readily available (continued).

Colony Name	Ownership	Nest Count (year)	Habitat Type	Comments
Georgia				
Little St. Simons Island	Pvt.	n/a	Barrier island	35 chicks
Brunswick Harbor Dredge Island	State	98 (2010)	Dredge island	144 chicks
Florida				
Bird/Big Bird Island	State	51 (2010)	Sand island	
Huguenot Memorial Park	Dept. Defense	1 (2010)	Coastal beach	125 nests in 2006
Little Talbot Isl. SP	State	21 (2009)	Barrier island	75 in 2008, 2 in 2010

No single source currently exists that lists all current or historic breeding locations in the study area. In South Carolina, black skimmers primarily nest/have nested on islands in Cape Romain NWR, in Charleston Harbor (since mid-1990s; Jodice et al., 2007), at the mouth of the Stono River on Bird Key and the North Edisto River on Deveaux Bank. In Georgia, black skimmers nest on Little St. Simons Island, Brunswick Harbor Dredge Island, and at Tomkins Island, a dredge spoil island created in 2005 and located in Savannah Harbor but managed in part by SC DNR (Bailey and Hatcher, 2005). Within the Florida portion of the study area, black skimmers nest primarily on Little Talbot Island although nest counts are variable within sites among years.

Data from Christmas Bird Counts show that skimmers occur throughout much of the coastal South Atlantic Planning Area during winter (Figure 8.10). In South Carolina, birds appear to concentrate in Cape Romain NWR and in the St. Helena Sound region. In Georgia, skimmers are counted on many of the barrier islands during mid-winter waterbird surveys but often on St. Simon's, Jekyll, and Sapello islands. In Florida, birds appear to occur primarily north of Jacksonville and in the Cape Canaveral area. Migratory routes are not well known and are inferred from casual observations and band return data. Snipes (2010) reports that black skimmers banded in South Carolina are reported during winter throughout the coastal South Atlantic Planning Area but primarily along the Florida Atlantic coast (Florida Gulf coast recoveries also were common). Southern breeders may migrate to the Caribbean or Central America. Therefore, areas outside of the study area and outside of the US likely play a critical role in population dynamics within the South Atlantic Planning Area given that individuals may overwinter there.

Skimmers have a unique foraging behavior: they fly just above the surface of the water with the lower bill extended below the surface of the water. When the mandible contacts a fish, the upper bill snaps closed. Direct studies of diet do not exist in the study area. Diet data from adults in



Figures 8.10 National Audubon Society Christmas Bird Count data for black skimmers in the Southeast US, 1992–1993 and 2002–2003.

other portions of the range and occasional collections from individuals within the South Atlantic Planning Area include a variety of items including *Fundulus* spp., anchovies, silversides, Atlantic menhaden, and shrimp. Detailed foraging studies have not been conducted. It is assumed that most foraging occurs in shallow waters of the nearshore or estuarine environment, particularly during crepuscular hours. Detailed tracking studies have not been conducted. Foraging ranges or habitat use has not been studied directly in the South Atlantic Planning Area,

but Tomkins (1951) reported that adults foraged within 5 km of colony. In the northern portion of the breeding range, adults were reported to forage within 8 km of colony (Gochfeld and Burger, 1994). Primary foraging habitat is often considered to be tidal pools, shallow waters, or other smooth-surfaced water where fish concentrate. Skimmers were not observed attending shrimp trawlers during two years of observations in nearshore waters of the South Carolina coast where pelicans, terns, and gulls foraged readily on discarded bycatch (Wickliffe and Jodice, 2010).

Gochfeld and Burger (1994) provide reviews of the annual cycle for skimmers; no apparent deviations occur within the South Atlantic Planning Area. Skimmers typically lay a 4-egg clutch and laying appears to peak in mid-June in the study area. Relaying can occur if a clutch is lost. Egg-laying is more synchronous within subsections of colonies than across the colony as a whole. Chicks are semiprecocial and can leave the nest scrape shortly after hatching (as soon as 1–3 days). Habitat use of chicks includes intertidal zones of beaches, vegetated areas above the high tide line, and dunes. Rates of chick growth have not been reported within the study area but Erwin (1977) and Schew and Collins (1990) do report growth constants for birds in Virginia and California, respectively. For this species, important aspects of chick growth are the fact that chicks diverge in size at about seventeen days post-hatch and that fledge mass differs substantially between males and females (the former is larger). The fact that male chicks are larger may mean that the energetic cost of raising males is greater. Eggert and Jodice (unpubl. data) conducted a pilot study of chick energetics but the scope of the project was insufficient to address this potentially interesting ecological question.

Rates of chick feeding have not been reported for skimmers in the study area, although Erwin (1977) reported that food was delivered to chicks at a Virginia colony on average every 14.6 minutes. It is not clear if nocturnal feeding rates differ, but if adults do forage readily during crepuscular and nocturnal hours then feeding rates may be greater than those indicated in Erwin's study.

Annual data on reproductive success is poorly known throughout the range. Gochfeld and Burger (1994) report in most years only about 50% of pairs raise at least one chick to fledging but this estimate is drawn primarily from data outside of the study area. Hatching rate appears to vary widely (0–85%) among colonies, based on a review of data across the species breeding range (excluding the South Atlantic Planning Area). Recent research in the study area has examined reproductive success and causes of nest failure at colonies in South Carolina. Productivity ranged from complete colony failure to 0.5 chicks/pair at three colonies (Crab Bank, Bird Key Stono, and Deveaux Bank) in South Carolina between 2006 and 2008 (Jodice and Eggert, 2010). An increase in productivity during this study coincided with a change in management regulations that improved protection from human disturbance. Additional research also was conducted at three colony sites in Cape Romain NWR (Lighthouse, Middle White Banks, and Cape islands) during the 2009 and 2010 breeding seasons. Rates of nest failure (i.e., 0 eggs hatched) ranged from 20% to 100% across the three colonies and in both breeding seasons (Jodice and Brooks, unpubl. data). In both studies, causes of nest failure were attributed primarily to flooding and predation, and this appears to be consistent with reports from other portions of the range (Gochfeld and Burger, 1994).

Predation of eggs and chicks from avian predators does occur. Laughing gulls, black vultures, and great-horned owls have all been observed predating eggs or chicks at colonies. Mammalian predation of chicks and eggs by raccoons and American mink also occurs. Ghost crabs have also been observed predating eggs and small chicks at colonies in South Carolina. Unattended eggs and small chicks are also susceptible to heat exposure.

Black skimmers are not currently listed as threatened or endangered within the US. Within the South Atlantic Planning Area, black skimmers are classified as rare in Georgia and as a Species of Special Concern in Florida and South Carolina (Appendix 8.1). Currently each state maintains its own records of nesting effort; these are currently gathered at varying levels of standardization within and among states. Availability of long-term data varies by state.

There is no systematic review of breeding effort across the study area; recent nest count estimates are presented in Table 8.9. Annual nest counts of black skimmers in South Carolina were reviewed by Wilkinson et al. (1994) and more recently by Snipes (2010). Surveys were conducted irregularly between 1975 and 2009 and statewide nest counts ranged from 324 to 1,426. There appeared to be an increase in the number of nests during this time period although counts still remain highly variable among years. For example, since 2005 nest counts have ranged from 700 to 1,200 within the state. The number of skimmer colonies used within the state within a single year was typically 4–6 during this same time period. Sites used most frequently (>50% of years) include islands within Cape Romain NWR, Crab Bank (Charleston Harbor), Bird Key Stono (mouth of Stono River), and Deveaux Bank (mouth of North Edisto River). In Georgia, three of the four sites currently being used are dredge spoil sites; it appears that skimmers were quick to colonize at least two of these (Tomkins, Brunswick), initiating nesting during the first year of availability. Skimmer nests are not counted annually throughout the entire state, so trend data are not readily available. Data have been collected each year, however, at Tomkins Island and the Savannah River Spoil sites where nest counts have ranged from 0–200 and 0–125, respectively, between 2005 and 2010. In Florida, nesting occurred at <10 sites between 2005 and 2010. The most consistently used sites where more than a few nests occurred were Little Talbot Island and the Bird Island group, where nesting occurred in two years only and annual nest counts ranged from 15–75 per site. Approximately 200 nests occurred at Amelia Island State Park and Huguenot Memorial Park in 2005 but nesting has not occurred at either location since then. Skimmers were observed using two rooftops in Brevard County during 2009 and 2010 but nest counts were <5 at each site.

Current conservation and management efforts for black skimmers in the South Atlantic Planning Area focus primarily on limiting human disturbance at breeding colonies and loss of nesting habitat. All three states prohibit access to colonies and limit access to islands supporting colonies to varying extents. Breeding skimmers appear to flush from nests much more readily compared to brown pelicans and similarly to terns, for example, and during incubation this can result in nest loss due to egg predation or egg exposure. In South Carolina, the size of the skimmer colony on Crab Bank in Charleston Harbor (a site prone to human activity) increased from <50 unsuccessful nests per year prior to 2006 to >175 nests per year that produced young in 2006–2008 when new regulations prohibited all human access to the entire island during the breeding season (Jodice and Eggert, 2010). During incubation and chick-rearing adults and chicks frequently use the intertidal zone for loafing and disturbance here, where human recreation is

often focused, can be substantial (Jodice and Eggert, 2010). Chicks also use areas above the high tide line for shelter and provisioning; therefore, these habitats are also critical. Predator control is also a management priority in the region.

8.4.1.1.7 Other Nearshore Seabirds

While the aforementioned species comprise the majority of nearshore seabirds in the region during the breeding a season, a few other nearshore species also breed in the area (Table 8.3). The most common of these are common tern and Forster's tern. In South Carolina, these two species nest primarily in Cape Romain NWR. Annual, statewide nest counts between 1979 and 2010 are $\leq$35 for each species. Neither species is reported breeding in Georgia or the Florida portion of the South Atlantic Planning Area, at least not in substantial numbers. Foraging behavior during the breeding season is likely similar to that of royal and sandwich terns (i.e., small fish from nearshore and estuarine waters). One or two nests per year of the more commonly tropical sooty tern have also been found regularly in South Carolina at colony sites at Cape Romain NWR, Bird Key Stono, or Deveaux Bank.

During the nonbreeding season many terns and gulls migrate through the South Atlantic Planning Area and use the nearshore environment. These species frequent coastal beaches and barrier islands including many of the islands that also support seabird colonies and many of the IBAs and protected areas noted in Figures 8.1 and 8.2 and Tables 8.1 and 8.2. However, surveys are not conducted specifically to monitor migratory or wintering nearshore seabirds, although many are counted while loafing on beaches during shorebird surveys. Nonetheless, habitat use at sea during winter may vary from that during the breeding season when birds are central-place foragers. Winter habitat use is thus poorly understood in the region. Common migrants that can be found using coastal beaches and foraging in nearshore and estuarine waters include ring-billed gull, Forster's tern, black tern, Arctic tern (*Sterna paradisaea*), and American white pelican (*Pelecanus erythrorhynchos*) and those species representing the nearshore breeding seabirds (Table 8.10).

Table 8.10
Occurrence and abundance of nearshore seabirds by season in the South Atlantic Planning Area. Only species that are scored as rare or better in at least one season are included.

Scientific Name	Common Name	SP	SU	FA	WI
Order PELECANIFORMES					
Family PELECANIDAE					
Pelecanus occidentalis	Brown pelican	C	C	C	C
Pelecanus erythrorhynchos	American white pelican	C		C	C

SP = spring, SU = summer, FA = fall, WI = winter. C = common, U = uncommon, R = rare, V = vagrant, PV = potential vagrant, EV = expected vagrant.

Table 8.10 Occurrence and abundance of nearshore seabirds by season in the South Atlantic Planning Area. Only species that are scored as rare or better in at least one season are included (continued).

Order CHARADRIIFORMES Family LARIDAE	Common Name	SP	SU	FA	WI
Larus atricilla	Laughing gull	C	C	C	C
Larus delawarensis	Ring-billed gull	C		C	C
Larus argentatus	Herring gull	C	U	C	C
Larus marinus	Great black-backed gull	U	U	C	C
Gelochelidon nilotica	Gull-billed tern	U	U		
Thalasseus maxima	Royal tern	C	C	C	C
Thalasseus sandvicensis	Sandwich tern	C	C	C	U
Hydroprogne caspia	Caspian tern	U	U	U	U
Chilodonias niger	Black tern	C		C	
Sterna dougallii	Roseate tern	U		U	
Sterna hirundo	Common tern	C	C	C	
Sterna forsteri	Forster's tern	C	C	C	C
Sternula antillarum	Least tern	C	C		
Onychoprion fuscata	Sooty tern	R	R		
Family RYNCHOPIDAE					
Rynchops niger	Black skimmer	C	C	C	C

SP = spring, SU = summer, FA = fall, WI = winter. C = common, U = uncommon, R = rare, V = vagrant, PV = potential vagrant, EV = expected vagrant.

8.4.1.1.8 Synopsis

Seven nearshore species breed in substantial numbers in the South Atlantic Planning Area: brown pelican, laughing gull, royal tern, Sandwich tern, gull-billed tern, least tern and black skimmer. This suite of nearshore seabirds relies heavily on beaches and coastal areas for nesting, loafing and chick-rearing, and they forage predominantly in nearshore, inshore, and estuarine waters although little detailed data exist. These species are not likely to occur more than a few kilometers from shore on a regular basis especially during the breeding season. Migration routes (distance from shore, height) are unknown but are likely coastal. While each state supports some colonies of most of these seven species, within the region South Carolina supports most of the nesting effort. The coastal area also supports abundant migrating and wintering nearshore seabirds although data on location and abundance are sparse.

8.4.1.2 Pelagic Seabirds

This section provides a synthesis of information for pelagic seabirds that occur in the South Atlantic Planning Area, including shearwaters, petrels, storm-petrels, sulids and their allies, pelagic gulls and terns, jaegers, and alcids. Population estimates noted in species headers are global estimates from BirdLife International; more regionally appropriate estimates are provided where available.

Pelagic seabirds are generally regarded as those species that do not frequently loaf or roost on islands or coastal areas and typically do not forage solely in the nearshore environment. The South Atlantic Planning Area does not support any nesting areas for pelagic seabirds and therefore observations of pelagic seabirds in the area represent birds that are either commuting during the breeding season, migrating or wintering, or wandering before the onset of breeding age. For example, black-capped petrel and Audubon's shearwater appear to forage in the area during incubation and chick-rearing periods. Typically these observations occur far from shore, although there are few to no data sets or surveys to verify the consistency or timing of such observations. Pelagic seabirds also spend portions of their nonbreeding season within the South Atlantic Planning Area. For austral breeding species, such as the greater or sooty shearwater (*Puffinus griseus*) or south polar skua (*Catharacta maccormicki*), individuals forage within the area during northern summer months. Northern migrants that are observed from autumn through spring include northern gannet (*Morus bassanus*), Leach's storm-petrel (*Oceanodroma leucorhoa*), and thick-billed murre (*Uria lomvia*), all of which breed in the Maritime Provinces of Canada. Migrating seabirds from the Bahamas and West Indies, such as Audubon's shearwater, brown booby (*Sula leucogaster*), and various species of pelagic terns also have been observed during winter months. Some pelagic seabirds also spend multiple years at sea before the initiation of breeding. This behavior is common in members of the Procellariiformes (e.g., shearwaters, petrels); hence it is possible that a range of species could be observed (uncommonly) in the region at any time of year. Table 8.11 lists pelagic seabirds most likely to occur in the South Atlantic Planning Area, the season they are mostly likely to occur, and their abundance during that season.

Table 8.11
Occurrence and abundance of pelagic seabirds by season in the South Atlantic Planning Area.

Scientific Name	Common Name	SP	SU	FA	WI
Order PROCELLARIIFORMES					
Family DIOMEDEIDAE					
Thalassarche chlororhynchos	Yellow-nosed albatross	V	V	V	V
Thalassarche melanophris	Black-browed albatross	EV	EV	EV	EV
Family PROCELLARIIDAE					
Fulmaris glacialis	Northern fulmar				R
Pterodroma arminjoniana	Herald petrel	EV	EV	EV	U
Pterodroma cahow	Bermuda petrel	EV	EV	EV	EV
Pterodroma hasitata	Black-capped petrel	U	U	U	U
Pterodroma feae	Fea's petrel	EV	EV	V	
Pterodroma madeira	Zino's petrel	EV	EV	EV	
Bulweria bulwerii	Bulwer's petrel	V	V		
Calonectris diomedia	Cory's shearwater	U	C	C	U
Puffinus gravis	Greater shearwater	C	R	U	R
Puffinus griseus	Sooty shearwater	U	U	U	
Puffinus puffinus	Manx shearwater	R	R	R	U
Puffinus lherminieri	Audubon's shearwater	U	C	C	R
Puffinus assimilis	Little shearwater			V	
Family HYDROBATIDAE					
Oceanites oceanicus	Wilson's storm-petrel	C	C	U	R
Pelagodroma marina	White-faced storm-petrel		PV		
Hydrobates pelagicus	European storm-petrel				PV
Oceanodroma leucorhoa	Leach's storm-petrel	R	U	R	R
Oceanodroma castro	Band-rumped storm-petrel				
Oceanodroma monorhis	Swinhoe's storm-petrel		PV		
Order PELECANIFORMES					
Family PHAETHONTIDAE					
Phaethon lepturus	White-tailed tropicbird		R		
Phaethon aethereus	Red-billed tropicbird		R		

SP = spring, SU = summer, FA = fall, WI = winter. C = common, U = uncommon, R = rare, V = vagrant, PV = potential vagrant, EV = expected vagrant.

Table 8.11 Occurrence and abundance of pelagic seabirds by season in the South Atlantic Planning Area (continued).

Scientific Name	Common Name	SP	SU	FA	WI
Family SULIDAE					
Sula dactylatra	Masked booby		R		
Sula leucogaster	Brown booby		V		
Sula sula	Red-footed booby		V		
Morus bassanus	Northern gannet	R	V	R	C
Family PELECANIDAE					
Pelecanus erythrorhynchos	American white pelican	C		C	C
Pelecanus occidentalis	Brown pelican	C	C	C	C
Suborder FREGATAE Family FREGATIDAE					
Fregata magnificens	Magnificent frigatebird		R		
Family LARIDAE					
Catharacta skua	Great skua				PV
Catharacta maccormicki	South polar skua	R	R	R	
Stercorarius pomarinus	Pomarine jaeger	C	R	C	U
Stercorarius parasiticus	Parasitic jaeger	C	U	C	
Stercorarius longicaudus	Long-tailed jaeger	C	U	C	
Larus pipixcan	Franklin's gull				R
Larus philadelphia	Bonaparte's gull				C
Larus delawarensis	Ring-billed gull	C		C	C
Larus argentatus	Herring gull	C	C	C	C
Larus glaucoides	Iceland gull				V
Larus fuscus	Lesser black-backed gull				R
Larus hyperboreus	Glaucous gull				V
Larus marinus	Great black-backed gull	C	C	C	C
Xema sabini	Sabine's gull				U
Rissa tridactyla	Black-legged kittiwake				U
Pagophila eburnea	Ivory gull				
Sterna anaethetus	Bridled tern		C		
Sterna fuscata	Sooty Tern		U		

SP = spring, SU = summer, FA = fall, WI = winter. C = common, U = uncommon, R = rare, V = vagrant, PV = potential vagrant, EV = expected vagrant..

Table 8.11 Occurrence and abundance of pelagic seabirds by season in the South Atlantic Planning Area (continued)

Scientific Name	Common Name	SP	SU	FA	WI
Family LARIDAE					
Anous stolidus	Brown noddy		U		
Family ALCIDAE					
Alle alle	Dovekie				R
Uria aalge	Common murre				R
Uria lomvia	Thick-billed murre				R
Alca torda	Razorbill				R
Cepphus grylle	Black guillemot				R
Fratercula arctica	Atlantic puffin				R

SP = spring, SU = summer, FA = fall, WI = winter. C = common, U = uncommon, R = rare, V = vagrant, PV = potential vagrant, EV = expected vagrant..

The presence of pelagic birds has been documented in opportunistic surveys on fishing vessels, scientific expeditions (e.g. see publications cited for C. Haney) and occasional seabird-specific birdwatching trips, but regular and systematic surveys to establish densities throughout the annual cycle have not been conducted in the study area. In general the abundance of pelagic seabirds does not appear to be high; this is likely due to oceanographic features that tend not to create consistent or predictable areas of enhanced productivity that are known to attract pelagic seabirds (e.g., upwelling zones, cold core eddies, Gulf Stream eddies). In fact, the extensive distance to these features from major ports in the area (e.g., Charleston, Savannah, and Jacksonville) has likely limited the opportunities to survey the area and may account for the relative lack of records and the poor state of knowledge for pelagic seabirds in the region.

Within species accounts include some data collected from at-sea surveys. Unless otherwise noted, these originate from NOAA marine mammal cruises conducted during 1992, 1998, and 1999 (Figure 8.11). Although seabirds were not the focus of these cruises, observational data were collected. Maps are presented of sightings for species with >50 records when summed among the three years.

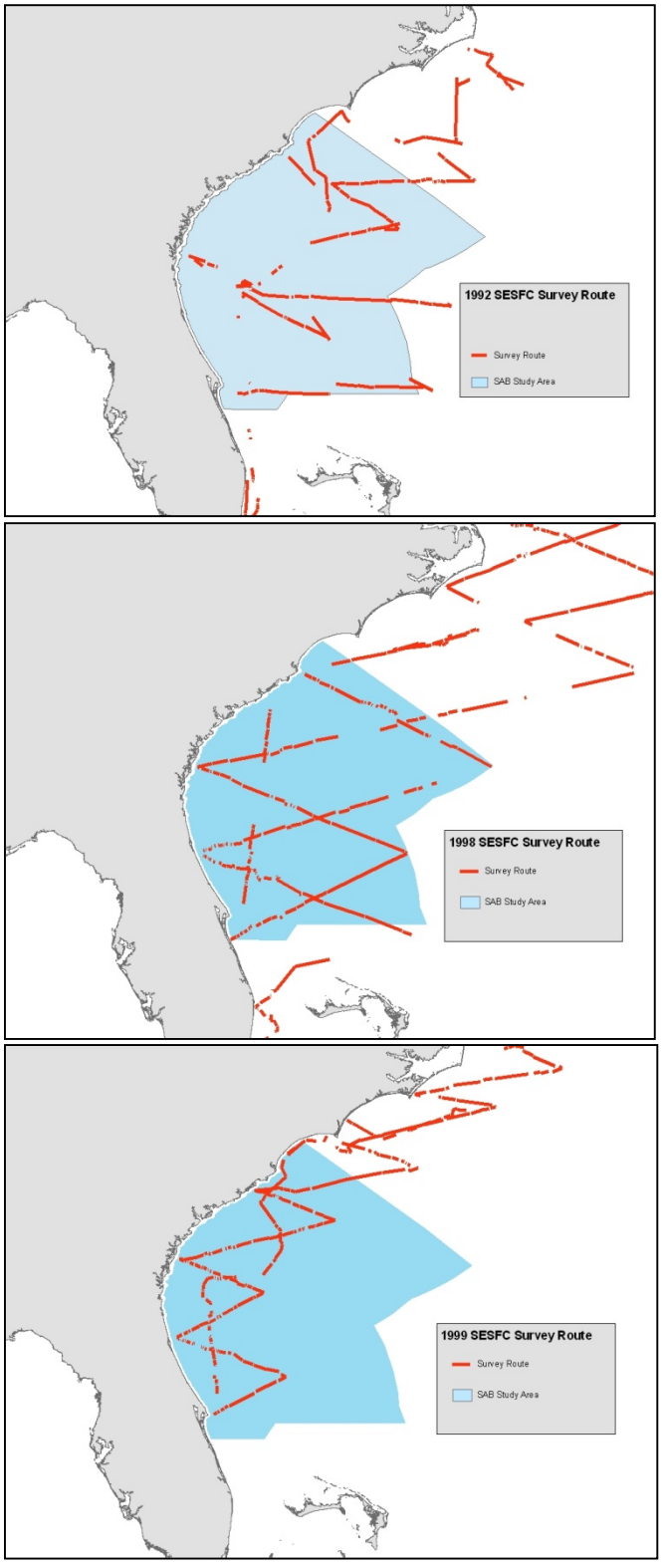


Figure 8.11 Survey routes for NOAA Southeast Fishery Science Center at-sea surveys, 1992, 1998, and 1999.

8.4.1.2.1 Petrels (Procellariiformes)

Members of this order are long-lived species that have protracted juvenile periods and exhibit high site fidelity with respect to nesting grounds. They are highly pelagic, returning to land only to nest. Their distinctive tube-shaped nasal passages on the bill are a synapomorphic characteristic uniting the order. They usually nest at their natal islands and, once pair bonds are formed at a particular nest, they will usually return to that spot for life. A single egg is laid per nesting attempt. Many species in the order are endangered because of invasive species at the nesting grounds and mortality as bycatch in commercial long-line fisheries (see review of bycatch in the South Atlantic Planning Area, below). Most petrels and shearwaters feed and attend nests at night. Their behavior is severely disrupted by light, to the extent that they circle and collide with fires, lighthouses, streetlights, ships, and other well-lit structures, particularly when the moon is not visible. Not surprising for species with high survivorship and low fecundity, they recover poorly from population crashes, and many have experienced substantial population declines since the arrival of humans within their breeding ranges.

EN Atlantic Yellow-nosed Albatross (*Thalassarche chlororhynchos*)
State of Knowledge-- Breeding: n/a; Foraging: 3; Distribution: 3; Status: 3; Population: 55,000 pairs

A rare vagrant from the Southern Mid-Atlantic (one confirmed sighting in the South Atlantic Planning Area) that breeds in large colonies in the Tristan de Cunha group and around Gough Island in the South Atlantic Ocean. The South Atlantic Planning Area is not an important area for its population as a whole, which is large but decreasing precipitously. The species is subject to heavy bycatch in long-line fisheries.

EN Black-browed Albatross (*Thalassarche melanophris*)
State of Knowledge-- Breeding: n/a; Foraging: 3; Distribution: 3; Status: 3; Population: 150,000 pairs

A rare vagrant from the South Atlantic (one confirmed sighting in the South Atlantic Planning Area) that breeds in large colonies in the Falkland, Diego Ramirez, and South Georgia Islands. The South Atlantic Planning Area is not an important area for its population as a whole, which is large but decreasing precipitously. The species is also subject to heavy bycatch in long-line fisheries.

LC Northern Fulmar (*Fulmarus glacialis*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution 4; Status: 5; Population: 15,000,000 pairs

A regular but uncommon winter visitor from the North Atlantic. The population is increasing; this is sometimes attributed to the additional food provided by offal and discarded bycatch from commercial fishing vessels. The bird is of least conservation concern, and the South Atlantic Planning Area is not thought to be an area of concentration.

EN Bermuda Petrel (*Pterodroma cahow*)
State of Knowledge - Breeding: n/a; Foraging: 2; Distribution: 2; Status: 4; Population: 100 pairs

One of the rarest seabirds in the world, it was thought to be extinct until eighteen pairs were rediscovered off of Bermuda. As of 2007, it has never been documented in the South Atlantic Planning Area. The lack of records is almost certainly due to lack of census effort, as the species is rare compared to black-capped petrels (*Pterodroma hasitata*) in the frequent searches for pelagics in the Gulf Stream off Cape Hatteras. Its behavior at sea is thought to be similar to the black-capped petrel.

EN Black-capped Petrel (*Pterodroma hasitata*)
State of Knowledge - Breeding: n/a; Foraging: 3; Distribution: 3; Status: 2; Population: 5,000 pairs (?)

A rare but regular inhabitant of the Gulf Stream seen year-round and likely commutes to the South Atlantic Planning Area from the Caribbean during the breeding season (Figure 8.12).

The status of the population is poorly known. BirdLife provides an estimate of 5,000 mature individuals and Lee (2000) provides an estimate of 1,000–2,000 breeding pairs. It is most frequently seen off of North Carolina despite nesting only in the Caribbean. The known nesting sites are on sheer, limestone cliffs in Haiti at Pic Macaya and La Selle Ridge, with <200 pairs nesting in the Dominican Republic at Loma del Toro. The species formerly occurred at lowland areas of Hispaniola and on the islands of Guadeloupe, Dominica, and Martinique, but only on Dominica has an adult bird been captured in recent years (2007). There may be a population on Cuba, although no breeding sites or subfossils have been found there; a strong area of upwelling occurs along the SW coast of Cuba and birds have been observed there (Lee and Vina, 1993). An all-dark congener, the Jamaica petrel (*Pterodroma caribbea*), is thought to be extinct and was last found in the 19th century. Invasive species, including rats and mongoose, are thought to have caused the precipitous decline of this once-common genus in the Caribbean. The black-capped petrel is endangered according to the Birdlife/IUCN categorization, but is not yet listed under the US Endangered Species Act.

The South Atlantic Planning Area is an important feeding area and migratory pathway for this species, which specializes on fish and squid in eddies, confluences, and meanders of the Gulf Stream (Haney, 1987). According to Haney (1987), black-capped petrels frequently approach feeding aggregations from upwind or directions not downwind. They also approach from downwind to areas where chum and fish oil have been used specifically to attract seabirds on pelagic birdwatching expeditions. Thus, the bird feeds opportunistically and appears to be attracted to both the sight and smell of feeding frenzies. Studies of tissues collected from individuals off the coast of North Carolina found mercury loads many times higher those of other species in the area (Lee, 2000; note that mercury levels given in grams should be in micrograms). There is no explanation for this observation.

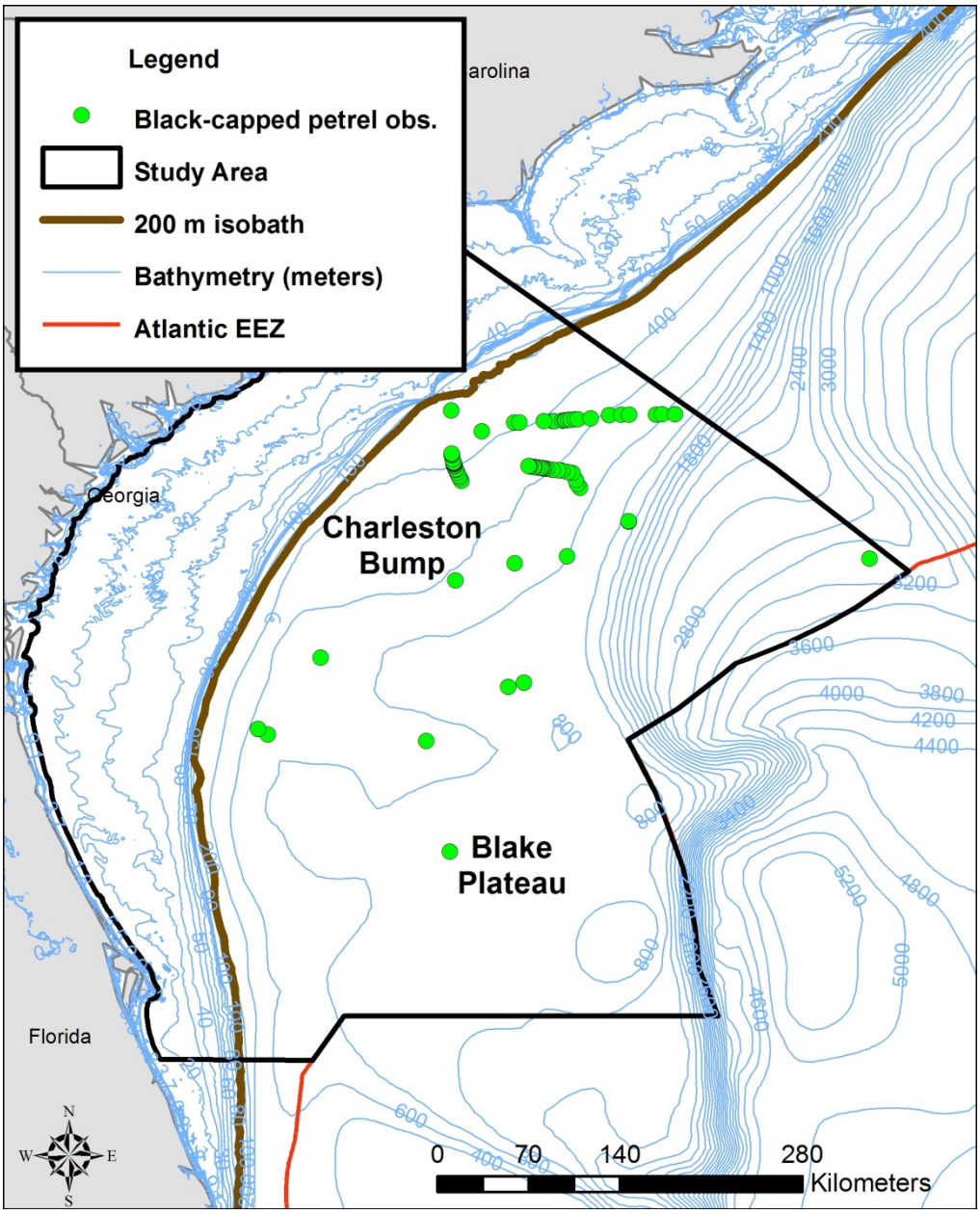


Figure 8.12 Observations of black-capped petrels during at-sea surveys conducted by NOAA in 1992, 1998, and 1999.

Almost all observations at sea are taken only in the daylight, but studies and stomach contents from *Pterodroma* petrels, including this species, indicate that they feed extensively on cephalopods that spend the daylight hours at depth and migrate to the surface to feed at night. *Pterodroma* petrels are not known to dive significantly below the surface. It appears they may seize their nocturnal prey from near or on the surface, as they do in diurnal feeding. Haney (1987) notes that black-capped petrels in the South Atlantic Planning Area are most often observed in early morning or late afternoon.

Pterodroma petrels are excellent dynamic soarers that use the wind to cover long distances at high speed. They are called "gadfly petrels" for their conspicuous bounding flight with ". . . three or four quick wingbeats to gain height followed by long downwards glide on bowed and angled wings" (Harrison, 1983). They are seen more often off of Cape Hatteras and in the South Atlantic Planning Area than at any location in the Caribbean region. This species is the most likely of all pelagic birds of the South Atlantic Planning Area to face conservation issues if there were an ecological disaster.

NT Fea's Petrel (*Pterodroma feae*)
State of Knowledge - Breeding: n/a; Foraging: 3; Distribution: 3; Status: 3; Population: 3,000 pairs

Fea's petrel (*Pterodroma feae*) breeds in the Cape Verde Islands and the Desertas Islands off Madeira in two populations that are variously considered subspecies or full species (*P. f. feae* and *P. f. desertas*). Adults have been captured on land in the Azores, but no breeding sites have been detected. Estimates of breeding pairs are thought to be conservative because cryptic nesting populations in remote cliffs are expected but have yet to be found. Fea's petrel is a vagrant in the South Atlantic Planning Area; there has been one sighting (Haney et al., 1993). It is very difficult to distinguish from Zino's petrel (*Pterodroma madeira*), but records of lone birds are usually assigned to this species because its population is much greater. Its behavior is thought to be similar to the black-capped petrel and they feed in and are associated with similar oceanographic conditions. Authorities in Cape Verde and Desertas are working to stabilize the populations and halt degradation of the nesting sites, exploitation of the birds for food by humans, and increased mortality from invasive species. The species is rare enough that any disturbance could affect the population, but there is no evidence yet that the South Atlantic Planning Area is an important area for this species.

EN Zino's Petrel (*Pterodroma madeira*)
State of Knowledge - Breeding: n/a; Foraging: 3; Distribution: 3; Status: 3; Population: 63 pairs

A very rare bird, Zino's petrel breeds on mountain ledges in Madeira at 1,600 m (Birdlife Factsheet, 2010). It has never been documented in the South Atlantic Planning Area and its range outside of Madeira is unknown. However, the South Atlantic Planning Area is well within the abilities and habits of similar species and the search effort is too poor to exclude it in terms of conservation preparations. Its behavior is likely to be similar to the other *Pterodroma* species in the area.

VU Herald or Trinidade Petrel (*Pterodroma arminjoniana*)
State of Knowledge-- Breeding: n/a; Foraging: 3; Distribution: 3; Status: 2; Population: 1,100–15,000 pairs

A potential vagrant in the South Atlantic Planning Area, this species has not been documented in the study area but is an uncommon spring and summer visitor nearby off of North Carolina. It breeds on two islands (Trinidade and Martin Vaz) in the South-Central Atlantic about 1000 km east of Brazil. The breeding sites are remote and rugged. Information is lacking and population

estimates vary by an order of magnitude, but invasive mammals that devastate other *Pterodroma* populations have been introduced at the nesting islands and the birds are restricted to inaccessible sites. Although its use of the South Atlantic Planning Area is unknown, it very likely occurs in the study area, if only in transit to "The Point" area off of Hatteras Island where pelagics from all over the Atlantic are regularly documented. The lack of records likely results from low search effort, and the bird is rare enough that even small numbers in any pelagic area could represent an important portion of the overall population.

LC Bulwer's Petrel (*Bulweria bulwerii*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 2; Population: 500,000 pairs

A single observation of a Bulwer's petrel (*Bulweria bulwerii*) for the South Atlantic Planning Area occurred in 1984 off Jacksonville (Haney and Wainright, 1985). Another Macronesian vagrant, it breeds from the Azores through Madeira, the Canaries, and Cape Verde Islands. There are Indian and Pacific Ocean populations, but Macronesia is the most likely source for birds that visit the study area. The species is thought to feed mostly at night on squid, fish, and arthropods, and it breeds in crevices and under vegetation on offshore islets. The variability this species displays in choosing nesting sites may explain the healthier status of its population in comparison to petrels such as the *Pterodroma* group. The bird is also a rare vagrant with a few documented and several suspected records off North Carolina (Tove et al., 1998). There is no evidence that the South Atlantic Planning Area is an important habitat for this species.

LC Cory's Shearwater (*Calonectris diomedea*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 5; Population: 600,000 pairs

Cory's shearwater (*Calonectris diomedea*) is a frequent visitor to the South Atlantic Planning Area. It can be found in all seasons but is most common in summer and fall. Both subspecies are found, including the nominate subspecies *diomedea,* which breeds on islands around the Mediterranean, and the more numerous Atlantic subspecies, *borealis*, which breeds in the Azores, Salvages, Madeira, and Canary Islands. All samples collected in North Carolina waters have been *diomedea* (Lee unpubl. data). The two are easiest to distinguish in the hand and many observations are too brief for the distinction to be made. This large shearwater is often found in mixed species flocks and, along with greater and sooty shearwaters, occurs closer to land than many petrels (Figure 8.13). It is not a deep diving shearwater, but usually feeds on the surface in *Sargassum* mats or with other shearwaters. The South Atlantic Planning Area appears to be an important migratory area for the species as a whole, as large numbers can often be found there (Wallace and Wigh, 2007).

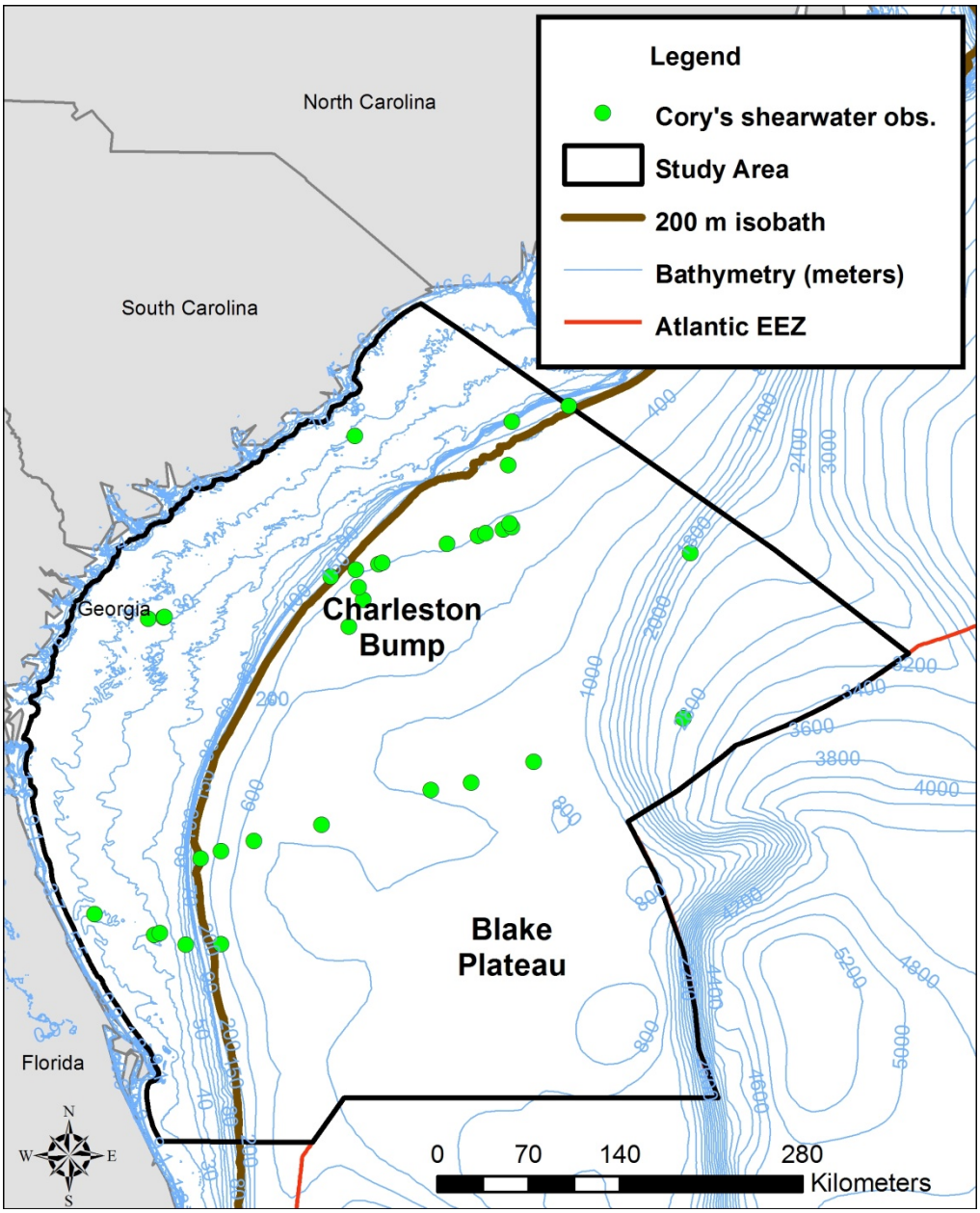


Figure 8.13 Observations of Cory's shearwaters during at-sea surveys conducted by NOAA in 1992, 1998, and 1999.

NT Cape Verde Shearwater (*Calonectris edwardsii*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Population: 20,000 pairs

This rare potential vagrant that has been documented off of North Carolina at least once (Patteson and Armistead, 2004). It may occur in small numbers in the South Atlantic Planning Area but has not been documented before. Its behavior is similar to Cory's shearwater. The single documented individual observed off the coast of North Carolina was within a flock of Cory's in the convergence zone of continental shelf water and the Gulf Stream.

LC Great Shearwater (*Puffinus gravis*)
State of Knowledge-- Breeding: n/a; Foraging: 3; Distribution: 4; Status: 4; Population: 5,600,000 pairs

This common transequatorial migrant in the South Atlantic Planning Area spends the austral winter in the North Atlantic. It breeds on three islands of the remote Tristan de Cunha group and on Gough Island, all in the South Atlantic. The species is found in all months and sometimes in high abundance from mid-May to early November (Wallace and Wigh, 2007). The South Atlantic Planning Area thus appears to be an important migratory and feeding area for this species, and any event or change in the South Atlantic Planning Area that causes increased mortality in great shearwaters could impact the population. In May and June of some years, thousands of dead and dying great shearwaters are found along the eastern side of the North Atlantic from the Lesser Antilles to New England. Most of these individuals are emaciated fledglings making their first migrations; the frequency of the die offs appears to be increasing, even considering greater search effort (Lee, 1995; 2009). The cause of the mass strandings is not clear.
Great shearwaters eat squid and tough-bodied fish, such as mackerel (Brown et al., 1981). There have been few studies of the birds at their breeding grounds (Rowan, 1952) because they are remote and inaccessible. In the South Atlantic Planning Area, they are attracted to frontal eddies of the Gulf Stream along the continental slope (Haney, 1986a) but they are not associated with rafts of *Sargassum* to the extent that other birds in the area appear to be (Haney, 1986b).

Recently, research on large-scale movements of great and sooty shearwaters has been initiated (Ronconi et al., unpubl. data). Satellite tags have been deployed on several individuals of each species. Data have yet to be fully analyzed or published but results are anticipated to substantially enhance what is known about the ecology and habitat use of these two pelagic seabirds.

NT Sooty Shearwater (*Puffinus griseus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 20,000,000 pairs

Another transequatorial migrant, the sooty shearwater breeds in the Southern Hemisphere and winters in the Northern Hemisphere in both the Pacific and Atlantic Oceans. The bulk of the population breeds in the South Pacific near Australia, New Zealand, and Chile, but tens of thousands breed in the Falkland Islands in the South Atlantic. It is suspected that the South Atlantic population migrates to the North Atlantic while most Pacific birds remain in that ocean during migration. Nineteen birds in New Zealand all migrated to the North Pacific (Shaffer et al., 2006).

BirdLife rates the species as Near Threatened because the populations at breeding colonies and on pelagic surveys off [Western] North America have all seen significant declines. Few data and no population estimates are available for this species in the South Atlantic Planning Area where the species is rare to uncommon in May–October (Wallace and Wigh, 2007). Sooty shearwaters are often observed from the beach in May if a strong east wind pushes them towards shore. Most

of the Atlantic population appears to summer in the waters off New England and the Maritime Provinces.

Sooty shearwaters are excellent divers, reaching depths of 67 m (Weimerskirch and Sagar, 1996). They will dive from several meters in the air if they detect prey; however, rather than spearing into the water as a booby or gannet would, they flop on the belly and duck under, flying down at a 45 degree angle (Brown et al., 1978). In comparison to great shearwaters, they consume more Euphausiids and soft-bodied fish, such as herring (Brown et al., 1981). Little is known about their feeding behavior in the South Atlantic Planning Area. Sooty shearwaters are frequently caught as by-catch in drift nests and long line fisheries in the Pacific Ocean (Uhlmann, 2003).

Recently, research on large-scale movements of great and sooty shearwaters has been initiated (Ronconi et al., unpubl. data). Satellite tags have been deployed on several individuals of each species. Data have yet to be fully analyzed or published but results are anticipated to substantially enhance what is known about the ecology and habitat use of these two pelagic seabirds.

LC Manx Shearwater (*Puffinus puffinus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Population: 1,000,000 pairs

The Manx shearwater (*Puffinus puffinus*) is an uncommon visitor year-round in the pelagic waters of the South Atlantic Planning Area. It breeds in large colonies in Ireland and Great Britain and there are small satellite populations from Massachusetts, Newfoundland, Iceland, the Azores, and the Canaries. This species has been studied continuously at the two largest colonies in Wales since the 1950s. After the breeding season, adults abandon their chicks and fly across the Central Atlantic to waters off the coast of Brazil. The fledglings follow several weeks later. During their return migration, many pass through the South Atlantic Planning Area. Their time of peak abundance is December through March (Lee, 1995), as they make their way back to their breeding sites.

LC Audubon's Shearwater (*Puffinus lherminieri*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 2; Population: 500,000 pairs

Audubon's shearwater is a common visitor to the South Atlantic Planning Area in summer but can be found there year-round. It is one of two Procellariiforms that is known to use the area for foraging during the breeding season. This species has populations in all tropical oceans; the taxonomy is undergoing review because mitochondrial DNA indicates that the little (*Puffinus assimilis*) and Audubon's shearwaters in the North Atlantic from Macronesia, the Bahamas, and Caribbean are more closely related to each other than to populations that share more similar morphology in the Pacific and Indian Oceans (Austin et al., 2004). The birds seen in the South Atlantic Planning Area are from the West Indian population, which has a fragmented and decreasing population of at least 2,700 pairs and is at risk of extinction in the region (Bradley and Norton, 2009). The population is difficult to census and has never been properly counted at

the majority of breeding sites, but recent fieldwork indicates that the population may have 10,000 to 20,000 breeding pairs (Mackin, unpubl. data), most of which are concentrated on a few small, low cays that are free of introduced predators. Current estimates suggest the population is a fragment of its prehistoric size.

The species is common offshore in the South Atlantic Planning Area (Figure 8.14) and off North Carolina from August through September, to the extent that it was thought the entire population might migrate to the area off the southeastern US (Lee, 1995). However, birds tracked by geolocators from the Central Bahamas show that, while the birds do spend time in the South Atlantic Planning Area and off North Carolina, they also move north in the fall and reach the continental slope near Newfoundland (Jodice et al., unpubl. data). This species dives regularly to depths up to 35 m (Burger, 2001; Mackin, 2004). In the Bahamas, it is often found diving for sardine-sized fish that are also targeted by schools of tuna. It also frequently picks prey out of small *Sargassum* reefs in the Bahamas near breeding sites (pers. obs.) and in the South Atlantic Planning Area (Haney, 1986b) where it also feeds at frontal eddies and continental slope waters at the edge of the Gulf Stream (Haney, 1986a). The South Atlantic Planning Area is an important feeding area and migratory route for the population; any threat there could contribute to the continued decline of the population.

LC Little Shearwater (*Puffinus assimilis*)
State of Knowledge - Breeding: n/a; Foraging: 3; Distribution: 3; Status: 2; Population: ~500,000 pairs

The little shearwater is a vagrant species in the South Atlantic Planning Area that breeds in Macronesia. As with Audubon's shearwater, the taxonomy of this species is a matter of some dispute. One confirmed specimen for the South Atlantic Planning Area was found in 1883 after a storm (Peters, 1924). It was incorrectly labeled as an Audubon's shearwater at first. It is unclear whether the bird was of the Azores, Salvages, Madeira, and Canary Subspecies, *P. a. baroli*, or of the Cape Verde subspecies *P. a. boydi*. This species differs slightly from Audubon's shearwater in that its plumage is more black than brown, it is smaller, has shorter wings, and it has different characteristics in flight. Lee (1988) and a few others report potential sightings off Cape Hatteras but none have been accepted as confirmed records (Lee, 1995; Tove et al., 1998). As is the case of the Cape Verde shearwater, there are probably individuals of the species within flocks of Audubon's shearwaters in the study area that are overlooked because they are so similar. However, there is no evidence as of yet that the South Atlantic Planning Area or Cape Hatteras to the north are important areas for the species. From an ecological perspective, the species behaves like Audubon's shearwater and specimens should be carefully examined to determine specific identity.

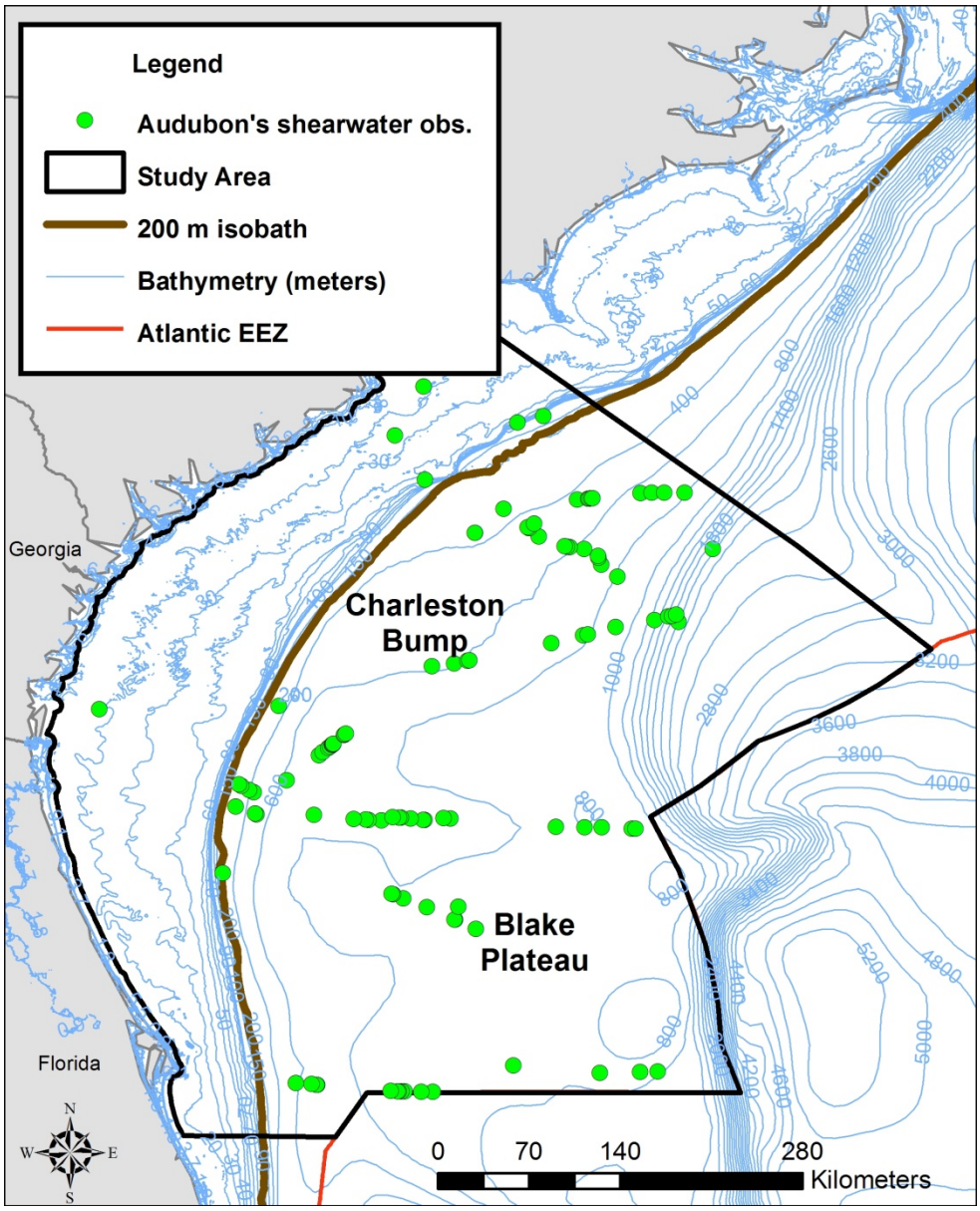


Figure 8.14 Observations of Audubon's shearwaters during at-sea surveys conducted by NOAA in 1992, 1998, and 1999.

LC Wilson's Storm-Petrel (*Oceanites oceanicus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 3; Population: 4,000,000 pairs

A fairly common visitor to the South Atlantic Planning Area, Wilson's storm-petrel nests in huge numbers in the Sub-Antarctic region and spends the Austral Winter in the northern Pacific and northern Atlantic Oceans. It is found, sometimes in large flocks, April–December in the South Atlantic Planning Area. This species feeds on small items at the surface, frequently using its outstretched wings to glide just above the waves while walking on the water with its long legs. It

feeds on planktonic crustaceans and fish, and it often picks up droplets of oil on the sea which occur in areas of chum or above feeding frenzies where the oils of fish float to the surface.

LC White-faced Storm-Petrel (*Pelagodroma marina*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 1,900,000 pairs

A species that has not yet been spotted in the South Atlantic Planning Area, white-faced storm-petrels breed in Tristan de Cunha and Macronesia in the Atlantic Ocean and Australia and New Zealand in the Pacific. Watson et al. (1986) found that all specimens collected in the northwest Atlantic were of the Cape Verde subspecies *P. m. eadesi*. The species is regularly looked for and spotted off Cape Hatteras North Carolina in late August, and it is likely to also occur in the South Atlantic Planning Area.

LC European Storm-Petrel (*Hydrobates pelagicus*)
State of Knowledge-- Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Population: 430,000 pairs
Another species that is likely vagrant off of North Carolina and has not yet been documented in the South Atlantic Planning Area, European storm-petrels breed from Norway, Iceland, and the Faroes, and small colonies are found in the Mediterranean and south to the Canary Islands. Its foods and behaviors are similar to other storm-petrels and, if present, would likely be found within mixed species flocks. There is no evidence that the South Atlantic Planning Area is an important area for this species.

LC Leach's Storm-Petrel (*Oceanodroma leucorhoa*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Population: 6,670,000 pairs

Leach's storm-petrel is a regular, uncommon migrant to the South Atlantic Planning Area in the summer that can also be found in the fall and winter. The Atlantic population breeds from Maine through Iceland to Great Britain and Norway in colonies that can number in the millions of pairs. Because the species is rarely seen in significant numbers off Hatteras, Lee (1995) posits that the migratory route is far to the east of the southeastern US. The peak of occurrence in late spring coincides with the breeding season, and it is possible, given the bird's excellent flying capabilities, that some individuals found in the South Atlantic Planning Area are breeding birds. With the abundance of good feeding areas nearer their breeding grounds, that result would be surprising. It is more likely that the birds off North Carolina are non-breeders or individuals that failed early in the breeding process and left the nesting grounds. This species feeds in a manner similar to that of other storm-petrels and the South Atlantic Planning Area does not appear to be an important foraging range.

LC Madeiran (Band-rumped) Storm-Petrel (*Oceanodroma castro*)
State of Knowledge - Breeding: n/a; Foraging: 3; Distribution: 3; Status: 3; Population: ~50,000 pairs

Uncommon but regular in the South Atlantic Planning Area (Wallace and Wigh, 2007), the population breeds in Madeira and the Azores south to Cape Verde and St. Helena. It is most common in the study area in the summer. Like other storm-petrels, it patters and gleans from the surface while gliding or sometimes sitting on the surface. This species is found most often from May–July in the South Atlantic Planning Area and is a vagrant at other times.

VU Monteiro's (Band-rumped) Storm-Petrel (*Oceanodroma monteiroi*)
State of Knowledge - Breeding: n/a; Foraging: 3; Distribution: 3; Status: 2; Population: 250 pairs

This is a cryptic species that is nearly identical to band-rumped storm-petrel (*Oceanodroma castro*) but is reproductively isolated by a breeding phenology opposite that of its sister species. Only two nesting sites are known but more are suspected. No distinctions are suspected or known between its behavior and ecology at sea and that of band-rumped storm-petrel. Since the band-rumped storm-petrels of the South Atlantic Planning Area are found in the summer, when the Monteiro's storm-petrel is breeding, and this species is very rare compared to *O. castro*, the birds seen in the South Atlantic Planning Area are likely *O. castro*.

LC Swinhoe's Storm-Petrel (*Oceanodroma monorhis*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 2; Population: 33,000 pairs

This species has been observed as a vagrant off North Carolina (O'Brien et al., 1999) but has not been documented in the South Atlantic Planning Area. A common bird in the Pacific, this species has now been spotted around the North Atlantic; the sighting includes an individual defending a nest site in Madeira. However, there is no evidence that the South Atlantic Planning Area is an important habitat for this species.

LC Black-bellied Storm-Petrel (*Fregetta tropica*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 2; Population: 167,000 pairs

Another potential vagrant that has been documented off North Carolina, this Antarctic and Subantarctic breeder disperses to the tropics during the Austral Winter and a few straggle as far north as the South Atlantic Planning Area. There is no indication that the South Atlantic Planning Area is an important area for this species and it is not of conservation concern.

8.4.1.2.2 Sulids, Tropicbirds, and Pelicans (Pelecaniformes)

This group includes large seabirds that are mostly tropical and temperate in distribution. The taxonomy of the group is in question, particularly for the tropicbirds, which are placed here for historical reasons but lack the distinctive throat pouch that all other members have. Genetic studies indicate that tropicbirds might be convergently evolved, forming a fourth order of birds that contains true seabirds (Hackett et al., 2008), but for now they are placed within this order. While tropicbirds, boobies, and frigatebirds are true seabirds, the cormorants and pelicans are primarily nearshore, inshore, or freshwater species.

LC White-tailed Tropicbird (*Phaethon lepturus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 16,000 pairs

This species is a rare, regular summer visitor to the South Atlantic Planning Area that ranges very far at sea. This bird is highly pelagic and nests on tropical and sub-tropical islands. The North Atlantic population is an endemic subspecies that primarily nests in Bermuda and The Bahamas with approximately 3,000 pairs in small, loose colonies. The species also occurs in good numbers from the Cayman Islands through the Greater and Lesser Antilles to St. Vincent. The population is declining and at risk in the Caribbean (Bradley and Norton, 2009), but the Pacific and Indian Ocean populations are thought to be healthier. Despite its LC rating, the worldwide population is only 16,000 pairs. Its habit of nesting in many, small colonies and staying with chicks until they are large (Wingate, pers. comm.) may protect it from extinction, but it has declined at most areas and is much less common than it was when humans began settling small islands around the world.

Haney (1986b) found that white-tailed tropicbirds were common near large aggregations of *Sargassum* that form around frontal eddies or other features near the Gulf Stream. Tropicbirds usually travel alone; they feed by plunge diving to capture flying fish, squid, and other substantial prey items. Breeding individuals might feed in the South Atlantic Planning Area, as indicated by geolocators recovered from three individuals nesting in the Exuma Cays, Bahamas (Jodice et al., unpubl. data) but an even mix of adults and chicks is found in the study area; most of the birds are probably not commuting from nest sites to the South Atlantic Planning Area but instead are visiting after breeding is complete. Most items brought to chicks in the Bahamas are squid that are probably captured at night fairly close to the breeding sites, since feedings of chicks take place daily (Schaffner, 1990; Mackin, unpublished data). The population is highly diffuse in the North Atlantic, but the South Atlantic Planning Area is an important feeding area and the Caribbean subspecies could be impacted by any disturbances in this area. The birds appear to be affected by oil pollution in the Sargasso Sea (Wingate in Lee and Walsh-McGehee, 2000).

LC Red-billed Tropicbird (*Phaethon aetherus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 2; Population: 5000 pairs

A significantly larger bird but similar to the white-tailed tropicbird, the red-billed tropicbird is also a rare, regular summer visitor to the South Atlantic Planning Area. This species nests from Puerto Rico through the Lesser Antilles and islands off South America. It outcompetes white-tailed tropicbirds for nest sites in areas where the two species overlap. Population estimates are lacking, out of date, or both for most colonies. The best estimates available indicate 1,900–3,400 pairs in the Northwest Atlantic. Other populations of this subspecies (*P. a. mesonauta*) occur in the Galapagos Islands, the Gulf of California, Peru, and Ecuador as well as the Canary Islands in the Atlantic (Lee and Walsh-McGehee, 2000). This species is rare worldwide, with only 5,000 to 20,000 breeding pairs. It is at-risk in the Caribbean (Bradley and Norton, 2009) despite its LC status by BirdLife, and, as for the Caribbean white-tailed tropicbird, the red-billed tropicbird

population could be significantly impacted by disturbances in the South Atlantic Planning Area. Behavior at sea is similar to white-tailed tropicbird.

LC Masked Booby (*Sula dactylatra*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 2; Population: Unknown

A rare summer visitor in the South Atlantic Planning Area, the masked booby is a highly pelagic, pan-tropical bird. Most of the North Atlantic population nests in the Campeche Banks in Mexico, but other significant colonies are in Puerto Rico, the Virgin Islands, Anguilla, and islands off the Coast of South America. The Atlantic subspecies, *S. d. dactylatra,* also breeds at Ascension Island and off the coast of Brazil. BirdLife does not list its global population due to poor information. The Caribbean population is thought to be 1,000–5,000 breeding pairs, but few colonies have been surveyed this century. Based on plumage characteristics, it's been determined that many of the individuals seen in the South Atlantic Planning Area and off North Carolina are juveniles (Lee, 1995). In the South Atlantic Planning Area, masked boobies are usually seen without conspecifics, feeding among other seabirds on squid, flying fish, and fish associated with *Sargassum* including young mahi mahi (Lee and Haney, 1984).

LC Brown Booby (*Sula leucogaster*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 3; Population: 66,000 pairs

Brown boobies are vagrants from tropical seas; they have seldom been documented in the South Atlantic Planning Area. This is a smaller but more common booby than the masked booby, but it is much less pelagic and displays more localized feeding in shelf, bank, and other inshore waters around the West Indies. Only one has been documented off Georgia in the South Atlantic Planning Area, several have been found off South Carolina, but it is seen regularly south of the study area off of Florida and in the Florida Keys (Lee and Haney, 1984). The bird breeds in small colonies around the Bahamas and West Indies, and has declined in a similar way to most other Caribbean seabirds because of introduced predators and predation by humans. Its diet consists of fish and squid caught by high-speed, vertical plunge diving. The South Atlantic Planning Area is not a critical migratory route or important feeding area for this species.

LC Red-footed Booby (*Sula sula*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 3; Population: 333,000 pairs

The red-footed booby is a tropical, tree-nesting sulid that is a vagrant in the South Atlantic Planning Area with one seen 138 km off of Central Florida on the eastern side of the Gulf Stream (Wallace and Wigh, 2007). About 12,000 breeding pairs occur in the Caribbean including the Cayman Islands, Campeche Banks, Coastal Central America, Puerto Rico, and the Lesser Antilles (Lee and Mackin, 2009). The South Atlantic Planning Area is not an important area for this species.

LC Northern Gannet (*Morus bassanus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 5; Population: 316,000 pairs

The northern gannet is a common winter resident observed in nearshore waters of the South Atlantic Planning Area. While they are very common in winter off Cape Hatteras, counts of individuals are lower but the species is still common in the region from November to March (Lee and Haney, 1984). This species is strictly inshore and rarely encountered in water deeper than 20 m, although it may venture farther out in the wide continental shelf area off Georgia. All records of banded individuals indicate that this population breeds in the northwest Atlantic off Quebec and Newfoundland. Reported foods while wintering off North Carolina include squid, Atlantic menhaden, silversides, and other fish. They often follow pods of feeding dolphins and porpoises and are attracted to chum and bycatch from fishing vessels (Lee and Haney, 1984). The species does not warrant conservation concern, but is a very significant part of the seabird fauna of the South Atlantic Planning Area in winter. Its relative abundance in nearshore habitats is reflected, in part, by the frequency with which it is observed during Christmas Bird Counts (Figure 8.15). Recently, efforts to track migrating gannets from Newfoundland have been initiated (Montevecchi et al., unpub. data). Satellite telemetry locations indicate migratory paths primarily nearshore. These data are sure to enhance our understanding of gannet ecology and habitat use at sea.

LC Double-crested Cormorant (*Phalacrocorax auritus*)
State of Knowledge - Breeding: 4; Foraging: 4; Distribution: 3; Status: 5; Population: 366,000 pairs

Double-crested cormorants are a common, year-round resident of the South Atlantic Planning Area with winter populations bolstered by migrants from the north.

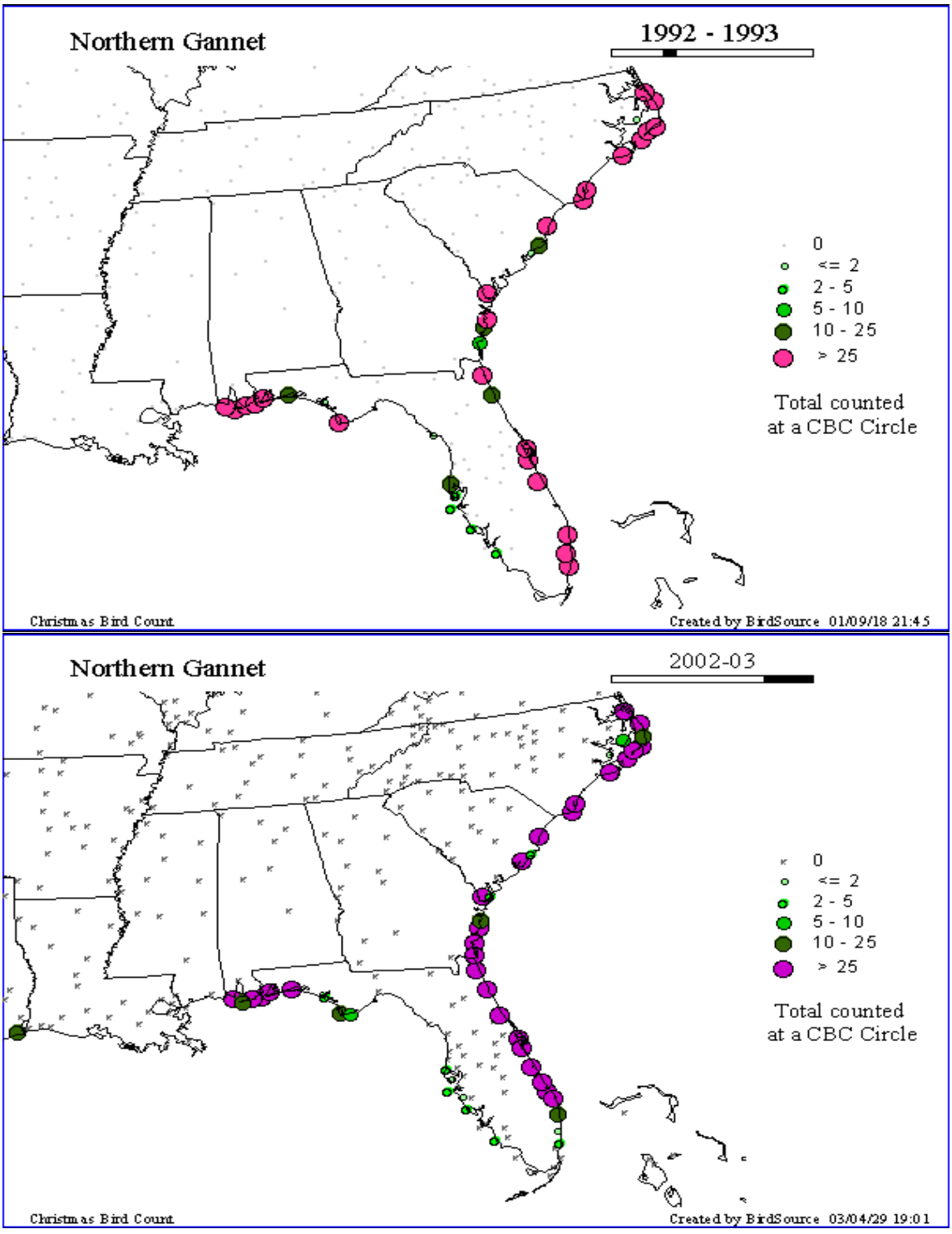


Figure 8.15 National Audubon Society Christmas Bird Count data for northern gannets in the Southeast US, 1992-1993 and 2002-2003.

8.4.1.2.3 Gulls, Shorebirds, and Allies (Charadriiformes)

Charadriiform birds are primarily inshore or coastal species in the South Atlantic Planning Area, except for the phalaropes, jaegers, and alcids, which winter at sea and breed in the Arctic, sub-Arctic, and temperate areas.

Skuas and Jaegers

These large predators appear similar to but much larger than their gull-relatives. Skuas and jaegers harass, steal food from, and prey upon other seabirds. They are excellent, fast flyers and migrate thousands of kilometers. They tend to dominate other seabirds in foraging aggregations. While skuas feed on fish and invertebrates, parasitizing, or eating other seabirds, jaegers often eat mammalian prey on the breeding grounds and feed at sea in the non-breeding season.

LC South Polar Skua (*Catharacta maccormicki*) and Great Skua (*Catharacta skua*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 3; Population: 3,300/16,000 pairs

South polar skua is a regular but rare visitor during summer. This species breeds around Antarctica and spends the Austral winter in the North Atlantic and Pacific Oceans. Lee (1995) reports that all North Carolina records occur in deep Gulf Stream waters, but Tove et al. (1998) reported that some individuals are also photographed inshore each year on the Outer Banks. Wallace and Wigh (2007) give a similar report for the South Atlantic Planning Area. The total population is only 3,300 to 6,600 breeding pairs. The South Atlantic Planning Area is not known to be a critical feeding area for the population. The great skua breeds in the Arctic and is a potential vagrant that has been seen off North Carolina but never in the study area, where it would be expected to occur inshore.

LC Pomarine Jaeger (*Stercorarius pomarinus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 2; Population: 80,000 pairs

This species is an uncommon year-round visitor that primarily migrates through and to the south of the South Atlantic Planning Area and is sometimes abundant in late fall (Lee, 1995; Tove et al., 1998; Wallace and Wigh, 2007). This species breeds in the high Arctic and feeds on almost exclusively on lemmings during breeding (Wiley and Lee, 2000). BirdLife's population estimates of this species run from 80,000 to 1,000,000 pairs, probably relating to the fact that breeding only occurs in years when and where lemming populations are high. Timing and abundance of sightings of jaegers will also vary between seasons due to the high variability in breeding success each year. In winter, it can be found inshore. In migration, it is usually in the Gulf Stream. In summer, it is found around schools of tuna (Wallace and Wigh, 2007). Large numbers pass through or winter in the South Atlantic Planning Area and would be exposed to any ecological disturbance there, but the population is large. Wiley and Lee (2000) warn that the nomadic and clustered nature of the breeding population around areas of high abundance of lemmings makes the population susceptible to disturbances in the tundra. Furthermore, if climate change impacts the high arctic lemming cycles, this species is certainly susceptible.

LC Parasitic Jaeger (*Stercorarius parasiticus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 2; Population: 160,000 pairs

Parasitic jaeger is a common migrant that is usually seen nearshore, passing through the South Atlantic Planning Area in spring and fall. Parasitic jaegers winter in the tropics and southern temperate areas. It is rare to uncommon in winter but can be found year-round in the South Atlantic Planning Area (Wallace and Wigh, 2007). Where it nests near large seabird colonies, it steals food from other seabirds. In the majority of its range, it eats small birds, mammals, and eggs (Wiley and Lee, 1999). At sea, it is a kleptoparasite. Population estimates vary from 160,000 to 3,300,000 pairs. Large numbers pass through or winter in the South Atlantic Planning Area and would be exposed to any ecological disturbance there, but the population is large and stable. It may be susceptible to climate change because of its dependence on high Arctic breeding areas.

LC Long-tailed Jaeger (*Stercorarius longicaudus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 50,000 pairs

Long-tailed jaegers are uncommon during migration through the South Atlantic Planning Area with some occurrence during spring, summer, and fall. Birds that pass through the area winter mostly in the South Atlantic. Wiley and Lee (1998) state that it is the most abundant jaeger, and BirdLife estimates its population at between 50,000 and 1,600,000 pairs. It is highly dependent on lemmings and voles, and during years of poor lemming populations it leaves the breeding grounds and goes off to sea to feed. This bird is rarely seen from shore, instead migrating offshore. Thus, Lee (1995) argues that it is more abundant off the southeastern US than was previously thought. Like the other jaegers, it is susceptible to impacts of climate change in the Arctic breeding grounds.

Pelagic Gulls (Larinae)

While most gulls associate with beaches and inshore waters, four species can be found nearshore or even offshore during the winter in the South Atlantic Planning Area.

LC Black-legged Kittiwake (*Rissa tridactyla*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 5,660,000 pairs

This species is an extremely numerous arctic breeder that is common to uncommon in winter in the South Atlantic Planning Area. It is mostly pelagic in winter, feeding in areas of upwelling, but Lee (1995) notes that it seems less restricted to particular habitats than other pelagic birds in winter.

LC Sabine's Gull (*Xema sabini*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 110,000 pairs

Sabine's gull is a polarctic, rare winter visitor. Most of the population probably migrates in the open ocean east of the South Atlantic Planning Area, and most birds are seen in spring and fall (Lee, 1995). It forages in coastal upwelling zones during winter (Day et al., 2001). The South Atlantic Planning Area does not appear to be an important habitat for this species.

LC Little Gull (*Larus minutus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 33,000 pairs

LC Bonaparte's Gull (*Larus philadelphia*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 90,000 pairs

Bonaparte's gulls breed in taiga and boreal forest areas of North America in loose colonies, and their breeding behavior is not well documented (Burger and Gochfeld, 2002). They feed on insects in the breeding season and small crustaceans and fish in the winter. The South Atlantic Planning Area is an important wintering area for Bonaparte's gull and the increasing but rare North American population of little gulls.

Terns (Sterninae)

LC Bridled Tern (*Sterna anaethetus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 200,000 pairs

LC Sooty Tern (*Sterna fuscata*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 7,000,000 pairs

LC Brown Noddy (*Anous stolidus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 300,000 pairs

Of the many terns that occur in the South Atlantic Planning Area, most are inshore or nearshore species. These three pelagic or partly pelagic species from the tropics can be found primarily in summer in the South Atlantic Planning Area. All are found most often in or east of the Gulf Stream and are more common in the southern part of the region. They tend to feed over *Sargassum* (bridled tern; Haney 1986b) or over schooling fish (sooty tern and brown noddy).

Alcids (Alcidae)

LC Dovekie (*Alle alle*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 200,000 pairs

LC Common Murre (*Uria aalge*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Population: 6,000,000 pairs

LC Thick-billed Murre (*Uria lomvia*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 7,333,000 pairs

LC Razorbill (*Alca torda*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 500,000 pairs

LC Atlantic Puffin (*Fratercula arctica*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 3; Status: 3; Population: 1,900,000 pairs

The alcids that occur in the South Atlantic Planning Area are Arctic and sub-Arctic birds that are rare but occasionally numerous visitors during cold snaps in winter. They are generally inshore of the Gulf Stream and can often be seen feeding in the surf off of beaches. Wallace and Wigh (2007) use the term "irruptive" to describe the pattern of occurrence because they tend to move as flocks and show up together. The South Atlantic Planning Area is not known to be an important habitat for these populations.

8.4.1.2.4 Synopsis

Pelagic seabirds do not breed in the South Atlantic Planning Area; those species that do occur there are either commuting breeders from the Caribbean or Bahamas, migrating or nonbreeding species from outside the region, or pre-breeding individuals from outside the region that wander before the onset of breeding. Most of what is known about pelagic seabirds in the South Atlantic Planning Area originates from either anecdotal observation of birds at sea or from a series of publications from the late 1980s and early 1990s. The pelagic seabird community of the South Atlantic Planning Area appears to be less rich, abundant, and diverse than that in the adjacent mid-Atlantic region, particularly the coast off of the Outer Banks. The primary factor leading to this apparent disparity in seabird communities between the South Atlantic Planning Area and mid-Atlantic is likely the lack of enhanced or predictable productivity from physical oceanographic features, such as upwelling created by the Gulf Stream, eddies, or sea mounts. A unique microhabitat within pelagic areas of the South Atlantic Planning Area is *Sargassum* mats, which attract a community of potential prey items for seabirds. Haney (1986b) reported 23 seabird species foraging on *Sargassum* mats in the South Atlantic Planning Area, with >50% of foraging white-tailed tropicbirds, masked boobies, and bridled terns observed at *Sargassum* mats (Haney, 1986b). These mats can grow to a hectare in size in certain vortex circulations and even may support roosting birds (e.g., bridled and black tern). Conservation concerns for this guild are broadly defined because of a lack of detailed, species-specific data. Mortality from fisheries bycatch and degradation of marine habitats through pollution events are two primary concerns in the pelagic zone. Pelagic seabirds in the region also may experience threats at nesting grounds 1000s of km from the South Atlantic Planning Area.

8.4.2 Shorebirds

Two groups of shorebirds are discussed: breeding shorebirds and migratory shorebirds (Table 8.12).

Four species of shorebirds from one order and four families breed in all three states in the South Atlantic Planning Area in or adjacent to marine habitats: Wilson's plover (*Charadrius wilsonia*), black-necked stilt (*Himantopus mexicanus*), willet (*Catoptrophorus semipalmatus*), and American oystercatcher. This guild is relatively disparate in terms of their nesting habits and behavior. Wilson's plovers nest singly along beaches, stilts commonly nest in coastal freshwater marshes, willets commonly nest in salt marshes, and American oystercatchers nest on barrier island beaches, on shell rakes that occur in estuaries, bays, and along the Intracoastal Waterway. Each of these species but stilts can commonly be found foraging on barrier island beaches and in tidal estuaries. American oystercatchers and Wilson's plovers are both species of conservation concern (Appendix 8.1) with survey efforts, research and management directed toward them throughout the South Atlantic Planning Area; hence additional information for these two species is provided.

8.4.2.1 American Oystercatcher and Wilson's Plover

State of Knowledge American Oystercatcher – Breeding: 5; Foraging: 4; Distribution: n/a; Status: 5; Population: 500 – 750 pairs

State of Knowledge Wilson's Plover – Breeding: 3; Foraging: 3; Distribution: n/a; Status: 3; Population: n/a

American oystercatchers breed and winter in the South Atlantic Planning Area. The species is listed as a Species of High Concern by the US Shorebird Conservation Plan (Brown et al., 2001). American oystercatchers range along the eastern coast of the US from New England through Florida and also along the Gulf coast. The most recent population estimate is approximately 10,000 individuals; of these, it is estimated that 3,000 are breeding adults (Brown et al., 2005). While there is evidence of range expansion in the northeastern US, surveys and census data indicated a decline in the mid- and south-Atlantic states at least through the early 2000s (Mawhinney et al., 1999; Davis et al., 2001; Sanders et al., 2008). It is unclear if increases in more recent counts in some states (e.g., Virginia) are due to changes in survey methodology or to an actual increase in the population size. In the South Atlantic Planning Area, oystercatchers forage in tidal estuaries, bays, tidal creeks, and salt marshes on mollusks, primarily eastern oysters and mussels (Thibault, 2008; Hand et al., 2010). Nests are located on beaches of barrier, coastal, and dredge islands and on shell rakes along the Atlantic Intracoastal Waterway and the edges of bays and sounds. Reproductive success along the US Atlantic Coast appears to be low, with productivity estimates commonly <0.25 fledglings per pair (Nol, 1989; Davis et al., 2001; McGowan et al., 2005; Thibault, 2008).

Table 8.12
Occurrence and abundance of shorebirds by season in the South Atlantic Planning Area.

Scientific Name	Common Name	SP	SU	FA	WI
Order CHARADRIIFORMES					
Family CHARADRIIDAE					
Pluvialis squatarola	Black-bellied plover			C	C
Pluvialis dominica	America golden-plover	C	R	C	
Charadrius alexandrinus	Snowy plover				
Charadrius wilsonia	Wilson's plover	C	C	C	R
Charadrius semipalmatus	Semipalmated plover	C	R	C	C
Charadrius melodus	Piping plover	U	U	U	U
Family HAEMATOPODIDAE					
Haematopus palliatus	America oystercatcher	C	C	C	C
Family RECURVIROSTRIDAE					
Himantopus mexicanus	Black-necked stilt	C	C	C	U
Recurvirostra americana	American avocet	R	R	R	R
Family SCOLOPACIDAE					
Tringa melanoleuca	Greater yellowlegs	C	R	C	R
Tringa flavipes	Lesser yellowlegs	C	R	C	R
Tringa solitaria	Solitary sandpiper	C	C	C	R
Catoptrophorus semipalmatus	Willet	C	C	C	C
Actitis macularia	Spotted sandpiper	C	C	C	R
Numenius phaeopus	Whimbrel	C	C	C	C
Numenius americanus	Long-billed curlew			R	R
Limosa haemastica	Hudsonian godwit				R
Limosa fedoa	Marbled codwit			C	C
Arenaria interpres	Ruddy turnstone			C	C
Calidris canutus	Red knot			C	C
Calidris alba	Sanderling			C	C
Calidris pusilla	Semipalmated sandpiper			C	C

SP = spring, SU = summer, FA = fall, WI = winter. C = common, U = uncommon, R = rare, V = vagrant, PV = potential vagrant, EV = expected vagrant. Only species that are scored as 'rare' or better in at least one season are included. Underlined common names indicate species the breed in the South Atlantic Planning Area.

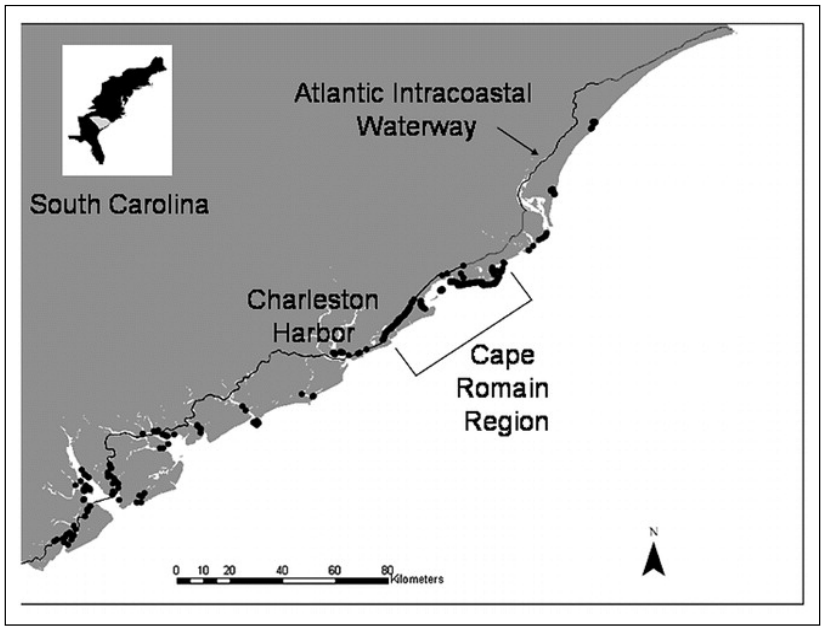
Table 8.12 Occurrence and abundance of shorebirds by season in the South Atlantic Planning Area (continued).

Scientific Name	Common Name	SP	SU	FA	WI
Calidris mauri	Western sandpiper			C	C
Calidris minutilla	Least sandpiper			C	C
Calidris fuscicollis	White-rumped sandpiper	U		U	
Calidris bairdii	Baird's sandpiper	U		U	
Calidris melanotos	Pectoral sandpiper	U		U	
Calidris ptilocnemis	Rock sandpiper				
Calidris alpina	Dunlin	C		C	C
Calidris ferruginea	Curlew sandpiper				
Calidris himantopus	Stilt sandpiper			C	
Limnodromus griseus	Short-billed dowitcher			C	C
Limnodromus scolopaceus	Long-billed dowitcher			U	U
Subfamily Phalaropodinae					
Phalaropus lobatus	Red-necked phalarope	C		C	C
Phalaropus fulicaria	Red phalarope	C		C	C

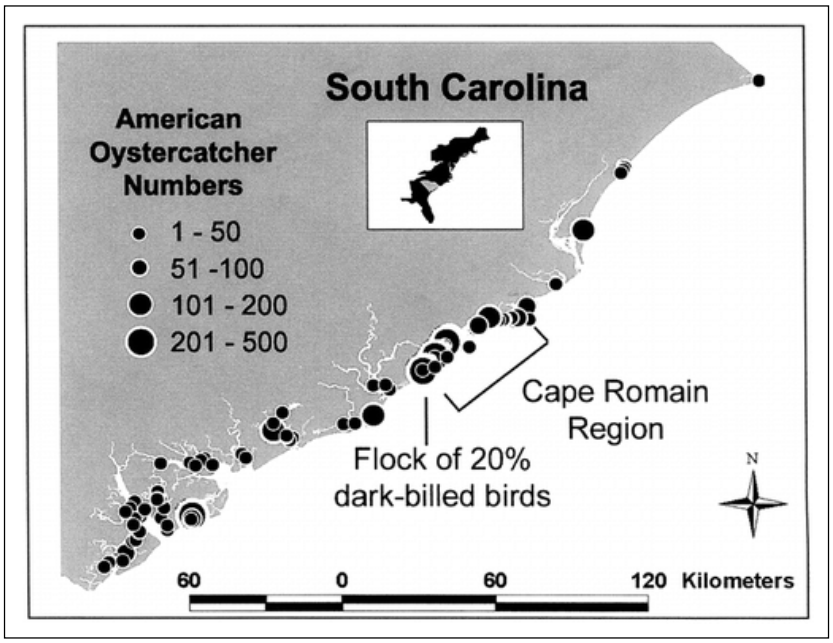
SP = spring, SU = summer, FA = fall, WI = winter. C = common, U = uncommon, R = rare, V = vagrant, PV = potential vagrant, EV = expected vagrant. Only species that are scored as 'rare' or better in at least one season are included. Underlined common names indicate species the breed in the South Atlantic Planning Area.

Approximately 400 pairs of oystercatchers nest in South Carolina; 230 of these pairs nest in the Cape Romain region, predominantly on shell rakes and sandy beaches (Figure 8.16A). The most recent nesting data that are readily available for Georgia are from 1999; efforts are currently underway to update these data. In 1999, 86 nests were located along the Georgia coast, and this appeared to be slightly fewer than were counted in 1980 (Winn, 2000). The highest nest counts occurred on Little St. Simons, Cumberland, St. Catherine's, and Little Tybee islands. There are no nesting records beyond scattered individuals reported during 2005–2010 in the South Atlantic Planning Area portion of Florida in that states' shorebird monitoring database.

The Cape Romain region also supports approximately one-fifth of the wintering oystercatcher population on the US Atlantic and Gulf coasts (Brown et al., 2005; Sanders et al., 2004; Figure 8.16B). Survey data suggest that the number of oystercatchers wintering in Cape Romain region has declined by 21% since the late 1980s (Sanders et al., 2004). Wintering waterbird surveys in Georgia suggest oystercatchers may occur on most of the barrier islands along the coast and are common on many of the same barrier islands that support nesting birds (e.g., Tybee and Little Islands, Little St. Simon's Island, and Cumberland Island). It is likely that oystercatchers are also common on beaches throughout north Florida during the nonbreeding season (Figure 8.17).



(A) Breeding season



(B) Nonbreeding season

Figure 8.16 Distrubution of American oystercatchers along the South Carolina coast during (A) breeding season (Sanders et al., 2008) and (B) nonbreeding season (Sanders et al., 2004).

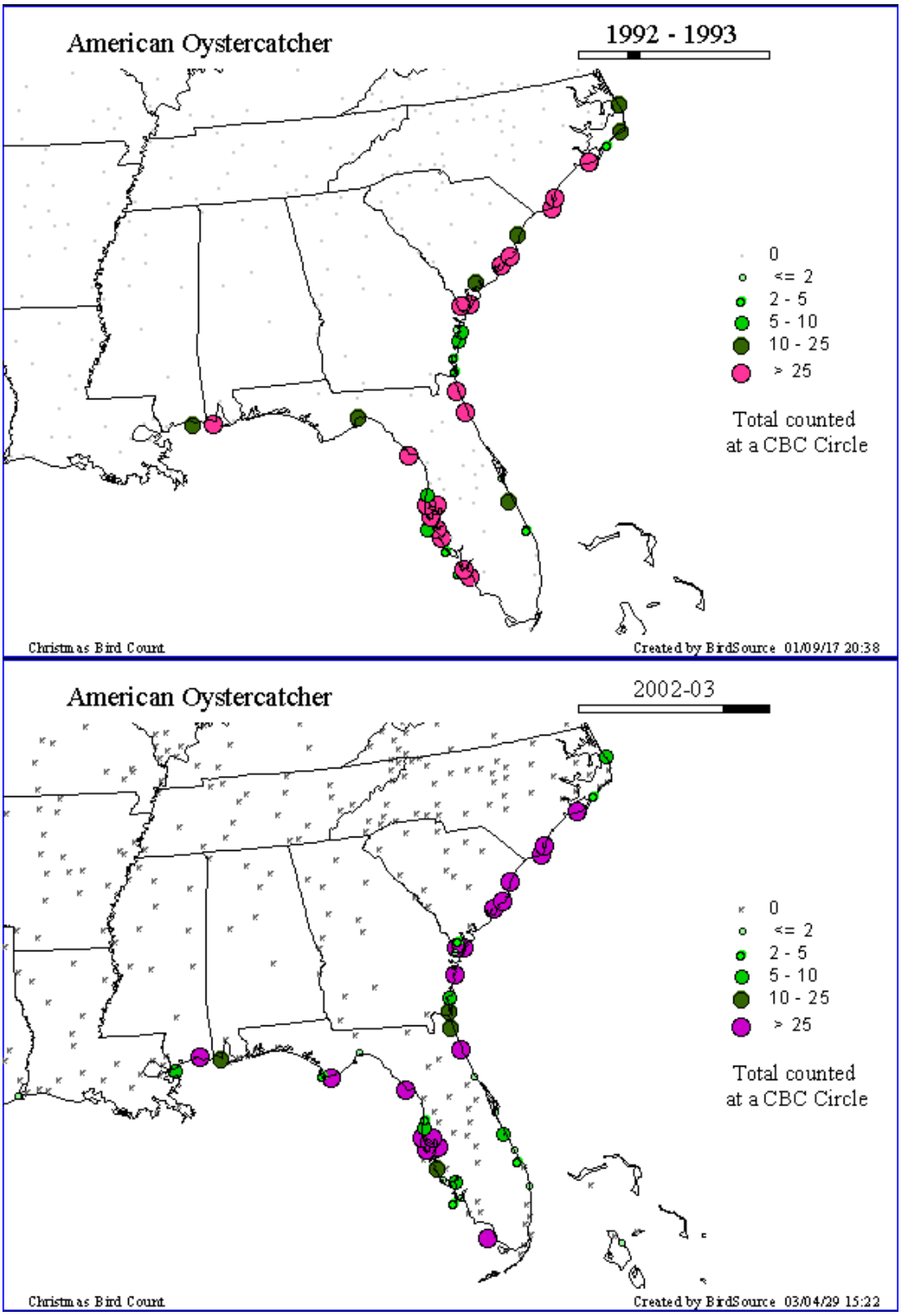


Figure 8.17 National Audubon Society Christmas Bird Count data for American oystercatchers in the Southeast US, 1992-1993 and 2002-2003.

Wilson's plovers nest solitarily along beaches where they also forage and raise chicks. This species is understudied in the region. Nests are cryptic and notoriously difficult to locate. In South Carolina, nests have been documented along beaches and shell islands in Cape Romain NWR, on beaches near the mouth of the North Edisto River (similar to locations for least terns), and, more recently, at the Savannah Spoil site and at South and Sand islands (SCDNR, unpubl. data). It is likely plovers are nesting elsewhere but nest surveys are difficult to conduct. In Georgia, a survey conducted in 2000 of 97% of Georgia's beaches resulted in the recognition of 107 possible breeding territories (Winn and George, 2000). Density of territories varied; the highest density was found on the south end of Cumberland Island, with approximately 7.5 territories per km. No plovers were found on the developed islands of Tybee and St. Simons. In Florida, nesting for Wilson's plovers has been documented on many of the same sites listed for least terns and black skimmers (e.g., Table 8.8 and 8.9; Amelia Island SP, Ft. Clinch SP, Huguenot Memorial Park, Bird Island group, Anastasia SP, Matanzas CWA). Wilson's plovers are recorded in low numbers and in scattered locations during winter in the South Atlantic Planning Area.

Major threats for oystercatchers and Wilson's plovers in this region include, but are not limited to, coastal development, human disturbance, avian and mammalian predation, loss of and disturbance to habitat, and flooding and overwash of nests. Many of these threats occur during both incubation and chick-rearing; it appears that, while some of these factors may be common throughout the range, the exact nature of a specific threat (e.g., its timing and severity) may vary among habitat types within a locale. The extent to which these threats are caused by or exacerbated by humans also may vary among regions and habitat types. A revised version of the Birds of North America species account for American oystercatcher is being developed.

8.4.2.2 Migratory Shorebirds

Warnock et al. (2002) provide an excellent review of the ecology of shorebirds in the marine environment. The South Atlantic Planning Area supports a greater diversity and abundance of migratory shorebirds compared to breeding shorebirds. Table 8.12 lists the most commonly occurring migratory shorebirds in the region; sites of importance mirror those listed for nearshore seabirds. Migrants represent primarily three families: Scolopacidae (sandpipers), Charadriidae (plovers), and Recurvirostridae (avocets). Along the Atlantic coast, migratory shorebirds are more common during the fall migration; during spring, the central flyway is a more likely route (Warnock et al., 2002). Migration altitudes can vary substantially from just beyond sea level to over 6,000 m.

Shorebirds can be tightly linked to productive marine areas and hence can be locally very abundant. For example, red knots (*Calidris canutus*) depend heavily on the eggs of horseshoe crabs as a food source during migration and highly productive coastal habitats can support thousands of knots for brief periods. Most shorebirds nest near or in the Arctic and use the coastal or marine areas of the South Atlantic Planning Area for feeding during migration to sub-tropical shores or as a wintering area. Piping plovers (*Charadrius melodus*) are the shorebird species of greatest conservation concern in the region (Appendix 8.1), although there has been increased management and research attention directed at red knots as of late.

With respect to use of the marine environment, shorebirds are found primarily on beaches or along the shores of estuaries. Foraging activity is often focused on beaches and tidal flats around low tide. At high tide, when foraging grounds are covered, birds require roosting habitats which may include shell rakes, beaches, estuarine islands and, occasionally, docks. Dunlin (*Calidris alpina*), sanderlings (*Calidris alba*), red knots, small sandpipers, and plovers primarily use beaches. Short-billed dowitchers (*Limnodromus griseus*) and marbled godwits (*Limosa fedoa*) are found on oyster reefs and docks. Greater yellowlegs (*Tringa melanoleuca*), spotted sandpipers (*Actitis macularia*), and ruddy turnstones (*Arenaria interpres*) use a variety of habitats (Dodd and Spinks, 2001). Data suggest that many of the beaches and islands that support nesting and wintering nearshore seabirds also support migratory shorebirds, although region-wide, coordinated surveys are lacking. For example, midwinter shorebird surveys at Cape Romain, ACE Basin, and Merritt Island NWRs show that these protected coastal areas are readily used by a variety of migratory and wintering shorebirds (Table 8.13).

Table 8.13
Relative abundance of wintering shorebirds at Cape Romain (2008-2010), ACE Basin (2000 – 2010), and Merritt Island NWRs (1999, 2001, 2003, 2006, 2007, 2008)

	Cape Romain	ACE Basin	Merritt Island
>100	Black-bellied plover Ruddy turnstone Marbled godwit	Dunlin Western sandpiper dowitcher spp.	Black-bellied plover Dunlin Sanderling Red knot Avocet Dowitcher
>500	Short-billed dowitcher Western sandpiper Willet American oystercatcher Semi-palmated plover	Least sandpiper Semi-palmated Sandpiper Greater yellowlegs	Western sandpiper
>1,000	Semi-palmated sandpiper Sanderling Red knot	Lesser yellowlegs Semi-palmated plover	
>5,000			
>10,000	Dunlin		
Data were summarized from aerial survey data available through a USFWS web portal: http://samigbird.ncusfws.org/sasindex.html. Species are listed if at least one count yielded >100 individuals.			

Primary management and conservation concerns for this suite of species include disturbance by humans at foraging and loafing areas. There is some question as to whether beach nourishment reduces access to invertebrates for shorebirds (Rakocinski et al., 1996). Finally, oil spills that degrade marine environments can have potentially major impacts on migrating shorebirds, both by disrupting feeding patterns and by leading to the direct mortality of food sources.

Unique among the shorebirds are phalaropes (*Phalaropus* spp.) which forage and roost regularly in open marine habitats during the nonbreeding season. Two species of phalaropes occur in the

South Atlantic Planning Area during winter: red-necked (*Phalaropus lobatus*, ~1.2 million pairs) and red (*Phalaropus fulicaria*, ~370,000 pairs). These two species are similar and have similar patterns of occurrence in the South Atlantic Planning Area. They breed in the tundra and winter in pelagic waters of the tropics and sub-tropics. Phalaropes form tight flocks at sea and feed in a distinctive circling motion that apparently stirs up prey (small crustaceans and fish). The South Atlantic Planning Area is an important area for both species, with counts much higher in the northern parts of the region than off of Florida (Wallace and Wigh, 2007), but populations are currently large and apparently stable. Both are ranked as least concern. Phalaropes appear to be attracted to areas of high frontal activity during fall and winter, particularly in the midshelf region 40–80 km offshore (Haney, 1985).

State of Knowledge Phalaropes spp.- Breeding: n/a; Foraging: 4; Distribution: 4; Status: 3;

8.4.3 Wading Birds

Frederick (2002) provides an excellent review of the ecology of long-legged wading birds in the marine environment. Several wading birds (e.g., great egret [*Ardea alba*], snowy egret) were nearly hunted to extinction for the millinery industry by the turn of the 20th century. The wood stork (*Mycteria americana*) is a federally listed endangered species (Appendix 8.1). Many populations of wading birds appear to be experiencing declines in the South Atlantic Planning Area.

Within marine or estuarine systems, these birds nest in colonies on barrier or river islands. Fifteen species of wading birds from one order (Ciconiiformes) and three families (Ardeidae, Threskiornithidae, Ciconiidae) nest in the South Atlantic Planning Area (Table 8.14). Species that are most likely to nest on the coast and thus are more prone to disturbances in the marine zone include great egret, snowy egret, tricolored heron (*Egretta tricolor*), and glossy ibis (*Plegadis falcinellus*). Dodd and Murphy (1997) found that 38% of all wading bird colonies in South Carolina were within 2 km of the coast. It is not uncommon for wading birds to nest adjacent to or as part of pelican colonies. Wood storks also can nest in coastal areas of the South Atlantic Planning Area although this appears to be more common in Georgia and along the central Florida coast compared to South Carolina (Brooks and Dean, 2008). Wading birds frequently forage in estuarine and tidal areas and even along the intertidal zone of beaches. Because their foraging ranges can be substantial, even individuals that nest several kilometers inland can forage in coastal marine and estuarine habitats (e.g., Gaines et al., 1998). For example, individuals often forage 5-10 km from colonies but maximum distances can be >100 km (Frederick, 2002). Therefore, wading birds that nest several kilometers inland can still be affected by conditions in coastal systems.

Table 8.14
Occurrence and abundance of wading birds by season in the South Atlantic Planning Area.

Scientific Name	Common Name	SP	SU	FA	WI
Order CICONIIFORMES					
Family ARDEIDAE					
Botaurus lentiginosus	American bittern	R	V	R	R
Ixobrychus exilis	Least bittern	R	R	R	V
Ardea herodias	Great blue heron	C	C	C	C
Ardea alba	Great egret	C	C	C	C
Egretta thula	Snowy egret	C	C	C	C
Egretta caerulea	Little blue heron	C	C	C	C
Egretta tricolor	Tricolored heron	C	C	C	C
Egretta rufescens	Reddish egret	C	C	C	C
Bubulcus ibis	Cattle egret	C	C	C	C
Butorides virescens	Green heron	C	C	C	C
Nycticorax nycticorax	Black-crowned night-heron	C	C	C	C
Nyctanassa violacea	Yellow-crowned night-heron	C	C	C	C
Family THRESKIORNITHIDAE					
Eudocimus albus	White ibis	C	C	C	C
Plegadis falcinellus	Glossy ibis	U	U	U	U
Subfamily Plataleinae					
Ajaia ajaia	Roseate spoonbill	R	R	R	R
Family CICONIIDAE					
Mycteria americana	Wood stork	C	C	C	C

SP = spring, SU = summer, FA = fall, WI = winter. C = common, U = uncommon, R = rare, V = vagrant, PV = potential vagrant, EV = expected vagrant.

8.4.4 Ducks and Divers

While numerous species of waterfowl and their allies are found in the study area, the species that are particularly relevant to the marine environment are limited. These can be grouped as bay ducks, sea ducks, and allies (loons and grebes).

The USFWS monitors waterfowl at NWRs during winter months. These data are summarized as counts per survey and survey effort varies within and among refuges and years. Areas surveyed are primarily inshore, coastal, and estuarine. Within the South Atlantic Planning Area, aerial survey data were available at four NWRs: Cape Romain, ACE Basin, Savannah River, and Merritt Island. The relative abundance of waterfowl varied among these coastal refuges (Table 8.15). Bay ducks appeared to be more abundant at Cape Romain and Merritt Island, the two

refuges with a greater marine component. Aside from the midwinter waterfowl surveys, there appears to be little research effort expended on bay ducks in the South Atlantic Planning Area and therefore detailed knowledge of use patterns is limited. Bay ducks are often associated with bays and tidal areas and less so with open water. These ducks feed on vegetation and benthic organisms and so are often found in shallow areas of these habitat types. Like many wintering waterfowl, they appear to show a high degree of site fidelity to wintering use areas.

Table 8.15
Relative abundance of wintering waterfowl at Cape Romain (2003, 2004, 2005, 2008), ACE Basin (2006, 2007, 2009), Savannah River (2002), and Merritt Island NWRs (1999, 2001, 2003, 2006, 2007, 2008)

	Cape Romain	ACE Basin	Savannah River	Merritt Island
>100	Northern shoveler Blue-winged teal Green-winged teal Bufflehead Northern pintail	Bufflehead Widgeon Mallard Gadwall Black duck	Northern pintail Blue-winged teal	Hooded merganser Ruddy duck Mottled duck
>500	Hooded merganser Canvasback Ruddy duck	Northern shoveler		Ring-necked duck Northern shoveler
>1,000		Wood duck Blue-winged teal	Ring-necked duck Northern shoveler	Green-winged teal Blue-winged teal Widgeon
>5,000		Ring-necked duck Northern pintail	Green-winged teal	Lesser scaup Northern pintail
>10,000	Lesser scaup	Green-winged teal		

Data were summarized from aerial survey data available through a USFWS web portal: http://samigbird.ncusfws.org/sawindex.html. Species are listed if at least one count yielded >100 individuals.

Seaducks are primarily found in nearshore waters exclusively during the nonbreeding season. Like pelagic seabirds, this group is entirely reliant on open water and does not roost on land during the nonbreeding season. Hence, seaducks regularly forage, commute, and traverse both nearshore and in some cases offshore waters. Common seaducks in the South Atlantic Planning Area include scoters (*Melanitta* spp.), bufflehead (*Bucephala albeola*), and mergansers (*Lophodytes* spp.). Current efforts are underway to survey sea ducks in southeastern US marine waters (Silverman et al., 2011). Surveys were initiated in 2008 and are scheduled to continue through 2010. All of the South Atlantic Planning Area is included in the survey zone. Preliminary results indicate that, along the southern coastline, scoters comprised the vast majority of individuals counted and occurred <10 km from shore. Aside from the midwinter waterfowl surveys, there appears to be little research effort expended on sea ducks in the South Atlantic Planning Area and therefore detailed knowledge of use patterns is limited.

Loons (Gaviformes)

LC Red-throated Loon (*Gavia stellata*) and Common Loon (*Gavia immer*)

State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Populations: 66,000 / 200,000 pairs

Loons are common winter residents in the South Atlantic Planning Area that breed in northern latitudes. Common loons (*Gavia immer*) are far more frequent than red-throated loons (*Gavia stellata*). Loons are pursuit divers that occur regularly in nearshore or inshore waters (e.g., bays, inlets, intracoastal waterway). Loons also occur to 100 km from shore, and it appears they move greater distances offshore as river discharge and turbidity increase in nearshore waters (Haney, 1990). Haney (1990) estimated density of loons in the South Atlantic Planning Area <1.0 km^2 and aerial seaduck surveys report loons at densities ranging from 2–19 per nautical mile of transect (Silverman et al., 2011). Loons are often observed in large flocks particularly in nearshore waters but can also be quite dispersed when foraging. During winter loons undergo a simultaneous wing molt that leaves them flightless for an extended period of time. It is thought that this requires loons to overwinter in areas with predictable food sources. This flightless period also may place loons at risk from disturbances to wintering habitat as their ability to vacate a disturbed area while flightless is likely reduced. The South Atlantic Planning Area is an important part of the wintering range for common loons. Their relative abundance in nearshore habitats is reflected in part by the frequency with which it is observed during Christmas Bird Counts (Figure 8.18).

Grebes (Podicipediformes)

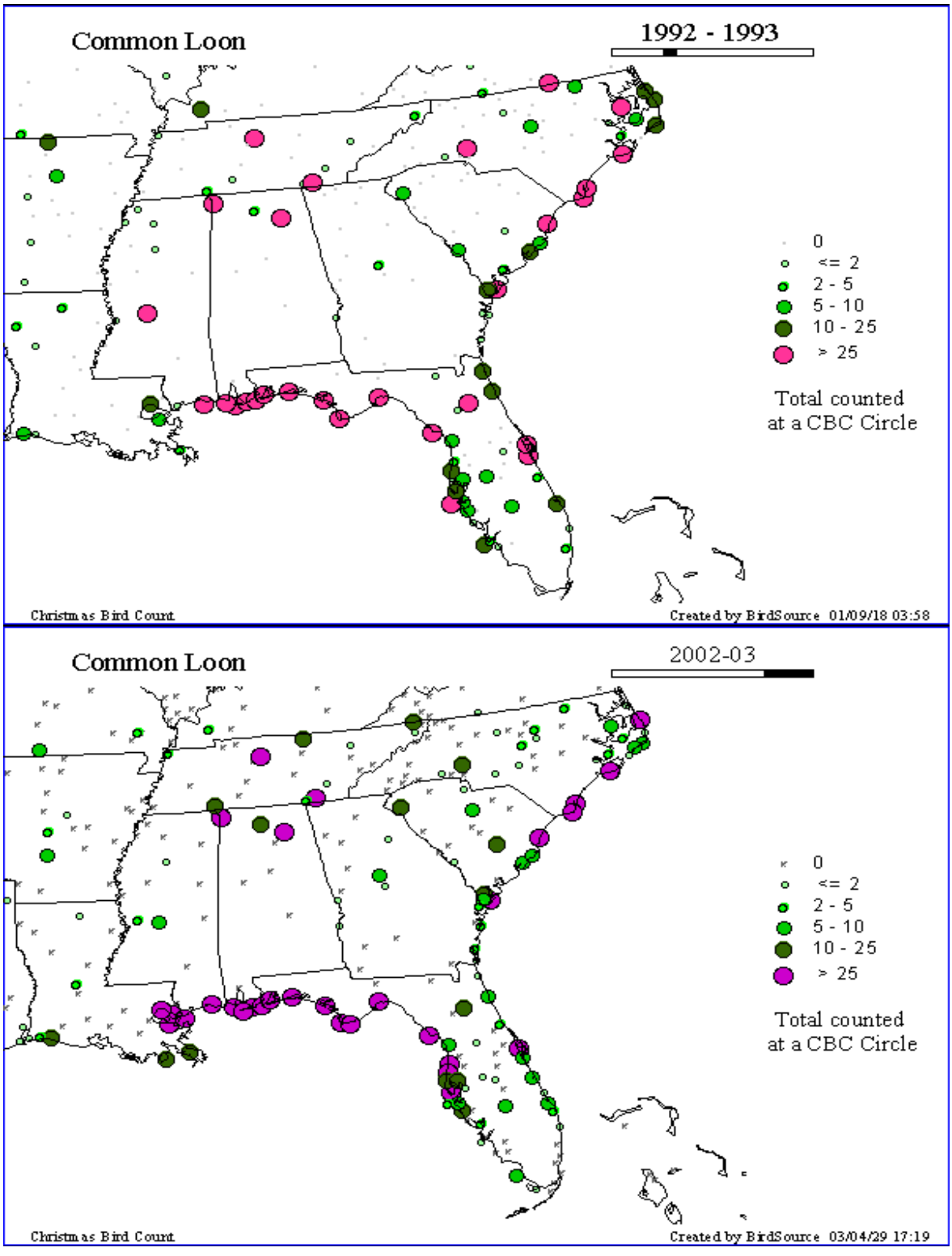
Three grebes occur regularly in the South Atlantic Planning Area with one breeding and two wintering. These birds nest in floating nests attached to vegetation or built up on shallow lake bottoms or rock piles. They winter in inshore waters of estuaries, bays, and lagoons up to 20 m in depth, eating fish and invertebrates captured by diving.

LC Pied-billed Grebe (*Podilymbus podiceps*)
State of Knowledge - Breeding: 4; Foraging: 4; Distribution: 4; Status: 4; Populations: 40,000 pairs

Pied-billed grebe is a small, common grebe that breeds and winters in the coastal estuaries and lakes of the South Atlantic Planning Area. Any waters without ice are acceptable wintering grounds.

LC Horned Grebe (*Podiceps auritus*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Populations: 46,000 pairs

Horned grebe is a common winter resident of the South Atlantic Planning Area that inhabits shallow brackish or marine waters. It breeds in the great basin region of Canada and Alaska. Not a species of conservation concern. Food and breeding behavior is similar to that of other grebes.



Figures 8.18 National Audubon Society Christmas Bird Count data for common loons in the Southeast US, 1992–1993 and 2002–2003.

LC Eared Grebe (*Podiceps nigricollis*)
State of Knowledge - Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Populations: 1,300,000 pairs

Eared grebe is a rare vagrant wintering in nearshore estuaries, bays, and lagoons and feeding on fish and invertebrates. It is not a species of conservation concern. It breeds in northern continental lakes and ponds and moves to hypersaline environments after breeding to put on mass before migration. It undergoes long stretches of flightlessness with changes in physiology that favor increased fat reserves to power migration (Cullen et al., 1999). It is numerous and is not a species of conservation concern.

LC Western Grebe (*Aechmophorus occidentalis*)
State of Knowledge -- Breeding: n/a; Foraging: 4; Distribution: 4; Status: 4; Populations: 40,000 pairs

Western grebe is a vagrant in winter in the South Atlantic Planning Area with habitat use and behavior similar to other grebes. Most of the population winters from Washington to the Gulf of California with a small population in the Texas Gulf Coast. It breeds from the Great Basin east of the Rockies through central Mexico; the easternmost birds nest in Wisconsin.

8.4.5 Other Birds and Bats

8.4.5.1 Raptors and Songbirds

A number of landbirds reside in coastal areas of the South Atlantic Planning Area throughout the year and may be found foraging or nesting adjacent to marine areas (e.g., salt marshes) or on barrier islands. It is impractical to provide a complete synthesis of the ecology of these species here; however, a brief review of the types of birds most likely to be found over coastal waters is provided. Among these are raptors, vultures, cranes, rails, coots, kingfishers, and perching birds.

Several species of Falconiformes rely on coastal ecosystems during at least part of the year. Merlins (*Falco columbarius*) migrate from their northern breeding grounds and winter across the Southern US including the South Atlantic Planning Area. They are an important predator of shorebirds and migrate along the coastline to take advantage of prime foraging areas in wetlands and over the beaches (Sodhi et al., 2005). Peregrine falcons (*Falco peregrinus*) show a similar preference for open coastal areas in their wintering range, which stretches along the South Atlantic Planning Area. The bald eagle (*Haliaeetus leucocephalus*) is protected under the Bald and Golden Eagle Protection Act and is addressed under National Bald Eagle Management Guidelines. Ospreys (*Pandion haliaetus*) nest in the northern part of the South Atlantic Planning Area, and some winter in the southern regions. Their nesting habits are often supplemented by platforms near channels over water, and they are common along the Intracoastal Waterway. Osprey forage regularly in estuaries and near-shore waters. Northern harriers (*Circus cyaneus*) winter in the South Atlantic Planning Area and forage on mammals in open wetlands and marshes. Swallow-tailed kites (*Elanoides forficatus*) breed often in coastal areas where they forage on marsh insects and frogs. Current population declines have been attributed in large part to wetland loss. Turkey and black vultures also occur along the coast. They often forage in tidal marshes and also prey upon eggs and chicks of colonial nesting seabirds (e.g., black skimmers,

least terns) and other coastal waterbirds (e.g., American oystercatchers). Raptors are well known to migrate along coastlines and, therefore, they are common over beaches during spring and fall migrations. Details pertaining to the distance raptors may migrate offshore are lacking in the South Atlantic Planning Area.

The Rallidae family is iconic, though inconspicuous, in salt marshes. Clapper rails (*Rallus longirostris*) are year-round residents and inhabit dense grassy brackish marshes. King rails (*Rallus elegans*) are more common residents in freshwater habitats. Virginia rail (*Rallus limicola*), yellow rail (*Coturnicops noveboracensis*), and sora (*Porzana carolina*) only occur in the South Atlantic Planning Area during winter. Virginia rail prefers reedy marshes; the yellow rail is most often present in sedge marshes, and sora is mostly found in grassy marshes. Arguably the highest conservation concern within the Rallidae family should be placed on the black rail (*Laterallus jamaicensis*), an IUCN near-threatened species that inhabits the South Atlantic Planning Area continually throughout the year (Hunter et al., 2001). Like the king rail, this species tends toward fresher brackish marshes and can only survive in high marsh where the water is shallow enough for the rail to walk.

Smaller avian species that depend directly on aquatic habitats are more limited, but still noteworthy. Coraciiformes has a single species, the belted kingfisher (*Megaceryle alcyon*), which inhabits most of the South Atlantic Planning Area year-round. It forages in any open water habitat that has small fish, perching and hovering to locate prey. The remaining smaller species that use marsh habitats are of the order Passeriformes. Some nest and/or forage in or adjacent to salt marshes, such as marsh wrens (*Cistothorus palustris*), seaside sparrows (*Ammodramus maritimus*), and painted buntings (*Passerina ciris*). Salt marsh sharp-tailed sparrows (*Ammodramus caudacutus*) and Nelson's sharp-tailed sparrows (*A. nelsoni*) winter in marshes throughout the South Atlantic Planning Area. Tree swallows (*Tachycyneta bicolor*) which winter in the region, and bank swallows (*Riparia riparia*) which migrate through also forage for insects over open water. By far the greatest potential use of the marine zone for passerines is during migration. While it is well established that migrating songbirds will cross expansive areas of open water (e.g., Gulf of Mexico), it is not clear to what extent they migrate over coastal waters in comparison to coastal lands that are adjacent to these waters. Coastal beaches and barrier islands are important staging and stopover sites for many migrating passerines, and it is presumed that all federally endangered Kirtland's warblers (*Dendroica kirtlandii*) migrate to and from the Bahamas crossing the coastline and sea islands (Hunter et al., 2001).

8.4.5.2 Bats of the South Atlantic Region and Offshore Activity

Twelve species of bats inhabit the coastal counties of the South Atlantic Planning Area (Marks and Marks, 2006; Menzel et al., 2000; 2003). These are the silver-haired bat (*Lasionycteris noctivagans*), hoary bat (*Lasiurus cinereus*), red bat (*L. borealis*), Seminole bat (*L. seminolus*), northern yellow bat (*L. intermedius*), Rafinesque's big-eared bat (*Corynorhinus rafinesquii*), big brown bat (*Eptesicus fuscus*), little brown bat (*Myotis lucifugus*), southeastern bat (*M. austroriparius*), tri-colored bat (*Perimyotis subflavus*), evening bat (*Nycticeius humeralis*), and Brazilian free-tailed bat (*Tadarida brasiliensis*). The silver-haired bat and hoary bat occur in the area primarily during the spring and fall migration periods and during the over-wintering period, and records of the little brown bat are limited to one county in South Carolina (Beaufort). None of the species are federally listed as threatened or endangered, but the southeastern bat,

Rafinesque's big-eared bat, and northern yellow bat are listed as either state endangered or species of special concern in Florida, Georgia, and South Carolina.

A limited amount of data exists about bats' use of the offshore area. The northern yellow bat, Seminole bat, evening bat, southeastern bat, and tri-colored bat inhabit the barrier islands of Georgia (Menzel et al., 1999, 2000), and high bat activity was recorded over Fort Sumter in Charleston Harbor, SC (Loeb, 2006). There are also several anecdotal accounts of bats foraging or migrating far off US coasts. For example, red bats have been found 105–145 km off the coasts of Maine and New York (Carter, 1950; Mackiewicz and Backus, 1956), and silver-haired bats have been found approximately 95–145 km south-southeast off of Long Island (Mackiewicz and Backus, 1956). In the western US, hoary bats commonly stop over on Southeast Farallon Island, which is 48 km west of San Francisco, during their fall migration.

More detailed data on offshore bat activity have been obtained in Europe than North America. Using bat detectors, radar, infrared thermal imaging, and incandescent spotlights, researchers documented that 11 of 18 species that inhabit the Scandinavian Peninsula and islands of southern Sweden and Denmark also were commonly found flying over the southern Baltic Sea (Ahlén et al., 2009). Although some of these flights were migratory, others represented foraging activity over the sea during non-migratory periods (Ahlén et al., 2007; 2009). Further, individuals of three species have been observed roosting in the nacelles of wind turbines 5.8 km offshore.

The most critical research need is a systematic study of bat use of offshore areas of the South Atlantic Planning Area and how it varies with season, weather (particularly wind speed), distance from shore, landscape features, and species. Specific questions that should be addressed include: 1) Are only long-distance migrants most likely to be active in the offshore area, or are other more local species such as Brazilian free-tailed bats, yellow bats, and big brown bats also using the offshore areas? 2) Is offshore bat activity concentrated during the fall migration and mating season, or does it occur throughout the active season (or even year round)? 3) Is activity correlated with weather variables (e.g., wind speed, temperature, rainfall) or approaching weather fronts? and 4) Does activity vary with distance from shore, and does this vary with weather variables, season, or landscape configuration?

8.4.6 Marine Zone Use by Guild

Each of the aforementioned guilds uses the marine zone for different activities and during different phases of the annual cycle. Table 8.16 summarizes this use by activity for each guild. The cell entries refer to activities, not seasons. For example, "breeding" indicates that a zone is used for activities such as nesting and chick-rearing, not simply that the zone is used during the breeding season (previous tables present that information).

Table 8.16
Summary of marine zone use by avian guild.

Guild	Estuary	Coastal Beach	Nearshore	Offshore
Nearshore seabirds	Breeding[a], foraging, migrating,wintering	Breeding, foraging, migrating, wintering	Breeding, foraging, migrating, wintering	Foraging, migrating
Pelagic seabirds			Breeding, foraging, migrating, wintering	Foraging, migrating, wintering
Shorebirds	Breeding, foraging migrating, wintering	Breeding, foraging, migrating, wintering	Migrating	Migrating, wintering, (phalaropes)
Wading birds	Breeding, foraging, migrating, wintering	Breeding, foraging, migrating, wintering	Migrating	
Seaducks and allies	Foraging, migrating wintering		Foraging, migrating, wintering	Foraging,, migrating, wintering
Rails and allies	Breeding, foraging migrating, wintering			
Passerines and raptors	Breeding, foraging, migrating, wintering	Breeding, foraging, migrating, wintering	Migrating	

[a] Breeding refers to activities (e.g., nesting, chick-rearing), not season.

8.5 MANAGEMENT ISSUES NOT DIRECTLY RELATED TO ENERGY DEVELOPMENT

8.5.1 Management of Coastal Habitat

Coastal habitats, particularly those located on marsh, river, and barrier islands, provide a critical habitat component, particularly for nearshore seabirds and shorebirds in the South Atlantic Planning Area. As many of the previous species accounts showed, the upland, dune, beach, and intertidal areas along the coast and on islands provide habitat for nesting, loafing, foraging, and chick-rearing. Islands that support breeding colonies of seabirds are generally devoid of mammalian predators, are nearby to food resources, and possess physical features that provide suitable habitat for nesting and rearing young (Erwin et al., 1995; Visser et al., 2005). A limited number of islands meet these criteria, and therefore protection of available and suitable islands is critical for the protection of these species. This review of the ecology and conservation of nearshore seabirds and shorebirds in the South Atlantic Planning Area demonstrates that human

disturbance at colonies and loafing areas is an important threat to coastal habitats that requires continued management attention.

Human disturbance to seabirds and shorebirds on coastal islands is an important management issue along the eastern coast of the US (Hunter et al., 2001; Kushlan et al., 2002). In response to human disturbance in or near nesting areas, entire colonies of seabirds may leave their nests, thereby exposing eggs or young to lethal temperatures and potential predators. Over time, effects of disturbance may result in reduced reproductive success (Beale and Monaghan, 2004) and increased energy expenditure on the part of adults and young (Regel and Putz, 1997). Human disturbance can also lead to permanent abandonment of the colony. While posting signs around the perimeter of a colony may reduce the risk of disturbance within nesting areas, even compliant visitors may cause disturbance to birds as they occupy locations adjacent to protected areas (Lafferty et al., 2006). Human disturbance has been identified as a primary concern for the management of colonial seabirds by each state in the South Atlantic Planning Area. While protection of nesting areas is crucial for the success of breeding pairs, areas used for loafing (resting away from the nest) and feeding (which extends into nearshore marine areas) are also essential components of the breeding habitat. Disturbance in any part of the breeding habitat can affect incubation, resting, and feeding activities and thereby may alter reproductive success. Because recreation is common year-round on beaches and islands throughout the region, this issue will likely continue to be a focus of management and conservation agencies.

8.5.2 Sea-level Rise

Sea-level rise scenarios have been developed at a broad, regional scale for coastal areas of the Atlantic but species- or guild-specific models, which would likely be needed to begin planning for proper conservation and management, are currently lacking or dated (Daniels et al., 1993; Kushlan et al., 2002). Studies aimed at determining the potential effects of sea level rise on individual species or suites of species sharing common habitat needs also are lacking (Fish et al., 2005; LaFever et al., 2007). Habitat such as sea-islands, low-lying coastal beaches, and shell mounds are used by seabirds and shorebirds for nesting, loafing, foraging, and wintering habitat and are often limited in availability. These habitats are prone to flooding by both anthropogenic and natural causes (e.g., high tide events, storm surges) as well as by human disturbance (e.g., recreation, development, or disturbance). Currently many of these habitats receive some level of protection and management targeted specifically at seabirds and shorebirds. It is unclear how these habitats will be affected, however, by sea level rise or if currently unused habitats may provide an alternative under various sea level rise scenarios. Implications of sea-level rise on coastal wildlife have been identified as a management or research need in Comprehensive Conservation Plans for NWRs and in the U.S Climate Change Science Program.

8.5.3 Fishery Bycatch

Longline fisheries are one of the greatest threats to global seabird populations. Albatrosses and petrels typically experience the highest rates of bycatch mortality at longline vessels, and many species are now endangered due, in large part, to bycatch. Hata (2006) reviewed the effects of pelagic long-line fisheries on seabirds in the North Atlantic region. The Pelagic Observer Program placed observers for by-catch on a small proportion of the fishing vessels. The observers recorded the number and identity of each bird that was captured as bycatch on the longlining vessels. Between 1992 and 2006, 872 longline sets were observed in the South

Atlantic Bight with almost 500,000 hooks. On 7 of the sets, 17 total birds were retrieved with 14 of those dead and 3 unhooked and released. The capture rate was 0.034 birds per 1,000 hooks. Unfortunately, most of the birds caught in these fisheries were not identified to species. While great shearwaters and northern gannets were among the most frequently observed species caught in the fishery, no great shearwaters were identified in the bycatch. Most of the lines that captured seabirds were set along the continental shelf area and pulled in unidentified seabirds (five longline sets). One set caught two gannets, another, two gulls, and another caught a Cory's shearwater. Birds that were killed but consumed by scavengers underwater were not recorded and may represent a substantial portion of the catch.

Because most of the seabirds were not identified to species, it is not possible to quantify from these data whether longlines are a significant threat to the seabird community. The rarest of the birds that occur in the South Atlantic Planning Area (*Pterodroma* species) are not known to follow ships closely but may circle and follow at a distance, and hence may be subject to bycatch during some conditions. If longlines are set where the birds are feeding, then some of the bycatch could include rare species like black-capped petrels. Therefore, while the levels of bycatch recorded to date within the South Atlantic Planning Area do not seem significant for any of the species that were identified, it is still unclear if sufficient effort has been expended to identify and measure seabird bycatch in this region. Improving our understanding of bycatch of pelagic seabirds in the region has been identified as a priority by the Northwest Atlantic Marine Bird Conservation Cooperative. It should also be noted that gillnet fisheries also are responsible for bycatch mortality of seabirds, seaducks, and divers although this fishery is not common in the region. A national-level report by NMFS (2011) was produced after this draft was prepared and should be consulted.

8.6 Potential Impacts of OCS Development on Marine and Coastal Birds and Bats

8.6.1 Oil and Gas Exploration and Development

Oil and gas development may affect marine avifauna during the exploration and production phases through two main pathways: interactions with the physical structures and oil spills. Based on studies in the Gulf of Mexico, Russell (2005) found that oil and gas platforms provide habitat for resting and refueling, induce nocturnal circulations, and result in some mortality through collisions. Oil platforms can create localized collision hazards for seabirds in a variety of manners (Wiese et al., 2001). For example, platforms often function as artificial reefs that attract fish and, subsequently, seabirds, and so increase the opportunity for both collisions and foraging (Inger et al., 2009). Seabirds also can be attracted towards light from platforms (Reed et al., 1985; Telfer et al., 1987; LeCorre et al., 2002; Poot et al., 2008). Bright, stationary lights, such as those on platforms, disorient birds as they attempt to navigate. When other cues are distorted, as during storms, birds will often spiral in towards bright objects, including fire and light (e.g., flares and spotlights on platforms). This can create strandings, collisions, or in the case of flares, incineration (Wiese et al., 2001).

Oil platforms also may create localized pollution hazards for seabirds from the regular discharge of oils or chemicals that may occur routinely. Such events can lead to increased mortality

through oiling or fouling of feathers and ingestion of oil or other substances (Camphuysen et al., 2009). Oil spills are known to have adverse effects on individuals and populations. Birds are exposed to oil primarily through direct contact and through contamination of their prey base. Effects may be lethal or sublethal, occur proximate to or distant from seabird colonies, and be persistent. For example, seabird colonies may experience direct and immediate oiling if they are directly in the path of the spill trajectory. In contrast, seabird colonies hundreds of kilometers from the spill site may become oiled as the spill spreads and moves with oceanic or coastal currents or as birds commute to feeding sites that have been contaminated. Hence spilled oil may act as a proximate and somewhat predictable source of contamination at nearby colonies, but also as a distant and somewhat less predictable source of contamination elsewhere. This latter effect is one of many transboundary issues that affect seabirds (Jodice and Suryan, 2010).

Seabirds also may be exposed to oil indirectly at the foraging grounds when they ingest prey that have been exposed to oil, and these effects may be quite persistent over time (Jewett et al., 2002). For example, yellow-legged gulls (*Larus michahellis*) experienced changes in plasma biochemistry and elevated levels of polycyclic aromatic hydrocarbons that were consistent with the ingestion of fuel oil 17 months after the T/V *Prestige* oil spill occurred off the coast of Spain (Alonso-Alvarez et al., 2007a, 2007b). Similarly, nine years after the *Exxon Valdez* oil spill, adult pigeon guillemots in Prince William Sound had elevated levels of CYP1A, a detoxification enzyme associated with exposure to oil (Golet et al., 2002). These examples demonstrate that seabirds may be affected by oil both at and away from the colony, and that these effects can span temporal scales of months to decades.

We suggest three steps to consider in the event of an oil spill in the South Atlantic Planning Area: (1) identify key areas of concern, (2) predict trajectory of spilled oil, and (3) assess adequacy of baseline data from which change or damage would be assessed.

(1) *Identify key areas of concern*. The potential for oil to affect seabirds is based largely on the probability of birds encountering oil or oil-related chemicals (e.g., dispersants) at sea or along the shore. In the event of a spill, therefore, it becomes critical to understand the spatial distribution and abundance of birds and the ways in which distribution and abundance change over time (i.e., differences between the breeding season and nonbreeding season).

Key areas of concern for coastal avifauna in the South Atlantic Planning Area are better understood during the breeding season than during the nonbreeding season. Previous sections of this chapter include maps of and information about current and historical seabird colonies in the South Atlantic Planning Area and as such presents baseline data during the breeding season for key areas of concern. These data should be updated regularly (e.g., every 3–5 years) to remain current. Also of importance are the locations of key loafing and wintering sites, although this chapter clearly demonstrates that such data are not well documented in the study area.

Birds also encounter oil at sea while foraging, and an understanding of the likely distribution and density of birds at sea is critical. At-sea distribution can be considered in both the nearshore and pelagic zones. In the South Atlantic Planning Area the nearshore zone supports thousands of foraging seabirds. All of the seabirds that breed in the area are considered to be “nearshore species” and hence most forage within several kilometers of land. Detailed data on foraging

ranges do not exist for the breeding seabirds of the study area; hence, it is difficult to accurately predict areas likely to be used based on colony locations. Similarly, few data exist that accurately document movement patterns and foraging areas during the nonbreeding season. Such data would be necessary to evaluate the impacts of a spill or predict the probability of birds encountering oil and could be gathered with systematic surveys over several years.

The distribution and density of seabirds in pelagic areas of the South Atlantic Planning Area are also poorly understood and, therefore, predicting the potential for birds to encounter oil in this region is difficult. It appears that the density of pelagic seabirds in the South Atlantic is less than that in the adjacent mid-Atlantic, particularly the Cape Hatteras area. The data that do exist for the South Atlantic Planning Area suggest that seabirds are scattered at low densities throughout the region and that potential hot spots occur along the western edge of the Gulf Stream and near the Charleston Bump. Species of particular importance in the pelagic zone include black-capped petrels, Audubon's shearwaters, Cory's shearwaters, red and red-necked phalaropes, and common loons. Seasonal distribution and abundance data would be necessary to evaluate the impacts of a spill or predict the probability of pelagic birds encountering oil and could be gathered with systematic surveys over several years. To date (and currently), offshore surveys have been conducted more regularly in the mid-Atlantic region compared to the South Atlantic Planning Area. Due to differences in the oceanography between the two regions as well as differences in the seabird community, however, the data collected there cannot be applied to represent the South Atlantic Planning Area.

(2) *Predict trajectory of spilled oil*. Predicting the trajectories of spilled oil and quantifying the potential effects are done for both planning and emergency response. In the planning mode, models can be run hundreds of times using climatology and different spill scenarios, to generate maps showing the probabilities of oil of different amounts reaching certain areas (French-McKay et al., 2005). Hence, probabilities of spill encounters could be developed for various locations and these could be chosen based on their biological importance to the resource in question. If such models were to be developed, one approach would be to consider nearshore and offshore models. In the nearshore environment, models could be developed for areas nearby major colonies (e.g., along the central South Carolina coast from Cape Romain to the ACE Basin). In the offshore environment the most important area in the South Atlantic Planning Area would likely be the Charleston Bump. However, the potential for pollution of the Gulf Stream deserves specific attention. Whereas favorable, rare currents ("Eddy Franklin") during the 2010 *Deepwater Horizon* Oil Spill prevented migration of large amounts of surface oil around the tip of Florida, a spill in the offshore region of the South Atlantic Planning Area could disperse via the Gulf Stream into the Mid-Atlantic region. The increased difficulty of managing such a spill as it entered the Gulf Stream and its potential effects on a system that supports abundant marine wildlife requires attention in any planning efforts.

(3) *Assess adequacy of baseline data.* In the case of an oil spill at sea, colonial seabirds are often one of the most quickly and adversely affected vertebrate groups. Colonial seabirds can also be indicators of marine system health. In order to assess damage to a population of seabirds, a variety of data are needed. While obvious metrics like mortality rates of individual species are needed, there are also requirements for data on population sizes, adult body mass, diet, and other parameters that, over time, can be examined to develop a more complete understanding of long-

term effects. Many such investigations were conducted following the *Exxon Valdez* oil spill and some of these efforts are still ongoing. Here, we provide a brief summary of data needs specific to seabirds in the South Atlantic Planning Area in the event of a spill. The focus is on breeding colonies because of the high density of birds that occur there, and because many of the data needed to understand long- and short-term effects of spills can be collected there. The approach used is similar to that developed by Wiens et al. (1984) in which the quality and availability of data that would be needed to assess damage to colonial seabirds from a spill are scored and ranked. Here this approach is applied to the most abundant nearshore breeding seabirds in the study area (Table 8.17).

Four categories of data are included in the assessment: population characteristics; reproductive ecology; foraging ecology; and diet and energetics. Each is scored for the primary nesting species in the South Atlantic Planning Area: brown pelicans, royal and sandwich terns, and black skimmers. For each data type, a score is provided that indicates the quality of existing data within the South Atlantic Planning Area for each species. An assessment of data needs with respect to the specificity, accuracy, and priority of required data is also provided.

Although basic population characteristics, such as colony location, are well documented for each species, more detailed data, such as the age structure of the population, are for the most part absent for nearshore seabirds in the study area. Similarly, while general information on reproductive ecology is well known for each species, specific data from the South Atlantic Planning Area are lacking. Additional data on colony size, and its annual variability, are needed for each species and would be critical when assessing the potential damage of a spill to a colony. There have been few efforts to consistently measure basic parameters such as adult survivorship, reproductive success, or growth rates of chicks; these three variables are required to assess damage to breeding populations. Because these data can vary both spatially and temporally, they should be collected at least within the region or a similar region. Foraging ecology is often impacted during a spill and data focused on foraging ranges, foraging behavior, and diet are all lacking in the South Atlantic Planning Area. Furthermore, few to no dedicated studies have examined specific components of foraging ecology which can serve as useful metrics when assessing immediate and long-term damage from spills (e.g., foraging trip duration or parental attendance). Because of spatial and temporal variability in foraging ecology, these data also need to be collected within the study area. Last, data pertaining to energetics and diet are also lacking for seabirds in the South Atlantic Planning Area. While general data pertaining to diet are available, there have been few to no detailed studies in the region. Such data can elucidate mechanisms underlying population change. For example, shifts in forage fish communities can occur in response to environmental stressors. Subsequently, these shifts can result not only in changes to the taxonomic composition of the prey base but also can result in changes to diet quality (i.e., energy density, proximate composition) than ultimately may affect foraging ecology, chick growth, or reproductive success (Suryan et al., 2002; Suryan et al., 2006; Jodice et al., 2006). In summary, the data that currently exist for birds that feed and nest in the nearshore areas of the South Atlantic Planning Area are not sufficient to provide a pre-impact baseline for oil and gas operations that might occur, and the primary needs for research are for year-to-year variability in survivorship, fecundity, and foraging ecology for pelicans, terns, and skimmers.

Table 8.17
Estimation of the quality and availability of data for various parameters of seabird biology needed to assess damage from an oil spill in the South Atlantic Planning Area to colonies of nearshore seabirds (modified from Weins et al., 1984).

	Quality of Data[a]			Data Requirements		
	Brown pelican	Royal and sandwich terns	Black skimmer	Specificity[b]	Accuracy[c]	Priority[d]
Population Characteristics						
Colony size	3	3	3	POP	High	High
Time of occupancy/breeding dates	3	3	3	SIM	Moderate	High
Age structure of population	0	0	0	SIM	High	Intermediate
Proportion of population breeding	0	0	0	SIM	High	Intermediate
Reproductive Ecology						
Prior measures of reproductive success	2	1	1	POP	High	High
Prior measures of chick growth rates	1	0	0	SPP	Moderate	High
Adult body mass	2	2	2	SPP	Moderate	High
Age-specific fecundity and survivorship	0	0	0	SIM	High	High
Foraging Ecology						
Foraging trip duration	0	0	0	POP	High	Intermediate
Foraging activity budget	0	0	0	SIM	Moderate	Intermediate
Flight path (home range)	1	1	0	POP	Moderate	High
Parental attendance	1	0	0	SIM	Moderate	Intermediate
Meal delivery rate	1	0	0	SIM	Moderate	Intermediate
Diet and Energetics						
Field metabolic rate	0	0	0	SPP	Moderate	Intermediate
Diet taxonomic composition	2	1	1	POP	Moderate	High
Diet proximate composition	2	2	1	POP	Moderate	High

[a]Quality of data within the South Atlantic Planning Area: absent (0), poor (1), marginal (2), good (3), excellent (4). These categories are taken directly from Wiens et al. (1984).
[b]Specificity of data needed: POP (population specific, i.e., data required from within the South Atlantic Planning Area), SIM (data required from similar populations, e.g., mid-Atlantic or Gulf coast), SPP (data required at the species level, i.e., anywhere in the range). Categories are taken directly from Wiens et al. (1984).
[c]Accuracy of data needed: High or moderate. Categories are taken directly from Wiens et al. (1984).
[d]Priority: 1 = low, 2 = intermediate, 3 = high. Categories are taken directly from Wiens et al. (1984) although scores are unique to this assessment.

8.6.2 Sand and Gravel Extraction

Sand and gravel borrow sites within the South Atlantic Planning Area tend to occur in shallow waters; therefore, dredging activity is most likely to affect coastal and nearshore avian species. Sand dredging can also result in the creation of avian habitat. To date few studies have focused on the effects of dredging and nourishment on coastal and marine birds (but see Grippo et al., 2007). For example, a recent review on the environmental impacts of beach nourishment indicated that only 2 of 46 examined studies included any focus on avian ecology (Peterson and Bishop, 2005).

Three types of avian habitat may be affected by sand dredging and beach nourishment: coastal lands (i.e., beaches), nearshore waters, and underwater benthos. Coastal lands are used by avifauna for nesting, loafing, and foraging; nearshore waters are used for foraging by seabirds, ducks, and divers; and benthos are used for foraging by divers and ducks. In the following discussion, a brief summary is presented of the data needed (Table 8.18) for assessing potential impacts of sand and gravel extraction to coastal avifauna in the South Atlantic Planning Area (i.e., similar to Table 8.17 but focused on sand extraction).

The extent to which sand dredging in the OCS affects beach habitat along the shoreline is still unclear. Zarillo et al. (2009) used models developed by the US Army Corps of Engineers for Florida beaches and suggested that beaches adjacent to borrow sites would experience small losses of sand due to changes in sediment deposition at the borrow sites. However, each site would have to be modeled independently.

On coastal lands, sand nourishment on beaches can result in habitat alteration for coastal avifauna. For example, placement of nourishment sand on beaches may reduce the availability of invertebrates for shorebirds (Peterson et al., 2006; Schmitt and Haines, 2003; Greene, 2002; Rakocinski et al. 1996). The effects appear to extend for at least one season (Peterson et al., 2000) but the longer-term effects are poorly understood. Nourishment also can change the substrate type, vegetation structure, or topography, all of which can affect habitat suitability (Cohen et al., 2008). To date, most research that considers the potential effects of nourishment on foraging or breeding ecology of shorebirds has focused on piping plovers outside of the South Atlantic Planning Area. Beach nourishment, if conducted during the breeding season, would lead to high levels of disturbance for any birds nesting or loafing on the nourished beach.

Sand dredging also may affect foraging birds in the vicinity of dredging. Dredging operations could disturb foraging birds while at the borrow site and during transit between the borrow site and the placment site. Dredging results in localized and short-term (i.e., the duration of the dredging activity) increases in turbidity, which can differentially affect foraging conditions for plunge-diving seabirds such as pelicans or pursuit divers such as loons (Haney, 1986; Greene, 2002; Henkel, 2006; Speybroeck et al., 2006; Hao, 2008). Removal of offshore sandbars and shoals also can occur as a result of dredging and often these areas provide foraging areas for birds (e.g., White et al. 2009). The extent to which fish communities (i.e., prey for some birds) are disrupted or displaced from sand dredging is covered in Chapter 7.

Table 8.18
Estimation of the quality and availability of data for various parameters of avifaunal ecology needed to assess potential and proximate impacts from sand extraction in the South Atlantic Planning Area (modified from Weins et al., 1984).

	Quality of Data[a]			Data Requirements		
	Shorebirds	Nearshore seabirds	Seaducks/ divers	Specificity[b]	Accuracy[c]	Priority[d]
Population Characteristics						
Time of occupancy (breeding)	3	3	n/a	POP	High	High
Colony size or nesting abundance	2	3	n/a	POP	High	High
Colony/Nesting location	3	4	n/a	POP	High	High
Time of occupancy (nonbreeding)	2	2	2	POP	High	High
Abundance (nonbreeding)	2	2	2	POP	High	High
Distribution (nonbreeding)	2	2	2	POP	High	High
Reproductive Ecology						
Prior measures of reproductive success	2	1	n/a	POP	Moderate	Moderate
Prior measures of chick-growth rates	0	1	n/a	SIM	Moderate	Moderate
Foraging Ecology						
Foraging habitat use	3	2	2	POP	High	High
Foraging time-activity budget	1	0	0	SIM	Moderate	Moderate
Parental attendance	1	1	n/a	POP	Moderate	Moderate
Diet and Energetics						
Field metabolic rate	0	0	0	SIM	Moderate	Moderate
Diet taxonomic composition	1	2	2	POP	Moderage	High
Prey availability	2	2	2	POP	High	Moderate

[a]Quality of data within the South Atlantic Planning Area: absent (0), poor (1), marginal (2), good (3), excellent (4). Categories are taken directly from Wiens et al. (1984). Estimates are averages across all species within the group within the South Atlantic Planning Area.

[b]Specificity of data needed: POP (population specific, i.e., data required from within the South Atlantic Planning Area), SIM (data required from similar populations, e.g., mid-Atlantic or Gulf coast), SPP (data required at the species level, i.e. anywhere in the range). Categories are taken directly from Wiens et al. (1984).

[c]Accuracy of data needed: High or moderate. Categories are taken directly from Wiens et al. (1984).

[d]Priority: 1 = low, 2 = intermediate, 3 = high. Categories are taken directly from Wiens et al. (1984) although scores are unique to this assessment. Scores are averaged across species within groups.

Benthic communities at the borrow site are directly affected by sand dredging operations and this is discussed in Chapter 6. Species, such as diving ducks, that forage on benthic organisms could be disturbed by dredging in a specific area, and the temporal extent of such disturbance also is likely to be dependent on local conditions. There have been no focused studies of these issues in the South Atlantic Planning Area, although work from outside the region may provide some insights (e.g., Llanso et al. (unpubl. data), Einarsson and Magnúsdóttir, 1993). Little is known about the importance of OCS sand shoals as foraging habitat; thus, long-term impacts to birds from either fragmentation or complete removal of offshore shoals are unknown.

8.6.3 Renewable Energy Development

8.6.3.1 Potential Impacts to Birds

Current technology requires that turbines be placed in shallow water (<30 m deep) within relatively close proximity to land to allow for efficient transfer of energy. Therefore, current plans are not focused on deep waters near the continental shelf break but rather on shallower, nearshore waters. For example, current feasibility studies off the South Carolina coast suggest structures would need to be placed within 18 km of shore. Given this spatial restriction, the remainder of this review focuses on issues related to the siting of wind power structures in the nearshore system (i.e., <20 km from shore). This review covers the groups of avifauna and bats that could potentially be affected by the development of wind-energy structures, potential conflicts between wind energy development and associated structures and these flying animals, and the state of existing data particularly as it pertains to determining potential impact of structure placement. More in-depth aspects of potential conflicts (e.g., data required to measure mortality rates) are not reviewed, as these would only be needed once structures were in place. Given that no structures currently exist in the nearshore region of the South Atlantic Planning Area it seems prudent to focus on the initial data needs.

Earlier sections of this chapter provide a thorough review of the coastal and marine avifauna that occur in the South Atlantic Planning Area (bats are also discussed). Based on data presented there, the following guilds or groups of flying animals should be considered when assessing the potential impacts of wind facilities in the marine environment: pelagic seabirds, nearshore seabirds, seaducks and divers, shorebirds, other land birds, and bats. *Pelagic seabirds* forage away from the coastal zone and over open oceans during both the breeding and non-breeding seasons and are often associated with regions such as the western edge of the Gulf Stream. This guild includes various shearwaters, petrels, alcids, and some pelecaniformes (e.g., tropicbirds, boobies, gannets). *Breeding nearshore seabirds* include those species that breed in the South Atlantic Planning Area, forage primarily in nearshore (<20 km from shore) or estuarine waters, and often are found loafing on beaches. This discrete suite of species primarily includes brown pelican, royal tern, sandwich tern, least tern, laughing gull, and black skimmer. These species also may be present year-round.

Other *migratory nearshore seabirds* may winter in or pass through the South Atlantic Planning Area; this guild includes terns, gulls, and northern gannets. Most *shorebirds* such as red knots and piping plovers are primarily migratory, although American oystercatchers, willets, and Wilson's plovers breed in the region. Phalaropes, however, occur regularly in pelagic waters.

Seaducks and divers winter in the marine environment of the South Atlantic Planning Area. This guild includes eiders, scoters, mergansers, goldeneyes, buffleheads, long-tailed ducks, and harlequin ducks. This group also includes loons and grebes which, although occurring each in their own order, are discussed alongside of sea ducks due to similarities in certain behaviors. *Other land-birds*, which include a diverse array of species such as wading birds (e.g., herons and their allies), passerines (e.g., warblers, sparrows), and raptors (e.g., hawks, falcons), are also considered. These species are visitors but not regular residents of the marine environment but do have the potential to be affected by the development of wind energy. Similarly, bats are included because of their potential to fly through and over nearshore waters.

The most likely impacts to flying animals from wind energy structures are collision (a direct impact) and behavioral changes (an indirect impact). Behavioral changes primarily include avoidance or attraction of individuals to structures. These are thoroughly reviewed in Michel et al. (2007; see Table 5-11) but are briefly summarized here. Avoidance can result in a lateral deflection such that a structure functions as a barrier to movement and a flying animal changes course to avoid it. This avoidance can be short term (e.g., migratory path is changed) or long term (e.g., frequent path to foraging area from colony is changed). In each case the collision risk is likely reduced because of the avoidance but energy expenditure may be increased. The "cost" to the individual would be based in large part on the change in energy expenditure or energy gain due to the avoidance. Avoidance also can result in habitat displacement such that an individual alters its habitat use due to the presence of a structure. The most likely scenario for such avoidance is displacement from foraging or at-sea loafing areas and as with lateral displacement this could be a short- or long-term effect depending on the species. Attraction to structures can occur when the structures themselves create some type of habitat. For example, structures in marine zones often act as fish-attracting devices and as such some species may be attracted to an enhanced food source. Structures also could provide perching opportunities. Also, flying animals can be attracted, but disoriented, by lights on structures. This could result in interference with migration or flight paths.

As a means to explore potential impacts of wind energy structures on flying animals, possible exposures at the macro-scale, meso-scale, and micro-scale are explored. This approach was used by Burger et al. (2011) to assess the risk of impact from wind energy structures on three federally listed birds (piping plover, red knot, and roseate tern) along the mid-Atlantic coast. This approach is used because of the lack of studies that have examined the reaction of species in the South Atlantic Planning Area to wind energy structures. For the purposes of this discussion, nearshore includes over-water areas out to 20 km, but does not include the shoreline, beaches, Intracoastal Waterway, or estuaries.

Brief definitions of the three exposure scales are summarized directly from Burger et al. (2011). Macro-scale exposure is defined as occurrence of individuals in the nearshore zone of the South Atlantic Planning Area (i.e., over open water). Meso-scale exposure refers to flight height, specifically whether or not an individual flies at or near the rotor-sweep altitude. Micro-scale exposure refers to the rotor-sweep zone specifically, not just the altitude of the rotors. Burger et al. (2011) suggest a species may experience substantial meso-scale exposure but, based on the species flight dynamics or visual acuity, may be able to avoid the sweep zone proper and hence

experience little to no micro-scale exposure. Hence it is relevant to consider all three scales of exposure.

Macro-scale Exposure. The potential for exposure to wind energy structures at the macro-scale is driven by patterns of broad-scale distribution and habitat use which is influenced both by the location of terrestrial (breeding grounds, loafing areas) and marine habitats (foraging grounds, loafing areas, flight paths). In general, the potential for macro-scale exposure can be assessed by determining if the focal group breeds, loafs (breeding or nonbreeding season), forages, or migrates adjacent to or through the focal development area.

Pelagic seabirds do not breed nearby or adjacent to areas likely to be developed for wind energy within the South Atlantic Planning Area and, therefore, exposure to colonies is nonexistent. However, pelagic seabirds do occur within the South Atlantic Planning Area during all phases of the annual cycle. Most of the pelagic species that do occur in the nearshore region migrate or travel through the area and are not resident. These species include southern migrants (e.g., greater and sooty shearwaters) and northern migrants (e.g., parasitic jaegers, razorbills, and dovekies). Pelagic seabirds also have an extended wandering phase during the pre-breeding years and species such as Cory's shearwater may appear in the focal habitat irrespective of the phase of the annual cycle. Detailed foraging habits of pelagic seabirds are not well documented within the nearshore zone of the South Atlantic Planning Area; therefore, the risk of exposure is difficult to assess. In contrast, northern gannets are a common migrant and wintering species in the nearshore zone of the area (primarily September–April). Wind energy structures may function as opportunistic or disorienting attractors to the scattered pelagic seabirds that do occur in the nearshore region. In summary the risk of exposure for most pelagic seabirds is likely low in the nearshore zone due primarily to their relatively low abundance and density in this region. Northern gannets, however, occur regularly in the area and thus macro-scale exposure may be substantial for this species.

Nearshore seabirds are abundant in the area during all phases of the annual cycle; hence, the potential for macro-scale exposure appears to be great. Colony locations are well documented and clustered along the central South Carolina coast and in north Georgia (although colonies do occur elsewhere; see Figure 8.2). The South Atlantic Planning Area also supports abundant migrating and wintering nearshore seabirds, although wintering sites have been documented with far less precision. Although there are limited data documenting habitat use during foraging (e.g., distance from shore), most observational and anecdotal data suggest that the common nearshore seabirds typically forage within 20 km of shore throughout the year. Similarly, distances offshore at which nearshore seabirds migrate are not well known; however, these species appear to occur regularly within 20 km of the coast throughout the year. Nearshore seabirds that already occur within the macro-scale exposure zone may adjust their habitat use based on location of structures. For example, nearshore seabirds may be attracted to nearshore structures because fish also are attracted there or if the structures provide perching opportunities (Michel et al., 2007). In contrast, nearshore seabirds may avoid structures by deflecting their movements around areas of development or altering habitat use (Michel et al., 2007). The potential for exposure of nearshore seabirds to wind structures in the South Atlantic Planning Area appears to be high based on their abundance throughout the year and their foraging habits, although detailed habitat-use data would be needed to conduct a detailed risk assessment.

Seaducks and divers do not breed in the South Atlantic Planning Area; therefore, exposure would be limited to wintering and migrating individuals. These species are entirely reliant on open water and do not loaf on beaches or shoreline. Seaducks regularly forage, commute, and traverse both nearshore and in some cases offshore waters. As with pelagic seabirds, there are few detailed data on distribution and abundance in the nearshore zone of the South Atlantic Planning Area. The most common species in the nearshore zone of the South Atlantic Planning Area are likely to be the scoters, double-crested cormorants, and common loons. Ongoing survey data suggest scoters tend to occur <10 km from shore; hence, this species would be exposed to structures at the macro-scale. Data from aerial seaduck surveys suggest common loons tend to occur regularly but at low densities in the nearshore zone, although large flocks can form particularly in nearshore or protected waters. Common loons can also occur out to 100 km from shore in the study area (Haney, 1990). Therefore, common loons also are likely to be regularly exposed to wind energy structures at the macro-scale. Seaducks, divers, and migrating waterfowl (e.g., bay ducks) in other regions appear to alter their flight patterns and habitat use away from wind energy structures (Desholm and Kahlert, 2005; Michel et al., 2007).

Shorebirds that breed in the South Atlantic Planning Area are limited to American oystercatchers, willets, and Wilson's plover. The former two species can be locally abundant. Nonetheless, foraging and flight paths for each species appear to be restricted to areas very near the shoreline or within the intracoastal and estuarine zones (although detailed data are lacking). The migratory shorebird community is far more abundant and diverse compared to the breeding community. Shorebirds are abundant especially during migration periods and are often found on coastal beaches and barrier islands throughout the year. As such this group often occurs over nearshore waters. Exposure to wind energy structures could occur regularly during migratory or commuting flights which tend to occur in the nearshore zone. Red knots, a federally listed species, are regular migrants through the South Atlantic Planning Area and are a species of particular concern with respect to exposure to wind energy structures (Burger et al., 2011). Red-necked and red phalaropes are shorebirds that can be common migrants and residents during the nonbreeding season. These species appear to be most common in pelagic waters, thus exposure to structures in the nearshore zone may be limited. Nonetheless, data on distribution and abundance of these two shorebirds are limited, making it difficult to assess exposure to wind energy structures at the macro-scale.

Other landbirds such as raptors, passerines, and wading birds, while common along the coastline, occur only occasionally in the nearshore zone of the South Atlantic Planning Area. Raptors and passerines migrate along the coastline and in the nearshore zone although detailed data on offshore distances, abundance, and timing are not available in the study area; hence it is difficult to accurately assess exposure to structures. Raptors and passerines also roost, forage, and nest on barrier and sea islands, but again there are little data available to indicate the extent to which they may be exposed to wind energy structures in the nearshore zone particularly in the study area. While it is well established that migrating songbirds will cross expansive areas of open water (e.g., Gulf of Mexico), it is not clear the extent to which they migrate over coastal waters in comparison to coastal lands that are adjacent to these waters. Coastal beaches and barrier islands are important staging and stopover sites for many migrating passerines, and it is presumed that all federally endangered Kirtland's warblers (*Dendroica kirtlandii*) migrate to and from the Bahamas crossing the coastline and sea islands (Hunter et al., 2001). Wading birds breed, forage,

and fly along the coast but appear to rarely occur over nearshore waters even during migration although, as with many groups, data are not readily available (AWS Truepower, 2010; Frederick, 2002).

Bats that are most likely to be exposed to wind energy structures are the long-distance migrants–hoary bats, red bats, and silver-haired bats. Individuals of all three species migrate to South Carolina, Georgia, and Florida during fall and this migration may be concentrated along coastlines (Cryan, 2003). Northern yellow bats, seminole bats, big brown bats, and Brazilian free-tailed bats have the potential to forage over open ocean given their morphology, echolocation call structure, and foraging ranges. Brazilian free-tailed bats in the eastern US form large colonies of up to 20,000 individuals in anthropogenic structures, such as buildings and bridges, particularly in coastal regions (Whitaker and Hamilton, 1998).

Meso- and Micro-scale Exposure. These types of exposure are treated together because the availability of data for each is similar. Meso- and micro-scale exposure occur during flight and are impacted by flight height, visibility, and flight conditions (e.g., visibility) as well as by the height of the rotor sweep zone (likely 20–120 m above sea level [ASL]). Flight height can vary depending upon the activity in which the individual is engaged (e.g., foraging, migrating/ commuting, courtship) and deserves attention when considering exposure at these two scales.

Pelagic seabirds in the South Atlantic Planning Area are often observed flying close to the surface of the sea although detailed data are lacking. Paton et al. (2010) reported that shearwaters, alcids, and storm-petrels observed off the coast of Rhode Island during surveys almost always were observed flying <10 m ASL. Jaegers also were observed flying primarily at or near 10 m ASL but also were observed between 10 and 125 m ASL (Paton et al., 2010). Northern gannets, however, were observed at a range of altitudes (<10 m to >100 m ASL; Paton et al., 2010) even during foraging activities. Approximately 4% of northern gannets visually observed during boat vessel-surveys off the coast of New Jersey occurred in the rotor-sweep zone (Geo-Marine, 2010). All of these species or species groups occur in the South Atlantic Planning Area, and these data appear to be the best available for a preliminary assessment of exposure at the meso- and micro-scales. It appears from these data that pelagic seabirds would likely not experience high levels of meso- or micro-scale exposure with the exception perhaps of jaegers and northern gannets.

Most available data on meso-scale exposure for nearshore seabirds in general are from studies of terns (but not royal, sandwich, or least terns which are common in the South Atlantic Planning Area) in Massachusetts (i.e., data associated with the Cape Wind project) and Europe. These data suggest that foraging and migration flights of common and roseate terns tend to occur beneath the height of the rotor-swept zone, hence minimizing both meso- and micro-scale exposure (reviewed in Burger et al., 2011). Paton et al. (2010) observed most gulls and terns surveyed off the Rhode Island coast to be flying at <25 m ASL, although a small proportion were observed flying up to 125 m ASL (Paton et al., 2010). Courtship flights in terns can occur at higher elevations which could result in meso-scale exposure (Burger et al., 2011). There are no detailed data on flight height for nearshore seabirds in the South Atlantic Planning Area; therefore, this is a major data gap to be filled. It cannot be assumed that flight heights for royal and sandwich terns would be identical to those of different terns in other regions. Furthermore, although brown

pelicans appear to forage and commute at heights below the rotor-swept zone, this species can regularly be observed across a wide range of elevations from <1 m to >100 m ASL. It is unlikely that black skimmers would experience meso-scale exposure during foraging flights, although it is unknown what elevation skimmers use while migrating or commuting.

Exposure at the micro-scale for common and roseate terns in Massachusetts and Europe appears to be variable. While some terns avoided the rotors at this micro-scale, there is evidence that some individuals flew closer to this zone when returning to provision chicks (reviewed in Burger et al., 2011). It is unclear how exposure at this scale may differ for the suite of nearshore seabirds in the South Atlantic Planning Area. It is also difficult to measure the effect of reduced visibility on flight patterns and, therefore, this may be difficult to assess. Determining the proportion of days in the South Atlantic Planning Area where visibility is reduced to some specific distance (e.g., 100 m) may be a reasonable first-level assessment.

Data on flight height in the nearshore environment are not available for the remaining suites of species. Loons and sea ducks appear to fly mostly <10 m ASL but occasionally between 25 and 100 m ASL (Paton et al., 2010). Approximately 9% of loons and 25-46% of waterfowl were observed flying at altitudes within the rotor-sweep zone during vessel-based surveys off the coast of New Jersey (Geo-Marine, 2010). Shorebirds are most often observed <10 m ASL but may migrate at higher altitudes up to 125 m ASL (Paton et al., 2010). Burger et al. (2011) considered meso-scale exposure to be low for piping plovers during commuting flights but acknowledged that flight height during migration was unknown and that conditions (e.g., low cloud ceiling) could affect flight height. Red knots were also considered to have low meso-scale exposure during migration (flights typically between 1,000 and 3,000 m) but during commuting flights or during approaches to beaches the extent of exposure was less clear (Burger et al., 2011). Depending upon conditions, raptors migrate across a range of altitudes (but often between 50 and 300 m) when in the nearshore zone (Kerlinger and Gauthreaux, 1985; Niles et al., 1996). Foraging raptors appear to fly at a range of elevations including the 20–120 m zone although such data are not readily available. Paton et al. (2010) observed most passerines flying offshore of Rhode Island at altitudes of <25 m although this is likely biased due to detectability of small birds at greater altitudes. Mizrahi et al. (2010; Appendix to Paton et al., 2010) detected ~ 20-30% of targets <200 m ASL and about 50% of targets between 0 and 400 m ASL during all seasons using radar (it should be noted that these data were not restricted to passerines but likely included these species as well as bats). Most passerine targets in a recent radar study in Atlantic Canada along the St. Lawrence estuary were observed flying at altitudes <500 m ASL (Gagnon et al., 2011). Data that would allow for an assessment of meso- or micro-scale exposure of bats to towers in the nearshore environment are not available.

In summary, the extent to which exposure to birds from wind energy structures can be assessed in the South Atlantic Planning Area is severely limited by a lack of species- and location-specific data. From the scant data available on similar species or from other areas, it appears that nearshore seabirds face the greatest potential for exposure to wind energy structures at all three scales. Nearshore seabirds are abundant in the areas in which wind energy structures are most likely to be developed, and these species appear to fly regularly (although perhaps not often) at the height of the rotor-swept zone. Their ability/propensity to avoid moving rotors is not well understood.

8.6.3.2 Potential Impacts to Bats

No data are available on bat mortality associated with offshore wind turbines. However, data are available on bat mortality at land-based wind power plants. The majority of bats killed at US terrestrial wind power facilities are hoary bats, silver-haired bats, and red bats, all of which are long-distance migrants (Arnett et al., 2008; Kunz et al., 2007b). Tri-colored bats, which are not considered to be long-distance migrants, have also suffered relatively high mortality rates at some sites (Arnett et al., 2008). Most of the mortality occurs during the fall migration period from late July through mid-September (Arnett et al., 2008; Cryan and Brown, 2007; Johnson et al., 2003), and activity and mortality are lower on nights when wind speeds are <6 m/s (Arnett et al., 2008; Horn et al., 2008; Reynolds, 2006). Mortality rates are also positively correlated with tower height, particularly at towers >65 m high (Barclay et al., 2007). The proximate causes of mortality are collisions with moving blades and barotrauma (Baerwald et al., 2008; Johnson et al., 2003), but the ultimate causes of mortality are still unknown (Kunz et al., 2007b). However, several hypotheses about the ultimate causes of mortality have been developed and fall into three groups: 1) mortality is random (i.e., proportional to number of bats passing by); 2) mortality is coincidental to migratory or feeding behavior; and 3) mortality occurs because bats are attracted to turbines (Cryan and Barclay, 2009). Bats may be attracted to turbines due to their lights, the sounds they create, aggregations of insects, or because they provide roost, mating, or gathering sites. Bats have been observed actively investigating rotor blades as well as hunting insects near blades of turbines at sea (Ahlén et al., 2007) and on land (Horn et al., 2008), which suggests that attraction may be a significant factor.

Although there are no data on offshore foraging or migrating activity by bats of the South Atlantic Planning Area or on mortalities associated with offshore wind power facilities in any area, information on the ecology and natural history of each species as well as information from land-based wind power plants can be used to make an initial assessment of the species that are most likely at risk. The group that is most likely at highest risk includes the long-distance migrants: hoary bats, red bats, and silver-haired bats. Individuals of all three species migrate to South Carolina, Georgia, and Florida during the fall, and this migration may be concentrated along coastlines (Cryan, 2003). Other species that may be at high risk are those with the potential to forage over the ocean. Although in the same genus as hoary and red bats, northern yellow bats and Seminole bats are considered to be non-migratory (Whitaker and Hamilton, 1998; Wilkins, 1989). However, both are strong flyers, and their morphology and echolocation call structure suggest that offshore foraging may be a possibility. Other non-migratory species that have the potential to forage offshore are big brown bats and Brazilian free-tailed bats. Big brown bats can forage >18 km from their roosts (Everette et al., 2001), and Brazilian free-tailed bats in the western US often fly >50 km over open areas to forage (Best and Geluso, 2003; Cleveland et al., 2006). Brazilian free-tailed bats in the eastern US form large colonies of up to 20,000 individuals in anthropogenic structures such as buildings and bridges particularly in coastal regions (Whitaker and Hamilton, 1998). Thus, there is the potential for high mortality rates, although their propensity to fly at high altitudes (>3,000 m; Williams et al., 1973) may lower their risk of contact with wind turbines. The remaining species are most likely at lower risk. Evening bats and tri-colored bats use open areas for foraging, but are more likely to be associated with edges and interior forests (Morris et al., 2010). Southeastern bats are strongly associated with bottomland hardwood forests and riparian areas (Jones and Manning, 1989) and thus are unlikely to forage offshore. Rafinesque's big-eared bats have relatively small home ranges with maximum flight

distances of 1.1 km (Lacki and Dodd, *in press*) and are unlikely to come into contact with turbines, while little brown bats are very rare in the coastal region.

Several options may minimize bat fatalities at offshore wind power generating facilities. One option involves placing turbines in areas with low bat activity (Baerwald and Barclay, 2009). Reducing tower height or the number of towers within a group may also decrease mortalities (Baerwald and Barclay, 2009; Barclay et al., 2007). Broadcasting electromagnetic radiation (Nicholls and Racey, 2009) or ultrasonic noise (Szewczak and Arnett, 2008) have been suggested as means to deter bats from approaching turbines, but these techniques have not been sufficiently developed to make them feasible or cost-effective at present. Increasing the cut-in speed of turbines to 5.0–6.5 m per second resulted in a 44–93% decrease in bat mortality at wind power facilities in Pennsylvania and Alberta, Canada (Arnett et al., 2010; Baerwald et al., 2009).

8.6.4 *Sargassum* Harvesting

Many seabirds in the South Atlantic Planning Area are particularly attracted to rafts of *Sargassum* that grow in the warm waters of the Gulf Stream and Sargasso Sea. Any development to commercially exploit significant quantities of *Sargassum* could affect these species and decrease the abundance of feeding habitat available. The rafts are also important for sea turtles and for commercial and sport fishing. Harvesting of *Sargassum* is currently banned in the South Atlantic Planning Area as defined in this study, although >2,000 kg are harvested each year under a permit in North Carolina waters.

8.7 Summary and Data Gaps in the State of Knowledge for Marine and Coastal Birds and Bats with Regard to OCS Development

Ordinal scores for state of knowledge for nearshore seabirds are very similar among species. Breeding sites are generally well documented within the South Atlantic Planning Area, and some level of survey effort is expended each year in each state to continue to document breeding sites. Continued monitoring that is organized across the region is critical particularly in light of conservation threats such as human disturbance, predation, and sea-level rise, all of which may lead to abandonment of colonies by nesting seabirds. Nearly 25 years ago, Clapp and Buckley (1984) also recommended that range-wide colony surveys be conducted every 5–10 years.

Foraging ecology and diet of nearshore seabirds in the South Atlantic Planning Area, while not a complete unknown, lacks sufficient data to allow scientists and managers to assess changes in these parameters in the face of ecosystem disturbance or change. Diet data collected during the breeding season would benefit our understanding of the ecology of each of these nearshore seabirds, although such data would be far easier to collect for some species (e.g., pelicans) than others (e.g., skimmers). Diet databases have been established for seabirds in other regions and these can provide both a real-time and long-term reference for health of marine systems. Seabird diets can reflect immediate changes in forage fish communities.

The habitat from which nearshore species obtain prey is also not a complete unknown for this suite of seabirds although detailed data are lacking for all of these species not just within the study area but elsewhere. Information pertaining to foraging habitats, feeding trip durations, meal delivery rates, and meal sizes are all lacking and have all proven to be valuable data sets in

other seabird systems for discerning effects of ecosystem change. There is little-to-no detailed information on the distance offshore or along the coast these species will commute to forage during the breeding season or nonbreeding season. Telemetry studies, at-sea surveys, and beach-based surveys all would provide data that would be useful for predicting potential impacts to seabirds from developments or disturbances in the marine zone.

The status of nearshore seabirds in the South Atlantic Planning Area is reasonably well understood. However, the trends for each species are not well understood. Jodice et al. (2007) conducted a recent review of annual nest counts for pelicans and royal and sandwich terns, but this analysis only considered South Carolina. Biological Status Reviews are currently being conducted for these species in Florida, and those efforts may provide insight for the Florida portion of the study area. The state of Georgia is attempting to coordinate annual nest count data. To date, however, there has been no effort to assess these data beyond the level of the state, and therefore regional trends are not well understood. Perhaps more importantly, data on reproductive ecology (i.e., the parameters that set trends) are sparse for most of these species in the South Atlantic Planning Area.

The state of knowledge and the data needs for pelagic seabirds are, to a certain extent, somewhat simpler to define. The most apparent need for pelagic seabirds is the development of coordinated at-sea surveys throughout the annual cycle to determine the composition, density, and use areas for this suite of species (Hunter et al., 2001). There have been few such efforts to date, particularly in comparison to the mid-Atlantic and New England offshore areas. Proposals to conduct such surveys are currently being developed but the lack of an obvious threat appears to be hampering their progress. One area of particular interest for at-sea surveys of seabirds in the South Atlantic Planning Area is the Charleston Bump area. The predictable upwelling there and documented productivity appears to provide the type of pelagic habitat frequented by pelagic seabirds. Tracking efforts directed at individual pelagic seabirds also are needed. Satellite and geolocator tracking has consistently resulted in data that vastly expand what is known about resource selection and range in pelagic seabirds, although these techniques have not been readily applied in the South Atlantic Planning Area or even the northwest Atlantic. A stratified, systematic monitoring regime for the *Sargassum* community that takes into account the patchy and seasonal nature of this oceanographic feature also would benefit our understanding of resource selection by pelagic seabirds.

When all avifauna of the South Atlantic Planning Area are considered, the greatest need appears to be for dedicated, frequent surveys throughout the annual cycle. Surveys of beaches, nearshore waters, and offshore waters are needed to document temporal and spatial patterns of use. Stratification of such surveys by distance from shore would ensure that all zones are covered and hence that all avifauna are considered. Surveys throughout the annual cycle would cover breeding as well as migrating/wintering periods when species composition and perhaps avian density changes. Surveys should include visual observations as well as remote detection of targets. Individual-based research efforts (e.g., telemetry studies) would enhance the level of detail that could be gathered with respect to habitat use and foraging locations. The combination of the two techniques would likely yield highly informative data that could be applied to multiple management issues.

Specific data needs pertaining to assessing the potential impacts of OCS development are summarized below. In general, all of the potential impacts discussed require similar baseline data to adequately assess potential impacts. These can be defined broadly as distribution, abundance, and behavior. A thorough but general (i.e., not specific to the South Atlantic Planning Area) review of these needs is also provided in Michel et al. (2007).

Although a diverse array of avifauna use the South Atlantic Planning Area throughout the year, the spatial and temporal details of that use are not clearly understood. There have been few avifaunal surveys of the nearshore or offshore waters of the South Atlantic Planning Area; hence our understanding of the timing, intensity, and type of use by each avian group is limited. This lack of data is a hindrance to marine spatial planning, particularly with respect to risk assessments associated with the siting, construction, and operation of offshore wind facilities or for response planning for oil spills. Similarly, although it is clear that the beaches are used year-round by nearshore seabirds, shorebirds, and wading birds, the spatial and temporal detail of that use is not clear. For example, there are few to no standardized or regularly occurring breeding or wintering beach surveys. The ability to assess potential impact from any of the aforementioned activities would benefit from multi-year surveys designed to document distribution and abundance of avifauna along the beaches and in the nearshore zone.

Along with the spatially explicit data outlined above, more administrative or logistical types of data are also needed. Such data are particularly relevant in the case of an emergency response where time is limited (e.g., oil spill response, post-hurricane monitoring). For example, for colonies and beaches (i.e., loafing or wintering sites) information regarding ownership, access limitations, and permitting are needed to determine how access can be achieved. A site register for important areas within the South Atlantic Planning Area that included basic ecological information as well as this type of administrative information is needed.

Above and beyond baseline data that focuses on distribution and abundance, there is also a need for behavior data that are relevant to oil and gas exploration, sand and gravel extraction, and offshore energy development. For example, there are few to no data on the distance offshore or altitude at which birds fly over nearshore waters of the South Atlantic Planning Area. Similarly, for breeding nearshore seabirds there are little to no data that document either alongshore or offshore foraging movements, the number of foraging trips taken per day, or the diet. The lack of such data impedes our ability to assess the risk of siting a specific project, to assess the potential damage from an event like on oil spill, or to determine if "post-event" changes in behavior occur or are biologically relevant. Detailed surveys by boat, plane, and radar installation at all seasons would improve the baseline, as would continuing surveys that track changes in abundance. Surveys spanning several years and continuing after installation would enable assessment of changes in behavior and effects on the populations. Nocturnal observations around towers using radar and infrared monitors would be very useful in examining changes in nocturnal flight patterns around installations.

Allison et al. (2008) and Burger et al. (2011) recently reviewed data needs specifically with respect to wind energy development, although not specific to the South Atlantic Planning Area. Many of their suggestions also are applicable to the types of data needed to support any potential impact in the South Atlantic Planning Area.

Allison et al. (2008) listed five high-priority topics for improving our understanding of interactions between flying animals and wind energy structures in the marine environment: (1) determining the extent of loss of wintering habitat due to displacement for sea ducks and waterfowl; (2) determining breeding locations for wintering populations of waterfowl as a means to better understand the potential effects of increased mortality at the population level; (3) improving estimates of mortality due to collision, specifically during periods of reduced variability; (4) improving measures of bird and bat activity over marine waters; and (5) developing measures comparing the environmental impacts of different sources of energy. Burger et al. (2011) specifically focused their assessment of data needs on three focal species along the mid-Atlantic coast: roseate terns, piping plovers, and red knots. High priority and broader-scale questions focused on determining the distribution and abundance of each species in the target zone, as well as determining the proportion of the population that would occur in the target zone and hence be likely to be exposed. At a finer scale, Burger et al. (2011) suggested that data were needed on multiple aspects of flight behavior, including altitude, common trajectories in the target area, effects of environmental conditions (e.g., visibility, wind), and ability to avoid moving rotors.

Bats present a unique challenge with respect to data needs and the potential impacts listed above. Several investigators have outlined research necessary to understand and curtail bat fatalities at land-based wind turbine facilities (Arnett et al., 2008; Cryan and Barclay, 2009; Kunz et al., 2007b) and many of these research needs apply also to offshore facilities. In particular, the following questions should be addressed: 1) Does use of project areas change post-construction? 2) Are bats attracted to turbines and if so, is it for roosting, foraging, and/or mating? 3) Are particular species attracted to turbines? Answers to these questions will aid in placing turbines in areas that are least likely to cause fatalities or designing mitigation practices to reduce fatalities. Because it will be difficult, if not impossible, to document mortalities at offshore wind facilities, more emphasis will have to be placed on testing hypotheses about bat behavior and activity associated with turbines and their use of offshore areas. Although testing various hypotheses about bats and offshore turbines will be particularly challenging due to the difficulty of accessing offshore structures, many new tools are available that can be used alone or in combination to make inferences about bat behavior including ultrasonic detectors, thermal infrared imaging, radar, and radio-telemetry (Kunz et al., 2007a).

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CHAPTER 9: SEA TURTLES

9.1 INTRODUCTION

This chapter reviews knowledge of the five species of sea turtle known to occur in the South Atlantic Planning Area waters. All five of these species are listed under the federal Endangered Species Act.

9.2 DATA SOURCES

Most information on the occurrence and biology of sea turtles in this region comes from shore-based or aerial monitoring of nesting beaches (e.g., Hopkins-Murphy et al., 2001), dedicated aerial surveys for sea turtles in coastal waters (e.g., Schroeder and Thompson, 1987), and strandings. The US Sea Turtle Stranding and Salvage Network co-ordinates reports of stranded sea turtles in the southeastern US (SEFSC, 2010).

There is only a limited amount of information on in-water occurrence of sea turtles in the South Atlantic Planning Area. Since 2009, a consortium of academic institutions, including the University of North Carolina at Wilmington, St. Andrews University, Scripps Institution of Oceanography, and Duke University, has been conducting year-round aerial and shipboard, line-transect surveys of cetaceans and sea turtles off Jacksonville, FL. This monitoring program is designed to provide information on the occurrence of cetaceans and sea turtles and quantitative estimates of their density in the proposed site of an Undersea Warfare Training Range (USWTR), to be developed by the US Navy (Department of the Navy, 2009).

The University of Rhode Island conducted line-transect, aerial surveys between October 1978 and January 1982 as part of the Cetacean and Turtle Assessment Program (CETAP), sponsored by the Bureau of Land Management. Most of these surveys were conducted in outer continental shelf (OCS) waters of the eastern US from Cape Hatteras to the Gulf of Maine, but some survey effort extended south into the South Atlantic Planning Area (CETAP, 1982). The CETAP surveys were designed to assess the distribution and abundance of whales, dolphins, and sea turtles in the OCS.

Several other useful resources have compiled information on the occurrence and distribution of sea turtles in the southeastern US OBIS-SEAMAP (Ocean Biogeographic Information System-Spatial Ecological Analysis of Mega-vertebrate Populations) is a spatially referenced online database that aggregates geo-referenced data on sea turtles, including surveys, telemetry, and shore-based counts. The online collection can be searched and visualized through a set of advanced online mapping applications (Halpin et al., 2009).

In addition, the US Navy Marine Resource Assessment (MRA) program contains a comprehensive compilation of data and literature concerning protected resources found in its various marine operating areas. Each MRA reviews information on the occurrence of these resources within a particular marine operating area. A MRA was prepared for the Charleston/ Jacksonville Operating Area in October 2008 (Department of the Navy, 2008a). This MRA also provides a comprehensive review of all survey efforts in the region prior to 2008. The MRAs

present the technical background for specific Navy actions, such as requests for Letters of Authorization under the MMPA (e.g., Department of the Navy, 2008b).

Also, as part of the Atlantic Marine Assessment Program for Protected Species (AMAPPS), the NOAA, BOEM, USFWS, and US Navy are working to develop spatially explicit models of seasonal density estimates for sea turtles in the western North Atlantic Ocean. These models will be created with survey data collected using direct aerial and shipboard surveys conducted by scientists from NOAA. This program has already generated preliminary estimates of the abundance of juvenile and adult loggerhead turtles (*Caretta caretta*) in the northwestern Atlantic continental shelf between Florida and the Gulf of St. Lawrence in Canada (NEFSC, 2011).

9.3 SPECIES SUMMARIES

Five species of sea turtles occur in waters of the South Atlantic Planning Area: the green sea turtle (*Chelonia mydas*); Hawksbill sea turtle (*Eretmochelys imbricata*); Kemp's ridley sea turtle (*Lepidochelys kempii*); leatherback sea turtle (*Dermochelys coreacea*); and loggerhead sea turtle (*Caretta caretta*). Figure 9.1 shows the relative sizes of these species. As noted above, all five of these species are listed under the ESA. No critical habitat has been designated for any of these species within the South Atlantic Planning Area.

Until recently, all loggerhead sea turtles were considered threatened under the ESA. However, the National Marine Fisheries Services (NMFS) and USFWS recently designated nine distinct population segments (DPS) of this species, including one that nests in the western North Atlantic. Now, this DPS of loggerhead sea turtles is considered endangered (NMFS and USFWS, 2011). The Florida population of green turtles and the other three species are all listed as endangered (NMFS and USFWS, 1991a, b; 1992; 1993).

Assessment of sea turtle populations is complicated by their long, complex life histories, in which different life stages inhabit separate environments (Bolten, 2003). All marine turtles incubate their eggs on tropical or sub-tropical sandy beaches. Hatchlings leave the beach immediately, and small juveniles typically spend years to decades in the pelagic zone. At some point, large juveniles return to coastal waters where they undergo a niche shift and feed either on vegetation (green turtles) or mollusks and crustaceans (the other four species). Most female sea turtles return to, or return close to, their natal beach to nest. Thus, it is particularly difficult to estimate total population size because not all stages are available to be counted in any particular habitat. In addition, it is difficult to ascertain trends in abundance because of the long time that it takes these species to reach sexual maturity and the difficulty of conducting research on early life stages (NRC, 2010).

Green turtles are distributed worldwide in tropical and sub-tropical waters (Hirth, 1997). After hatching, small juvenile green turtles inhabit the open ocean, likely along convergence zones (Carr, 1987). Post-hatchling green turtles are common in surface patches of *Sargassum* near the Gulf Stream (Carr and Meylan, 1980). As they grow and develop, juvenile green turtles return to coastal waters to feed in estuaries along the US Atlantic coast as far north as Long Island Sound. The bays, sounds, and estuaries of North Carolina are particularly important neritic habitat for these large juvenile green turtles (Epperly et al., 1995). Large juvenile and adult green turtles

feed on submerged vegetation in coastal waters, either in sea grass beds in shallow, protected lagoons or along nearshore reef environments. Adult green turtles are only occasionally found north of Florida (Hirth, 1997). From 2001-2005, an average 5,055 green turtles nested in Florida (Meylan et al., 2006). This is one of approximately ten large nesting aggregations in the Atlantic basin (Witherington et al., 2006a). Green turtles are the second most abundant sea turtle in the southeastern US, in terms of number of nests laid, and Florida is the principal nesting site for green turtles in the continental US. Green turtles along the Atlantic coast of Florida accounts for the vast majority (more than 95%) of sea turtle nests in the state (Meylan et al., 2006). Thus, adult and juvenile green turtles occur year-round in the southeastern US (NMFS and USFWS, 1991b; Department of the Navy, 2008a).

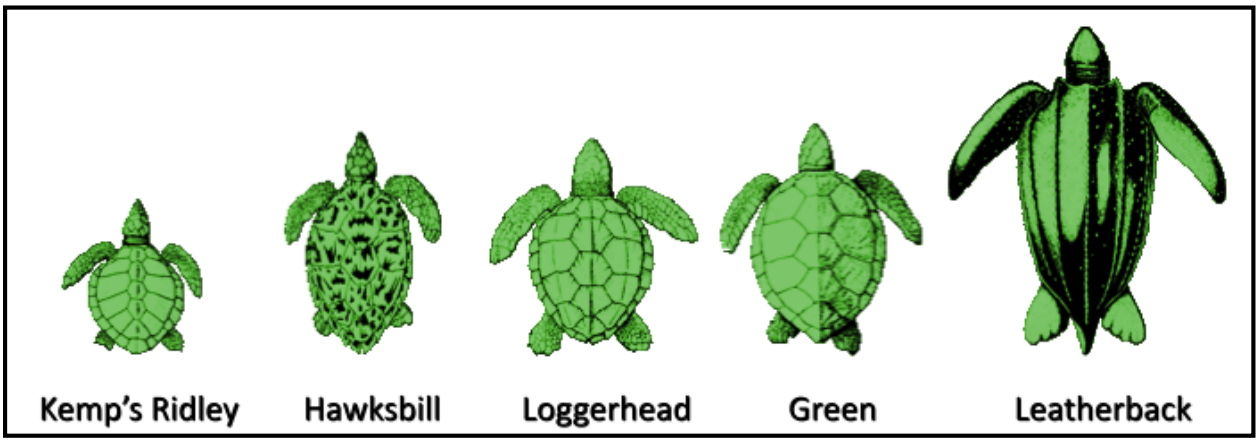

Figure 9.1 Relative sizes of sea turtles with Kemp's ridley as the smallest at 62–70 cm and leatherback as the largest at 121–243 cm.

Hawksbill turtles occur in tropical and sub-tropical waters of the Atlantic, Pacific, and Indian Oceans (Witzell, 1983). After hatching, juvenile hawksbills enter pelagic waters and forage in convergence zones. Larger juveniles re-enter coastal waters and forage on sponges and other invertebrates in coral reef, hard-bottom, or mangrove habitats as large juveniles, sub-adults, and adults (Witzell, 1983; Musick and Limpus, 1997). In US waters of the western North Atlantic, hawksbill sea turtles are found throughout the Gulf of Mexico and southern Florida, although the species is more common in Puerto Rico and the US Virgin Islands (NMFS and USFWS, 1993). Most nesting records are from the Caribbean, but a few nests are recorded each year in southeast Florida and the Florida Keys. The species is rare north of Florida, but strandings and sightings have been recorded as far north as Massachusetts (Hirth, 1997). Thus, although this is a relatively rare species, it is found throughout the year in the South Atlantic Planning Area.

Kemp's ridley sea turtles nest primarily in the Gulf of Mexico, although juveniles and sub-adults are distributed along the U.S Atlantic coast as far north as Cape Cod. Almost all nesting occurs at a single site, Rancho Nuevo, on the eastern coast of Mexico, with a few additional nests in Texas, Florida, South Carolina, and North Carolina (USFWS and NMFS, 1992). Based on trends in the number of nests laid each year at Rancho Nuevo, the population is recovering from past over-harvest and fisheries by-catch (Turtle Expert Working Group, 2000). Kemp's ridley sea turtles occur year-round within the South Atlantic Planning Area. Sightings are recorded throughout the winter in both Early Warning System and USWTR aerial surveys (Department of

the Navy, 2008a). Kemp's ridley hatchlings occur offshore of the shelf break in floating mats of *Sargassum*. Large sub-adults, and even some adults, occur year-round in coastal waters and in the Gulf Stream during colder months.

Leatherback sea turtles are distributed throughout the world's oceans in tropical and subtropical waters throughout the year and in temperate waters during summer and early fall (NMFS and USFWS, 1992). Leatherbacks have the widest distribution range of any sea turtle (Boulon et al., 1988). In the North Atlantic, leatherbacks are found from the Caribbean to Newfoundland with extensive seasonal migrations between temperate and tropical waters (James et al., 2005). There is limited information available regarding the habitats utilized by young juvenile leatherbacks because these age classes are entirely oceanic, but they do not associate with *Sargassum* or other flotsam, as is the case for juveniles of the other sea turtle species (NMFS and USFWS, 1992; Musick and Limpus, 1997). Juno Beach, FL is the most important leatherback nesting colony in the continental US (Stewart and Johnson, 2006). A small number of leatherbacks nest further north along the Florida coast and a few scattered nests occur as far north as North Carolina (NMFS and USFWS, 1992). Unlike other areas in the western North Atlantic, the number of nests in Florida is increasing rapidly (Turtle Expert Working Group, 2007). Due to their migratory behavior, the occurrence of leatherback sea turtles is highly seasonal along the South Atlantic Planning Area, with the greatest concentrations off the northeast Florida coast during the winter. This species is seen relatively frequently in the ESW and USWTR surveys off the northeast coast of Florida.

The loggerhead is the most abundant sea turtle occurring in US waters. NMFS and USFWS have identified five nesting subpopulations in the northwestern Atlantic: the Northern US (Florida/Georgia border to southern Virginia); Peninsular Florida; Dry Tortugas; Northern Gulf of Mexico; and Greater Caribbean. All of these subpopulations are exhibiting declining trends in the annual number of nests, although some of these negative trends have ameliorated in the most recent years for which data are available. The most significant decline occurred in Peninsular Florida, where nesting declined 26% from 1989-2008 and 41% from 1998-2008 (Witherington et al., 2009). With the addition of more recent data in which a large number of nests have been documented in 2009 and 2010, however, the long-term nesting trend for Peninsular Florida is not statistically different from zero (NMFS and USFWS, 2011). Nesting occurs from April through September, with a peak in June and July (NMFS and USFWS, 2011). Post-hatchling loggerheads enter the Gulf Stream and forage in the North Atlantic Gyre (Carr, 1987). After spending several years in the oceanic zone, juvenile loggerheads migrate into neritic waters from Cape Cod to Florida. Some of these juveniles may re-enter the pelagic environment after foraging in neritic waters for a year or more (McClellan and Read, 2007). Large juvenile turtles forage in semi-enclosed, shallow water estuarine habitats, such as Pamlico Sound and the Indian River Lagoon. Adults tend to utilize estuarine areas with more open ocean access, such as Chesapeake Bay. In addition, adult and large juvenile loggerheads can also be found over continental shelf waters, from New York to Florida. Loggerhead sea turtles are the most common species in the South Atlantic Planning Area and occur year-round in the region, using this area for foraging, migrating, nesting, and overwintering.

9.4. POTENTIAL IMPACTS OF OCS DEVELOPMENT ON SEA TURTLES

9.4.1 Oil and Gas Exploration and Development

The sensitivity of sea turtles to oil and gas exploration and development has been covered extensively elsewhere (Lutcavage et al., 1995; NOAA, 2010) and will be reviewed here only briefly.

Oil and gas exploration and development may have adverse indirect effects on populations of sea turtles during exploration (seismic activities) or production (drilling or ship noise) phases. As noted below, very little is known of the effects of these activities on populations of sea turtles. The most intense sounds associated with oil and gas exploration and development are typically associated with seismic activities during the exploration phase. As described by Nowacek et al. (2007), seismic exploration activities produce short broadband sounds with high peak source levels, typically 220-255 dB re 1 µPa at 1 m (decibel value peak-to-peak relative to the reference pressure one micropascal at a reference distance of 1 meter). During these activities airgun arrays are used to send low-frequency (<300 hertz [Hz]) impulse sounds into the sea floor. Considerable sound is also introduced into surrounding waters, although the propagation into these adjacent waters has not been well documented (Madsen et al., 2006).

Very little is known about how sea turtles hear or respond to potentially harmful sources of anthropogenic noise. No evidence exists that sea turtles use acoustics for communication, but they may use sound for navigation, locating prey, and general environmental awareness. Our limited understanding of the auditory biology of these animals suggests that sea turtles have a narrow range of hearing between 100 and 1,000 Hz in air or partially submerged (Ridgway et al., 1969; Bartol and Musick, 2003; Swimmer and Brill, 2006). A few opportunistic observations suggest sea turtles may respond behaviorally to the sounds of airgun arrays (Weir, 2007; DeRuiter and Doukara, 2012), but in general our knowledge is inadequate to understand how they may respond to noise associated with oil and gas exploration and development (O'Hara and Wilcox, 1990; Samuel et al., 2005).

Also of concern are the potential direct impacts of production as a result of operational discharges or spills. Direct exposure to oil can affect all life stages of sea turtles, from eggs and hatchlings on nesting beaches, to pelagic juveniles far from shore. Little is known about the toxicity of oil to these different life stages (partly due to legal and ethical difficulties of conducting experiments with endangered and threatened species). In general, however, the earlier life stages are believed to be at greater risk (NOAA, 2010).

Finally, oil and gas production platforms modify the physical habitats of sea turtles, which can have both positive and negative effects on their populations. For example, physical structures associated with oil and gas production facilities may provide habitat for foraging sea turtles, particularly those that feed on hard surfaces, such as loggerheads (Hopkins-Murphy et al., 2003).

9.4.2 Sand and Gravel Extraction

Multiple potential sand borrow sites exist off the coast of the southeastern US, with several sites off the coasts of South Carolina and eastern Florida. BOEM and the Bureau of Safety and Environmental Enforcement have funded cooperative sand evaluation programs with both of

these states to identify and evaluate sand resources as potential sources for future beach replenishment projects (Michel, 2004). Potential borrow sites vary considerably in size, from 1.24 million yd^3 off Jacksonville, Florida to 150,000 yd^3 off Myrtle Beach, South Carolina (Drucker et al., 2004), and there considerably larger sand resource areas offshore of the northeast coast of Florida. Most potential borrow sites occur in relatively shallow water, however, between 5 m and 15 m deep (Michel et al., 2001).

Due to the proximity of these resources to shore, only coastal sea turtles will be at risk from sand dredging activities. The risks associated with sand extraction include: direct mortality through entrainment in hopper and cutter-head dredges; collisions with dredge and support vessels; production of noise; and modification of habitat and prey fields through substrate removal (Michel et al., 2001; Brooks et al., 2006; Thomsen et al. 2009). This does not include consideration of any adverse effects on beach habitats used by sea turtles for nesting (e.g., Rumbold et al., 2001).

Of particular concern in the southeastern US are loggerhead sea turtles, which forage in sand borrow areas, although green, Kemp's ridley, and hawksbill sea turtles may also be at some risk from dredging activities. Leatherback sea turtles nest in eastern Florida; these turtles are at risk from collisions with vessels in this area.

Robinson et al. (2011) conducted field studies of noise generated by six vessels during dredging of marine aggregates in the UK. They reported that:

- Source levels at frequencies below 500 Hz are generally in line with those expected for a cargo ship travelling at modest speed;
- Source levels at frequencies above 1 kHz show elevated levels of broadband noise generated by the aggregate extraction process; and
- The elevated broadband noise is dependent on the aggregate type being extracted, with gravel generating higher noise levels than sand.

At present, there is insufficient knowledge to determine what effects, if any, dredging at OCS sand borrow sites in the South Atlantic Planning Area would have on populations of sea turtles in the southeastern US. Acoustic harassment thresholds for sea turtles have not been established. Research into the hearing capabilities of these species and their response to anthropogenic sound is ongoing (Dow, 2010.). However, because dredging activities occur infrequently and in areas not known to be sea turtle concentration areas, any impacts are likely to be transient and minor.

Mitigation of the most direct risk, entrainment in dredges, can be facilitated by placing observers aboard vessels working in sand removal and installation of sea turtle deflectors on hopper dredges where risk of entrainment is of concern. Detailed protocols for such mitigation activities have been developed, and include monitoring the presence of sea turtles in the dredge area and documenting adverse interactions between these animals, the dredge vessel, or support craft (Michel et al., 2001; Nairn et al., 2004). In some cases, trawlers have been deployed ahead of dredges to capture and relocate sea turtles away from the project area, and there has been some mortality of turtles in these trawls. NMFS and the US Army Corps of Engineers are currently evaluating appropriateness of dredging windows and trawling measures. Such monitoring

protocols are required as a condition of Section 7 consultations and permits required under the ESA.

9.4.3 Renewable Energy Development

The development of offshore renewable energy resources is likely to expand rapidly in the coming few decades (Boehlert and Gill, 2010). With the technology currently available, projects harnessing offshore wind energy are likely to be sited in shallow water (typically less than 15 m deep), adjacent to shore-based transmission facilities, in areas of relatively high and predictable wind energy (Michel et al., 2007). The continental shelf extends a considerable distance off the coast of the southeastern US, offering a relatively large area for wind energy projects.

Offshore wind energy projects can potentially affect sea turtles in several ways: from noise produced during construction and operation; from modification to habitat caused by installation of monopiles; and from emission of low frequency electromagnetic fields (Boehlert and Gill, 2010). Nothing is known about the effects of electromagnetic fields on sea turtles; this is an area that requires future research. This review focuses, therefore, on the potential effects of acoustics and habitat modification.

Most concern regarding the potential effects of wind farms on sea turtles involves the potential effects of noise generated during construction (Madsen et al., 2006; Thomsen et al., 2006). During construction noise is produced by seismic profiling, vessels, pile driving, and trenching. Pile driving is of particular concern (Madsen et al., 2006) because it generates transient sounds of very high source level and broad bandwidth (Richardson et al., 1995; Rodkin and Reyff, 2004; Bailey et al., 2010). Most sound energy created by pile driving is of low frequency (below 500 Hz), although some energy extends into the ultrasonic frequency range. Received levels can be above 200 dB re 1 μPa at a distance of 100 m (see Wahlberg and Westerberg 2005 for a review). Sea turtles likely hear sounds in these low frequencies and are thus potentially vulnerable to the sounds of pile driving. Proposed mitigation practices to reduce these potential impacts include a "soft start" procedure and cessation of pile driving if sea turtles are reported within a certain distance from the pile driving activity.

The noise created by operational wind turbines is less intense and restricted to frequencies below 1 kHz, often below 700 Hz (Madsen et al., 2006). Sound propagation in these shallow water is complex and poorly understood; transmission loss may be significant in these environments, further complicating assessment of exposure and effects on sea turtles (Boehlert and Gill, 2010).

At present, there is insufficient knowledge to determine what effects, if any, construction and operation of wind farms would have on populations of sea turtles in the southeastern US. Acoustic harassment thresholds for sea turtles have not been established. Research into the hearing capabilities of these species and their response to anthropogenic sound is ongoing (W. Dow, Duke University, pers. comm.). On the positive side, some species, such as loggerhead turtles, may benefit from the creation of foraging habitat provided by monopiles in coastal waters.

Based on the limited evidence to date, it seems likely that most effects of projects harnessing offshore wind energy will be felt during the construction phase. Research should be conducted

into the effects of construction and operation on sea turtles likely to be exposed to these activities, including exposure to noise and electromagnetic fields.

9.5 Summary and Data Gaps in the State of Sea Turtle Knowledge with Regard to OCS Development

There is a good scientific understanding of the distribution and trends of nesting sea turtles along beaches in the South Atlantic Planning Area. All sea turtles occurring in this area are listed under the ESA and there is particular concern regarding the status of loggerhead sea turtles due to the widespread decline in the number of female turtles nesting along the beaches of the Florida peninsula. Our understanding of the distribution of sea turtles at sea, however, is quite poor, as most volunteer and scientific efforts have been expended on nesting beaches. In particular, there is little information on the at-sea distribution and trends of non-nesting turtles, especially in areas where oil and gas or alternative energy development are likely to occur. Addressing this data gap should be a priority for future research.

In addition, there is almost no information on the response of sea turtles to anthropogenic noise. Our understanding of sea turtle hearing is only rudimentary for most species and almost entirely lacking for others (such as leatherback turtles). Fundamental research on sea turtle hearing in water, combined with experimental work on their response to sounds associated with seismic exploration and pile driving (both of which produce intense, low frequency sound) should also be a priority for future research.

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CHAPTER 10: MARINE MAMMALS

10.1 INTRODUCTION

This chapter reviews knowledge of the marine mammal species that occur in the South Atlantic Planning Area waters. In total, 33 species of marine mammals (30 cetaceans, one sirenian, and two pinnipeds) are known or believed to occur in this region. Some of these species, such as the bottlenose dolphin, *Tursiops truncatus*, are year-round residents, while others, such as the North Atlantic right whale, *Eubalaena glacialis*, occur as seasonal migrants. Several species are known only from extra-limital records. All cetacean, pinniped, and sirenian species are covered by the federal Marine Mammal Protection Act (MMPA). In addition, seven species of marine mammals in the South Atlantic Planning Area are listed under the federal ESA.

10.2 DATA SOURCES

Much of the available knowledge of the distribution of cetaceans in this region is derived from an ongoing program of shipboard and aerial line-transect surveys conducted by NOAA. The surveys are designed to provide quantitative estimates of density for each cetacean species, on a stock-by-stock basis. These data are used to fulfill the requirements of the marine mammal stock assessment program mandated under Section 117 of the MMPA. Stock assessment reports are updated at least every three years and more frequently for stocks of concern (Waring et al., 2011).

Each winter, a comprehensive aerial survey is conducted of the calving grounds of right whales off the coasts of northern Florida and Georgia. These aerial surveys, known as the Early Warning System (EWS), are designed to provide near real-time locations of right whales to commercial mariners and other interested parties. The Wildlife Trust, Florida Fish and Wildlife Conservation Commission, and New England Aquarium conduct the EWS surveys (Slay et al., 2002).

Since 2009 a consortium of academic institutions, including the University of North Carolina at Wilmington, St. Andrews University, Scripps Institution of Oceanography, and Duke University, has been conducting year-round aerial and shipboard, line-transect surveys of cetaceans and sea turtles off Jacksonville, FL. In addition, passive acoustic monitoring systems (both mobile and fixed) are employed to document the occurrence of vocalizing cetaceans. This monitoring program is designed to provide information on the occurrence of cetaceans and quantitative estimates of their density in the proposed site of an USWTR, to be developed by the US Navy (Department of the Navy, 2009).

The University of Rhode Island conducted line-transect, aerial surveys between October 1978 and January 1982 as part of the CETAP, sponsored by the Bureau of Land Management. Most of these surveys were conducted in OCS waters of the eastern US from Cape Hatteras to the Gulf of Maine, but some survey effort extended south into the South Atlantic Planning Area (CETAP, 1982). The CETAP surveys were designed to assess the distribution and abundance of whales, dolphins, and sea turtles in the OCS.

The surveys described above are augmented by information derived from observations of stranded marine mammals made by the volunteer members of the Southeast Marine Mammal Health and Stranding Response Program. One must take care when interpreting the stranding database, as these records often include individuals beyond the limit of the normal range of a species. For example, records of both pinnipeds in the southeastern US exist only as seasonal strandings, well outside the normal range of both species.

Information on the distribution of the Florida manatee, *Trichechus manatus*, comes from aerial surveys, satellite-linked telemetry, and carcass salvage programs conducted by the US Geological Survey and the Florida Fish and Wildlife Conservation Commission.

Several other useful resources have compiled information on the occurrence and distribution of marine mammals in the southeastern US OBIS-SEAMAP (Ocean Biogeographic Information System-Spatial Ecological Analysis of Mega-vertebrate Populations) is a spatially referenced online database that aggregates geo-referenced data on marine mammals and sea turtles, including surveys, telemetry, and shore-based counts. The online collection can be searched and visualized through a set of advanced online mapping applications (Halpin et al., 2009). Most of the NOAA, CETAP, and USWTR marine mammal survey data sets are available online through the OBIS-SEAMAP portal.

In addition, the US Navy MRA program contains a comprehensive compilation of data and literature concerning protected resources found in its various marine operating areas. Each MRA reviews information on the occurrence of these resources within a particular marine operating area. An MRA was prepared for the Charleston/ Jacksonville Operating Area in October 2008 (Department of the Navy, 2008a). This MRA also provides a comprehensive review of all survey efforts in the region prior to 2008. The MRAs present the technical background for specific Navy actions, such as requests for Letters of Authorization under the MMPA (e.g., Department of the Navy, 2008b).

Finally, as part of the Atlantic Marine Assessment Program for Protected Species, NOAA, BOEM, USFWS, and US Navy are working to develop spatially explicit models of seasonal density estimates for marine mammals in the western North Atlantic Ocean. These models will be created from survey data collected over multiple years using direct aerial and shipboard surveys conducted by scientists from NOAA.

10.3 Spatial Models of Habitat and Density

Two large-scale projects have generated spatially explicit estimates of cetacean occurrence and density in the South Atlantic Planning Area. No similar efforts have been made for pinnipeds or sirenians.

In the first effort, researchers from Duke University, supported by the Strategic Environmental Research and Development Program (SERDP), produced a series of spatio-temporal models of cetacean distribution, as predicted by physical conditions of the marine environment (Best et al., 2007; Halpin et al., 2009; Best et al., 2012). The general additive models (GAMs) were parameterized using line-transect survey data contained in OBIS-SEAMAP and a variety of

remotely sensed environmental variables. The model outputs predict the likelihood of occurrence, or habitat suitability, for individual species or species guilds, along the US east coast and Gulf of Mexico on a seasonal basis, where sufficient data exist. For many species, there were too few observations to create robust habitat models.

The US Navy has also produced spatially explicit estimates of cetacean density in their Operating Areas (Department of the Navy, 2007). These estimates were derived from: spatial models using line-transect survey data provided by the National Marine Fisheries Service (NMFS); abundance estimates presented by Mullin and Fulling (2003); or abundance estimates found in current NOAA stock assessment reports (Department of the Navy, 2007; Waring et al. 2011). The model outputs are referred to as Navy Operating Area Density Estimates (NODEs).

Maps of the SERDP and NODE model outputs are available online through the OBIS-SEAMAP data portal. In addition, several other taxon-specific modeling exercises have produced useful products, particularly for right whales (e.g., Garrison, 2007a; Firestone et al., 2008; Good, 2008; Schick et al., 2009).

10.4 CETACEAN SPECIES SUMMARIES

Extant cetaceans belong to one of two sub-orders: the baleen whales (*Mysticetes*) and toothed odontocetes (*Odontocetes*). The cetacean assemblage in the South Atlantic Planning Area contains seven mysticete and twenty-three odontocete species. Six of these cetaceans are listed as endangered under the ESA (Table 10.1).

Table 10.1
Cetacean species present in waters of the South Atlantic Planning Area. All estimates of abundance are taken from Waring et al. (2011).

Scientific Name	Common Name	ESA Status	Density (per km^2)	Abundance (CV)
Sub-Order Mysticeti				
Family Balaenidae				
Eubalaena glacialis	Right whale	Endangered	0.00073[1]	361 (NA)
Family Balaenopteridae				
Megaptera novaeangliae	Humpback whale	Endangered	0.00116[1]	847 (0.55)
Balaenoptera acutorostrata	Minke whale		0.00004[1]	8,987 (0.32)
Balaenoptera brydei	Bryde's whale			NA
Balaenoptera borealis	Sei whale	Endangered		386 (0.85)
Balaenoptera physalus	Fin whale	Endangered	0.00000[1]	3,985 (0.24)
Balaenoptera musculus	Blue whale	Endangered		unknown
Abundance estimates are not available for all species. CV = coefficient of variance.				

[1] Department of the Navy (2008b)
[2] Mullin and Fulling (2003)

Table 10.1 Cetacean species present in waters of the South Atlantic Planning Area. Estimates of abundance are taken from Waring et al. (2011) (continued).

Scientific Name	Common Name	ESA Status	Density (per km^2)	Abundance (CV)
Sub-Order Odontoceti				
Family Physeteridae				
Physeter macrocephalus	Sperm whale	Endan-gered	0.00206[2]	4,804 (0.38)
Family Kogiidae				
Kogia breviceps	Pygmy sperm whale		0.00101[2]	395 (0.40)
Kogia sima	Dwarf Sperm Whale		0.00101[2]	395 (0.40)
Family Ziphiidae				
Ziphius cavirostris	Cuvier's beaked whale			3,513 (0.63)
Mesoplodon mirus	True's beaked whale		0.00061[2]	3,513 (0.63)
Mesoplodon europaeus	Gervais' beaked whale		0.00061[2]	3,513 (0.63)
Mesoplodon densirostris	Blainville's beaked whale		0.00061[2]	3,513 (0.63)
Mesoplodon bidens	Sowerby's beaked whale		0.00061[2]	3,513 (0.63)
Family Delphinidae				
Tursiops truncatus	Bottlenose dolphin		0.19732[1]	See Note 3
Stenella attenuata	Pantropical spotted dolphin		0.02520[2]	4,439 (0.49)
Stenella frontalis	Atlantic spotted dolphin		0.43118[1]	50,978 (0.42)
Steno bredanensis	Rough-toothed dolphin		0.00048[2]	unknown
Grampus griseus	Risso's dolphin		0.05654[1]	20,479 (0.59)
Globicephala macrorhynchus	Short-finned pilot whale		0.01111[1]	24,674 (0.45)
Stenella longirostris	Spinner dolphin			unknown
Stenella clymene	Clymene dolphin		0.01063[2]	unknown
Stenella coeruleoalba	Striped dolphin		0.01785[2]	94,462 (0.40)
Delphinus delphis	Common dolphin		0.00000[1]	120,743 (0.23)
Lagenodelphis hosei	Fraser's dolphin			unknown
Peponcephala electra	Melon-headed whale			unknown
Feresa attenuata	Pygmy killer whale			unknown
Pseudorca crassidens	False killer whale			unknown
Orcinus orca	Killer whale			unknown

Abundance estimates are not available for all species. CV = coefficient of variance

[1] Department of the Navy (2008b)
[2] Mullin and Fulling (2003)
[3] Bottlenose dolphin have a complex mixture of stocks in the region of interest

10.4.1 Mysticetes

The northern right whale is one of the world's most endangered marine mammals (Clapham et al., 1999; IWC, 2001). Right whales were listed as endangered under the ESA in 1970 (NMFS, 2005). The species was one of the first to be depleted by commercial whaling and has not recovered despite complete protection since 1946 (Reeves and Mitchell, 1986). There are no estimates of total population size; but 361 individually recognized whales were known to be alive in 2009 (Waring et al., 2011). The species is threatened by entanglement in fishing gear and collisions with large vessels (Kraus et al., 2005).

Coastal waters off the coasts of northeastern Florida and Georgia are the only known calving grounds for this critically endangered species (Kraus et al., 1986; Winn et al., 1986; Kraus et al., 1993; Garrison, 2007a,b; Good, 2008). Approximately three-quarters of all known right whale births are believed to occur in this area (Kraus et al., 1993). Adult female whales take advantage of relatively calm nearshore waters to give birth and nurse their young calves (Knowlton et al., 1994; Keller et al., 2006; Good, 2008). A few juveniles and adult males also occur in this area each winter. This area was designated as critical habitat under the ESA in 1994 (NMFS, 1994; 2005). A few right whale births have been observed outside this area, including one in 2010 that occurred further offshore, adjacent to the proposed USWTR site off Jacksonville (Foley et al., 2011). NMFS is currently considering whether or not to expand this area of critical habitat.

Right whales arrive in the southeastern US in November and typically remain through March (Kraus et al., 1986; 1993; Keller et al., 2006). During this period, the whales fast, relying on stored energy deposited during the feeding season (Winn et al., 1986). In spring the whales return north to feeding grounds in the Gulf of Maine, the Bay of Fundy, and further north (Garrison, 2007a). The migratory corridors linking the calving and feeding grounds have not been well documented (Firestone et al., 2008), but limited observations suggest that migrating whales stay relatively close to shore as they travel north in the spring (Schick et al., 2009). Small numbers of right whales were taken in a shore-based fishery at Cape Lookout in the 18th and 19th centuries as the whales migrated north in the springtime (Simpson and Simpson, 1990). Today, right whales are vulnerable to ship strikes during this migratory period (Ward-Geiger et al., 2005; Knowlton and Brown, 2007). As a result, NMFS has implemented a series of regulations, including restricted vessel speeds near ports, to reduce the risk of such collisions (NMFS, 2008; see also Schick et al., 2009).

Good (2008) used a Bayesian approach to model the habitat of right whales in the southeastern US using presence-only observations of females and calves from the EWS, producing four separate models for the months of December, January, February, and March. These models were then combined to examine the temporal and spatial stability of right whale habitat during the winter calving period. A graphical representation of her model outputs, together with a depiction of the currently designated critical habitat area, is presented in Figure 10.1. It is important to note that these models depict the geographical extent of suitable habitat, not all of which is currently occupied by this extremely depleted population (Good, 2008).

To summarize, right whales are present in coastal waters of the South Atlantic Planning Area from November to March. Most whales are found very close to shore off the coasts of northern

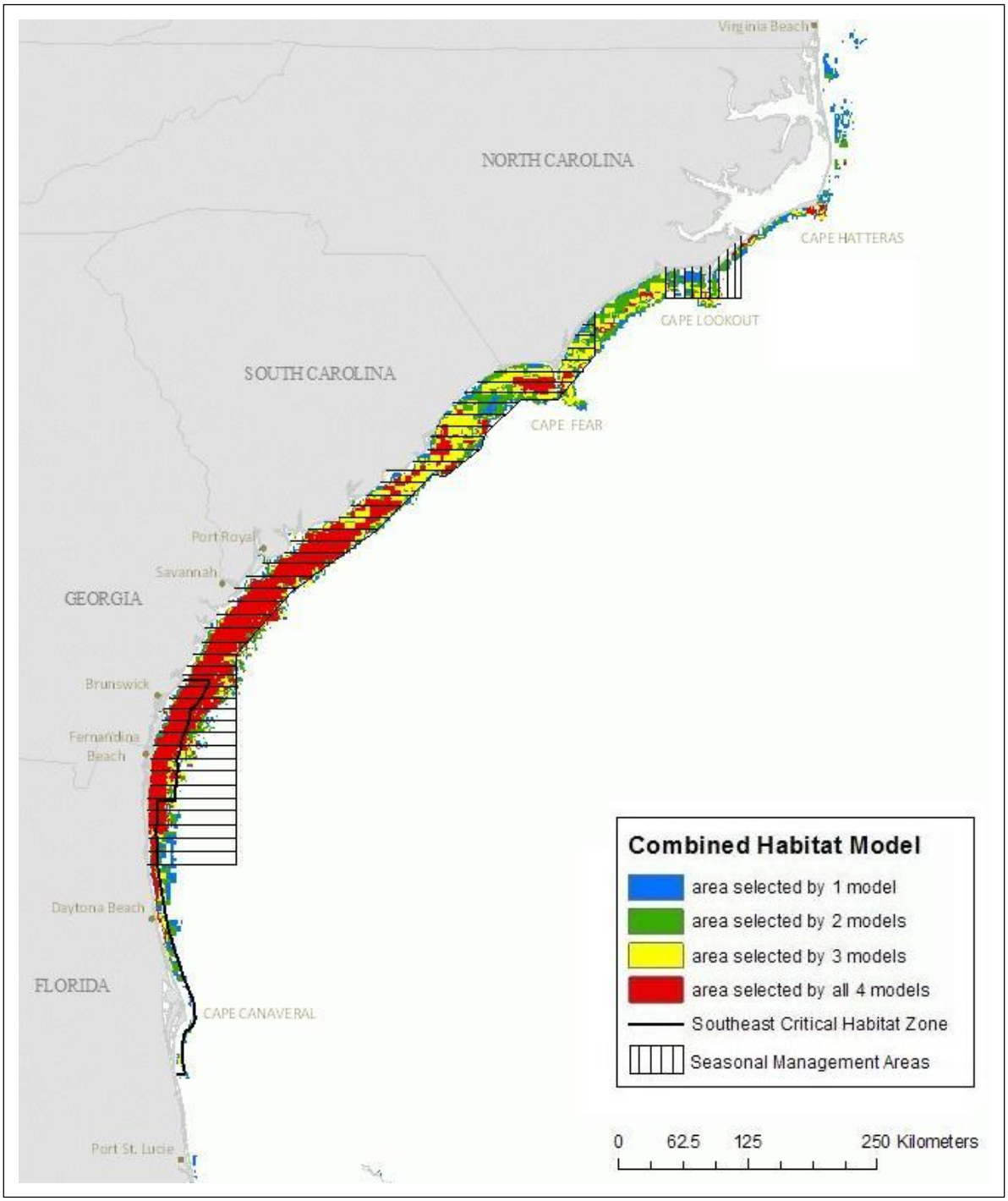

Figure 10.1 Habitat suitability for right whale mother-calf pairs in the southeastern US. Reproduced, with permission from Good (2008). Also shown are the Seasonal Management Areas where vessels 65 ft (19.8 m) or longer must travel at 10 knots or less during November 15 through April 15.

Florida and Georgia. A few whales may be found offshore or further north in coastal waters of South and North Carolina. In the late autumn and in early spring, whales migrate to and from these breeding grounds. During migration whales are found primarily in coastal waters. Due to their small population size, whale densities are low even in the core calving area. The US Navy estimated densities of between 0.00032 and 0.00124 whales per km^2 in this area during winter and spring (Department of the Navy, 2008b).

The humpback whale, *Megaptera novaeangliae*, was listed as endangered under the ESA in 1973 (NMFS, 1991). In 1992, the size of the North Atlantic meta-population was estimated as 11,570 animals (Stevick et al., 2003a). At least some of the humpback whales in the South Atlantic Planning Area are from the Gulf of Maine population (Barco et al., 2002). The best estimate for the feeding population of humpback whales in the Gulf of Maine is 847 animals (CV=0.55) (Waring et al., 2011). All breeding humpback whales in the North Atlantic migrate to calving grounds in the Caribbean in winter (Clapham et al., 1993; Stevick et al., 2003b). In recent years, an increasing number of juvenile whales have been documented along the Mid-Atlantic coast during winter (Swingle et al., 1993; Wiley et al., 1995). These juvenile whales spend the winter feeding in coastal waters (Laerm et al., 1997), rather than migrating with the adult population to the breeding grounds. The migratory routes linking tropical breeding and temperate feeding grounds are poorly understood (Winn et al., 1979; Stevick et al., 2003b), but it is likely that some migrating adult whales pass though shelf waters off the South Atlantic Planning Area in autumn and spring. In addition, a small number of juvenile whales may be present in nearshore waters during winter. The species is known from strandings (Layne, 1965; Caldwell et al., 1971) and historical whaling records (Townsend, 1935) in the region. The US Navy estimated densities of humpback whales from 0.00058 to 0.00116 whales per km^2 in the South Atlantic Planning Area during autumn, winter, and spring (Department of the Navy, 2008b).

The minke whale, *Balaenoptera acutorostrata*, is not listed under the ESA. Four populations of minke whales are recognized in the North Atlantic; those present in the eastern US belong to the Canadian East Coast stock, which had an estimated abundance of 8,987 (CV=0.32) (Waring et al., 2011). Like most other *Mysticetes*, minke whales are believed to undertake seasonal migrations between temperate feeding and tropical breeding grounds, but the exact location of the breeding grounds for the North Atlantic minke whales are not known (Mitchell, 1991). Recent aerial surveys in the Jacksonville USWTR site documented several adult female minke whales with newborn calves (W.A. McLellan, unpub. obs.). Otherwise, there are few records of this species in the South Atlantic Planning Area; the OBIS-SEAMAP data repository has no records from this area. The US Navy estimated year-round densities of 0.00004 minke whales per km^2 in the southeastern US (Department of the Navy, 2008b).

Bryde's whales, *Balaenoptera brydei*, have a more tropical distribution than most other baleen whales. These animals are difficult to distinguish from other rorqual whales. As a result, this is one of the most poorly known *Mysticetes*. The species is not listed under the ESA. NMFS has not conducted a stock assessment of Bryde's whales in the Atlantic due to a lack of information. It is likely that Bryde's whales occur in this area, but there are no records in OBIS-SEAMAP from the South Atlantic Planning Area. The US Navy was unable to estimate densities for this species in the Jacksonville and Charleston Operating Areas (Department of the Navy, 2008b).

The sei whale, *Balaenoptera borealis*, was listed as endangered under the ESA in 1973 (NMFS, 1998a). Three sei whale populations exist in the North Atlantic (Mitchell and Chapman, 1977); those in US waters form part of the Nova Scotia population (Waring et al., 2011). These whales are found in the Gulf of Maine during spring, summer, and autumn, feeding along the edge of the continental shelf and making episodic incursions into shallower waters. The breeding ground of these whales is unknown. The best estimate of abundance for Nova Scotia stock of sei whales is 386 (CV=0.85), but this estimate is acknowledged to be negatively biased (Waring et al., 2011). A few stranding records of this species exist in the southeastern US (e.g., Moore, 1953). Sei whales occur in the South Atlantic Planning Area, probably at the edge of and beyond the continental shelf during winter, but there are no records in OBIS-SEAMAP. The US Navy was unable to estimate densities for this species in the Jacksonville and Charleston Operating Areas (Department of the Navy, 2008b).

The fin whale, *Balaenoptera physalus*, was listed as endangered under the ESA in 1970 (NMFS, 1998a). All fin whales in eastern Canada and along the US Atlantic coast belong to the Western North Atlantic population, although some undescribed population sub-structure likely exists (Bérubé et al., 1998). Fin whales are one of the most common baleen whales along the US Atlantic coast. The Gulf of Maine is an important feeding ground for this species in the spring, summer, and autumn (Hain et al., 1992). The size of this population was estimated as 3,985 (CV=0.24) (Waring et al., 2011). The breeding grounds of fin whales in the North Atlantic are not known, but acoustic detection of their calls suggests that a diffuse southbound migration occurs in autumn (Clark, 1995). Apart from occasional strandings (Moore, 1953), there is little information on the occurrence of fin whales in the South Atlantic Planning Area, nor are there records from this area in OBIS-SEAMAP. The US Navy estimated a density of zero whales per km^2 but cautioned that the species was not necessarily absent from the area (Department of the Navy, 2008b). It is likely, therefore, that a small number of fin whales occur during autumn, winter, and spring in the South Atlantic Planning Area.

The blue whale, *Balaenoptera musculus*, was listed as endangered under the ESA in 1973 (NMFS, 1998b). This species occurs only rarely in US Atlantic waters and, consequently, there is little information on its occurrence and distribution (Waring et al., 2011). There is no current estimate of abundance for this species in the northwestern Atlantic, nor are there any records of fin whales in the southeastern US in OBIS-SEAMAP. The US Navy was unable to estimate the density of this species in the Charleston and Jacksonville Operating Areas (Department of the Navy, 2008b). It is possible that the blue whale is an occasional visitor to the South Atlantic Planning Area in autumn, winter, and spring.

10.4.2 Odontocetes

The sperm whale, *Physeter macrocephalus*, was listed as endangered under the ESA in 1973 (NMFS, 2006). This is perhaps the most widely distributed cetacean, occurring in most of the world's oceans. The species occurs along the margins of the continental shelf and into oceanic waters, far from shore. The population structure of sperm whales in the Atlantic has not been described (Dufault et al., 1999). The best estimate of abundance for sperm whales from Florida to the Bay of Fundy is 4,804 (CV=0.38), from surveys conducted in 2004 (Waring et al., 2011). Female sperm whales live in matriarchal groups and are generally restricted to tropical and sub-tropical waters. Adult males range more widely, feeding in temperate waters and visiting the

tropics to breed (Whitehead, 2003). Sperm whales have been recorded during NOAA line-transect surveys off the southeastern US (Mullin and Fulling, 2003) and occur relatively frequently as strandings in this area (Moore, 1953; Caldwell and Golley, 1965; Layne, 1965; Caldwell and Caldwell, 1980). In addition, sperm whales were taken in large numbers in what whalers referred to as the 'Charleston Ground' off the coast of South Carolina in the 19th century (Townsend, 1935). This species is an important component of the shelf edge and oceanic cetacean fauna in the southeastern US, particularly over the Blake Plateau and into deeper waters (Schmidly, 1981). The US Navy estimated a density of zero whales per km^2 over areas of the OCS in this region (Department of the Navy, 2008b), but this estimate did not include the deeper habitats in which sperm whales occur. A depiction of habitat suitability for sperm whales in the southeastern US is provided in Figure 10.2, using model outputs from the SERDP program (Best et al., 2012).

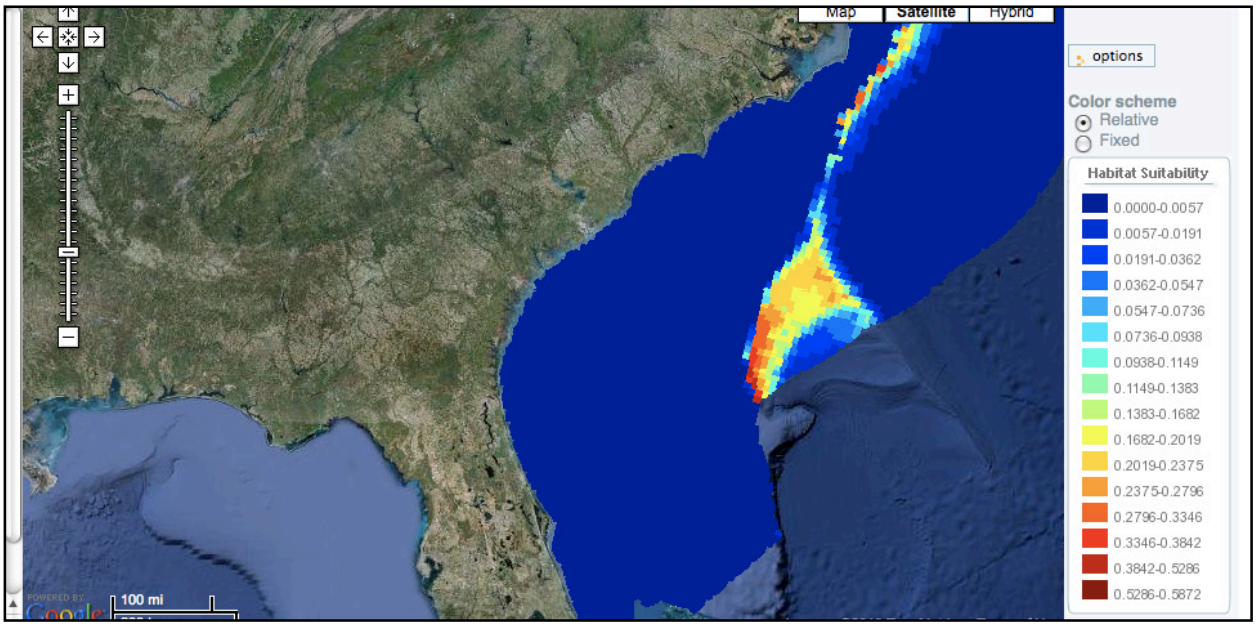

Figure 10.2 Habitat suitability index for sperm whales in the southeastern US during autumn. Values range from 0.0 (completely unsuitable habitat) to 1.0 (completely suitable habitat).

Dwarf and pygmy sperm whales, *Kogia sima* and *Kogia breviceps*, respectively, are cryptic, poorly known species known primarily from strandings. Both species are widely distributed in temperate and tropical waters throughout the world's oceans (Caldwell and Caldwell, 1989). These animals are very shy, avoid vessels, and are almost impossible to see in all but the best sea conditions. The two species are very difficult to distinguish in the field, so individuals are identified only to genus in most surveys (e.g., Mullin and Fulling, 2003). As a result, NMFS combines both species into a single stock assessment (Waring et al., 2011). Nothing is known about the population structure of either species. The best abundance estimate for both species of *Kogia* combined is 395 animals (CV=0.40), from surveys along the entire east coast in 2004 (Waring et al., 2011). The frequency with which these species strands in the South Atlantic Planning Area suggests that this estimate is negatively biased to a significant degree. Both species are distributed along the continental shelf break, the continental slope, and into deeper

waters (Baumgartner et al., 2001). Observations of stranded animals (e.g., Moore, 1953; Layne, 1965; Caldwell and Golley, 1965; Caldwell et al., 1971) suggest that both species are year-round residents in the South Atlantic Planning Area. The US Navy estimated year-round densities of 0.001 whales per km^2 in the study area, but noted that this estimate was likely to be negatively biased (Department of the Navy, 2008b).

Five species of beaked whales (Family *Ziphiidae*) in the genus *Ziphius* or *Mesoplodon* are either known or assumed to occur in the South Atlantic Planning Area. These are all deep-diving species that occur exclusively in the deep waters along and outside the continental shelf break (Mead, 1989). Most knowledge of these species comes from strandings. Cuvier's beaked whale is the most widely distributed beaked whale, occurring in all of the world's oceans (MacLeod et al., 2006). Cuvier's beaked whales are known from sightings and strandings (Moore, 1953; Layne, 1965; Caldwell et al., 1971; Mead, 1989) in the South Atlantic Planning Area.

The four beaked whale species of the genus *Mesoplodon* are cryptic and difficult to distinguish at sea. Three of these species, True's beaked whale, (*Mesoplodon mirus*), Gervais' beaked whale (*Mesoplodon europaeus*), and Blainville's beaked whale (*Mesoplodon densirostris*), are known from stranding records in the region (Caldwell and Golley, 1965; Caldwell and Caldwell, 1971a; Mead, 1989; MacLeod et al., 2006). Sowerby's beaked whale (*Mesoplodon bidens*) has a more northerly distribution than the other three; most records from north of Cape Hatteras. The presence of Sowerby's beaked whale in the South Atlantic Planning Area has been inferred from a single extra-limital stranding in the northern Gulf of Mexico (Bonde and O'Shea, 1989).

The best estimate for the abundance of all beaked whale species combined in the southeastern US Atlantic is 3,513 (CV=0.36) from surveys conducted in 2004 (Waring et al., 2011). The US Navy estimated a density of 0.00001 to 0.00063 beaked whales per km^2 for this region (Department of the Navy, 2008b). However, the density of these deep-water species is likely to be higher along the shelf break than this value, which was generated for the entire region. A depiction of habitat suitability for all beaked whales combined in the southeastern US is provided in Figure 10.3, using model outputs from the SERDP program (Best et al., 2012).

Fifteen species of dolphin (Family *Delphinidae*) are known or assumed to occur in this region. Six of these species are common and occur year-round: bottlenose dolphin (*Tursiops truncatus*), pan-tropical spotted dolphin (*Stenella attenuata*), Atlantic spotted dolphin (*Stenella frontalis*), rough-toothed dolphin (*Steno bredanensis*), Risso's dolphin (*Grampus griseus*), and short-finned pilot whale (*Globicephala macrorhynchus*).

Two ecotypes of bottlenose dolphin occur in the South Atlantic Planning Area: the coastal and offshore forms (Mead and Potter, 1995). The two forms exhibit fixed genetic differences and likely represent distinct species (Hoelzel et al., 1998). The distribution of the ecotypes overlaps on the continental shelf (Torres et al., 2003); coastal dolphins may be found in waters as deep as 31 m, and offshore dolphins may occur in waters as shallow as 13 m (Garrison et al., 2003).

NMFS recognizes a single population of offshore bottlenose dolphins in the western North Atlantic; this population ranges from Nova Scotia to Florida. Analysis of data from the CETAP

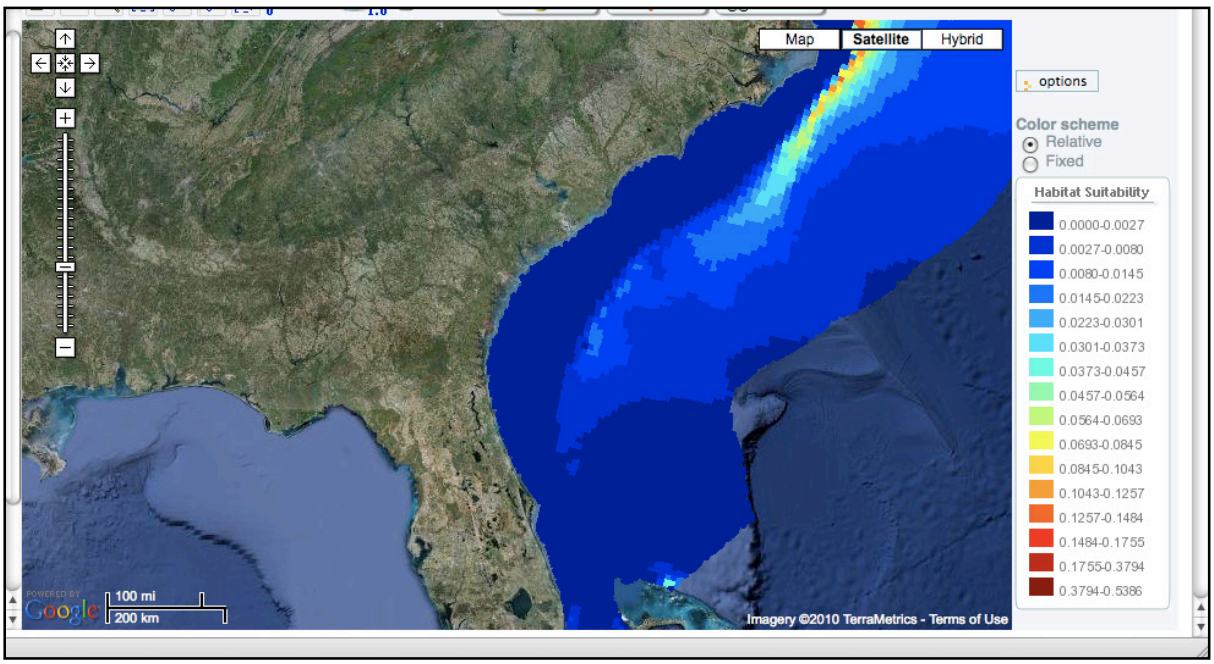

Figure 10.3 Habitat suitability index for beaked whales in the southeastern US during summer. Values range from 0.0 (completely unsuitable habitat) to 1.0 (completely suitable habitat).

surveys demonstrated that the highest densities of offshore bottlenose dolphins occurred along the shelf break (Kenney, 1990). The estimated abundance of this population is 81,588 (CV=0.17), generated from surveys in 2004 (Waring et al., 2011).

Population structure of coastal bottlenose dolphins in the South Atlantic Planning Area is complex and only partially understood (Waring et al., 2011). Coastal bottlenose dolphins occur in both ocean and estuarine environments. NMFS currently recognizes four estuarine stocks in this region: Charleston, Jacksonville, North Georgia/Southern South Carolina, and the Indian River. Dolphins in these stocks are year-round residents of estuarine waters, although animals may also use adjacent nearshore coastal waters. In addition, a single migratory population of dolphins (the Southern Migratory Stock) overlaps with these estuarine stocks in some coastal areas. This migratory stock moves as far north as Virginia during summer and is present off the coasts of Florida, Georgia, and South Carolina during winter. These seasonal movements are likely driven by variation in water temperature and prey availability (Torres et al., 2005). A considerable amount of current research is directed at refining this population structure and assessing individual stocks (Waring et al., 2011).

Bottlenose dolphins are one of the most common marine mammals in the South Atlantic Planning Area, in both coastal and offshore waters (Mullin and Fulling, 2003). The US Navy estimated densities of 0.03915 to 0.19732 dolphins per km^2 in this region (Department of the Navy, 2008b). These estimates do not differentiate between the two ecotypes. A depiction of habitat suitability for bottlenose dolphins in the South Atlantic Planning Area (including both ecotypes) is provided in Figure 10.4, using model outputs from the Duke SERDP program (Best et al., 2012).

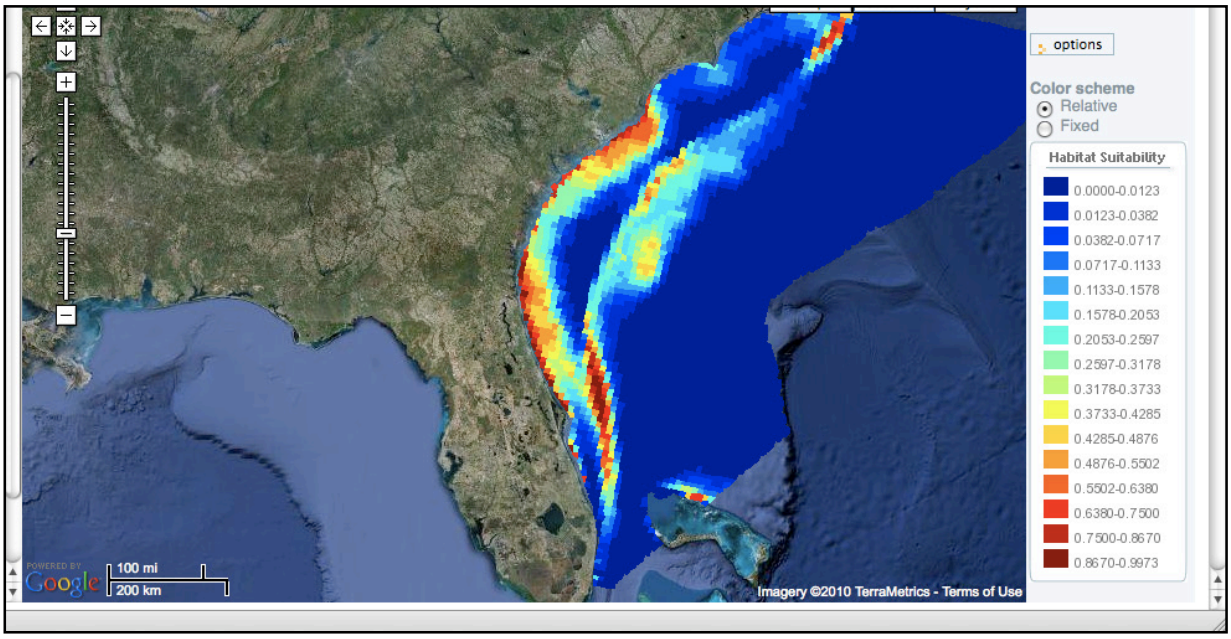

Figure 10.4 Habitat suitability index for bottlenose dolphins (both ecotypes) in the southeastern US during summer. Values range from 0.0 (completely unsuitable habitat) to 1.0 (completely suitable habitat).

Pan-tropical spotted dolphins occur over the continental slope and into deeper waters, particularly those associated with the Gulf Stream. The species seldom occurs on the shelf and is only rarely recorded in the stranding network. In these pelagic habitats, however, pan-tropical spotted dolphins are quite common (Mullin and Fulling, 2003). A single population is provisionally recognized, although there is very little information on population structure for this species in the North Atlantic. It can be difficult to differentiate pan-tropical and Atlantic spotted dolphins in offshore waters, complicating efforts to assess the two species. The best estimate of abundance for pan-tropical spotted dolphin is 4,439 (CV=0.49) from surveys conducted in 2004 (Waring et al., 2011). The US Navy estimated densities of 0.02225 dolphins per km^2 in this region (Department of the Navy, 2008b).

Two distinct ecotypes of Atlantic spotted dolphins occur in the study area: a relatively large and heavily spotted form that occurs over shelf waters; and a more slender, less spotted form that occurs in more pelagic areas (Adams and Rosel, 2006). The two forms may represent separate sub-species (Perrin et al., 1994). As noted above, the offshore ecotype of this species is sympatric with the pan-tropical spotted dolphin. Atlantic spotted dolphins are common over the shelf and, together with bottlenose dolphins, form the dominant cetacean fauna in this environment (Mullin and Fulling, 2003). The best estimate of abundance for Atlantic spotted dolphins in the South Atlantic Bight is 47,400 (CV=0.45) from surveys conducted from Florida to Maryland in 2004 (Waring et al., 2011). The US Navy estimated densities of 0.14929 to 0.43118 dolphins per km^2 in this region (Department of the Navy, 2008b).

Rough-toothed dolphins are an offshore species found in tropical and sub-tropical waters worldwide (Miyazaki and Perrin, 1994). They are present year-round in the southeastern US in

relatively low densities (Mullin and Fulling, 2003). Nothing is known of population structure for this species. There were too few observations to calculate an estimate of abundance for rough-toothed dolphins in the northwestern Atlantic (Waring et al., 2011). The US Navy estimated densities of 0.00048 dolphins per km^2 in this region (Department of the Navy, 2008b).

Risso's dolphins are a cosmopolitan species found along the continental shelf break and in deeper waters further offshore (Kruse et al., 1999). In the North Atlantic, they extend as far north as Nova Scotia (Waring et al., 2011). They are moderately common along the shelf break (Mullin and Fulling, 2003) and often form mixed schools with other delphinid species. Nothing is known of population structure for this species; NMFS assumes a single stock exists in the northwestern Atlantic. The best estimate of abundance for Risso's dolphins in the South Atlantic Bight is 5,426 (CV=0.54) from surveys conducted from Florida to Maryland in 2004 (Waring et al., 2011). The US Navy estimated densities of 0.0 to 0.05654 dolphins per km^2 in this region (Department of the Navy, 2008b).

Two species of pilot whales occur in the western North Atlantic: the long-finned pilot whale, *Globicephala melas*; and short-finned pilot whale, *G. macrorhynchus*. The two species are difficult to differentiate at sea and overlap off the mid-Atlantic states. Recent analysis by NMFS has been able to separate the habitat of these two species using water temperature, with the short-finned pilot whale occupying warmer, more tropical waters. Separate stock assessments are being prepared for the first time; all previous assessments have lumped the two species (Waring et al., 2011). In the South Atlantic Planning Area, short-finned pilot whales occur along the shelf break and into deeper waters, where they are moderately common (Mullin and Fulling, 2003). Mass strandings of this species occur relatively frequently in the region (e.g., Kritzler, 1949; Caldwell and Golley, 1965; Layne 1965; Caldwell et al., 1971; Irvine et al., 1979; Hohn et al., 2006). The most recent published stock assessment combines both species of pilot whales, so there is no species-specific estimate of abundance for short-finned pilot whales in the region (Waring et al., 2011). The US Navy estimated densities of 0.000002 to 0.0111 pilot whales per km^2 in this region (Department of the Navy, 2008b). A depiction of habitat suitability for pilot whales in the southeastern US is provided in Figure 10.5, using model outputs from the Duke SERDP program (Best et al., 2012).

The remaining delphinid species in the South Atlantic Planning Area can be grouped into two categories: five species of dolphins that occur at very low densities; and four species of "blackfish." The first category includes spinner dolphin (*Stenella longirostris*), Clymene dolphin (*Stenella clymene*), striped dolphin (*Stenella coeruleoalba*), common dolphin (*Delphinus delphis*), and Fraser's dolphin (*Lagenodelphis hosei*). Spinner dolphins are known only from strandings (Waring et al., 2011); there are no estimates of abundance or density for this species in the western Atlantic. The Clymene dolphin has been observed in small numbers along the shelf break during NMFS surveys (Mullin and Fulling, 2003), but there is no current estimate of abundance in the stock assessment report (Waring et al., 2011). The US Navy estimated densities of 0.01063 Clymene dolphin whales per km^2 in this region (Department of the Navy, 2008b). Striped and common dolphins are temperate species; the range of both species typically extends no further south than Cape Hatteras, although a few schools may stray into the South Atlantic Planning Area (e.g., Moore, 1953; Caldwell and Golley, 1965).

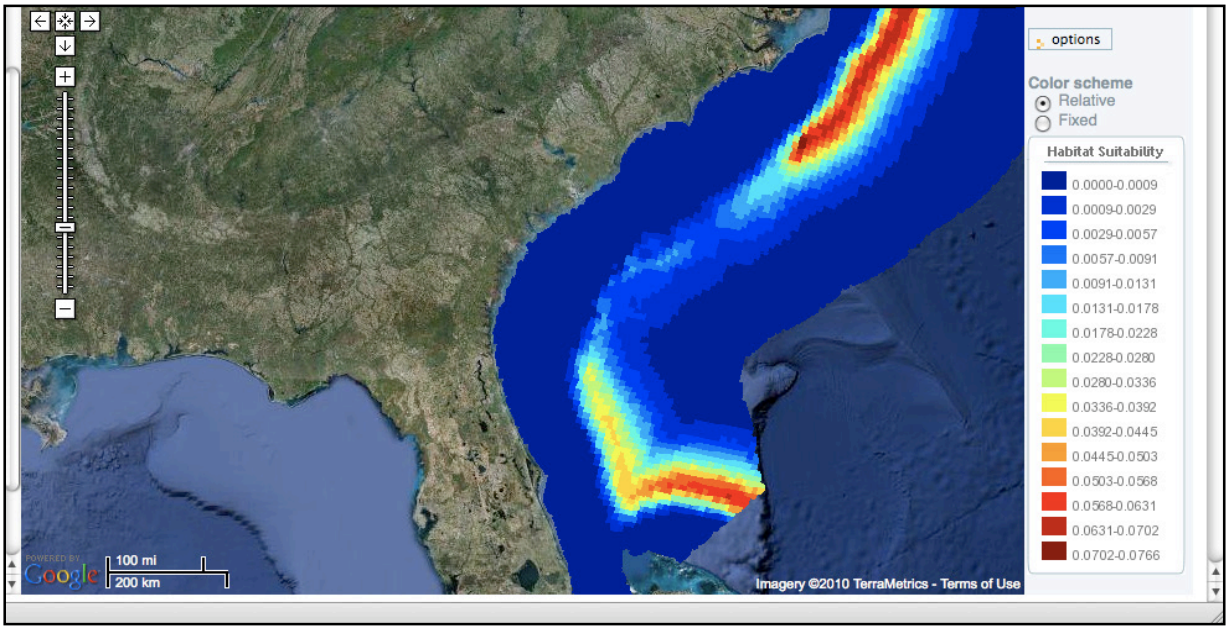

Figure 10.5 Habitat suitability index for pilot whales in the southeastern US during winter. Values range from 0.0 (completely unsuitable habitat) to 1.0 (completely suitable habitat).

Fraser's dolphins are a poorly known, tropical species that is restricted to pelagic waters. There are stranding records from Florida, but no sightings of the species in this region (Waring et al., 2011).

The category of blackfish includes melon-headed whale (*Peponcephala electra*), pygmy killer whale (*Feresa attenuata*), false killer whale (*Pseudorca crassidens*), and killer whale (*Orcinus orca*). All four species occur rarely in the region and are known primarily from strandings (Moore, 1953; Caldwell and Golley, 1965; Caldwell et al., 1970; Caldwell and Caldwell, 1971b; 1975; Katona et al., 1988). There are no estimates of abundance or density for any of these species.

10.4.3 Pinnipeds

Two species of the family *Phocidae* (earless seals) occur occasionally as extra-limital strays in the South Atlantic Planning Area. Harbor seals, *Phoca vitulina*, breed in eastern Canada and New England during early summer (Waring et al., 2011). In autumn, these seals migrate south, with regular occurrences as far as North Carolina in winter. A few juvenile harbor seals may venture further south into South Carolina, Georgia, and northeastern Florida during winter (Caldwell, 1961; Caldwell et al., 1971). Hooded seals, *Cystophora cristata*, breed on pack ice off the eastern coast of Canada during early spring (Waring et al., 2011). Weaned juvenile hooded seals disperse over great distances, and a small number of these individuals may make their way to the South Atlantic Planning Area each year, some reaching as far south as Florida (e.g., Moore, 1953). A few California sea lions, *Zalophus californianus*, have been reported from the region (Layne, 1965); these animals are escapees from captive facilities.

10.4.4 Sirenians

The Florida manatee (*Manatus trichechus latirostris*) is a sub-species of the West Indian manatee. Florida manatees are recognized as an endangered species under the ESA and are managed by the USFWS (USFWS, 2001). In 1976, critical habitat was designated for the Florida manatee including all of the known range at that time (USFWS, 1976). Two other categories of manatee protection areas exist in Florida: manatee sanctuaries and manatee refuges (USFWS, 2002). Manatee sanctuaries are areas where all human activities are prohibited, whereas manatee refuges allow human entry but regulate certain activities.

Manatees occur throughout the southeastern US, with most of the population found in coastal and estuarine waters of Florida. During summer, manatees occur regularly along the coast of the southeastern US as far north as North Carolina (Schwartz, 1995). A few individual manatees may move even further north, reaching Chesapeake Bay, before returning to more southern areas when water temperatures cool during autumn.

Based on patterns of movement and site fidelity (Deutsch et al., 2003), four population units have been recognized in Florida, each with distinct demographic trajectories (Runge et al., 2004). Despite this population structure, USFWS manages all four units together as a single stock. Two of these population units occur in the present study area: the Upper St. Johns River Region unit, which is increasing at an annual rate of 6.2%; and the Atlantic Coast Region unit, increasing at an annual rate of 3.7% (Runge et al., 2004).

This tropical species has a low metabolic rate and, consequently, a limited tolerance for cold water. During periods of cold weather during winter, manatees seek out areas of warm water, such as the discharge of power plants, natural springs, and other thermal refuges. During each winter, a coordinated series of statewide aerial surveys and ground counts are conducted to count over-wintering manatees (FWC, 2009). The best available count of Florida manatees is 3,802 animals, based on a synoptic survey of warm-water refuges in January 2009 (FWC, 2009). This is a minimum count, rather than an estimate of population size. Minimum population counts for the two population units in the region are 1,447 individuals for the Atlantic coast and 112 for the Upper St. Johns River (USFWS, 2007).

To summarize, manatees are present year-round in the southeastern US The vast majority of animals are found in estuarine and nearshore coastal waters, although a few individuals may migrate through waters further offshore. In cold periods, particularly in northeastern Florida, manatees congregate around warm water refuges.

10.5 Potential Impacts of OCS Development on Marine Mammals

10.5.1 Oil and Gas Exploration and Development

The sensitivity of marine mammals to oil and gas exploration and development has been reviewed extensively elsewhere (Geraci and St. Aubin, 1990; Loughlin et al., 1994; Richardson et al., 1995; NRC, 2000; 2005; Harwood and Wilson, 2001; MMC, 2006).

Oil and gas exploration and development may have adverse indirect effects on populations of marine mammals during either the exploration (seismic activities) or production (drilling or ship noise) phases. In addition, there can be direct impacts of production as a result of operational discharges or spills. Finally, oil and gas production platforms modify the physical habitats of marine mammals, which can have both positive and negative effects on their populations.

Most concern regarding oil and gas exploration and development on marine mammals (and also to renewable energy development – see below) pertains to the effects of anthropogenic sound. As reviewed by Nowacek et al. (2007) there are four primary concerns for animals exposed to elevated noise levels: permanent threshold shifts (PTS), temporary threshold shifts (TTS), acoustic masking, and behavioral disturbance. PTS and TTS represent a loss of ability to hear in a particular frequency range after exposure to sound. This loss of hearing may be either temporary or permanent. Anthropogenic sound can mask a signal produced or received by animal, reducing its ability to communicate or to use sound to navigate or detect objects. Marine mammals may also respond behaviorally to a sound stimulus, by moving away (or towards) the source or by changing behavioral state (such as interrupting foraging or social behavior).

The most intense sounds associated with oil and gas exploration and development are typically associated with seismic activities during the exploration phase. As described by Nowacek et al. (2007), seismic exploration activities produce short broadband sounds with high peak source levels, typically 220–255 dB re 1 µPa at 1 m (decibel value peak-to-peak relative to the reference pressure one micropascal at a reference distance of 1 meter). During these activities airgun arrays are used to send low-frequency (<300 hertz [Hz]) impulse sounds into the sea floor. Considerable sound is also introduced into surrounding waters, although the propagation into these adjacent waters has not been well documented (Madsen et al., 2006b).

Cetaceans are particularly sensitive to noise because they use sound as their primary method of communication and sensing the environment (Wartzok and Ketten, 1999). Odontocetes use echolocation to detect and discriminate prey and other objects. Cetaceans also produce sounds that serve a communicative function. Baleen whales produce low-frequency communicative calls to facilitate social interactions, particularly during the breeding season. Anthropogenic noise may mask some or all of these signals (Nowacek et al., 2007).

Ascertaining the effects of anthropogenic sound on populations of marine mammals is an area of extensive research supported by several federal agencies (MMC, 2006; Southall et al., 2009). As a result, our knowledge of the effects of noise on marine mammals is expanding rapidly (Nowacek et al., 2007; Hildebrand, 2009; Tyack, 2009). This growing body of research is in the process of being translated into management advice and regulation.

For example, Southall et al. (2007) proposed a series of sound levels for various marine mammal groups and sound types above which auditory injury or behavioral response would be expected. Some marine mammal groups, particularly the beaked whales and porpoises, are believed to be particularly sensitive to sound (see Tyack et al., 2011). Thus, NMFS has a separate exposure criterion specifically for harbor porpoise (*Phocoena phocoena*); any exposure above 120 dB SPL (sound pressure level) is expected to result in a change in behavior for harbor porpoises, compared to a variety of higher criteria that are used for other species.

Little seismic exploration has occurred in the past few decades in the southeastern US (see Figure 5 in Hildebrand, 2009). Deep-diving species such as sperm and beaked whales that inhabit the margins and slope of the continental shelf may, therefore, be especially sensitive to this source of anthropogenic noise. Playback experiments in the Gulf of Mexico, an area of intense seismic exploration, have demonstrated that sperm whales are more sensitive to these sounds than initially believed (Jochens et al., 2008; Tyack, 2009). The potential for disturbance is not limited to odontocetes; fin whales are known to react to the sounds of airgun arrays by moving away from the source of such sounds; this displacement may last for periods of weeks (Castellote et al., 2012).

Oil spills can have severe adverse effects on marine mammals, as seen in the *Exxon Valdez* spill. And, even 20 years after the *Exxon Valdez* spill, long-term impacts to marine mammal populations are still occurring (Matkin et al., 2008). Cetaceans do not avoid oil slicks and may become fouled if they surface in areas of oil; this can be particularly harmful to surface-feeding baleen whales (Geraci and St. Aubin, 1990). The 2010 *Deepwater Horizon* spill of 206 million gallons in the Gulf of Mexico may (or may not) improve our rather limited understanding of the population-level effects of large spills on marine mammals.

Physical structures associated with oil and gas production facilities may enhance foraging opportunities for bottlenose dolphins, which are adept at exploiting environments modified by human activities. Vessel traffic to and from such platforms may pose a hazard to large whales on the continental shelf. Of particular concern in this regard is the critical habitat for calving right whales located off the coasts of Florida and Georgia (Figure 10.1).

10.5.2 Sand and Gravel Extraction

Multiple potential sand borrow sites exist off the coast of the southeastern US, with several sites off the coasts of South Carolina and eastern Florida. BOEM has cooperative sand evaluation programs in place with both of these states to identify and evaluate sand resources as potential sources for future beach replenishment projects (Michel, 2004). Potential borrow sites vary considerably in size, from 1.24 million yd^3 off Jacksonville, Florida to 150,000 yd^3 off Myrtle Beach, Florida (Drucker et al., 2004) and there considerably larger sand resource areas offshore of the northeast coast of Florida. Most potential borrow sites occur in relatively shallow water, however, between 5 m and 15 m deep (Michel et al., 2001).

Due to the proximity of these resources to shore, only coastal marine mammals will be at risk from sand dredging activities. The risks associated with sand extraction include: collisions with dredge and support vessels; production of noise; and modification of habitat and prey fields through substrate removal (Michel et al., 2001; Brooks et al., 2006; Thomsen et al., 2009).

Robinson et al. (2011) conducted field studies of noise generated by six vessels during dredging of marine aggregates in the U.K. They reported that:

- Source levels at frequencies below 500 Hz are generally in line with those expected for a cargo ship travelling at modest speed;
- Source levels at frequencies above 1 kHz show elevated levels of broadband noise generated by the aggregate extraction process; and

- The elevated broadband noise is dependent on the aggregate type being extracted, with gravel generating higher noise levels than sand.

Mitigation of the most direct risk, collisions with support vessels, can be facilitated by measures such as placing observers aboard vessels implementing speed restrictions in areas of risk. For example, there are restrictions on vessel speeds during time periods when northern right whales are present in the region (e.g., 1 November to April 30). Such monitoring protocols are required as a condition of Section 7 consultations and permits required under the ESA and MMPA. NMFS Southeast Region has also developed standard Vessel Strike Avoidance Measures and Reporting for Mariners to reduce the risk associated with vessel strikes or disturbance of protected marine mammals in the region.

10.5.3 Renewable Energy Development

The development of offshore renewable energy resources is likely to expand rapidly in the coming few decades (Boehlert and Gill, 2010). With the technology currently available, projects harnessing offshore wind energy are likely to be sited in shallow water (typically less than 15 m deep), adjacent to shore-based transmission facilities, and in areas of relatively high and predictable wind energy (Michel et al., 2007). The continental shelf extends a considerable distance off the southeastern US coast, offering a relatively large area for wind energy projects.

Existing wind farms employ multiple turbines, each installed on a monopile. Each monopile consists of a large piling (4 to 5 m in diameter) driven into the seafloor (Michel et al., 2007). Some of the largest operational offshore wind farms currently in use are situated at Horns Rev and Nysted, Denmark. These two wind farms cover areas of 20–30 km^2 and have been operational since 2002 and 2004, respectively (Carstensen et al., 2006; Michel et al., 2007). Development of offshore wind energy has progressed more rapidly in Europe than North America; much of what is known about the potential effects of this technology on marine mammals comes from European research.

Offshore wind energy projects can potentially affect marine mammals in several ways: from noise produced during construction and operation; from modification to habitat caused by installation of monopiles; and from emission of low frequency electromagnetic fields (Boehlert and Gill, 2010). Nothing is known about the effects of electromagnetic fields on marine mammals; this is an area that requires future research. This review focuses, therefore, on the potential effects of acoustics and habitat modification.

Most concern regarding the potential effects of wind farms on marine mammals has addressed the potential effects of noise generated during construction (Madsen et al., 2006a; Thomsen et al., 2006). During construction noise is produced by seismic profiling, vessels, pile driving, and trenching. Pile driving is of particular concern because it generates transient sounds of very high source level and broad bandwidth (Richardson et al., 1995; Rodkin and Reyff, 2004; Madsen et al., 2006a; Bailey et al., 2010). Most sound energy created by pile driving is of low frequency (below 500 Hz), although some energy extends into the ultrasonic frequency range. Received levels can be above 200 dB re 1 μPa at a distance of 100 m (see Wahlberg and Westerberg, 2005 for a review). Efforts to reduce potential impacts during pile driving include “soft start” practices and cessation of pile driving when animals are observed within a certain distance of this activity.

The noise created by operational wind turbines is less intense and restricted to frequencies below 1 kHz, often below 700 Hz (Madsen et al., 2006a). Sound propagation in shallow water is complex and poorly understood; transmission loss may be significant in these environments, further complicating assessment of exposure and effects on marine mammals, such as bottlenose dolphins, manatees, and right whales, that may occur in such areas (Boehlert and Gill, 2010).

Relatively few studies have examined the impact of pile driving or other aspects of wind farm construction and operation on marine mammal populations. During construction of the Nysted wind farm in 2002 and 2003, Danish researchers used echolocation click detectors to monitor the presence of harbor porpoises (Carstensen et al., 2006). As noted above, this is one of the marine mammal species most sensitive to anthropogenic sound. The incidence of porpoise echolocation behavior decreased significantly during the construction period, indicating that the animals abandoned the area. This effect extended more than 15 km from one of the sites at which pile driving occurred. Similar results were documented during construction at Horns Reef, although faster recovery times were observed at this site (Tougaard et al., 2006). Short-term behavioral responses may be observed over large distances, therefore, particularly for sensitive species like the harbor porpoise. Direct effects, such as physical trauma, will occur only in very close proximity to construction operations. For example, Bailey et al. (2010) estimated that injury to any cetacean or pinniped caused by pile driving would be limited to a radius of no more than 100 m.

There have been no direct studies of the reaction of marine mammals to operating wind turbines (Madsen et al., 2006a). Koschinski et al. (2003) exposed harbor seals and harbor porpoises to simulated noise of turbines and observed only a slight response in a small area (60 to 200 m around the sound source). Porpoises are present around both the Nysted and Horns Reef wind farms in their operational phases (e.g., Tougaard et al., 2006), further indicating that the likely effects of wind farm development will be felt only during the construction phase.

Harbor porpoises do not occur in the southeastern US and harbor seals occur only occasionally as extra-limital strays. Thus, there are no species-specific lessons from European research for populations of marine mammals in the southeastern US. Given the likely location of offshore wind development in the South Atlantic Planning Area, the species likely to be exposed are bottlenose dolphins and right whales, and perhaps small numbers of manatees. Madsen et al. (2006a) used research on the related bowhead whale (*Balaena mysticetus*) to infer that right whales might show avoidance responses to transient sounds of pile driving over very large ranges, depending on the propagation conditions. It is not known whether the presence of multiple turbines in an area would affect the migratory behavior of right whales; proposals to construct wind farms in right whale habitat should consider this possibility carefully. There are no published observations of the reactions of bottlenose dolphins or manatees to such acoustic stimuli; this is a priority area for future research. The approach used to monitor harbor porpoise habitat use in Denmark around wind farms could also be applied to bottlenose dolphins, which also produce echolocation clicks.

Based on the limited evidence to date, however, it seems likely that most effects of projects harnessing offshore wind energy will be felt during the construction phase. Research should be

conducted into the effects of construction and operation on marine mammals likely to be exposed to these activities, including exposure to noise and electromagnetic fields.

10.6 Summary and Data Gaps in the State of Marine Mammal Knowledge with Regard to OCS Development

In general, there is a reasonably good scientific understanding of the occurrence of marine mammal species within the South Atlantic Planning Area. However, our understanding of the distribution and density of these animals is limited by the nature of past surveys. Most surveys have been conducted by NMFS to estimate density over large spatial scales, so very little is known about fine-scale variation in distribution or density, even for common species. In addition, almost all past NOAA surveys have been undertaken during the summer when sighting conditions are best. Very little is known of the occurrence during other seasons, and particularly during winter, when several migratory species likely occur in the area. These first of these data gaps could be resolved by dedicated fine-scale surveys in areas of interest, such as the current EWS and USWTR surveys off the coast of northeast Florida. Satellite-linked telemetry also offers a means of gaining insight into patterns of habitat use over a variety of spatial and temporal scales; this approach has been used successfully to document migratory pathways of right whales in this region (Schick et al., 2009). The second data gap will likely only be resolved through the use of passive acoustic monitoring techniques, as sighting conditions during winter preclude typical large-scale surveys. These techniques are currently being used as part of the USWTR monitoring program off Jacksonville, Florida.

Taken as a whole, the marine mammal fauna in the South Atlantic Planning Area is in relatively good conservation status. The two exceptions are Florida manatees and North Atlantic right whales, both of which are threatened by vessel strikes (right whales are also threatened by entanglement in fishing gear). Pilot whales and Risso's dolphins are taken in small numbers in pelagic longline fisheries along the continental shelf break, but otherwise there are very few interactions with commercial fisheries. Little is known about food habits and trophic relationships for most marine mammals in this region. It is possible that commercial fisheries have depleted some prey stocks, but this threat has not been evaluated for any species in the southeastern US. Finally, there is a potential threat from Naval training activities, particularly involving the use of Mid-Frequency Active sonar, both in the proposed USWTR off Jacksonville and associated with the broader Atlantic Fleet Active Sonar Training program. With the exception of the potential for prey depletion, all of these potential threats are being managed actively by relevant federal agencies and are the subject of ongoing research programs in the South Atlantic Planning Area.

Due to the lack of past OCS development in this region, very little is known about the response of marine mammal species to potential threats associated with these activities in the South Atlantic Planning Area. For some cosmopolitan species, such as sperm whales, we can gain insight from their response to anthropogenic sound in other areas, such as the Gulf of Mexico (for example, see Madsen et al., 2006b). However, these inferences may be limited due to the relatively quiet acoustic environment in the South Atlantic Planning Area, which, therefore, offers a unique opportunity for study. In addition, very little is known about the response of either common (e.g., bottlenose and spotted dolphins) or highly endangered (e.g., right whales)

marine mammal species to these sources of sound. In particular, there is a need to conduct research into the reaction of marine mammals to the sounds produced during construction activities, particularly pile driving, as has been done in Europe but for different species.

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CHAPTER 11: AREAS OF SPECIAL CONCERN

11.1 NATIONAL MARINE SANCTUARIES

Gray's Reef National Marine Sanctuary is the only national marine sanctuary in the South Atlantic Planning Area (Figure 11.1). It was established as the nation's fourth national marine sanctuary in 1981 for the purposes of protecting the quality of its unique and fragile ecological community, promoting scientific understanding of the live bottom ecosystem, and enhancing public awareness and wise use of this significant regional resource (15 CFR Part 922). It is located about 25 km off the coast of Georgia. Covering about 5,700 hectares, it is one of the largest near-shore "live-bottom" reefs of the southeast US. It has extensive but scattered rock outcroppings in about 20 m water depth. Archaeological research at the sanctuary has found fossil bivalves and gastropods and mastodon bones located in this area indicating that the reef was once a shallow coastal environment and an exposed land form. The habitats and resources of this sanctuary are described in detail in Chapter 6: Benthic Communities and in Chapter 7: Fish and Essential Fish Habitat. Loggerhead sea turtles, a threatened species, use the sanctuary year-round for foraging and resting, and the reef is adjacent to the only known winter calving ground for the endangered North Atlantic right whale.

11.2 NATIONAL PARK SYSTEM

There is one coastal National Park unit, Cumberland Island National Seashore, on the Georgia coast bordering the Atlantic coastline (Figure 11.1). It is a classic drumstick barrier island that is 28 km and totals 14,700 hectares of which 6,820 hectares are marsh, mud flats, and tidal creeks. The northern section of Cumberland Island includes 3,580 hectares of federally designated wilderness area. The island provides important habitat for federally listed species–loggerhead sea turtles, wood stork, and piping plovers. The island is an important stopover point for migrating birds on the transatlantic migratory flyway.

There are two National Park units in Florida that have a border on the Atlantic coastline (Figure 11.1). Fort Matanzas National Monument was established in 1924. The fort was constructed of coquina between 1740 and 1742. The fort is located on Rattlesnake Island inside the Matanzas River, but the monument includes the southern tip of Anastasia Island including about 1.4 km of beachfront. This park provides habitat for the following federally listed species: Anastasia Island beach mouse, least tern, piping plover, and green, leatherback, and loggerhead sea turtles.

Canaveral National Seashore includes 38 km of oceanfront beach, the longest stretch of undeveloped public beach on the east coast of Florida that draws over one million visitors per year. The beach is backed by a single dune ridge, averaging 3 m in height; however, in some areas, the dune has been obliterated by storm overwash into Mosquito Lagoon. The park provides habitat for twelve species of federally listed animals, the second greatest number in the entire National Park Service: Wood stork, Florida scrub jay, Southeastern beach mouse, West Indian manatee, right whale, eastern indigo snake, Atlantic salt marsh snake, and all five species of sea turtles.

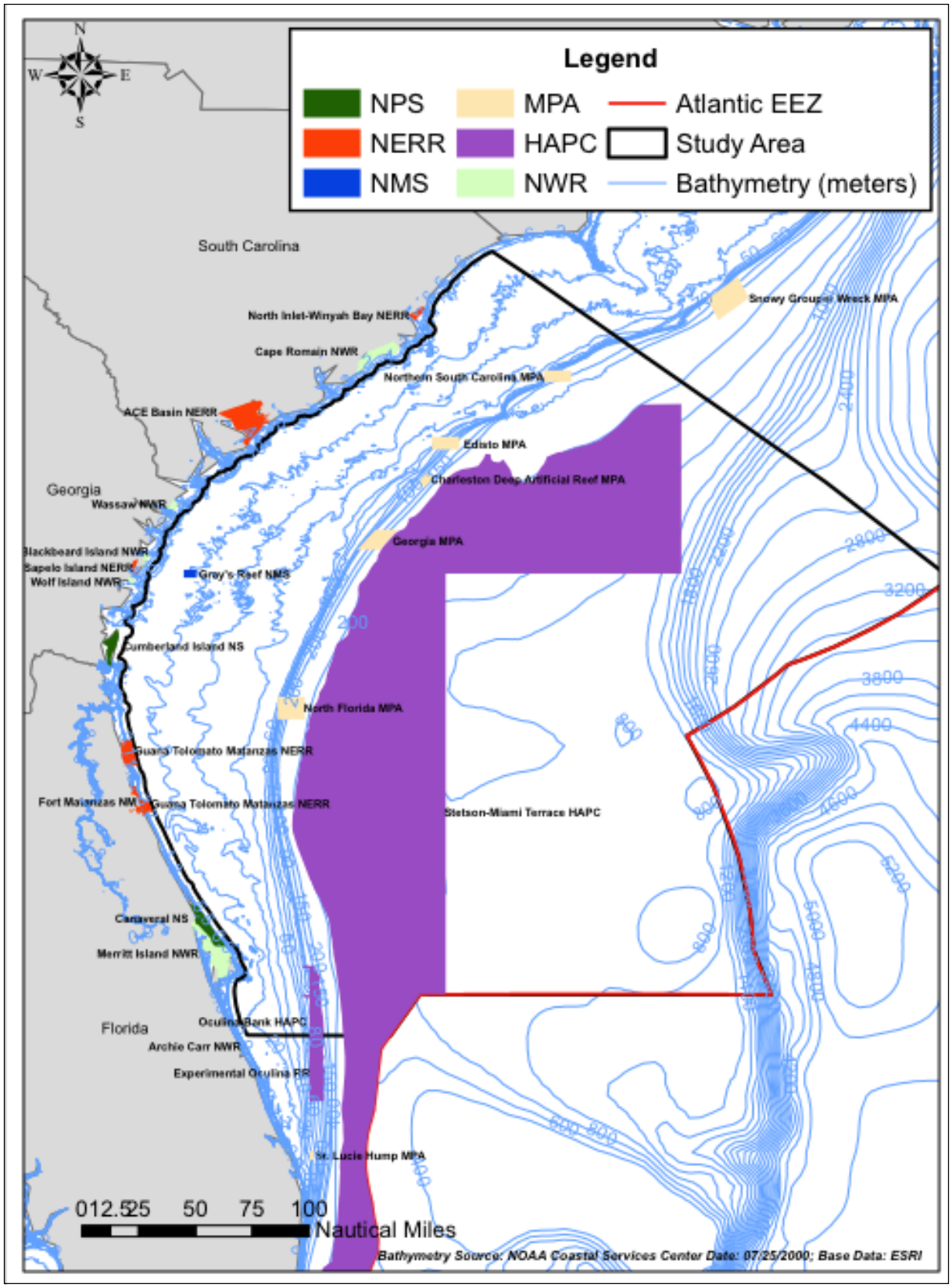

Figure 11.1 Areas of special concern in or bordering on the South Atlantic Planning Area.

11.3 COASTAL NATIONAL WILDLIFE REFUGES

There are six coastal National Wildlife Refuges (NWRs) in the South Atlantic Planning Area that border the shoreline (Figure 11.1). In South Carolina, the Cape Romain NWR extends for 35 km along the coast, encompassing 26,820 hectares of barrier islands, salt marshes, tidal channels, fresh and brackish water impoundments, and maritime forest. It was originally established in 1932 as a migratory bird refuge to preserve habitat for waterfowl, shorebirds, and resident species. The refuge's loggerhead sea turtle program includes relocating 500–800 sea turtle nests from erosional areas, which has resulted in the largest population of loggerhead sea turtles north of Florida. The refuge web site states (USFWS, 2011a): "Cape Romain NWR is one of only twenty Western Hemisphere Shorebird Reserve Network Hemispheric Sites of International Importance in North and South America. The refuge supports 18–22 shorebird species in the Atlantic Flyway including red knot, American oystercatcher, Wilson's plover, whimbrel, and least tern. The refuge's undeveloped and undisturbed coastal habitat supports two-thirds of the State's total wintering population of American oystercatcher, and 57% of the State's nesting population. The refuge also supports the largest population of marbled godwit on the Atlantic coast during southbound migration. The refuge has one of the largest eastern brown pelican rookeries in South Carolina."

On the Georgia coast, there are three NWRs: Wassaw, Blackbeard Island, and Wolf Island. Wassaw NWR was established in 1969. It consists of an 11 km-long and 1 km-wide barrier island with multiple old dune ridges covered by maritime forests, backed by extensive salt marshes and tidal flats. The primary management goal of the refuge is to protect the barrier island, adjacent hammocks, and salt marsh in their natural state. Federally listed species in the refuge include loggerhead sea turtle, wood stork, and piping plover.

Blackbeard Island NWR was established in 1940; in 1975, about half the island was designated as National Wilderness. It is a classic drumstick barrier island, accessible only by boat. According to the refuge web site (USFWS, 2011b): "The primary objectives of the refuge are to provide wintering habitat and protection for migratory birds; provide protection and habitat to promote resident and migratory wildlife diversity; and to provide protection and management for endangered and threatened species (loggerhead sea turtle, wood stork, piping plover."

Wolf Island NWR was established in 1930; it became a National Wilderness Area in 1975. It is closed to the public; access is only allowed on the adjacent waterways. It is mostly salt marsh and tidal flat, with a thin sand washover on the oceanfront. There is very little upland habitat.

On the Florida coast, there are two NWRs: Merritt Island and Archie Carr. Merritt Island NWR was established in August 1963 to provide a buffer zone around the Canaveral Space Center. Most of the refuge is closed 24 hours prior to a shuttle launch. The refuge provides habitat for fifteen federally listed species. The refuge is one of the most important sea turtle nesting sites in the US, averaging over 1,300 loggerhead nests each year. It is also an important nesting area for green sea turtle and leatherback sea turtle.

Archie Carr NWR, established in 1991, includes 33 km of sand beach. According to the refuge website: "The refuge was designated to protect habitat for what is the most significant area for loggerhead sea turtle nesting in the Western Hemisphere, and the most significant area for green

turtle nesting in North America. This represents 25–35% of all loggerhead and green sea turtle nests in the US. It also serves as a minor nesting area for the leatherback turtle, which is one of the world's largest and rarest sea turtles. The long stretches of quiet, undisturbed sandy beaches, with little or no artificial light, are essential to the reproductive success and survival of the 15,000 to 20,000 sea turtles nesting annually."

11.4 NATIONAL ESTUARINE RESEARCH RESERVES AND THE NATIONAL ESTUARY PROGRAM

The National Estuarine Research Reserve (NERR) System is administered and funded by NOAA and managed on daily basis by a lead state agency or university, with input from local partners. In the South Atlantic Planning Area, there are four NERRs (Figure 11.1): North Inlet-Winyah Bay and ACE Basin in South Carolina, Sapelo Island in Georgia, and Guana Tolomato Matanzas in Florida.

In South Carolina, the North Inlet-Winyah Bay NERR, designated in 1992, encompasses 7,655 hectares of tidal marshes and estuarine waters east of Georgetown, South Carolina. It is administered by the University of South Carolina Belle W. Baruch Institute for Marine and Coastal Sciences. It has a strong focus on research, education, and training, as well as scientific and technical aspects of coastal management issues. Current research activities include: Nutrient and Carbon Dynamics in Coastal Ponds; Long-term Composition and Abundance of Estuarine Macrofauna; Precipitation Chemistry Monitoring; Salt Marsh Emergent Vegetation Response to Sea Level Rise; and Microbial Heterotrophy in Tidal Creeks. There are also four long-term monitoring sites established as part of the NERR's System-Wide Monitoring Program which includes meteorological monitoring to quantify climatic changes or trends over time, water quality monitoring of specific conductivity, salinity, dissolved oxygen, water temperature, pH, turbidity, and water level, and water chemistry and chlorophyll. The ACE Basin NERR, designated in 1992 and managed by the South Carolina Department of Natural Resources (SCDNR), consists of about 23,000 hectares in one of the largest undeveloped estuaries on the US east coast. The System-wide Monitoring Program is a phased monitoring program that focuses on three different ecosystem characteristics: 1) Abiotic Parameters, including: atmospheric conditions and water quality (nutrients, salinity, dissolved oxygen, etc.); 2) Biological Monitoring, including: biodiversity, habitat and population characteristics; and 3) Watershed and Land Use Classifications, including: changes in human uses and land cover types.

In Georgia, the Sapelo Island NERR, designated as a National Estuarine Sanctuary (later a Reserve) in 1976, occupies one-third of Sapelo Island and comprises 2,110 acres of upland maritime forest and hammock land and 4,000 acres of tidal salt marsh. Managed by the Georgia Department of Natural Resources, the Sapelo Island NERR is accessible only by boat. The University of Georgia, School of Marine Sciences, operates the Marine Institute on the NERR, thus there is a strong emphasis on research and education. In addition to the System-wide Monitoring Program that includes water-quality and meteorological monitoring, other research projects include habitat restoration, oyster reef ecological studies, and invasive species monitoring. Sapelo Island NERR also participates in the Georgia Coastal Ecosystems Long Term Ecological Research program and is involved with the development of International Ocean Observing Systems efforts in the NERR system and on the Georgia coast.

In Florida, the Guana Tolomato Matanzas NERR, designated in 1999, encompasses 29,684 hectares of sand beach (21 km of oceanfront), dunes (at 12 m, they are among the highest in Florida), and estuarine habitats managed by the Florida Department of Environmental Protection. The reserve contains habitat for 48 animal and 8 plant species that are listed as endangered, threatened, or of special concern. In addition to water-quality studies under the System-wide Monitoring Program, other research includes: various vegetation surveys to monitor changes in species distributions, effects of the prescribed fire program, and laurel wilt deadly disease of redbay and other tree species; biota studies of invasive species (crabs, mussels, and barnacles); monitoring of sea turtle nesting, gopher tortoise populations, and Anastasia Island beach mouse populations; and a wide range of bird surveys (bald eagle, least terns, shorebirds, marsh birds, and peregrine falcon and merlin migrations).

The Indian River Lagoon National Estuary Program (NEP) study area (the only one in the study area) extends from New Smyrna Beach to just below Stuart, Florida. The watershed covers 3,575 square kilometers. Threatened and endangered species in the study area include: West Indian manatee, southeastern beach mouse, shortnose sturgeon, all five species of sea turtles, piping plover, roseate tern, snail kite, wood stork, red-cockaded woodpecker, Florida scrub jay, Bachman's warbler, American alligator, Atlantic salt marsh snake, and eastern indigo snake. It was established in 1990. Some of the priority issues in the coastal zone include nutrients, sedimentation, habitat and species loss, and freshwater inflows.

11.5 ARCHAEOLOGICAL SITES

The National Historic Preservation Act (NHPA) requires federal agencies to consider the effects of its undertaking on historic properties. In the South Atlantic, these likely include shipwrecks, historic fortifications, and coastal settlements, as well as prehistoric sites that have become submerged due to the global and local rise in sea level. Section 106 of the NHPA provides a process for Federal agencies to consider the effects of their actions on historic properties listed on or eligible for the National Register that involves consultation with various agencies.

At the state level, State Historic Preservation Officers (SHPOs) work with the public, tribes, Federal agencies, and the Advisory Council on Historic Preservation to ensure compliance with Section 106. Each SHPO maintains databases on known cultural and archaeological sites, which are not available to the public to prevent damage to them.

About 20,000 year ago, at the height of the last major glaciation, sea level was as much as 100–120 m lower than present. The low-stand shoreline was near the edge of the present continental shelf. Throughout the Holocene (since about 10,000 years ago), sea level has undergone a net rise, resulting in submergence and mostly destruction of these landforms through various processes, although some preservation of landforms is possible. Although scientific data concerning prehistoric sites on the shelf are limited, archaeologists have theorized for decades that prehistoric inhabitants of North America populated present-day continental shelf areas during the Late Wisconsin lower sea level (summarized in RPI et al., 2004). The South Atlantic cultural resources baseline study funded by the Bureau of Land Management covered the continental shelf between Cape Hatteras, North Carolina and Key West, Florida. The research and predictive models for south Atlantic submerged cultural resources were published in 1979

(Science Applications, Inc., 1981). The report identified high probability areas for both prehistoric and shipwreck submerged cultural resources. In a review of the potential of inundated prehistoric sites, RPI et al. (2004) noted: "In all likelihood, the archaeological integrity of sites in the inshore shallows, the surf zone, or on the beach does not survive. That area is dynamic and remains in a constant state of flux. As a consequence, evidence of prehistoric activity is likely to be limited to lithic and ceramic materials that have little or no provenience. One possible exception is where cultural material survives in association with denser sediments that are more resistant to reworking by waves." In addition, there has been no work to evaluate the potential for preservation of prehistoric sites on the shelf in the South Atlantic Planning Area. Therefore, most of the archaeological sites that have been studied are shipwrecks.

With a long maritime history, the South Atlantic Planning Area has the potential for historically significant shipwrecks. NOAA's Office of Coast Survey maintains the Automated Wreck and Obstruction Information System (AWOIS), which contains information on over 10,000 submerged wrecks and obstructions in the coastal waters of the US. Information includes latitude and longitude of each feature along with brief historic and descriptive details. A query of AWOIS identified 69 wrecks in the South Atlantic Planning Area, consisting of 1 barge, 15 cargo vessels, 1 destroyer, 9 fishing boats, 1 landing craft, 1 passenger vessel, 8 schooners, 11 tankers, 1 tugboat, 3 fishing trawlers, and 18 unknowns. AWOIS only incorporates hazards to navigation and is likely missing a lot of wrecks in deeper water. Thus, an unknown number of historically significant wrecks likely lie within the area (John Wagner, 2011). Figure 11.2 shows the locations of known shipwrecks in the study area, from the AWOIS database. All of the features labeled as Soundings, Obstruction, Rock, and Rock Awash were removed from this presentation of the data.

11.6 MARINE PROTECTED AREAS AND HABITAT AREAS OF PARTICULAR CONCERN

Eight deep-water MPAs (100-300 m deep) have been established in the South Atlantic (SAFMC, 2007; regulations effective in February 2009), and five of those are located within the South Atlantic Planning Area (Figure 11.1). The South Atlantic Fishery Management Council and NOAA established five deep-water CHAPCs in July 2010 and placed regulations to prevent bottom damage to the coral habitat from fishing activities. Within the CHAPCs, the possession of coral species and the use of all bottom-damaging gear are prohibited including bottom longline, trawl (bottom and mid-water), dredge, pot or trap, or the use of an anchor, anchor and chain, or grapple and chain by all fishing vessels. The Stetson-Miami Terrace CHAPC is located within the South Atlantic Planning Area (Figure 11.1). Part of the *Oculina* HAPC is also located in the study area.

See sections 6.3.6 and 7.2.4.1.2 for a detailed description of benthos and fish of these MPAs and HAPCs.

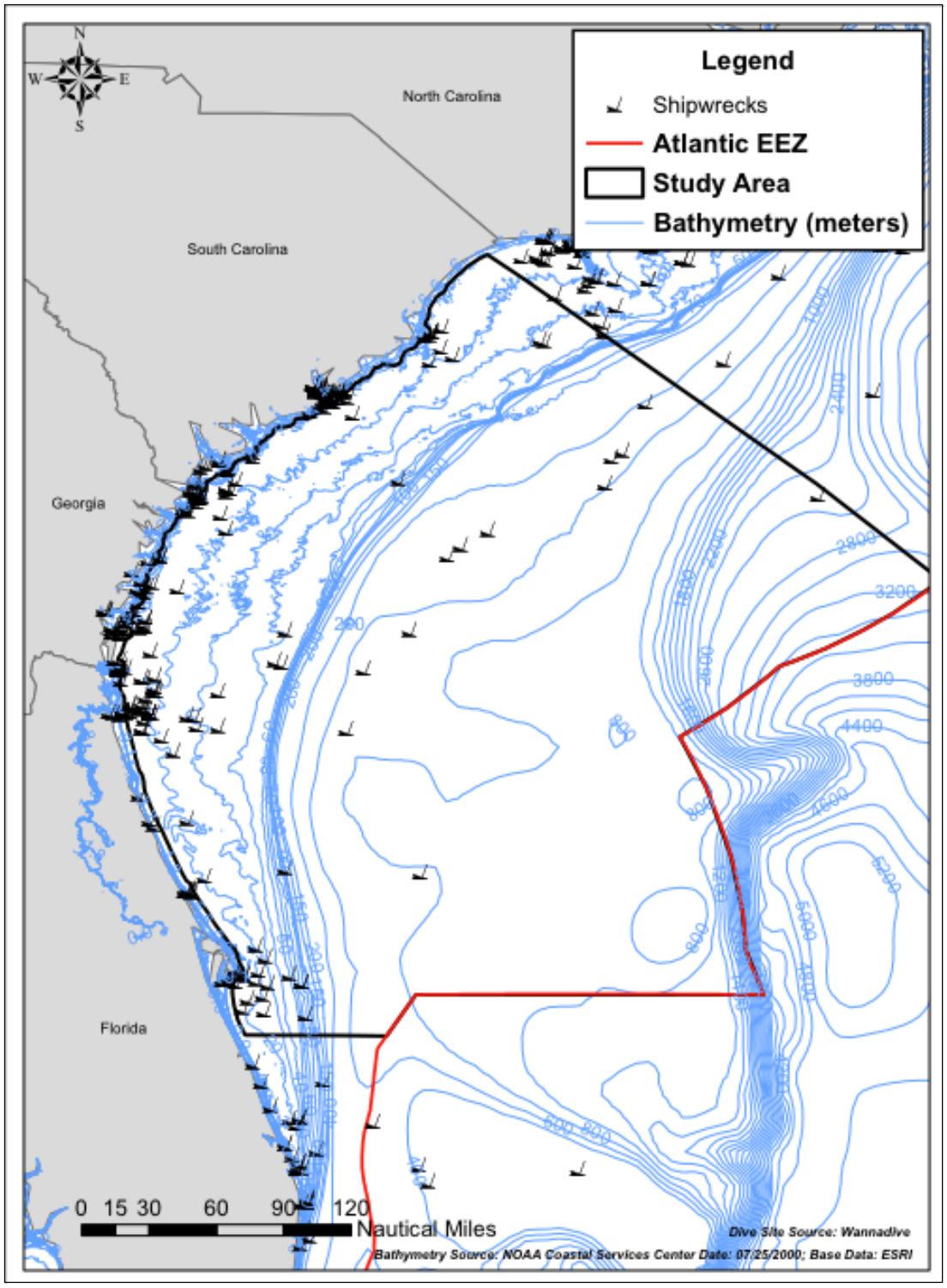

Figure 11.2 Known shipwrecks in the South Atlantic Planning Area (data from AWOIS, 2011).

11.7 RECREATIONAL DIVE SITES

There are numerous recreational dive sites in South Atlantic Planning Area (Figure 11.3). These sites are typically associated with habitats such as live hard bottom (i.e., natural reefs), artificial reefs, and shipwrecks. These structures range widely in size, type, and architecture.

11.8 MILITARY EXCLUSION AREAS

In August 2009, the US Navy announced that it will locate an USWTR that, when completed, will cover an approximately 1,713 km^2 area within the water space commonly referred as the Jacksonville OPAREA (Operating Area) (Site A in Figure 11.4). The range will be equipped with undersea cables and sensor nodes that will be connected by a single trunk cable to a landside cable termination facility. The US Navy will use the area for anti-submarine warfare training that would typically involve up to three vessels and two aircraft on the site at any one time. The US Navy plans to train throughout the year (running the exercise scenarios a finite number of times per year), with events evenly distributed across all four seasons. Up to 300 transducer nodes will be placed 1.8–5.5 km apart on the ocean floor over a 1,713 km^2 area, connected by commercial fiber optic undersea cable about 2.5 cm in diameter. The nodes, which are up to 1.2 m high and 2.5 in diameter, will be designed (and buried if deemed necessary) to be consistent with local geographic conditions and to accommodate area activities such as fishing. The total bottom area covered by these components would be approximately 2,945 m^2. Figure 11.5 shows a schematic of the cable layout. It is estimated that installation of the USWTR components will take 4–5 years (Department of the Navy, 2009). According to the Record of Decision, "Installation of the USWTR in the Preferred Alternative JAX OPAREA site would have no significant impact on socioeconomics. Mitigation measures are not necessary for the resource area" (Department of the Navy, 2009). Although the Navy states "The range will remain open to all recreational and commercial activities," it is not clear whether renewable energy development in the range would be an issue.

11.9 POTENTIAL IMPACTS OF OCS DEVELOPMENT ON AREAS OF SPECIAL CONCERN

Because of the protected status of most of the known Areas of Special Concern in the South Atlantic Planning Area, potential impacts are usually avoided during the initial siting process. Once a site is selected, detailed studies are conducted to identify and/or confirm the location and condition of unknown or poorly known sites such as archaeological and cultural resources. Appropriate buffers and best management practices are placed to prevent impacts to these areas of special concerns.

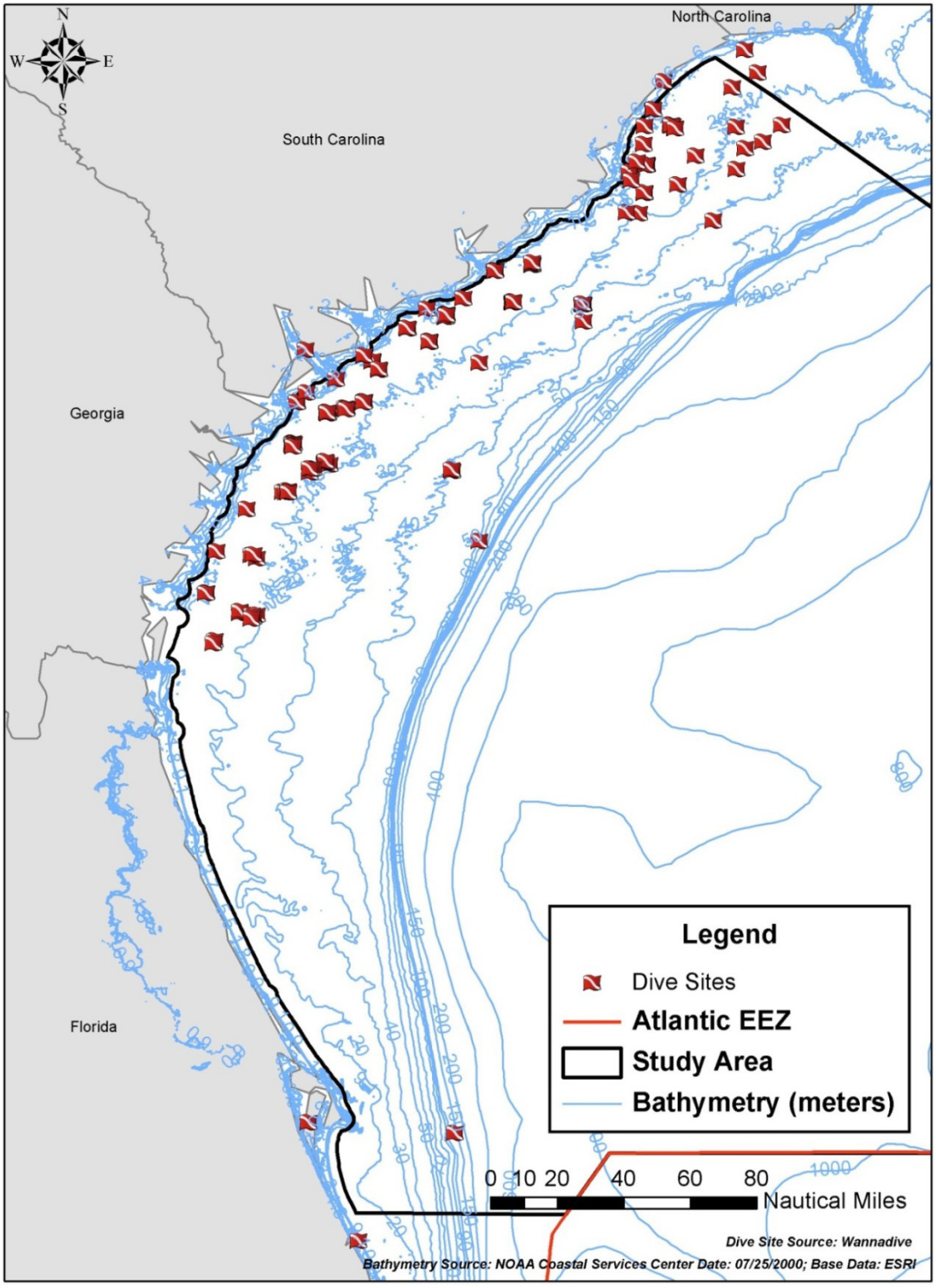

Figure 11.3 Popular dive sites in the South Atlantic Planning Area (data from Wannadive, 2011).

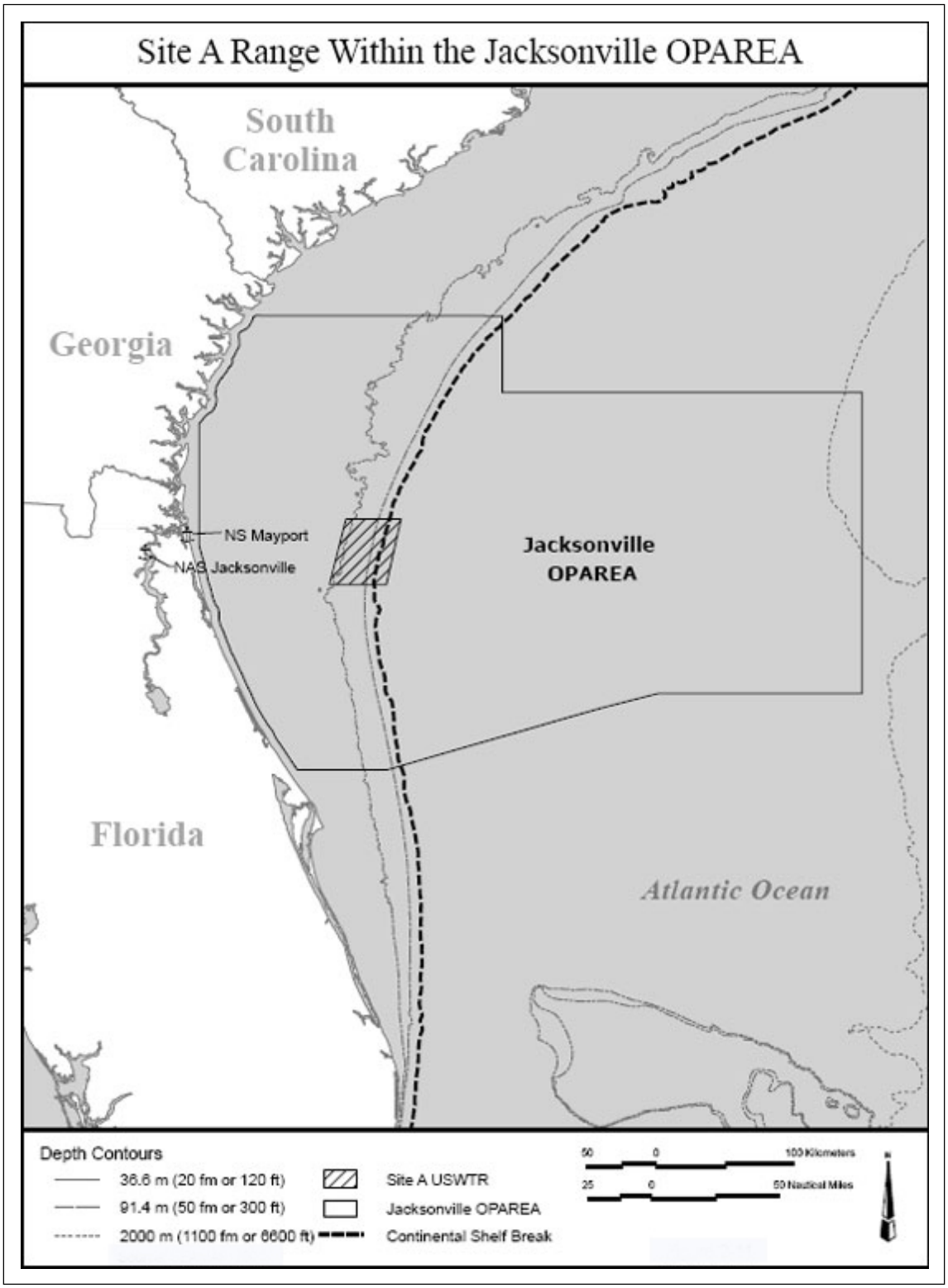

Figure 11.4 Location of the Undersea Warfare Training Range-Site A (Department of the Navy, 2008).

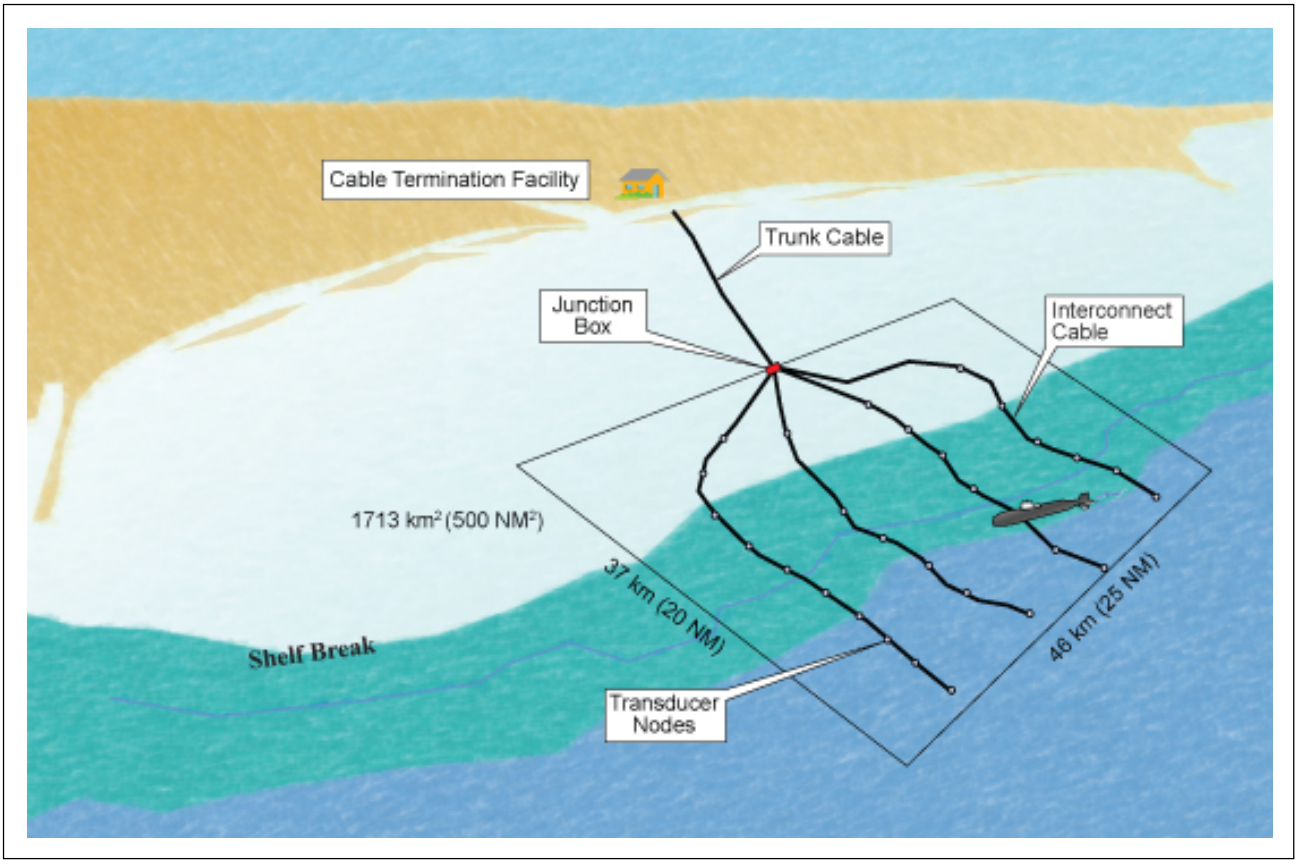

Figure 11.5 Layout of the cable network for the Undersea Warfare Training Range. (Department of the Navy, 2008).

11.10 SUMMARY AND DATA GAPS FOR AREAS OF SPECIAL CONCERN WITH REGARD TO OCS DEVELOPMENT

Known Areas of Special Concern in the South Atlantic Planning Area associated with the coastal zone include NPS lands, USFWS National Wildlife Refuges, and NERRS. There is only one National Marine Sanctuary. There are eight MPAs along the shelf edge. The *Oculina* Habitat Area of Particular Concern occurs in the southern part of the study area. A relatively large area in water depths of 600–900 m beyond the shelf edge has been designated as deep-water Coral Habitat Area of Particular Concern.

The continental shelf between the coast and the shelf edge has no designated areas of special concern, whereas this part of the OCS does have many sensitive hard-bottom habitats and communities that have not been well defined.

The potential conflict of the US Navy Undersea Warfare Training Range with OCS development has yet to be determined. However, it is likely that there could be conflicts with various components of the US Navy's planned activities in the region. These issues need to be addressed as soon as possible, to prevent future conflicts.

11.11 REFERENCES

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CHAPTER 12: SOCIOECONOMIC RESOURCES

12.1 INTRODUCTION

This literature review and synthesis identifies sources of socioeconomic data and information that may be relevant in evaluating potential offshore projects in the South Atlantic Planning Area. The synthesis includes general demographic and regional economic information for each state, a survey of literature describing applicable economic values associated with non-market resources, and a summary of relevant research on the impacts of energy projects on local socioeconomic conditions.

In general, literature that directly addresses questions concerning the potential impact of offshore alternative energy projects along the South Atlantic coast is extremely limited. This result is not unexpected given the low level of development activity relative to other US regions (e.g., wind energy development in the Northeast and Mid-Atlantic and wave energy development in the Pacific Northwest). At present, state- or regional-level demand for alternative sources of energy, including those that might be produced offshore, is influenced in large part by Renewable Portfolio Standards (RPS), which generally require utilities to ensure that a form of renewable energy is the source for a specific percentage of retail electricity sales or generating capacity. However, the three states in the South Atlantic Planning Area (South Carolina, Georgia, and Florida) are among only fourteen states that do not currently have RPS requirements or an RPS Goal. Even in those regions where market drivers like an RPS exist, resources are economically attractive, and offshore development activity is occurring, the literature on potential impacts is only now beginning to emerge. Given these factors, this review focuses on baseline characterization of key social and economic attributes of the region, supplemented by information from other regions that might be transferable to the South Atlantic or might at least inform the scope of future data collection efforts.

12.1.1 Approach and Scope

The research comprised four elements, including: 1) collecting demographic and economic data available from online sources (e.g., the Census); 2) contacting state natural resource management and other agencies to solicit recreational and commercial use data; 3) contacting several academic and professional economists in the region who have published in related areas; and 4) conducting searches of several online research databases.[1]

This review addresses both "baseline" social and economic information and the range of potential impacts associated with offshore development activity. The former category includes general demographic and employment data and information on port infrastructure, commercial fisheries, and tourism and recreation within the region. This review also includes select economic valuation data, with a focus on the value of recreational opportunities in the region. For the latter category, the available literature that examines infrastructure needs and potential socioeconomic effects attributable to offshore alternative energy development is described.

[1] Databases included EconLit, Social SciSearch, SciSearch, AGRICOLA, CAB Abstracts, GEOBASE and CSA Environmental Pollution and Management Database. General Internet searches were also conducted.

12.1.2 Economic Impact/Value Information

Expenditures and revenues provide measures of the relative importance of different industries or sectors within a local or regional economy. Regional economic modeling provides a means of estimating changes in local economic activity by quantifying changes in output (i.e., the dollar value of goods and services produced) and employment. Industries in a geographic area are interconnected (they supply goods and services to each other, and to consumers). Therefore, increased spending in one economic sector tends to have a proportionally larger impact on the regional economy as a whole. This concept is commonly referred to as the "multiplier" effect.

However, expenditures do not reveal the underlying value of those activities to participants. Value, more specifically net economic value or consumer surplus, is measured by what individuals are *willing to pay* for something above and beyond what they are required to spend. This concept of value is recognized as the appropriate measure to compare the costs and benefits of policy alternatives and measure damages resulting from injury to natural resources. The relationship between expenditures and consumer surplus is further illustrated in Figure 12.1.

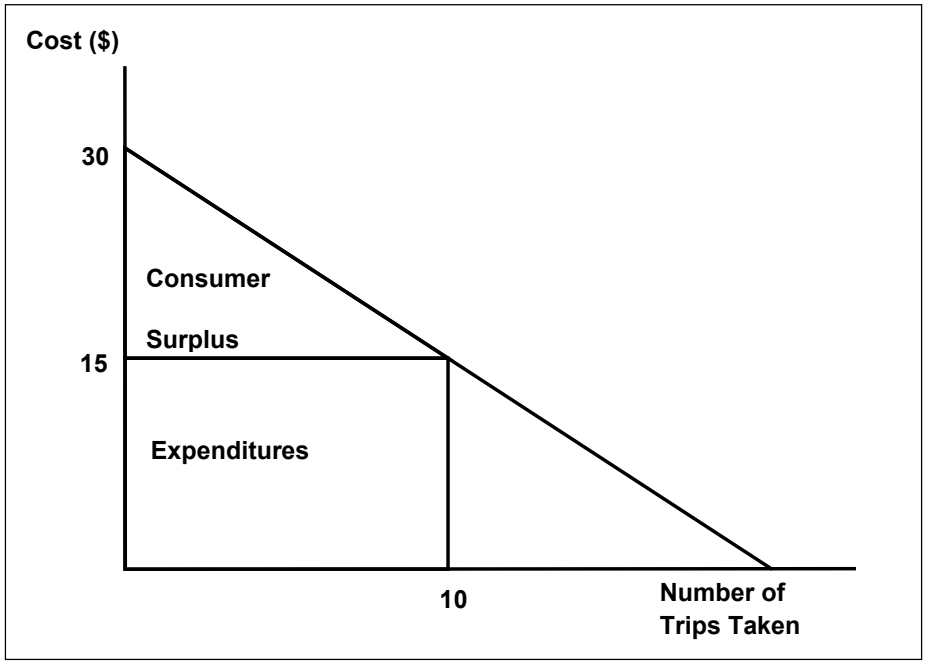

Figure 12.1 An individual's demand curve for recreational trips.

The illustrated demand curve indicates what an individual would be willing to pay for various numbers of recreational trips taken over the course of a particular period in time (e.g., a year or season). The downward slope reflects the conventional notion that the lower (higher) the cost per trip, the more (fewer) trips an individual will take. In this example, at a cost per trip of $15, the individual would take ten trips. Additional trips at that price would exceed what the individual is willing to pay. The individual's total expenditures for these ten trips are equal to the area of the rectangle labeled "Expenditures," or $150 ($15×10). Note that for each trip leading up to the tenth trip, the individual's willingness to pay exceeds the cost per trip. The area of this triangle,

labeled "Consumer Surplus," represents surplus value that accrues to the consumer, in this case $75 [(10÷2)×(30-15)]. The total value (or *social welfare* value) of recreational trips is calculated by summing each individual's consumer surplus across all participants.

As noted, it is changes in social welfare value that are typically measured when comparing policy alternatives or determining compensation for natural resource damages. Changes in regional expenditures and revenues may represent a transfer from one group or area to another. For example, if the quality of recreational activity is somehow compromised by offshore development projects, the amount that anglers or beachgoers are willing to pay may decrease, they may incur greater cost to travel to another area, or they simply may choose a different way to spend their leisure time. Any one of these adjustments would result in a reduction of consumer surplus. However, these individuals would continue to spend money to recreate (i.e., on equipment, supplies, access fees) whether it is at another location or for different activities in the same area.

As the above example suggests, the change in consumer surplus represents a *net* change in social welfare, while any change in expenditures is likely a redistribution from other groups or regions. However, within a local or regional economy, the level of expenditures affects revenues, employment, and tax receipts, all of which are of direct concern to residents and proprietors. Because offshore development projects have the potential to both attract and repel spending and economic activity within coastal economies, both of these types of economic impacts are considered.

Economic values (consumer surplus) and regional economic impacts (revenues, employment, etc.) measure different things, so they should not be summed together or directly compared. Instead, they should be viewed as providing complementary, yet different perspectives on potential economic implications of future offshore development projects.

12.2 REGIONAL DEMOGRAPHIC INFORMATION

This chapter characterizes the coastal regions within the South Atlantic Planning Area by presenting general information on population, income, education, and employment.

12.2.1 South Carolina

Coastal South Carolina comprises the eight counties highlighted in Figure 12.2. The Regional Economic Development Research Laboratory at Clemson University (Henry et al., 2002) describes these eight counties as the coastal zone management region.

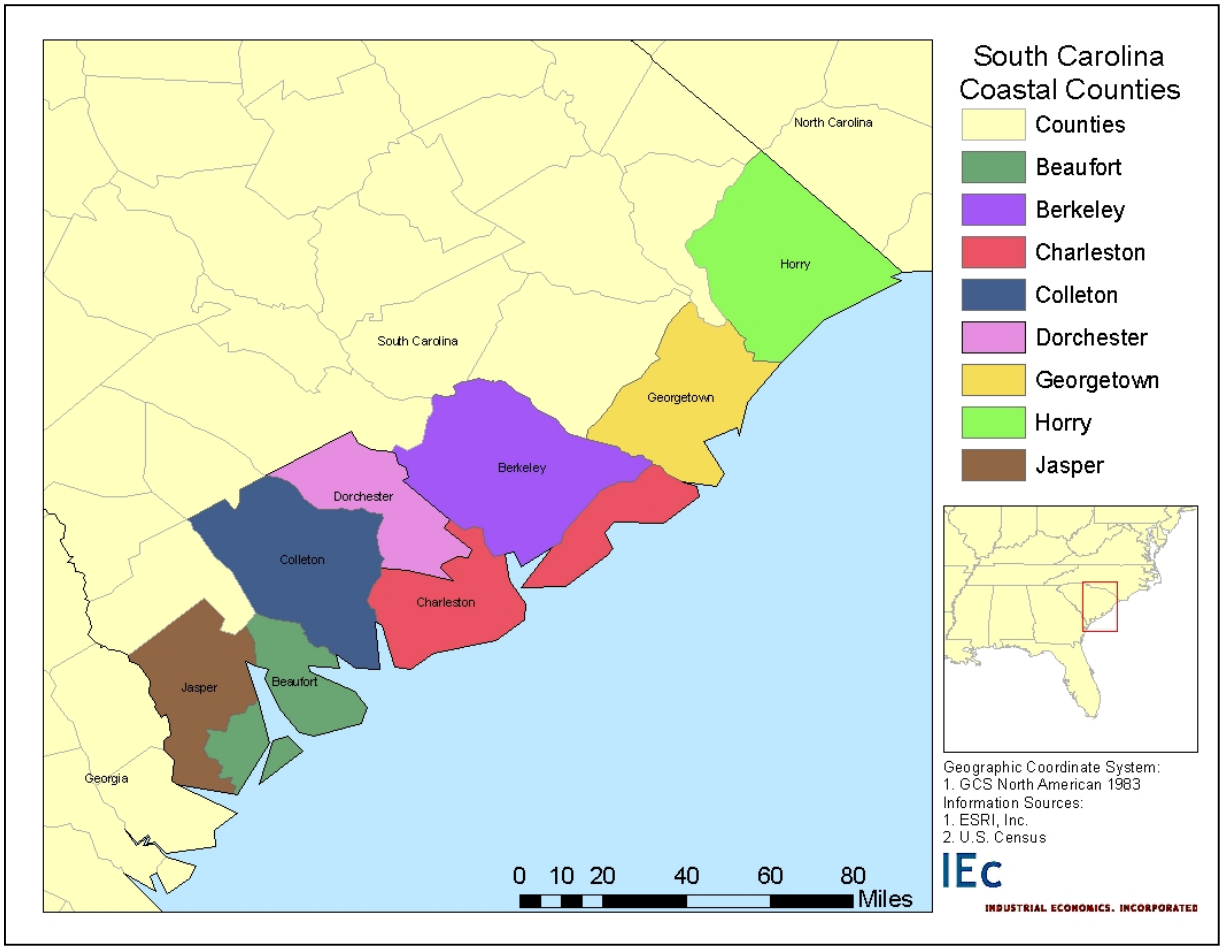

Figure 12.2 South Carolina coastal counties.

12.2.1.1 Population

Total population in South Carolina was over 4.6 million in 2010, with 26.4 percent of the population residing in the eight coastal counties (US Census Bureau, 2010a). Figure 12.3 illustrates the population distribution by census block group along the South Carolina coast.

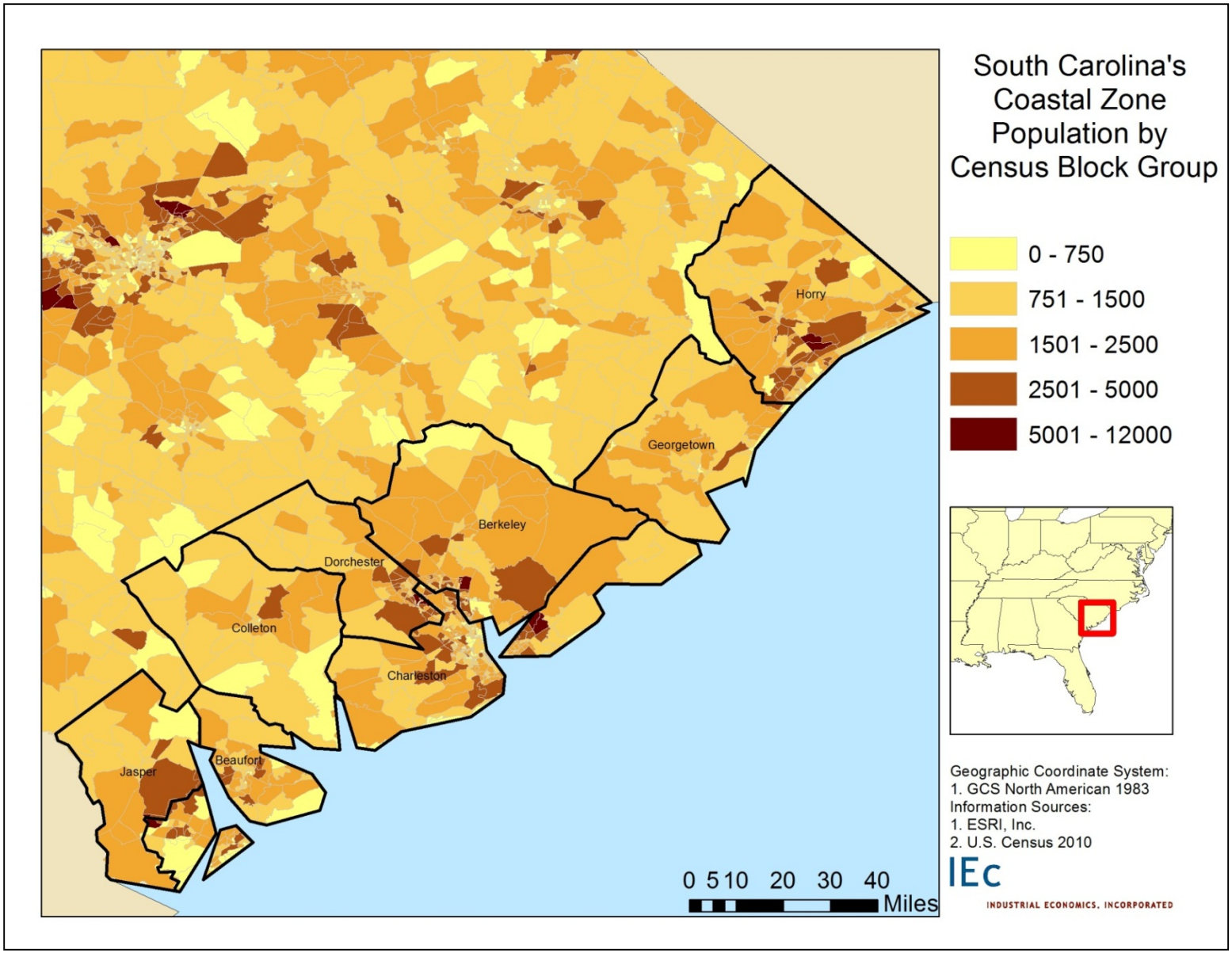

Figure 12.3 South Carolina's coastal zone population by census block group.

Table 12.1 presents population changes in South Carolina between 2000 and 2010. For context, population growth in the broader US is also presented. Population in South Carolina coastal counties grew by 26.4 percent between 2000 and 2010. This population growth was high relative to population growth in the broader state of South Carolina and the US as a whole. In fact, population growth in South Carolina coastal counties over this time period was almost three times that of the US (US Census Bureau, 2000, 2010a).

Table 12.1
Summary of South Carolina population.

Area	Population 2000	Population 2010	Percent Change
South Carolina coastal counties	981,338	1,219,958	26.4%
South Carolina	4,012,012	4,625,364	15.3%
United States	281,421,906	308,745,538	9.7%
Source: US Census Bureau (2000) and US Census Bureau (2010b).			

12.2.1.2 Income

NOAA (Crossett et al., 2004) estimates incomes to be 17 percent higher in coastal counties across all coastal regions except the Southeast Atlantic, where the average is only slightly higher in coastal versus inland counties. Median household income in South Carolina's coastal counties is high relative to non-coastal communities within the state. According to 2010 American Community Survey (ACS) five-year estimates (US Census Bureau, 2010a), median household income for South Carolina's coastal counties was $48,265, with a high of $55,286 in Beaufort County and a low of $33,263 in Colleton County.2 Median household income for the state of South Carolina was $43,939 and $51,914 for the US (US Census Bureau, 2010b).

The percent of the population living below the poverty level in South Carolina coastal counties is between that of the state of South Carolina and the US as a whole. Between 2006 and 2010, 14.9 percent of the population in South Carolina coastal counties lived below the poverty level, compared with 16.4 percent of the broader South Carolina population and 13.8 percent of the US population. These findings are consistent with relative income levels reported above.

12.2.1.3 Education

Educational attainment in South Carolina coastal counties is comparable to the state and national averages. Between 2006 and 2010, 29.9 percent of the population 25 years or older in South Carolina coastal counties reported a high school degree (or equivalent) as their highest level of education, and 17.9 percent reported a bachelor's degree. Similarly, of the broader South

[2] American Community Survey 5-year estimates should be interpreted as an average over the time period examined. For example, 2010 5-year estimates of median household income represent an average estimate of household income from 2006 to 2010, reported in 2010 dollars. Unlike single-year estimates, ACS 5-year estimates provide estimates for small geographies, such as some of the low-population counties included in this study.

Carolina population that was 25 years or older, 31.2 percent reported a high school degree as their level of education and 15.5 percent reported a bachelor's degree. For the US population 25 years and older, the proportion reporting a high school degree or a bachelor's degree as their highest level of education were 29.0 percent and 17.6 percent, respectively (US Census Bureau, 2010b).

12.2.1.4 Employment

Table 12.2 presents South Carolina employment by industry in coastal counties in 2009. Retail trade was the top industry, making up 17.5 percent of total employment in these counties. The accommodation and food services industry and the health care and social assistance industry followed, making up 16.7 percent and 13.2 percent of total employment, respectively (US Census Bureau, 2009).

Table 12.2
Top ten industries on the South Carolina coast by employment.

Industry	Percent
Retail trade	17.5
Accommodation and food services	16.7
Health care and social assistance	13.2
Administrative and support and waste management and remediation services	7.6
Manufacturing	6.5
Construction	6.4
Professional, scientific, and technical services	5.5
Other services (except public administration)	5.1
Finance and insurance	3.6
Wholesale trade	3.3
Source: US Census Bureau (2009).	

12.2.2 Georgia

The coastal area of Georgia includes six coastal counties and five "inland tier" counties, which together comprise the Georgia Coastal Zone, depicted in Figure 12.4 (NOAA, 2010).

12.2.2.1 Population

In 2010, approximately 6.5 percent of Georgia's population of 9.7 million residents lived in the 11-county coastal zone (US Census Bureau, 2010a). Figure 12.5 illustrates the population distribution in Georgia's coastal zone by census block group, indicating areas where offshore development projects could affect a disproportionately large number of people.

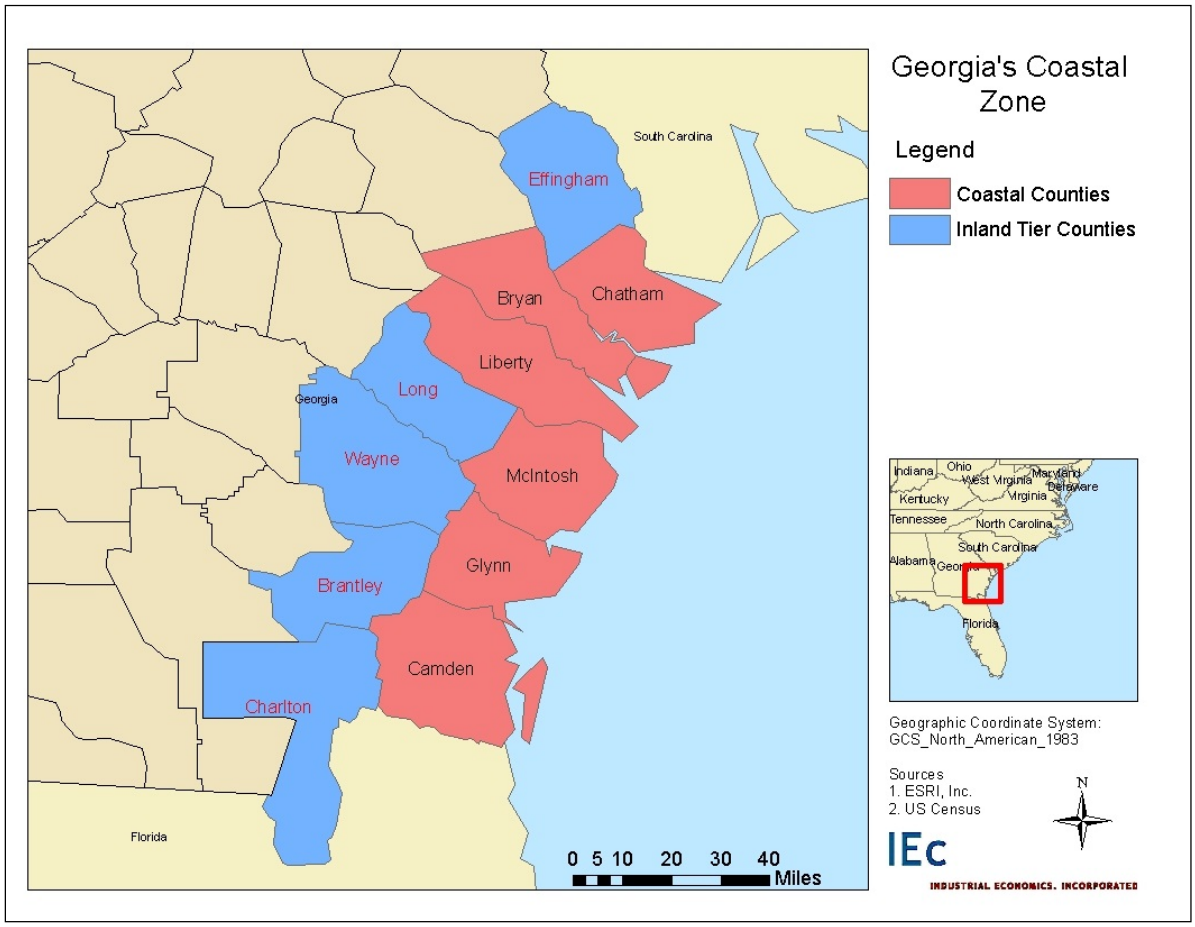

Figure 12.4 Georgia's coastal and inland tier counties.

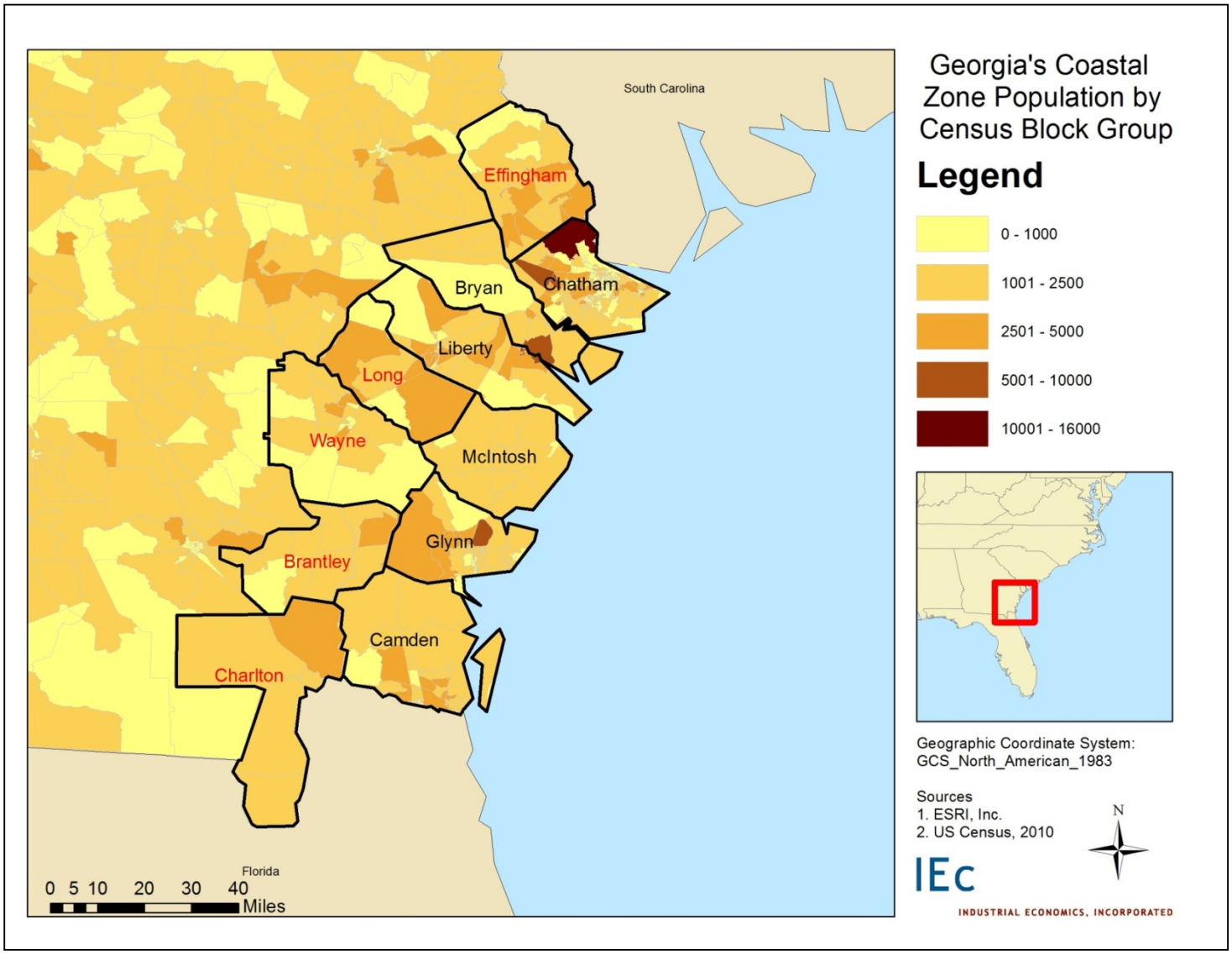

Figure 12.5 Georgia's coastal zone population by census block group..

As Table 12.3 illustrates, population growth in Georgia coastal and inland tier counties has outpaced that of the US as a whole. Georgia coastal counties experienced population growth of 14.6 percent between 2000 and 2010, while Georgia inland tier counties experienced population growth of 28.3 percent, nearly three times the national rate (US Census Bureau, 2010a).

Table 12.3
Summary of Georgia population.

Area	Population 2000	Population 2010	Percent Change
Georgia Coastal Counties	439,154	503,286	14.6%
Georgia Inland Tier Counties	99,315	127,395	28.3%
Georgia	8,186,453	9,829,211	18.3%
United States	281,421,906	308,745,538	9.7%
Source: US Census Bureau (2000) and US Census Bureau (2010b).			

12.2.2.2 Income

Between 2006 and 2010, the median household income for Georgia coastal counties was $46,865, and the median household income for Georgia inland tier counties was $46,136. These income levels are lower than the associated state and national statistics ($49,347 and $51,914, respectively). Over this same time period, 16.1 percent of the population in Georgia coastal counties lived below the poverty line, compared with 15.3 percent of the inland Georgia county population. These counties had a somewhat higher rate of poverty relative to the national population (13.8 percent living below the poverty line; US Census Bureau, 2010b).

12.2.2.3 Education

Between 2006 and 2010, 31.0 percent of the population in Georgia coastal counties 25 years and older reported a high school diploma as their highest level educational attainment. In Georgia inland counties, this same figure was 42.0 percent. These rates are high relative to the state and national averages (29.6 percent and 29.0 percent, respectively). Furthermore, coastal and inland counties had relatively low rates of people reporting a bachelor's degree as the highest level of education, at 16.5 percent and 7.6 percent, respectively (US Census Bureau, 2010b). This may indicate that a disproportionate number of people within these counties choose not to continue their education past high school, and could explain the relatively low income levels in the Georgia Coastal Zone.

12.2.2.4 Employment

Table 12.4 presents the top industries by employment in the Georgia coastal and inland counties. In 2009, accommodation and food services accounted for 15.9 percent of total employment within these counties, followed by retail trade at 15.7 percent and health care and social assistance at 14.5 percent (US Census Bureau, 2009).

Table 12.4
Top ten industries in the Georgia coastal and inland counties by employment.

Industry	Percent
Accommodation and food services	15.9
Retail trade	15.7
Health care and social assistance	14.5
Manufacturing	9.5
Administrative and support and waste management and remediation services	6.7
Transportation and warehousing	6.2
Construction	5.6
Other services (except public administration)	4.7
Professional, scientific, and technical services	3.8
Wholesale trade	3.1
Source: US Census Bureau (2009).	

12.2.3 Florida

The six South Atlantic coastal counties in Florida are Nassau, Duval, St. Johns, Flagler, Volusia, and Brevard (Figure 12.6).

12.2.3.1 Population

In 2010, the population of the state of Florida was 18,801,310 and that of the six South Atlantic coastal counties was 2,261,281, or 12.0 percent of the state's population (US Census Bureau, 2010a). Figure 12.7 shows the population distribution in Florida by census block group, indicating where offshore development projects have the potential to affect disproportionately small or large populations.

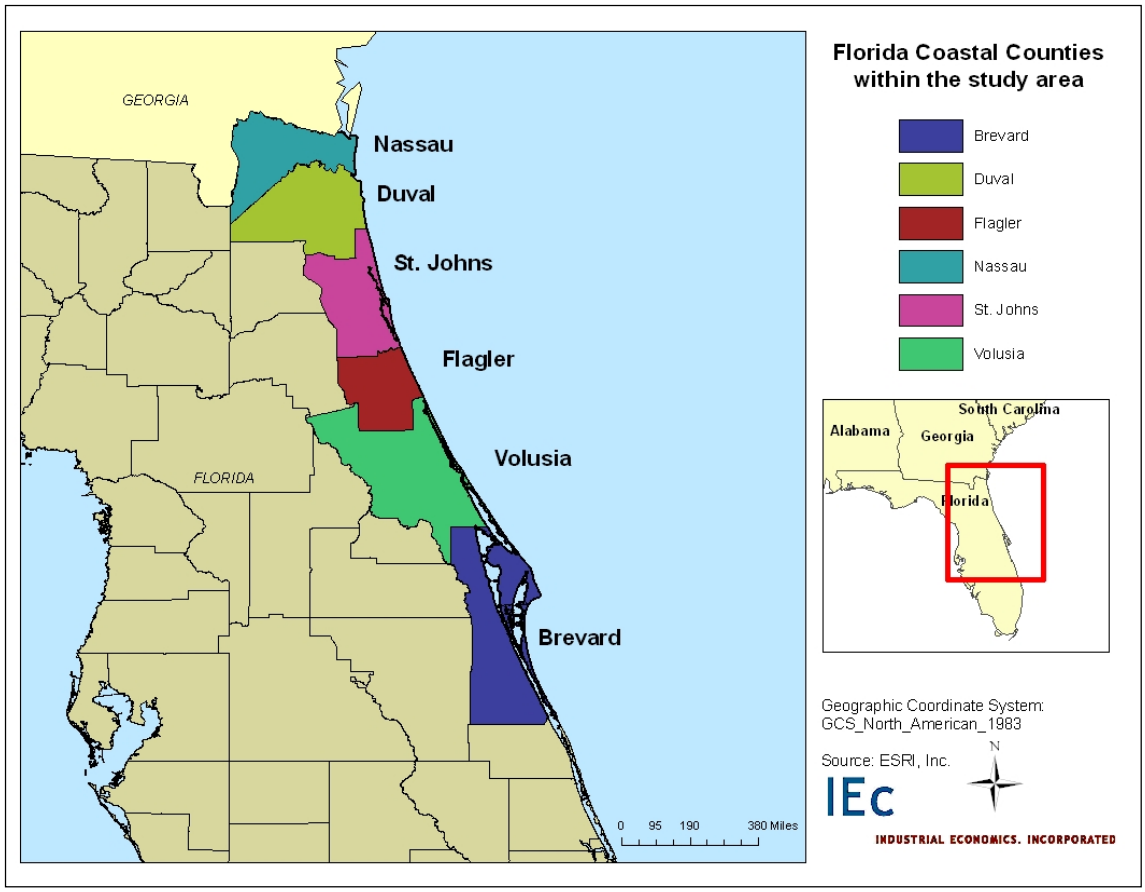

Figure 12.6 Florida's coastal counties within the study area.

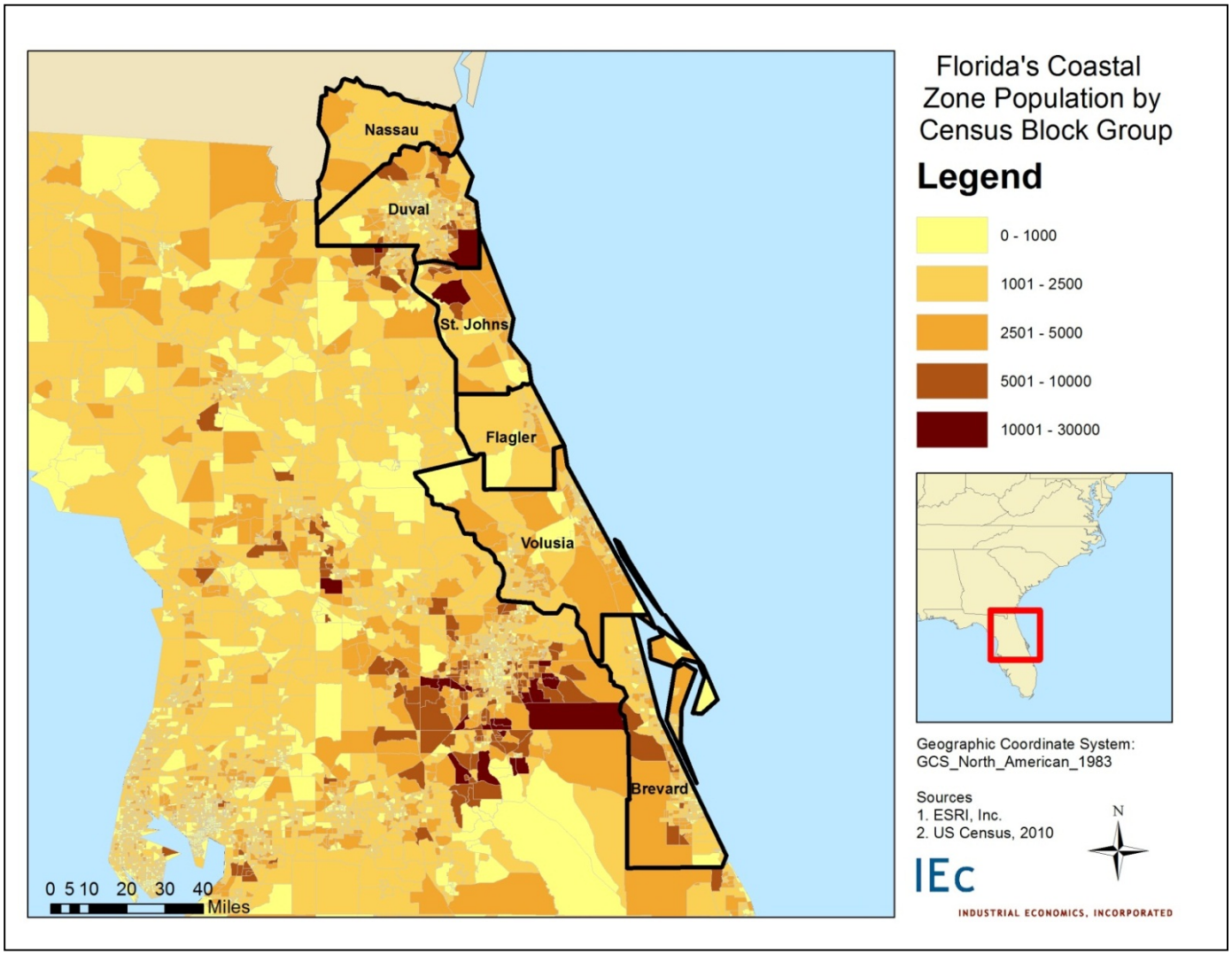

Figure 12.7 Florida's coastal zone population by census block group.

Table 12.5 provides a summary of Florida population growth between 2000 and 2010. Over this ten-year period, the population of Florida grew 17.6 percent. The population of the six South Atlantic coastal counties grew at a comparable rate of 17.2 percent. These rates of growth were significantly higher than population growth in the entire US over the same time period (US Census Bureau, 2010a).

Table 12.5
Summary of Florida population.

Area	Population 2000	Population 2010	Percent Change
Florida Coastal Counties	1,929,082	2,261,281	17.2%
Florida	15,982,378	18,801,310	17.6%
United States	281,421,906	308,745,538	9.7%
Source: US Census Bureau (2000) and US Census Bureau (2010).			

12.2.3.2 Income

According to ACS 2010 5-year estimates, median household income was $47,661 for the state of Florida and $49,721 for the six coastal counties within the South Atlantic Planning Area between 2006 and 2010. These income levels fell short of the national median household income over this time period, $51,914. The poverty rate was comparable to the national average, with 12.5 percent of the Florida coastal county population and 13.8 percent of both the Florida and national populations living below the poverty line (US Census Bureau, 2010b).

12.2.3.3 Education

In Florida coastal counties, 30.7 percent of the population 25 years or older reported a high school degree as their highest level of educational attainment between 2006 and 2010, and 16.6 percent reported a bachelor degree. These statistics were close to those for the entire state of Florida. Relative to the US as a whole, Florida had slightly higher rates of individuals with high school as their highest level of education and slightly lower rates of individuals with a bachelor's degree as their highest level of education (US Census Bureau, 2010b).

12.2.3.4 Employment

Table 12.6 presents employment by occupation in the six Florida counties within the South Atlantic Planning Area. The health care and social assistance industry accounts for the largest portion of employment within the counties, at 15.4 percent of total employment. Retail trade is the second largest industry by employment with 14.0 percent, and the accommodation and food services industry is the third largest with 10.9 percent (US Census Bureau, 2009).

Table 12.6
Top ten industries in the Florida coastal counties by employment.

Industry	Percent
Health care and social assistance	15.4
Retail trade	14.0
Accommodation and food services	10.9
Administrative and support and waste management and remediation services	8.5
Finance and insurance	7.4
Professional, scientific, and technical services	7.0
Manufacturing	6.7
Construction	5.9
Other services (except public administration)	4.6
Wholesale trade	4.0
Source: US Census Bureau (2009).	

12.3 REGIONAL ECONOMIC ACTIVITY

12.3.1 South Carolina

As described above, the US Census Bureau County Business Patterns Dataset reports the top three industries by employment as retail trade, accommodation and food services, and health care and social assistance within South Carolina's coastal counties (Table 12.2). South Carolina is a popular tourist destination and service jobs are largely related to the booming tourism economy. The waste management and remediation services industry, the manufacturing industry, the construction industry, the professional, scientific, and technical services industry, and other services each make up more than five percent of the workforce in these coastal counties. Charleston, South Carolina is the largest US Custom District in the Southeast United States, providing a significant source of employment opportunities (SCDC, 2009). In 2009, 26.7 percent of the state's employees worked within the coastal counties, earning 25.7 percent of the income within the state (US Census Bureau, 2009).

12.3.1.1 Ports

South Carolina has sea terminals in Charleston and Georgetown. In 2008, the South Carolina State Ports Authority (SCSPA) reported that South Carolina ports contributed 260,800 jobs, $11.8 billion in personal income, $1.5 billion in tax revenues, and had an overall economic impact of $44.8 billion. The majority of tonnage moves through the Port of Charleston. According to an SCSPA study, imports through the Charleston Harbor rose 34.2 percent between 2002 and 2007, reaching 18.1 million tons in 2007 (Wilbur Smith Associates, 2008). The Port of Charleston is the second largest seaport for waterborne foreign container trade on the southeast coast, handling nearly $61 billion worth of goods in 2007 (SCDC, 2009).

12.3.1.2 Fisheries

According to the National Ocean Economics Program (NOEP) commercial landings data, South Carolina commercial landings totaled almost 10.5 million live pounds and were valued at approximately $21 million in 2010. The South Atlantic Planning Area supports multiple fisheries, the most valuable of which are shrimp and blue crab. Commercial landings in the Penaeid shrimp fishery, which includes white and brown shrimp, totaled more than $7.5 million off the coast of South Carolina in 2010. This value was down from landings of over $15 million in 2000 (NOEP, 2010). Through the 1990s shrimp trawling licenses remained steady between 800 to 1,000 licenses per year. In 2005, only 488 licenses were issued, down from 915 in 2000 (SCDNR, 2006). These trends indicate that the South Carolina shrimp industry may be contracting. Table 12.7 shows landing weight and value for the top ten commercial species in South Carolina in 2010. Table 12.8 shows the actual landing weights and values by coastal county for commercial fish in 2008.

Table 12.7
Top ten commercial fish species in South Carolina by weight and landed value, 2010.

Rank	Species by Weight	Weight (pounds)	Landed Value Species	Landed Value
1	crab, blue	3,203,517	shrimp, white	$6,253,389
2	shrimp, white	2,806,889	crab, blue	$3,194,948
3	shrimp, brown	856,505	swordfish	$1,868,143
4	swordfish	602,185	oyster, eastern	$1,858,140
5	snapper, vermilion	356,237	shrimp, brown	$1,376,726
6	oyster, eastern	331,753	snapper, vermilion	$1,052,315
7	shad, American	296,421	clam, northern quahog	$688,337
8	shrimp, marine, other	287,566	gag	$577,298
9	finfishes, unc general	239,029	shrimp, marine, other	$538,171
10	clam, northern quahog	151,776	scamp	$507,561

Source: National Ocean Economics Program (2010).

Table 12.8
Commercial fishing landings by South Carolina county, 2008.

County	Live Pounds	Value
Beaufort	2,371,991	$3,891,817
Berkeley	5,134	$8,301
Charleston	3,883,581	$7,402,658
Colleton	345,907	$631,658
Dorchester	36,364	$39,215
Georgetown	2,748,994	$4,433,726
Horry	625,311	$1,604,388
Jasper	3,519	$6,417
State Total	10,054,693	$18,048,634
Source: Non-Confidential data from Atlantic Coastal Cooperative Statistics Program (2008).		

12.3.1.3 Tourism

Tourism is critical to the South Carolina economy. The South Carolina Budget and Control Board (SCBCB, 2007) estimated that 30 million visitors generated more than $16 billion in revenue and supported more than 10 percent of employment in 2007. In 2008, the South Carolina counties with the three highest travel expenditures, payroll income, and jobs from tourism were coastal counties. Horry County, which includes resort destination Myrtle Beach, led all South Carolina counties with $3.1 billion in domestic travel expenditures, roughly 32 percent of the state total. Charleston County ranked second with $1.6 billion in domestic travel spending and Beaufort County ranked third in the state with $1 billion in expenditures. Table 12.9 shows expenditures, payroll income, employment numbers, state ranking associated with domestic travel, and state and local tax receipts from tourism for each of the eight coastal counties in 2008. Total domestic travel expenditures for the eight coastal counties in 2008 were $6.3 billion or approximately 64 percent of the State's total domestic travel expenditures (US Travel Association, 2009b).

Table 12.9
South Carolina domestic tourism expenditures by county, 2008.

County	State Ranking	Expenditures ($ Millions)	Payroll ($ Millions)	Employment (Thousands)	State Tax Receipts ($ Millions)	Local Tax Receipts ($ Millions)
State Total		$9,870.42	$2,012.31	113.80	$560.67	$332.55
Beaufort	3	$1,019.97	$206.82	12.84	$60.23	$34.07
Berkley	14	$92.22	$16.13	0.96	$5.75	$3.34
Charleston	2	$1,629.66	$348.90	20.50	$92.59	$58.60
Colleton	15	$86.83	$16.72	1.00	$5.30	$2.81
Dorchester	18	$63.67	$11.63	0.67	$4.04	$1.29
Georgetown	8	$266.07	$51.28	3.10	$16.09	$12.44
Horry	1	$3,118.6	$628.40	38.60	$191.50	$128.50
Jasper	20	$47.48	$9.67	0.61	$2.86	$1.70
Total of Coastal Counties		$6,324.50	$1,289.55	78.28	$378.36	$242.75

Source: US Travel Association (2009b).

12.3.1.4 Recreation

The South Carolina Department of Parks, Recreation and Tourism conducted an extensive recreation survey in 2005 (SCDPRT, 2008). The survey was organized by planning district with results described in terms of percentage of participation (i.e., the percentage of the population that participates in a given activity). Table 12.10 summarizes survey results for the three planning districts that include the coastal counties, with comparisons to statewide results. Figure 12.8 illustrates the location of these planning districts. Activities that are marine-related naturally have higher participation rates in coastal counties when compared to the state average. The activities in boldface have higher participation rates in each of the coastal planning districts than the state average. Beach swimming/sunbathing, motorboating, and watching wildlife are generally the most popular recreational activities in South Carolina.

Table 12.10
Recreation participation rates in South Carolina.

Activity	Waccamaw Planning District	Berkeley-Charleston-Dorchester Planning District	Low country Planning District	State
Beach swimming/sunbathing	69.6	68.4	73.3	62.5
Motorboating	34.1	36.2	35.8	34.1
Watching wildlife	43.5	28.2	34.5	33.4
Saltwater Fishing	29.2	21.1	30.1	16.2
Jetskiing	8.4	13.1	13.2	11.8
Canoeing, kayaking, rafting	12.5	10.8	10.1	10.7
Shellfishing/shrimping	13.3	15.1	30.3	7.1
Waterskiing	4.0	7.5	4.5	6.1
Sailing	3.8	4.5	3.8	2.7

Source: South Carolina Department of Parks, Recreation and Tourism (2008).
Note: The Waccamaw Planning District includes Horry, Georgetown, and Williamsburg counties. The Lowcountry Planning District includes Beaufort, Colleton, Hampton, and Jasper counties.

12.3.1.4.1 Boating

The majority of boats registered in South Carolina are for personal use (Southwick Associates, 2009). There were 381,117 boats registered as of February 2009; of those 0.3 percent were registered as commercial fishing, 0.3 percent as commercial passenger, 0.03 percent as demo/repair/test boats, 0.4 percent as rental/lease, 98.2 percent as personal or pleasure, and the remaining 0.8 percent of boats were characterized as "other." The 374,244 pleasure boats were registered to 315,886 different individuals. Note that this information is for all South Carolina boaters and not just boats used on the Atlantic; information on boat registration does not indicate where the boat will be used.

The US Coast Guard Vessel Information System lists 4,218 registered vessels with South Carolina as their hailing port state (USCG, 2009). The breakdown by type of boat is presented in Table 12.11.

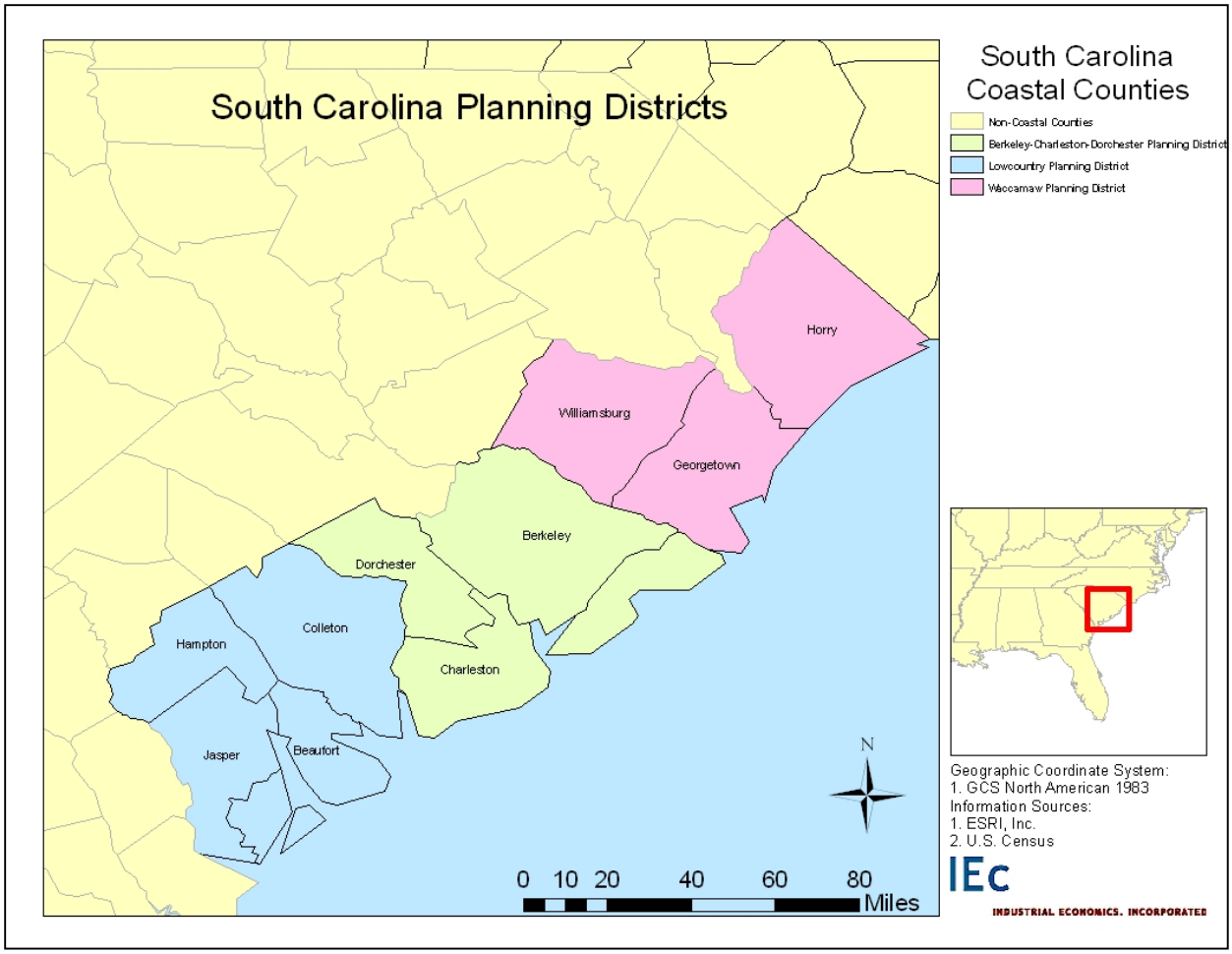

Figure 12.8 Recreation planning districts in South Carolina.

Table 12.11
Number of US Coast Guard documented vessels with SC hailing port.

Vessel Count*	Type of Vessel
3,504	Recreational
281	Commercial Fishing
223	Passenger
163	Shipping/Industrial
45	Unclassified
2	Scientific
4,218	Total Documented Vessels
*The database tracks merchant vessels and recreational vessels with a valid Certificate of Documentation (documented vessels). Source: USCG (2009).	

Of the documented recreational vessels listing South Carolina as the hailing port state, 73 percent have in-state owners and 27 percent list out-of-state owners. The out-of-state owners are from 42 different states; the states with the largest ownership are North Carolina, Georgia, and Florida. Of the commercial fishing vessels that list South Carolina as the hailing port state, 92 percent are owned by individuals in South Carolina; approximately 8 percent of the remaining owners are from out of state (USCG, 2009).

South Carolina also supports a boat manufacturing industry. It is estimated that the South Carolina boat building industry had a direct economic impact of $238.5 million dollars in 2008 and supported 7,125 jobs (SCDNR, 2009).

12.3.1.4.2 Recreational Fishing

In South Carolina 325,000 people engaged in saltwater fishing activities during 2,174,000 participant days and 1,574,000 trips in 2006. Targeted species include striped bass, flatfish (flounder, halibut), red drum (redfish), and sea trout (weakfish). South Carolina anglers tended to be slightly older than the general population and predominantly male. Saltwater anglers spent an average of $1,196 (per person) in 2006 on food and lodging, transportation, other trip costs, and equipment (USDOI et al., 2008a). Tables 12.12 and 12.13 summarize saltwater fishing participants, days, trips and expenditures.

Table 12.12
Saltwater fishing trips in South Carolina by resident and non-resident, 2006.

Anglers, Trips, and Days of Fishing	Total (state residents and non-residents)	State Residents	
Saltwater	Number	Number	Percent of Total
Total Anglers	325,000	142,000	44
Total Trips	1,574,000	1,275,000	81
Total Days	2,174,000	1,425,000	66
Average Days	7	10	

Note: Statistics reported for the entire state population 16 years and older. Source: USDOI et al. (2008a).

Table 12.13
South Carolina saltwater fishing expenditures, 2006.

Expenditure Item	Amount	Spenders	Average per Spender	Average per Angler
Saltwater Fishing				
Total	$572,142,000	324,000	$1,764	$1,196
Food and Lodging	$85,039,000	280,000	$304	$262
Transportation	$38,315,000	243,000	$158	$118
Other trip costs	$67,482,000	263,000	$257	$208
Equipment	$381,307,000	115,000	$3,320	$608
Note: Statistics reported for the entire state population 16 years and older. Spenders represent anyone spending money on fishing-related activity; anglers represent only those that actually participated in fishing. Source: USDOI et al. (2008a).				

Comparing 2006 estimates of fishing to previous surveys (2001, 1996, and 1991), the number of persons fishing declined from 1996 to 2001 and continued to decline in 2006. The amount of time spent fishing increased between 1991 and 1996, but fell between 1996 and 2001 and continued to decline from 2001 to 2006 (USDOI et al., 2003a, 2008a).

12.3.1.4.3 Beaches

As noted in Table 12.10, beach visits are one of the most popular recreational activities in South Carolina in terms of percent participation. The direct economic impact of beach tourism from out-of-state visitors to the state was estimated to be $1.25 billion in 2006 and $1.64 billion in 2010 (Oh et al., 2006). The direct economic impacts at the county level, which included impacts of out-of-state tourists as well as in-state visitors who are not residents of the coastal counties, were estimated to be $1.63 billion in 2006 and $2.07 billion in 2010. Direct expenditures included items such as lodging, grocery, retail, restaurants, recreational activities, entertainment, and transportation. Beach visitation is expected to increase in the future as the South Carolina and US populations increase (Oh et al., 2006).

12.3.2 Georgia

The US Census Bureau County Business Patterns Dataset reports that within Georgia's coastal and inland counties, the top three industries by employment are accommodation and food services, retail trade, and health care and social assistance, (Table 12.4). The manufacturing industry, the waste management and remediation services industry, and the transportation and warehousing industry each make up more than five percent of the workforce in these counties. In contrast to South Carolina, the coastal zone employs only a small portion of Georgia's working populace. In 2009, 5.1 percent of the state's employees worked within the state's coastal counties, and 0.5 percent worked in Georgia's inland counties. Coastal and inland counties in Georgia accounted for 4.3 percent and 0.4 percent of statewide income, respectively (US Census Bureau, 2009). From 1980 to 2005 there was significant economic growth in Georgia's coastal counties, with total regional earnings increasing from $4.3 billion to $8.7 billion (Oh et al., 2006).

12.3.2.1 Ports

Georgia has sea terminals in Savannah and Brunswick. In 2009, the Port of Savannah moved $52.6 billion in cargo, comprising 2.4 million twenty-foot equivalent units. The Port of Brunswick moved over 1.3 million tons of cargo in 2009, still its second-highest annual volume ever despite a 17.7 percent decline from 2008 (GPA, 2010a, 2010b). The Georgia Port Authority (GPA) directly employs nearly 1,000 people (GPA, n.d.). The Atlantic Coastal Cooperative Statistics Program estimated that Georgia ports contributed to 295,000 full- and part-time jobs, $61.7 billion in sales, and $15.5 billion in income (Humphreys, 2010). The port of Savannah is planning future expansions, projecting a capacity of 6.5 million twenty-foot equivalent units by 2020 (GPA, 2010a).

12.3.2.2 Fisheries

According to commercial landings data (NOEP, 2010), Georgia commercial landings in 2010 totaled over 7.3 million live pounds valued at approximately $13.4 million. The most valuable fishery in Georgia is the Penaeid shrimp fishery, which includes white and brown shrimp. In 2010, commercial landings totaled almost 4.5 million pounds with a value of more than $9.6 million, of which $8.5 million was white shrimp. Shrimp landings were down from over $17 million in 2000 (NOEP, 2010). Through the 1990s trawling licenses remained steady between 400 to 600 licenses per year. In 2009, only 225 licenses were issued, down from 534 in 2000 (GDNR, n.d.). Table 12.14 displays landing weight and value for the top ten commercial species in Georgia in 2010. Table 12.15 shows the actual landing weights and values by coastal county for commercial fish in 2008.

Table 12.14
Top ten commercial fish species in Georgia by weight and landed value, 2010.

Rank	Species by Weight	Weight (pounds)	Landed Value Species	Landed Value
1	shrimp, white	3,861,266	shrimp, white	$8,519,046
2	crab, blue	2,464,593	crab, blue	$2,293,818
3	shrimp, brown	599,039	shrimp, brown	$1,102,454
4	finfishes, unc general	127,638	clam, quahog	$430,410
5	clam, quahog	81,141	finfishes, unc general	$239,028
6	crab, blue, peeler	47,777	shrimp, dendrobranchiata	$197,530
7	crab, Florida stone claws	37,344	crab, blue, soft	$184,905
8	shrimp, dendrobranchiata	35,641	crab, blue, peeler	$137,859
9	oyster, eastern	19,464	shellfish	$136,862
10	finfishes, unc for food	19,002	oyster, eastern	$93,830
Source: National Ocean Economics Program (2010).				

Table 12.15
Commercial fish landings by Georgia County, 2008.

County	Live Pounds	Value
Bryan	74,825	$114,493
Camden	390,865	$492,576
Chatham	1,933,317	$3,684,558
Glynn	1,269,571	$2,653,355
Liberty	454,704	$436,399
Lowndes	28,913	$20,782
McIntosh	3,582,017	$5,591,617
State Total	7,734,212	$12,993,781
Source: Non-Confidential data from Atlantic Coastal Cooperative Statistics Program (2008).		

12.3.2.3 Tourism

Tourism is a growing part of the coastal economy in Georgia, with employment in tourism-related sectors making up more than 60 percent of the economic base in 2005 (GDCA, 2005). However, the tourism industry in these counties remains a small part of the state's total, generating 8.9 percent of total state tourism expenditures. Only two of the eleven coastal counties were among the top ten counties for the state in terms of travel expenditures, payroll income, and jobs, with several ranking close to the bottom of Georgia's 159 counties. Chatham

County, which includes the City of Savannah, generated nearly two-thirds of all coastal county tourism expenditures, but only 5.8 percent of total state expenditures. Table 12.16 displays expenditures, payroll income, employment numbers, state ranking, and state and local tax receipts associated with domestic travel for each of the eight coastal counties in 2008. Total domestic tourism expenditures for the eight coastal counties in 2008 were $1.69 billion (US Travel Association, 2009a).

Table 12.16
Georgia domestic tourism expenditures by county, 2008.

County	State Ranking	Expenditure (Millions)	Payroll (Millions)	Employment (Thousands)	State Tax Receipts (Millions)	Local Tax Receipts (Millions)
State Total		$19,025.63	$6,339.67	$220.79	$850.61	$574.65
Brantley	122	$6.82	$0.94	$0.05	$0.22	$0.20
Bryan	58	$33.93	$7.12	$0.35	$1.24	$1.01
Camden	31	$78.95	$15.88	$0.83	$2.87	$2.37
Charlton	110	$9.57	$1.90	$0.10	$0.34	$0.28
Chatham	3	$1,096.56	$285.29	$11.74	$43.93	$33.47
Effingham	73	$24.86	$4.50	$0.25	$0.87	$0.74
Glynn	9	$312.64	$80.76	$3.69	$12.47	$9.53
Liberty	30	$88.15	$12.21	$0.59	$2.97	$2.66
Long	151	$1.56	$0.25	$0.02	$0.05	$0.04
McIntosh	97	$12.58	$2.70	$0.14	$0.46	$0.37
Wayne	70	$27.43	$5.31	$0.29	$0.96	$0.80
Total of coastal counties		$1,693.05	$416.86	$18.05	$66.38	$51.47
Source: US Travel Association (2009a), Table 2.4.						

12.3.2.4 Recreation

The Georgia Department of Natural Resources (GDNR, 2008) has conducted numerous surveys to identify common recreational activities. Results are described in terms of percentage of participation (i.e., the percentage of the population that participates in a given activity). According to data gathered from the most recent GDNR survey, bicycling, tent camping, and hiking are the most popular activities in Georgia. Table 12.17 summarizes survey results for the state (detailed results were not available at the county level).

Table 12.17
Participation rates for recreational activities in Georgia.

Activity	Participation Rate (%)
Bicycling	32
Tent Camping	24
Hiking	23
Nature Study	19
Horseback Riding	19
Mountain Biking	18
Canoeing	18
Backpacking	17
Fishing	17
Dog Parks	17
Free Play Areas	16
Eco-Touring	13
Swimming	9
Wheelchair Activities	9
Boating	8
Walking/Jogging	6
Hunting	6
In-Line Skating	6
Rock Climbing	6
RV Camping	6
Golf	4
BMX Biking	3
Roller Hockey	2
Skateboarding	2
Tennis	2
Waterskiing	1
Note: This table describes statewide, rather than coastal county level, participation. Source: Georgia Department of Natural Resources (2008).	

12.3.2.4.1 Boating

The majority of boats registered in Georgia are for personal use. There were 36,073 boats registered in Georgia's coastal zone as of February 2011; of those 98.5 percent were registered as pleasure boats, with the remaining 1.5 percent comprising commercial fishing, commercial passenger, and livery boats (GDNR, 2010). Note that this information is for all boats registered in the coastal counties and not just boats used on the Atlantic; information on boat registration does not indicate where the boat will be used (Southwick, 2010). The breakdown of boat registrations by county is presented in Table 12.18 below.

Table 12.18
Number of boat registrations by Georgia County.

County	Number of Boat Registrations
Brantley	1,761
Bryan	3,263
Camden	2,950
Charlton	780
Chatham	10,885
Effingham	4,430
Glynn	4,892
Liberty	2,159
Long	618
McIntosh	1,950
Wayne	2,385
Total	36,073
Source: GDNR (2010).	

12.3.2.4.2 Recreational Fishing

In Georgia, 146,000 people engaged in saltwater fishing activities during 1,707,000 participant days and 1,103,000 trips in 2006. Targeted species for saltwater anglers focused on sea trout (weakfish), with nearly half of anglers identifying "anything" as a target. The vast majority of Georgia anglers tended to be residents, predominantly male, and slightly older than the general population. Saltwater anglers spent an average of $460 (per person) in 2006 on food and lodging, transportation, other trip costs, and equipment (USDOI et al., 2008b). Tables 12.19 and 12.20 summarize the saltwater fishing participants, days, trips, and expenditures in the entire state of Georgia. County level data on recreational fishing activity were unavailable.

Comparing 2006 estimates of fishing to previous surveys (2001, 1996, and 1991) the number of persons fishing declined from 1996 to 2001, but rose in 2006. The number of trips, number of angler days, and average days of fishing all increased between 2001 and 2006 (USDOI et al., 2003b, 2008b).

Table 12.19
Saltwater fishing trips in Georgia by resident and non-resident, 2006.

Anglers, Trips, and Days of Fishing	Total (state residents and non-residents)	State Residents	
Saltwater	Number	Number	Percent of Total
Total Anglers	146,000	125,000	85
Total Trips	1,103,000	1,029,000	93
Total Days	1,707,000	1,383,000	81
Average Days	12	11	

Note: Statistics reported for the entire state population 16 years and older.
Source: USDOI et al. (2008b).

Table 12.20
Georgia saltwater fishing expenditures, 2006.

Expenditure Item	Amount	Spenders	Average per Spender	Average per Angler
Total	$71,565,000	124,000	$576	$460
Food and Lodging	$14,131,000	74,000	$190	$96
Transportation	$13,119,000	72,000	$181	$90
Other trip costs	$26,915,000	91,000	$295	$184
Equipment	$17,399,000	75,000	$232	$90

Note: Statistics reported for the entire state population 16 years and older. Spenders represent anyone spending money on fishing-related activity; anglers represent only those that actually participated in fishing.
Source: USDOI et al. (2008b).

12.3.2.4.3 Beaches

According to the National Survey on Recreation and the Environment (NSRE, 2000), while beach visitation is a relatively popular activity in Georgia, participation rates remain relatively low at only 0.49 percent and 1.0 million participants in 2000. Perhaps due to the low volume of beach recreation within Georgia, more recent data and literature discussing the direct economic impact of beach tourism for the state are not readily available.

12.3.3 Florida

The US Census Bureau County Business Patterns Dataset reports the top three industries by employment as health care and social assistance, retail trade, and accommodation and food services within Florida's coastal counties (Table 12.6). The waste management and remediation services industry, the finance and insurance industry, the professional, scientific, and technical

services industry, the manufacturing industry, and the construction industry each make up more than five percent of the workforce in these counties. Like Georgia, the six counties examined comprise only a small portion of Florida's working populace. Approximately 11.3 percent of the state's employees work within the six counties (US Census Bureau, 2009).

12.3.3.1 Ports

The Port of Jacksonville, located in Duval County, is one of Florida's five largest seaports. In fiscal year 2007, the Port of Jacksonville handled approximately 24.5 million tons of cargo and 152,000 cruise passengers (FSTEDC, 2009). The Jacksonville Port Authority estimated that the Port contributed to 65,000 direct and indirect area jobs, $1.8 billion in personal wages, and $1.9 billion in revenues (JPA, 2009).

12.3.3.2 Fisheries

According to the NOEP commercial landings data, 2010 landings on the Florida Atlantic Coast totaled over 29.2 million live pounds valued at approximately $50.5 million. The most valuable fishery in Florida is the Penaeid shrimp fishery, which includes white and brown shrimp. In 2010, commercial landings totaled more than 5.4 million pounds with a value of almost $11.4 million, of which nearly $9.3 million was white shrimp. White and brown shrimp landings totaled approximately $10.4 million in 2000. The next most valuable fisheries, king and cero mackerel and blue crab, were valued at $6.9 million and $3.1 million, respectively (NOEP, 2010). Table 12.21 shows landing weight and value for the top ten commercial species for Florida's Atlantic coast in 2010. Table 12.22 shows the actual landing weights and values by coastal county for commercial fish in 2008.

Table 12.21
Top ten commercial fish species on the Florida Atlantic coast by weight and landed value.

Rank	Species by Weight	Weight (pounds)	Landed Value Species	Landed Value
1	shrimp, white	4,354,709	shrimp, white	$9,255,222
2	mackerel, king and cero	3,903,897	mackerel, king and cero	$6,901,981
3	mackerel, Spanish	3,552,644	swordfish	$3,677,289
4	crab, blue	2,527,453	crab, blue	$3,181,281
5	mullet, striped	1,346,375	lobster, Caribbean spiny	$2,820,125
6	shrimp, rock	1,112,446	mackerel, Spanish	$2,414,005
7	shrimp, brown	1,079,861	shrimp, brown	$2,138,890
8	swordfish	1,027,908	shrimp, rock	$1,608,018
9	shrimp, pink	1,009,197	shrimp, dendrobranchiata	$1,350,847
10	crab, deepsea golden	556,986	shrimp, pink	$1,204,112

Note: This table represents the entire Atlantic shoreline of Florida including counties beyond the six counties that are the focus of this report.
Source: National Ocean Economics Program (2010).

Table 12.22
Commercial fish landings by Florida county, 2008.

County	Live Pounds	Value
Brevard	5,186,460	$8,327,949
Duval	6,109,298	$12,221,788
Flagler	38,689	$28,293
Nassau	1,181,448	$2,170,172
St. Johns	1,634,503	$3,240,852
Volusia	1,677,623	$2,947,494
State Total	94,531,511	$175,895,991

Source: Non-Confidential data from Atlantic Coastal Cooperative Statistics Program (2008).

12.3.3.3 Tourism

Tourism is a key part of the Florida economy with several major tourist destinations located across the state. Within the relevant South Atlantic counties, key tourist areas include Cape Canaveral, Daytona Beach, and the City of Jacksonville. Total tourism spending for the state in

2009 exceeded $64.0 billion and supported more than 722,700 jobs. Table 12.23 shows expenditures, payroll income, and employment numbers associated with travel to the relevant area in 2008. Total domestic travel expenditures for the congressional districts that contain the six coastal counties in 2008 were $11.1 billion or approximately 15.7 percent of the State's total domestic travel expenditures (US Travel Association, 2009c).

Table 12.23
Florida domestic tourism expenditures by district, 2008.

Congressional District	Expenditures (Millions)	Payroll (Millions)	Employment (Thousands)
State Total	$70,521.8	$18,994.5	757.1
FL-4	$2,576.3	$645.5	28.7
FL-7	$2,668.6	$695.4	30.2
FL-15	$2,599.0	$672.0	28.2
FL-24	$3,260.4	$841.5	28.2
Total of coastal districts	$11,104.30	$2,854.40	$115.30

Note: Data were unavailable on a county basis. The congressional districts that include the relevant counties were selected.

Source: US Travel Association (2009c).

12.3.3.4 Recreation

The Florida Division of Recreation and Parks conducts periodic surveys of residents and tourists participating in outdoor recreation activities. Table 12.24 summarizes 2008 survey results for the two regions that include the coastal counties, with comparisons to statewide results. Because Florida also has a marine coast with the Gulf of Mexico, activities that are marine-related do not necessarily have a higher participation rate in South Atlantic counties compared to the state average. The activities in boldface have higher participation rates in each of the coastal planning districts compared to the state average (FDEP, 2008).

Table 12.24
Recreation participation rates (%) in Florida.

Activity	Northeast Region	East Central Region	State
Saltwater beach activities	58.8	61.6	57.2
Saltwater boat fishing	23.2	22.2	25.8
Saltwater non-boat fishing	24.3	21.4	20.7
Canoeing, kayaking	13.7	14.7	14.2
Visiting archaeological and historic sites	58.3	52.9	48.7
Nature study	39.6	42.1	37.1
Picnicking	44.9	47.7	44.4
Bicycle riding – paved trails	47.2	52.5	43.5
Hiking	25.1	24.3	22.6
Bicycle riding – unpaved trails	28.5	23.4	21.4
RV/trailer camping	13.2	9.3	9.7
Tent camping	19.8	18.9	15.9
Off-highway vehicle riding	19.5	13.7	16.0
Horseback riding	13.5	6.6	9.1
Hunting	12.7	6.2	11.6

Note: The Northeast region contains Nassau, County, St. Johns County, Flagler County, and Duval County, among other inland counties. The East Central region contains Brevard County and Volusia County, among other inland and coastal counties.

Source: Florida Department of Environmental Protection (2008).

12.3.3.4.1 Boating

The majority of boats registered in Florida are for personal use. Within the six counties, nearly 97 percent of registered vessels were identified as pleasure vessels, with approximately 2.1 percent used for commercial purposes. Boat registrations were the highest in Brevard, Duval, and Volusia counties (FHSMV, 2009). The breakdown by type of boat and county is presented in Table 12.25. Note that this information is based on where a boat is registered, and does not represent only boats used on the Atlantic. Information on boat registration does not indicate where the boat will be used.

In 2007, boaters spent more than $642 million in trip and craft sales in Northeast Florida, with another $1.078 billion in trip and craft sales in East Central Florida, which includes Brevard and Flagler counties. These trip expenditures supported approximately 19,000 jobs and $593 million in income (FFWCC, 2009).

Table 12.25
Vessel statistics by Florida county.

County	Dealer	Pleasure	Commercial	Total
Brevard	559	36,922	885	38,366
Duval	220	31,604	600	32,424
Flagler	29	5,329	83	5,441
Nassau	25	6,186	166	6,377
St. Johns	111	13,325	309	13,745
Volusia	269	29,507	677	30,453
Total for six counties	1,213	122,873	2,720	126,806
Source: Florida Highway Safety and Motor Vehicles (2009).				

12.3.3.4.2 Recreational Fishing

In Florida, 2 million people engaged in saltwater fishing activities during 23.1 million participant days and 17.6 million trips in 2006. Targeted species include red drum (redfish), sea trout (weakfish), mahi-mahi, and mackerel. Florida anglers tended to be slightly older than the general population and predominantly male. Saltwater anglers spent an average of $1,215 (per person) in 2006 on food and lodging, transportation, other trip costs, and equipment. Tables 12.26 and 12.27 summarize the saltwater fishing participants, days, trips and expenditures (USDOI et al., 2008c).

Comparing 2006 estimates of fishing to previous surveys (2001, 1996, and 1991) the number of persons fishing increased from 1996 to 2001, but then declined in 2006. Total anglers, trips, and angler days in 2006 were all lower than in both 2001 and 1996 (USDOI et al., 2003c, 2008c).

Table 12.26
Florida saltwater fishing trips by resident and non-resident, 2006.

Anglers, Trips, and Days of Fishing	Total (state residents and non-residents	State Residents	
Saltwater	Number	Number	Percent of Total
Total anglers	2,002,000	1,286,000	64
Total trips	17,620,000	15,936,000	90
Total days	23,077,000	19,533,000	85
Average days	12	15	

Note: Statistics reported for the entire state population 16 years and older.
Source: USDOI et al. (2008c).

Table 12.27
Florida saltwater fishing expenditures, 2006.

Expenditure Item	Amount	Spenders	Average per Spender	Average per Angler
Saltwater Fishing				
Total	$2,443,801,000	1,802,000	$1,356	$1,215
Food and lodging	$512,606,000	1,530,000	$335	$256
Transportation	$243,799,000	1,363,000	$179	$122
Other trip costs	$672,814,000	1,492,000	$451	$336
Equipment	$1,014,583,000	758,000	$1,339	$501

Note: Statistics reported for the entire state population 16 years and older. Spenders represent anyone spending money on fishing-related activity; anglers represent only those that actually participated in fishing.
Source: USDOI et al. (2008c).

12.3.3.4.3 Beaches

As noted above in Table 12.24, saltwater beach activities are one of the most popular recreational activities in northeast Florida with more than half of survey respondents identifying saltwater beach visits as one of their recreational activities. Beach tourists spent approximately $2.8 billion on 11.2 million trips to northeast Florida in 2003. The region's overall contribution to the state's economy, including indirect spending, was estimated at $2.0 billion. Notably, these estimates do not include Brevard County, which was grouped with the southeast beach region. The southeast beach region was the largest contributor to beach tourism spending with an estimated $9.1 billion in spending in 2003 (Murley et al., 2005).

12.4 ECONOMIC VALUE

12.4.1 Recreational Fishing

Several studies have estimated the economic value of saltwater recreational fishing opportunities in the southeast. Consumer surplus estimates for coastal recreational fishing along the entire Southeastern Atlantic Seaboard included Georgia, North Carolina, South Carolina, Virginia, and Florida and ranged from $88.98 to $159.61 per day and from $181.17 to $437.84 per trip in 2010 dollars (NOEP, 2008). Table 12.28 replicates a summary of values assembled by the National Ocean Economics Program.

Table 12.28
Summary of recreational fishing values.

State	Study	Consumer Surplus / Activity Day	Consumer Surplus / Activity Day (2010$)*
Florida (East Coast)	Bell (1997)	$100.64	$132.15
Georgia	McConnell and Strand (1994)	$66.06-$70.12	$91.84 - $97.48
North Carolina	Norton et al. (1983)	$277.15/trip	$437.84
North Carolina	McConnell and Strand (1994)	$111.23 -$114.81	$154.63 - $159.61
South Carolina	McConnell and Strand (1994)	$113.03-$114.44	$157.13 - $158.68
Virginia	Norton et al. (1983)	$93.99/trip	$181.17
Virginia	McConnell and Strand (1994)	$64.01-$77.48	$88.98 - $107.71

*Values adjusted to 2010 dollars using the GDP Implicit Price Deflator.
Source: National Ocean Economics Program (2008).

Milon et al. (1994) conducted a survey of saltwater anglers to estimate willingness to pay for changes in management for a variety of species including redfish, seatrout, mullet, sheepshead, pompano, and king mackerel. There were multiple potential management changes included in the study: 1) changes in bag limits, 2) changes in size limits, and 3) changes in average catch rates. Across six different fish species, willingness to pay ranged from $0.01 per fish for mullet to $5.97 per fish for King Mackerel.

Gillig et al. (2000) estimated consumer surplus associated with an increase in catch limits for the red snapper in the Gulf of Mexico. The study was conducted to address two main policy issues relating to fisheries management. Part of the regulatory effort to increase the red snapper population included by-catch reduction devices (BRDs) on shrimp trawls. This regulation would result in a decrease in shrimp catch numbers but a significant increase in red snapper spawning stocks. This study considered two questions: 1) “Is the value of the increased red snapper spawning stocks greater than the value of escapement of shrimp from shrimp trawls due to using the BRDs,” and 2) “How will the increased red snapper spawning stocks be allocated among commercial and recreational red snapper fishermen?” The study concluded that an increase in

catch limits from four to five resulted in an increase in consumer surplus of nine dollars. This study indicates how changes in the recreational fish stock affects social welfare; impacts in fish stock due to offshore development projects may similarly lead to changes in economic value provided by recreational fishing.

12.4.2 Beach Visitation

Numerous studies have been conducted on consumer surplus associated with beach recreation. Many estimates have been derived from respondents' willingness to pay for different management techniques related to erosion. Table 12.29 provides a summary of value estimates associated with beach recreation. Value estimates vary due to differences in methodologies and site characteristics across the studies examined. For example, a clean beach with many high-quality amenities, such as parking lots and bathrooms, may be valued more than a beach that is difficult to access, littered, and lacking amenities.

Table 12.29
Summary of beach recreation values.

State	Study	Consumer Surplus / Activity day	Consumer Surplus / Activity Day (2010$)*
Georgia	Kriesel et al. (2004)	$6.09	$6.99
South Carolina	Oh et al. (2006)	$9.10	$9.78
Florida	Bell and Leeworthy (1986)	$1.31 - $1.45	$2.31 - $2.56
Georgia	Landry et al. (2003)	$6.75 - $9.92	$7.96 - $11.70
Florida	Shivlani et al. (2003)	$1.69 - $2.12	$1.99 - $2.50
Mid-Atlantic	Van Houtven and Poulos (2009)	$28.77 - $29.16	$29.10 - $29.50
NC Southern Banks	Van Houtven and Poulos (2009)	$124.03	$125.46
* Values adjusted to 2010 dollars using the GDP Implicit Price Deflator.			

Several studies investigated the effects of beach erosion and willingness to pay for various beach restoration activities. Beach retreat has been a recurring issue for states along the east coast. Typical strategies used for dealing with beach retreat include: 1) nourishment; 2) the use of hard structures such as seawalls or bulkheads; or 3) allowing the beach to retreat naturally and moving houses and other properties further inland. Multiple studies have looked at the public's willingness to pay for these various measures.

Bell and Leeworthy (1986) estimated consumer surplus associated with saltwater beach recreation in Florida. The study elicited participants' perceptions of crowdedness, parking availability, cleanliness of coastal water, and physical appearance of the beach. The authors found that overcrowding and lack of parking reduced the value of the overall beach experience. Physical characteristics that were found to influence demand for beach recreation included beach dimensions, beach use or crowding, availability of parking, number of beach access points and facility availability. The study found that the willingness to pay per day was $1.31 for residents and $1.45 for tourists.

Smith et al. (1997) examined beach visitor's willingness to pay for removal of beach debris. The study focused on the importance of beach and coastal aesthetics. Varying levels of beach debris were described to survey participants followed by plans to modify these conditions. The participant was also informed of the total cost of the plan and the cost imposed on each individual. Participants were presented with one of four levels of debris and management plans. The study found that visitors were willing to pay increasing amounts ($21.38 to $72.18) with increasing levels of debris cleanup (Smith et al., 1997).

Loss of property value due to erosion has also been used to estimate beach value. A study conducted in Delaware (Parsons and Powell, 2001) considered erosion along the entire Delaware coast. The study examined retreat as a management option and calculated the lost property value. At the lowest rate of erosion (1 ft/yr), over a 50-year period (2000-2049) the study found a total loss of $33 million and a loss of $622 million at the highest rate of erosion (8 ft/yr).

Lew (2002) examined at the value of recreation and water quality improvements for San Diego beaches. The study identified multiple factors that determine beach users' willingness to pay for beach recreation. These included the presence of lifeguards and parking availability. The study also examined San Diego County's cobblestoning problem (where the beach surface becomes dominated by cobblestones); many beach users were willing to pay to prevent the problem from occurring. The study concluded that beach users were willing to pay to correct beach erosion problems to improve beach quality and that these values were higher for larger, more popular beaches.

Shivlani et al. (2003) examined three South Florida beaches and the amenities that most greatly influenced individuals' willingness to pay to stop or slow beach erosion. The study also investigated the presence of sea turtle habitat and its effect on willingness to pay. The study found differing motivations for site selection by beach goers, depending on the beach in question. At two of the beaches, the width of the beach (and therefore space availability) was motivation for site choice due to increased space for recreational activities. At the third beach, on-site amenities and distance from home were the most important factors in deciding to visit that beach.

Several studies have asked beach users how much extra in parking fees they would be willing to pay for a general improvement in beach conditions. For example, Landry et al. (2003) gave respondents four options of beach restoration, including: 1) wider beaches with similar shoreline armoring; 2) wider beaches with minimal shoreline armoring (no management policy specified); 3) wider beaches with minimal shoreline armoring (beach nourishment specified as management policy); 4) wider beaches with minimal shoreline armoring (adoption of a retreat policy specified for management). Respondents valued wider beaches with minimal shoreline armoring and specified management policies to the alternative options with no management policies (Landry et al., 2003). Table 12.30 describes the daily mean marginal willingness to pay for each scenario. Kriesel et al. (2004) set baseline conditions at the $2 parking fee already in place. Respondents were asked their willingness to pay an increased parking fee up to $25 for improved beach conditions through beach nourishment. The survey found a willingness to pay of $6.09 per day, or $23.75 per year, for these improvements.

Another study of South Carolina beaches indicated that each visitor was willing to pay $9.10 per day for beach access (Oh et al., 2006). That amount, when applied to the population of approximately seven million visitors, translates to a consumer surplus of $63 million. The same survey indicated that visitors preferred more beach access and less crowding and noise.

A popular method used to estimate consumer surplus is random utility travel cost (RUM) modeling. Parsons et al. (2009) examined consumer surplus losses due to beach closures. The study area included the Padre Island National Seashore on the Texas Gulf Coast. The study estimated per-trip loss and a loss-to-trips ratio, where the latter divides loss associated with closure by the number of trips that would be taken to the closed site or sites. The study found that closure of all beach areas on the seashore for an entire summer season resulted in a loss-to-trips ratio of $179.52 or a per-trip loss of $20.09.

Table 12.30
Willingness to pay for various management options.

Beach Description	Daily Mean Marginal WTP ($1996)	Daily Mean Marginal WTP ($2010)**	Annual Mean Marginal WTP ($1996)	Annual Mean Marginal WTP ($2010)**	Present Discount Value of Recreational Benefits ($1996)	Present Discount Value of Recreational Benefits ($2010)**
Wider beaches with similar shoreline armoring	$6.75	$9.02	$6,070,167	$8,111,579	$94,828,634	$126,722,901
Wider beaches with minimal shoreline armoring (no management policy specified)	$8.45	$11.29	$7,598,850	$10,154,615	$118,711,404	$158,638,303
Wider beaches with minimal shoreline armoring (beach nourishment specified as management policy)	$9.92	$13.26	$8,821,697	$11,788,750	$137,813,255	$184,164,791
Wider beaches with minimal shoreline armoring (adoption of a retreat policy specified for management)	$9.08	$12.14	$8,074,698	$10,790,507	$126,143,577	$168,570,182

*Table taken from Landry et al. (2003).

** Values adjusted to 2010 dollars using the GDP Implicit Price Deflator.

12.5 POTENTIAL DEVELOPMENT IMPACTS

Our literature search included sources and references relating to socioeconomic impacts of offshore renewable energy projects. This literature is not well developed, and no studies specific to the southeast region exist. Therefore, this review covered all available literature to the extent that relevant analogies may exist with a focus on six relevant topics: infrastructure and economic impact, general space and use conflicts, and the potential effect of offshore development on property values, tourism, public attitudes, and aesthetics.

12.5.1 Infrastructure and Economic Impact

A key consideration is the ability of local infrastructure, particularly ports, to support an offshore renewable energy industry. In particular, the size and availability of storage and work space at a port must be considered, and any constraints to development (e.g., availability of skilled workforce) that might exist.

An analysis of port and infrastructure needs for offshore wind energy development in Massachusetts is currently the best available literature on this topic. Tetra Tech (2010) teamed with the Massachusetts Clean Energy Center in a comprehensive study of particular ports in Massachusetts to determine their ability to support offshore renewable energy projects. The report focused on port regulations and physical limitations, the adaptability of vessels compared to specially designed vessels, and turbine construction and maintenance needs. The analysis resulted in a list of three-tier criteria for Massachusetts ports and recommendations including cost-benefit analysis of wind turbine construction. The study also noted that a port providing space, equipment, and personnel for off shore wind energy is better equipped to support other offshore renewable energy, providing an incentive for alternatives uses in the future. The following information is excerpted from the Tetra Tech (2010) report.

To handle commercial-scale offshore wind projects, ports need space for construction and storage, must meet standards for height and width clearances, and have a water depth compatible with vessels for turbine transport and maintenance. An offshore wind project requires more equipment and space than is typically available at a traditional port. Turbine construction and transport to the wind project site are aided by large storage space and several or longer berths for the multiple vessels. The minimum recommended berth size is 450 feet and a minimum water depth at low tide of 24 feet. The harbor should meet horizontal and vertical clearances up to 150 feet overhead and 425 feet laterally. The laydown space at the port allows for delivery, storage and assembly of components, especially in inclement weather.

Also, physical obstacles, available railway and highway access, distance to the wind project, and regulations must be considered. Bridges, bridge cables, and airports can prevent the port from supporting offshore renewable energy projects. Components for turbine construction can be transported by train or highway, but the conditions of routes such as curvature and weight and height limits must be considered. The greater the distance between the port and the wind project site, the more costly and risky it is to construct the turbines as it can increase the time for construction, cost in fuel and insurance.

Specialized vessels to carry and install turbines are not yet generally available in the US, but are more cost effective than existing, smaller jack-up vessels. Offshore wind turbines are generally

larger than 2 MW in generation capacity. The specialized vessels are better equipped to handle the larger size and weight but require up to 300 feet of overhead clearance. Growth in the US small vessel industry of tugs and barges is positive as it can meet offshore wind turbine needs. On the other hand, tank barge construction and a decline in shipyard capacity may constrain the construction of large vessels in the US.

A regulation affecting harbors, shipyards, and vessels is the Jones Act, which requires that the passage of people and cargo within the US take place in US built, crewed, and flagged vessels. This presents a challenge given much of current off shore wind turbine equipment will be imported from Europe and specialized vessels are not yet American made. Currently, there is not enough demand for the manufacturing of larger turbines and specialized vessels in the US.

Existing industries that may exhibit similarities and possibility for adaptation of equipment and maintenance to the offshore wind industry include petroleum extraction, liquid natural gas ports, commercial shipping, and commercial fishing. An understanding of these industries is useful for consideration of port requirements and possible utilization of existing equipment and vessels. The reliance on piles and jackets for the construction of wind turbine foundations is similar to that of petroleum structures. The operational needs of offshore wind turbines are similar to those of commercial fishing. The port and vessel maintenance needs for wind projects are similar to those of commercial fishing, offshore liquid natural gas ports, and petroleum extraction operations.

Tetra Tech (2010) created a 3-tier system to determine the feasibility of offshore renewable energy given port, vessel, and regulation constraints. The "1st Tier Hard Criteria" to consider for harbors include: protection or shelter from severe weather, shipping channel depth of 24 feet, overhead clearance, horizontal clearance, around the clock access to operations, and exclusive use of port facility for construction and storage. The "2nd Tier Hard Criteria" to consider for the port facilities include: berth length, shipping vessel water depth, total wharf and yard upland area, rail access, highway access, and proximity to construction site. The 3rd "Soft Criteria" include the availability of labor, facilities that offer training and education, the policies and regulations of the local community, and federal regulations.

The analysis provided tax, revenue, and employment estimates related to the projects in the ports that passed the three criteria tests. Economic effects were measured based on outputs, permanent and temporary jobs created, the income generated in households as a result of construction and maintenance, and the gross domestic product (GDP) increase in Massachusetts. During the port facility and offshore installation construction phase, the analysis estimated that 1,890–2,240 jobs and $175.4–$189.0 million in income would be generated in Massachusetts. During the operations phase, the analysis estimated that 280 jobs and $14.2 million in income would be generated in Massachusetts.

A technical report on the economic impacts of the South Carolina State Ports Authority (SCSPA) prepared by Wilbur Smith Associates in 2008 does not provide insights for renewable energy but does detail the economic activity related to ports within the state. The SCSPA has an extensive database with information on port users and service providers which lends information on output, expenditures, and employment attributed to the movement and storage of cargo. Specifically, the

study examined port data, tonnage flow in terms of volume and value, region industry data including employment and output, surveys, and economic models.

The SCSPA handles 56 percent of the total cargo tonnage in the state but accounts for over 88 percent of total tonnage value, compared to private terminals. The manufacturing industry in South Carolina is a major port user and provides 122,000 port-related manufacturing jobs (47.3 percent of all manufacturing jobs), but the industry declined 7.8 percent between 2002 and 2007. A closer look at the current and potential manufacturing industry will be necessary for an offshore wind project, as it can boost the economy. An offshore wind project will also depend on the transport and warehousing sector, which experienced 21.9 percent growth between 2002 and 2007, where 35,140 statewide jobs depend directly and indirectly on port movements. The transport of turbine component parts will rely on water, rail, trucking and freight, while the assembly requires ample warehouse or storage space. Finally, noteworthy in the study is that the SCSPA has increased its capital improvements on infrastructure, construction, and equipment to average $80 million per year in comparison to $35 million a year before 2008.

Flynn and Carey (2007) evaluated the potential economic and fiscal impacts of a 120-turbine wind farm with a maximum capacity of 480 MW off of the coast of South Carolina. This is the only study to date that examines the impacts of offshore wind development on coastal economies in the Southeast US. Considering decreasing costs for renewable energy, the authors estimated that the wind project would cost $700 million and take 24 months for manufacturing and installation. A wind project of this size and capacity could generate power for over 600,000 homes and alleviate a burden of one million tons of greenhouse gases annually. Offshore wind production can attract manufacturing industries to the state, create permanent high-paying jobs, attract some tourism, and increase output, income, and revenues. The authors note that the waters off of South Carolina are suitable for an offshore wind development because the water is shallow, which allows the wind turbines to be far enough away from the shore to prevent the obstruction of vistas while benefitting from stronger winds.

Flynn and Carey (2007) further studied the economic changes such a project would bring to South Carolina, examining both the manufacturing/installation and operations/maintenance phases and modeling the results using three spending scenarios. The manufacturing/installation phase is assumed to occur over 24 months and require skilled labor to design and build components such as rotor blades, structural towers, gear boxes, and generators. For installation, local firms are needed to lay monopiles or other types of foundation, assemble the turbines and towers, and lay cables; these activities are assumed to require up to 75 workers on site. In general, the authors assume that approximately 80 percent of the employment created during the first phase would be in manufacturing, with 20 percent for installation. The maximum resulting number of full time jobs potentially created, including indirect and induced affects, was estimated to be 1,881. While the majority of project-related manufacturing would likely occur outside South Carolina, Flynn and Carey (2007) note that General Electric manufactures 1.8 MW wind turbines in Greenville, South Carolina and could potentially develop larger offshore wind turbines at this location.

The operation and maintenance phase of the wind project are assumed to begin in project year three and extend over a 30-year period at an annual cost of approximately $3 million. This phase

necessitates well-trained staff at a close proximity to the port, resulting in the addition of 50 to 75 permanent high quality and high paying jobs.

Flynn and Carey (2007) created three scenarios to model the potential economic effects of a wind farm off the South Carolina coast. These scenarios assumed in-state manufacturing and assembly expenditures of 10, 30, and 100 percent of total project costs. The results were reported in two phases, "Manufacturing and Installation" and "Operation and Tourism." The jobs created in the first phase ranged between 939 and 1,789 resulting in up to $287 million from output and $93 million in disposable income. State income tax and corporate tax revenues could be up to $2.8 million and $190,000, respectively. In the second phase, between 99 and159 jobs would be created, resulting in an increase in state output of up to $15 million, and an increase in disposable income of up to $7 million. Increases in personal and corporate income tax revenues associated with this phase were estimated to be up to $181,000 and $13,000 per year, respectively.

12.5.2 Space and Use Conflicts

As interest in the development of offshore renewable energy resources spreads along the Atlantic coast, a growing body of literature is examining the potential conflicts with other uses of coastal and marine resources. The Georgia Institute of Technology (2007), as part of a study of the wind power generation potential off the Georgia coast, noted but did not examine in detail several general conflicts, including viewshed effects, the ecological impacts of noise and vibrations during construction, and the need to consider the compatibility of a project with existing commercial and recreational activities.

The OCS Alternative Energy Programmatic EIS (MMS, 2007) broadly notes the potential space and use conflicts applicable to the Atlantic coast. The report provides demographic information to highlight the possible effects of offshore projects on people and communities- particularly noting that incomes in Georgia and South Carolina are lower than the Atlantic coast average, that the coastline from Virginia to Florida relies to some degree on agriculture, fishing, recreation and tourism, and that coastal communities in this region are not very diverse. This study notes possible conflicts associated with environmental justice policies, protection of historical resources, beaches and existing infrastructure, visual obstruction, tourism and recreation, and commercial and recreational fishing.

Harte et al. (2010) completed a literature review on space-use conflicts and mitigation strategies for renewable energy on the outer continental shelf. This review includes a total of 165 citations related to space and use conflicts in the coastal and marine planning context. Many of the studies are general in nature, and thus potentially applicable to the South Atlantic region; however, none of the identified literature is specific to this region. Categories of potentially conflicting uses noted in this report include:

- Marine protected areas
- Military operations
- Submarine cables, pipelines, transmission lines
- Disposal sites
- Navigation and shipping lanes
- Areas of archaeological, historic, or cultural interest

- Search and rescue operations
- Civil air traffic
- Sand, gravel, and mineral extraction
- Offshore oil and gas activities
- Recreational and commercial fisheries
- Viewshed
- Tourism and other recreational activities
- Scientific research

The OSPAR Commission (2008) developed guidance to assist European nations as well as responsible parties in understanding the environmental effects of offshore wind. The possible impacts are not deeply considered but more focused on the various phases of the wind project.

A synthesis of literature describing the potential environmental effects of alternative energy development on the outer continental shelf was compiled by Michel et al. (2007) and includes information about potential conflicts arising from regulations and prohibited access. The report identifies information needs and current offshore technologies, public reactions, potential impacts, and available models for determining environmental impacts.

Navigation conflicts arising from an offshore renewable energy project are addressed by the OSPAR Commission (2008) and Michel et al. (2007), which note that the construction, operation, and retiring of offshore renewable energy projects must consider existing rules and activities such as shipping lanes and traffic, freedom of navigation, anchoring near transmission cables, and collision risks, such as between vessels, renewable energy devices, and aircrafts.

MMS (2009) completed a Final Environmental Impact Statement for Cape Wind off of Nantucket. Although it does not apply to the South Atlantic region, it does identify potential use conflicts, such as commercial fishing, submarine cables, navigation dredging, vessel anchoring, sand mining, marine radar, recreational fishing and boating, air navigation, and marine transport. In particular, it notes the possibility of interference with radar and communication systems as well as physical interference with emergency radar and equipment needed for searches and rescues.

12.5.3 Property Values

The concern that property values would be adversely affected by proximity to wind energy development has been investigated quantitatively in studies in the US and abroad, though not in the context of offshore development. Hoen et al. (2009) collected data on over 7,000 sales of single-family homes situated within 10 miles of 24 existing wind facilities in 9 different US states. The study used eight different hedonic pricing models as well as repeat sales and sales volume models and concluded neither the view of the wind facilities nor the distance of the home to those facilities had any consistent, measurable, and statistically significant effect on home sales prices.

A study by Sterzinger et al. (2003) examined the prices of properties located within five miles of ten different wind projects throughout the US. The study investigated the change in price over the entire study period, how the prices changed before and after the projects came online, and

then how prices changed within the project viewshed and a comparable region. Of the 30 different analyses, 26 resulted in property values in the project area performing better than the alternative. Similarly, a British study by Sims et al. (2008) examined 200 home sales within a half mile of Cornwall's 16-turbine wind farm. The study found no causal link between proximity to the wind farm and price; however, there was some evidence that noise and light from the turbines could affect some properties, as well as hinder the view of the countryside.

Property value impacts associated with US offshore development will not be observable until several years after construction of at least one project. No studies that measure property value impacts attributable to existing offshore wind energy projects in Europe were identified.

12.5.4 Tourism

Several studies have investigated renewable energy impacts, and in particular wind farms, on local tourism. A study by Lilley et al. (2010) in Delaware surveyed more than 1,000 randomly sampled, out-of-state tourists at Delaware beaches. Using photo-simulations, researchers questioned participants about the effect wind power development would have on visitation. Approximately one-quarter of the participants stated they would switch beaches if an offshore wind project was located 10 km from the coast; avoidance diminished with the locations further from shore.

Two other studies examined actual offshore wind project impacts (and one proposed) in the U.K. None of these studies were conducted using random sampling. The first study, a survey by British Wind Energy Association (2006), appeared to favor wind farm development. The study provided anecdotal evidence that some larger locations have experienced increased tourism rates after wind farms were constructed. No causal link was found between increased tourism and the presence of wind farms, but the results indicated that tourism rates are not hindered by the presence of wind farms. The second British study conducted by the University of West England (2004) interviewed 379 day tourists at three locations in England. One, North Devon, was the future location of an offshore wind project, while the other two, Cornwall and Mid Wales, are home to active offshore wind farms. In North Devon, 86.7 percent (n=170) of respondents stated that a wind farm would neither encourage nor discourage them from visiting; 7.2 percent (n=14) of respondents said a wind farm would either marginally encourage or strongly encourage them to visit the areas; 6.1 percent (n=12) of respondents said that a wind farm would marginally discourage or strongly discourage them from visiting. More than half of the North Devon respondents answered yes (51.0 percent, n=98) to the question, "Do you think wind farms can be tourist attractions?" while 43.8 percent (n=84) of the respondents said no, and 5.2 percent (n=10) did not know or had no opinion. The majority of North Devon respondents (58.2 percent, n=114) thought that wind farms had no impact on the tourist experience, while 14.8 percent (n=29) thought it had a negative impact. The validity of these results are questionable, however, as the majority of people sampled indicated strong positive support for renewable energy with only 4.1 percent of respondents in North Devon opposed to renewable energy.

12.5.5 Public Attitudes

Peoples' attitudes towards wind farms (renewable energy development) will impact socioeconomics in the development area. Negative attitudes toward renewable energy development may affect other socioeconomic areas, such as tourism and property values.

12.5.5.1 Denmark

ECON Analysis (2005) qualitatively studied sociological attitudes towards the Nysted and Horns Rev offshore wind farms in Denmark before and after the wind farms were developed. Questionnaires and interviews, studying local media coverage, and follow-up interviews were used to gauge communities' attitudes and change in attitudes after the wind farms were constructed. Negative opinions differed between the sites; at Horns Rev the opposition was based on business interests in tourism, and at Nysted the opponents did not want the natural view obstructed by human construction. Opposition to the wind farms seemed to be stronger at Horns Rev than at Nysted; however, tourists did not stop frequenting the area because of visual landscape change. The aesthetic argument was strong at Nysted (located ~10 km offshore, whereas Horns Rev is located ~14 km offshore) and the opponents generally maintained their negative opinions.

Not surprisingly, the Danish study by Ladenburg (2007) showed that consumers preferred offshore wind farms to on-land wind farms. Younger respondents were found to be more positive towards wind power than older respondents. Respondents who lived closer to wind turbines were not necessarily more negative towards wind power generation, compared to respondents who live farther from turbines.

12.5.5.2 Scotland

Several studies of Scottish wind farms were undertaken to better understand public attitudes and preferences toward wind farm developments including whether views changed over time and valuation of wildlife impacts and job creation. Dudleston (2010) studied public attitudes toward wind farms in Scotland and whether those views had changed over time. Respondents were generally positive about wind farms and those who live closer were even more positive. Participants were asked if they expected any of several potential problems associated with the wind farms, including noise from the turbines, landscape "spoiling," interference with TV and radio reception, damage to plants and animals, noise or disturbance during construction, extra traffic during construction, and/or a reduction in house prices. The proportion of respondents who anticipated problems before development was higher than the proportion of respondents who actually experienced problems after development (40 percent anticipating and only 9 percent experiencing problems). Of the respondents who actually experienced problems related to the wind turbines, two percent had problems with TV and radio reception, five percent believed the turbines spoiled the landscape, and one percent experienced problems with noise from the turbines.

A study by Bergmann et al. (2008) attempted to quantify the differences between urban and rural preferences over environmental and employment impacts resulting from renewable energy development in Scotland. In general, Scottish citizens supported the expansion of renewable energy projects. Urban respondents were willing to pay for reduced landscape impacts, for wildlife improvements, and for a reduction in air pollution. Urban respondents did not place a significant value on job creation from renewable energy projects. The rural sample valued wildlife and reductions in air pollution more highly than the urban sample. Employment creation was significant to the rural sample; rural respondents valued a renewable energy project that improved job opportunities in their area.

An earlier study by Bergmann et al. (2006) estimated the external costs and benefits of renewable energy in terms of landscape quality, wildlife, and air quality. The study also tested for differences in preferences between rural and urban communities and high and low income houses. The rural sample was more accepting of negative landscape impacts, and had a willingness to pay of an additional £1.08 per year for each additional full time job created by renewable projects. Income groups did not differ in their preferences towards renewable energy.

12.5.5.3 United States

Firestone and Kempton (2007) investigated the factors underlying public opinions regarding offshore wind power based on a survey of residents near the proposed Cape Wind development. Supporters were found to be younger, better educated, and more likely to own their own home. Opponents were more likely to earn over $200,000 annually, and more likely to expect to see the project on a daily basis. The majority expected negative impacts from the project including damage to marine life/environmental impacts, followed by higher electricity rates, aesthetics, and impacts on fishing or boating.

Krueger et al. (2008) found that Delaware had strong support for offshore wind development, including coastal residents. The study found support was strong for wind development in Delaware Bay, although less than support of development in the open ocean. Over 90 percent of the respondents indicated they would vote to expand electricity capacity through offshore wind power rather than coal or natural gas, when told they would pay a premium for wind power. When the wind options had the same initial price as coal or gas power offshore, wind power was preferred by 95 percent of respondents.

12.5.6 Aesthetics

A Danish study by Ladenburg et al. (2005) (subsequently published as Ladenburg and Dubgaard, 2007) estimated willingness to pay for reducing the visual disamenities from future offshore wind farms. The study described 720 offshore wind turbines in farms located 12, 18, or 50 km from shore. This correlated to average willingness to pay amounts of 46, 96, or 121 Euros/household/year for farms located at 12, 18, and 50 km from the coast as opposed to 8 km. The willingness to pay varied significantly depending on the age of respondents and their experiences with offshore wind farms. In general, the study revealed a significant willingness to pay for locating wind farms at distances where the visual disamenities were fairly small (up to 18 km from the shore), but a weaker preference for moving them to a distance of 50 km where they are virtually invisible from the shore.

Ladenburg et al. (2005) also tracked the attitudes of respondents from local areas along with environmental impacts of the two wind farms. More than 80 percent of respondents were "positive" or "very positive" towards the wind farms. The general perception was that impacts on birds and marine life were "neutral." Almost two-thirds of respondents found the wind farm effects on the landscape were either "neutral" or "positive." However, more than 40 percent stated that they would prefer future wind farms to be moved out of sight.

A paper by Ek (2002) evaluated Swedish attitudes toward wind power, and the value placed on the external impacts associated with using wind power, through a choice experiment approach using a 1,000 household mail survey. Swedish homeowners preferred offshore to onshore wind

farms, assuming all measures toward reducing external impacts of wind farms (noise, etc.) were low cost.

A study of onshore wind farms in the US by Groothuis et al. (2007) investigated the compensation required to allow wind turbines on the mountains in Watauga County, North Carolina. Individuals who were willing to participate in green energy programs required less compensation than individuals who did not participate in such programs. Individuals who retired to the mountains required more compensation than residents who had ancestors in the county. Household compensation was estimated at $23 annually, or approximately $426,500 annually for the county.

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CHAPTER 13: RESEARCH AND DEVELOPMENT TECHNOLOGIES ANTICIPATED IN THE SOUTH ATLANTIC PLANNING AREA

13.1 INTRODUCTION

This chapter addresses research and technology development in the following areas:

- Oil and gas exploration and development
- Oil and chemical spill prevention and response
- Sand and gravel extraction
- Renewable energy

13.2 OIL AND GAS EXPLORATION AND DEVELOPMENT

The BOEM 2007–2012 OCS oil and gas leasing program does not include any lease sales for the South Atlantic Planning Area. Oil and gas leases for 106 blocks in the area were issued in 1978, 1982, and 1983. Six exploratory wells and one COST well were drilled in this planning area. There are no active leases in this area as of 2011. Undiscovered, technically recoverable resource estimates for oil and gas reserves based on MMS 2006 assessment data (see Figure 2.15 in Chapter 2: Geological Oceanography) show peak values in 200–-800 m water depth. This region includes the edge of the Florida-Hatteras Shelf and the inner Blake Plateau. In 2008, the South Carolina General Assembly established the South Carolina Natural Gas Exploration Feasibility Study Committee to examine the feasibility of natural gas exploration off the coast of South Carolina. The Committee recommended that the state consider the development of an offshore natural gas industry, but only when BOEM executes a five-year plan that includes natural gas exploration off the South Carolina coast (South Carolina Natural Gas Exploration Feasibility Study Committee, 2009). Because gas production in the South Atlantic Planning Area is unlikely for the foreseeable future, this review focuses on geological (i.e., coring and test drilling) and geophysical (i.e., 2D, 3D, and high-energy seismic, gravity, and electromagnetic surveys) technologies for gas exploration.

BOEM is conducting a Programmatic Environmental Impact Statement (PEIS) for geological and geophysical activities in the Mid-Atlantic and South Atlantic Planning Areas; the draft PEIS was sent out for public comment in March 2012. The purpose of the PEIS is to: 1) Assess potential environmental effects of multiple geological and geophysical activities on the Atlantic OCS; 2) Evaluate mitigation and monitoring measures to reduce or eliminate the potential for impacts to the environment; and 3) Provide information and analyses to BOEM and other agencies prior to decisions to authorize geological and geophysical activities. The PEIS will cover the following topics:

- Noise
- Test drilling/coring
- Operational wastes
- Air emissions
- Vessel traffic (supply vessels and helicopters)
- Trash and debris

- Seabed-impacting equipment (e.g., anchors, sensors, wire lines, cable lines, etc.)
- Electromagnetic emissions

The PEIS will be a comprehensive analysis of the current technologies, potential impacts, and mitigation needed to reduce short-term and cumulative impacts; therefore, it is appropriate to briefly describe the seismic and test drilling technologies proposed for use in the South Atlantic Planning Area, but defer to the soon-to-be completed PEIS for a complete assessment.

Seismic surveys for offshore exploration use large, purpose-built ships to tow an array of air guns that generate sound waves by firing off explosive blasts of air; the reflections are detected by a hydrophone array. Modern 3D surveys use multiple energy sources (commonly two) and as many as sixteen streamers (cables containing the hydrophones) deployed in parallel. A single vessel may tow as many as sixteen streamers, which can be as long as 8–10 km and spaced 5–150 m apart. An array of 15–45 pneumatic air guns is towed behind the survey vessel and emits sound pulses of a predominantly low frequency (10–300 hertz) and high intensity (215–250 decibels). Compared to seismic operations conducted ten years ago, the use of multiple streamers greatly improves operational efficiency. The number of source pulses needed to record data over a given area is decreased proportionally to the number of streamers. Seismic surveys are conducted at speeds of around nine km/hour; therefore, the survey duration depends on the area to be surveyed. Because there are so few existing data for the South Atlantic Planning Area, extensive surveys would be needed to identify promising areas for more detailed surveys; therefore, the initial surveys could take months to complete.

Offshore gravity and magnetic surveys for initial oil and gas exploration use passive systems often deployed on aircraft to measure small changes in the earth's density and magnetic fields. Detailed magnetic surveys are conducted before drilling. Using ship-towed magnetometers close to the seafloor, these surveys identify detect ferric objects that have a distinct magnetic signature and that may be potential hazards or cultural resources.

Test drilling is conducted using a mobile drilling platform to collect cores for detailed geological and hydrocarbon analysis. Nearly all wells are drilled using rotary drilling and require the use of drilling mud to transport the cutting out of the well bore, cool the drill bit, stabilize the well bore during drilling, and control formation fluids that may flow into the well. Typically, a water-based mud composed of fresh or salt water, barite, clay, caustic soda, lignite, lignosulfonates, and water-soluble polymers is used. Under certain conditions, a synthetic-based drilling fluid or mud may be used, whose base fluid is a synthetic material, typically an olefin or ester.

New developments in drilling methods (PetroMin, 2011) include slimhole drilling, in which the drill bit is less than 15 cm and can be as small as 5 cm, compared to 30 cm for conventional wells. Slimhole drilling allows wells to be completed faster, to have a smaller footprint, and it generates less mud/cuttings. Other developments include use of flexible coiling tubing (rather than a rigid steel drill string) that can be continuously unreeled from a large spool, allowing for uninterrupted drilling.

A blowout preventer, a large valve at the top of a well that can be closed immediately if warranted by a change in pressure, is an integral component of any exploratory well drilling

program. Since the failure of the blowout preventer during the *Deepwater Horizon* spill, there have been significant improvements in all aspects of drilling safety, and many new products are being developed for the reliable operation of shearing tools.

In the absence of any significant geohazards in the South Atlantic Planning Area (see Chapter 2: Geological Oceanography), there do not appear to be any unusual conditions or challenges to gas exploration that would require specialized research and development technologies to overcome them.

13.3 OIL AND CHEMICAL SPILL PREVENTION AND RESPONSE TECHNOLOGIES

Because of the 2010 *Deepwater Horizon* spill, there have been and will be significant advances in oil spill prevention and response technologies. Many groups have conducted studies, formed workgroups, and started new initiatives in these areas. One example is the report published in January 2011 by the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011). This report contains many recommendations, including recommendations for the following topics dealing with oil spill prevention and response:

- Improving the safety of offshore operations
- Safeguarding the environment
- Strengthening oil spill response, planning, and capacity
- Advancing well-containment capabilities

The oil and gas industry has also taken on new efforts to develop standards which should be revised or developed in response to the both the *Deepwater Horizon* blowout in the Gulf of Mexico and the *Montara* blowout in West Australia. Figure 13.1 is from the International Organization for Standardization (ISO, 2011) Technical Committee TC 67, which deals with materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries. The figure summarizes the standards for drilling, well construction, and well operations that are being developed or revised, including many standards that are being developed by the American Petroleum Institute.

In September 2010, the Joint Industry Oil Spill Preparedness and Response Task Force (comprised of member companies and affiliates of the American Petroleum Institute, International Association of Drilling Contractors, Independent Petroleum Association of America, National Ocean Industries Association, and US Oil and Gas Association) developed recommendations to improve oil spill preparedness and response. These recommendations cover spill response planning, oil sensing and tracking, dispersants, in situ burning, mechanical recovery systems, shoreline protection and cleanup, and alternative response technologies. The report identified fifteen near-term actions (to be initiated before April 2011) and fifteen long-term actions (to be initiated before October 2011). It is important to note that the report states that "All actions are predicated on the availability of the appropriate federal and state agencies," acknowledging that all stakeholders have to be involved to agree on the priorities and develop the cooperative mechanisms essential for successful implementation.

ISO/TC67 N 1119

Table 2: Standards for drilling, well construction and well operations, relevant to the Montara and Macondo accidents. Available for use end December 2010 (unless stated as in development)

- API TR PER15K-1 HPHT Design Verification and Validation (in development)
- API Spec 16A /ISO 13533 Drill through equipment (BOPs) (API in revision)
- API Spec 16C Choke and kill systems (in revision)
- API Spec 16D/ISO 22830 Control systems for drilling well control equipment and diverter equipment (API in revision)
- API Spec 16RCD Drill Through Equipment Rotating Control Devices
- API RP 53 BOP equipment systems for drilling wells (in revision)
- API RP 59 Well Control Operations
- API RP 64 Diverter Systems Equipment and Operations
- API RP 65 Cementing Shallow Water Flow Zones in Deepwater Wells
- API Std 65-2 Isolating Potential Flow Zones During Well Construction (in revision)
- API RP 90 Annular Casing Pressure Management for Offshore Wells
- API Bull 96 Deep water well design considerations (in development)
- DNV OS-C101 Drilling plant
- ISO TR 10400/API TR 5C3 Equations and calculations for the properties of casing, tubing drill pipe and line pipe used as casing or tubing
- ISO 10405 Care and use of casing and tubing
- ISO 10423/API Spec 6A Wellhead and Christmas tree equipment
- ISO 10426-1/API Spec 10A Cements and materials for well cementing
- ISO 10426-2/API Spec 10B-2 Testing of well cements (in revision)
- ISO 10426-3/API Spec 10B-3 Testing of deepwater well cement formulations
- ISO 10426-4/API Spec 10B-4 Preparation and testing of foamed cement slurries at atmospheric pressure
- ISO 10426-5/API Spec 10B-5 Determination of shrinkage and expansion of well cement formations at atmospheric pressure
- ISO 10426-6/API Spec 10B-6 Methods of determining the static gel strength of cement formulations
- ISO 10427-3/API RP 10F Performance testing of cementing float equipment
- ISO 11960/API Spec 5CT Casing and tubing for wells (in revision)
- ISO 11961/API Spec 5D Steel drill pipe
- ISO TR 12489 Reliability modelling and calculation of safety systems (in development)
- ISO TR 13881Classification and conformity assessment of products, processes and services >>>continue on column on right side>>>

API RP 75 Development of a Safety and Environmental Management Program for Offshore Operations and Facilities
API Bull 97/ IADC Well Construction Interface Document (in development)
IADC HSE Case guidelines for MODUs
IADC Deepwater Well Control guidelines
IEC 61892-7 Mobile and fixed offshore units - Hazardous areas
IMO MODU (Mobile Offshore Drilling Units) Code
ISO 10418 Basic surface process safety systems (in revision)
ISO 13702 Control and mitigation of fires and explosions on offshore production installations (in revision)
ISO 15544 Requirements and guidelines for emergency response
ISO 17776 Guidelines on tools and techniques for hazard identification and risk assessment
ISO 28300/API Std 2000 Venting of atmospheric and low-pressure storage tanks (in revision)
ISO 23251/API Std 521 Pressure relieving and depressuring systems (in revision)
NORSOK Z-013 Risk and emergency preparedness analysis
OGP 210 HSE Management system (in revision)
OGP 415 Asset integrity
OGP 435 HSE culture tools

- ISO 13354 Shallow gas diverter equipment
- ISO 13624-1/API RP 16Q Design, selection and operation of marine drilling riser systems
- ISO 13625/API 16R Marine drilling riser couplings
- ISO 13628-1/API RP 17A Design and operation of subsea production systems (in revision)
- ISO 13628-2/API Spec 17J Unbonded flexible pipe systems for subsea and marine applications
- ISO 13628-4/API Spec 17D Subsea wellhead and tree equipment
- ISO 13628-5/API Spec 17E Subsea umbilicals
- ISO 13628-6/API Spec 17F Subsea production control systems (in revision)
- ISO 13628-7/API RP 17G Completion/workover riser systems (in revision)
- ISO 13628-8/API RP 17H Remotely operated tools and interfaces on subsea production systems (in revision)
- ISO 13628-11/API RP 17B Flexible pipe systems for subsea and marine applications
- ISO 13679/API RP 5C5 Procedures for testing of casing and tubing connections (in revision)
- ISO 13680/API Spec 5CRA CRA casing and tubing
- ISO 14224/API Std 689 Collection and exchange of reliability and maintenance data for equipment
- ISO 14310/API Spec 11D1 Packers and bridge plugs
- ISO 14998 Completion accessories (in development)
- ISO 16339 Well control equipments for HPHT (High Pressure High Temperature) drilling operations (in development)
- ISO 16530 Well integrity in the operational phase (in development)
- ISO 19901-6/API RP 2MOP Marine operations
- ISO 19901-7 Stationkeeping systems for floating offshore structures and mobile offshore units (in revision)
- ISO 19904-1 Floating offshore structures - Monohulls, semi-submersibles and spars
- ISO 20815 Production assurance and reliability management
- ISO 28781 Subsurface barrier valves and related equipment
- NORSOK D-001 Drilling facilities
- NORSOK D-002 System requirements well intervention equipment
- NORSOK D-SR-007 Well testing system
- NORSOK D-010 Well integrity in drilling and well operations (considered in API 96 and ISO 16530)
- OLF 117 Well integrity guideline

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Figure 13.1 International standards for drilling, well construction, and well operations under development or revision by ISC/TC67 (from IOS, 2011).

The South Atlantic Planning Area is under the jurisdiction of the Regional Response Team IV (RRT IV), which develops and coordinates preparedness activities before a pollution incident by addressing regional issues and providing guidance to Area Committees. During a pollution incident, the RRT IV also provides technical and regulatory support to On-Scene Coordinators. RRT IV has developed numerous guidance documents, policies, and technical plans for all aspects of oil and chemical preparedness and response that are available online.

RRT IV has provided guidelines for the use of dispersants and in situ burning for oil spill response, as summarized in Table 13.1. These guidelines were developed in 1995 and 1996, respectively, and have undergone only minor changes since then. In 2010, during the *Deepwater Horizon* spill, both dispersants and in situ burning were used extensively as part of the response, resulting in significant improvements in the operational effectiveness of both these response options. Although these improvements have not been published in the literature or applied during new incidents (as of July 2011), there were many responders involved in the use of these technologies who will be able to improve the state of the practice for years to come. One common lesson learned was that trained and experienced responders, from aerial spotters who identify slicks for treatment and determine effectiveness, to on-water teams monitoring effectiveness through visual observations and water sampling, are essential.

The RRTs are working to review their Area and Regional Contingency Plans with respect to dispersants, specifically to evaluate and document the net environmental benefit and trade-off rationale for using dispersants, as well as to identify favorable operating conditions, limitations, and upfront monitoring protocols. To assist this effort, the Office of Response and Restoration, NOAA, is conducting a study, "The Future of Dispersants in Spill Response." This study aims to synthesize the information about dispersant use during the *Deepwater Horizon* response, prepare white papers on different dispersant-related topics, and convene a workshop in September 2011 that includes academic and agency scientists to investigate the scientific evidence of both surface and subsurface dispersant application. The goal is to address the following questions: Do we understand the trade-offs? Would we decide to use them again on the surface and subsurface knowing what we know now? Are the existing analytical testing and field monitoring procedures adequate? Do we understand how the ingredients and components of the dispersants behave? What are the right application rates and loading thresholds? Are the existing National Research Council (NRC) and the Coastal Response Research Center (CRRC) Research and Development recommendations for dispersant research still the correct priorities, in the context of the *Deepwater Horizon* spill, other recent spill events, and likely future events? What could be done to improve risk communications? The project outcomes include:

- Strengthened partnerships with the academic research community
- Potential external consensus among agencies and stakeholders for future spills
- Standard procedures for measuring dispersant components in water and seafood
- Better technical basis and guidance for trade-off decision-making during spills
- Better understanding of dispersant composition and potential risk to aquatic resources
- Improved ability to quantify the operational and environmental effectiveness of dispersants, including modeling and mass balance calculations

- Better protocols for public risk communication
- Consensus for the plan for future research priorities

Table 13.1
Guidelines for use of dispersants and in situ burning in the South Atlantic Planning Area, based on Regional Response Team IV plans

Zone	Dispersants Use	In situ Burning Use
Green Zone	Pre-authorized if: 1) the waters are not classified within a "Yellow" or "Red" zone; 2) the waters are at least three miles seaward of any shoreline, and 3) the waters are at least 10 m in depth.	Pre-authorized if: at least 3 miles seaward from any state coastline; and seaward of any state waters, or as designated by separate Letters of Agreement from state or federal agencies.
Yellow Zone	Case-by-case approvals if not in a Red Zone and any of the following: a) The waters fall under state, or special federal management jurisdiction. This includes any waters designated as marine reserves, National Marine Sanctuaries, National or State Wildlife Refuges, units of the National Park Service, or proposed or designated Critical Habitats; b) The waters are within three miles of a shoreline, and/or falling under state jurisdiction; c) The waters are less than 10 min depth; or d) The waters are in mangrove or coastal wetland ecosystems, or directly over living coral communities, which are in less than 10 m of water. Coastal wetlands include submerged algal beds and submerged seagrass beds.	Case-by-case approvals if: 1) anywhere within state waters, 2) waters less than 30 ft in depth that contain living reefs, 3) waters designated as a marine reserve, National Marine Sanctuary, National or State Wildlife Refuge, unit of the National Park Service, proposed or designated Critical Habitats, and 4) mangrove areas, or coastal wetlands.
Red Zone (Dispersants) or R Zone (In situ burning)	Dispersant use is prohibited, except unless: 1) dispersant application is necessary to prevent or mitigate a risk to human health and safety, and/or 2) an emergency modification of this Agreement is made on an incident-specific basis. *There are no designated Red Zones in the South Atlantic Planning Area.*	In situ burning is prohibited in "R" zones, meaning any area in the RRT IV region falling under state or special management jurisdiction which is not classified as an "A" or "B" zone. The "R" zone is that area designated by the RRT IV as an exclusion zone. No in situ burning operations will be conducted in the "R" zone unless 1) in situ burning is necessary to prevent or mitigate a risk to human health and safety; and/or 2) an emergency modification of this agreement is made on an incident-specific basis. *There are no designated Red Zones in the South Atlantic Planning Area.*

Clearly, there will be new initiatives in research and development technologies in the coming years, as BOEM, NOAA, USEPA, and industry work together to advance the state of the

practice of using dispersants as an oil spill countermeasure. However, mechanical recovery will always be the preferred response option.

In situ burning was also used extensively during the *Deepwater Horizon* response; over 400 burns eliminated between 220,000 and 310,000 barrels of oil. According to Alan Allen (pers. comm., 2011), the responder who managed the in situ burning operations:

- During the *Deepwater Horizon* response, in situ burning eliminated 300,000 barrels or more, representing approximately 17% of oil available at the sea surface.
- Controlled burning has been shifted from an "Alternative" to "Primary" response option because of its demonstrated effectiveness, even for emulsified oils.
- Fire boom tools and tactics are now proven as effective for the rapid and efficient elimination of large quantities of oil at sea. Five types of fire boom were used extensively, and further refinements are under development.
- Costs per barrel eliminated are typically $20–40 (a fraction of the cost for dispersant application and mechanical recovery/disposal).
- Procedures for surveillance, spotting, and communications were established and refined. Spotters were essential to maximize the efficiency; the longest burn lasted more than 11 hours. A large pool of responders has been trained and is now highly experienced in all aspects of in situ burning operations.

In summary, the April–July 2010 *Deepwater Horizon* oil spill a spill of national significance, has triggered renewed efforts by industry, government, and other stakeholders to improve all aspects of oil spill prevention and response technologies, training, and planning. The results of these efforts are already evident and will continue to be implemented in the coming years.

13.4 SAND AND GRAVEL EXTRACTION

The purpose of extracting sand and gravel from the OCS is to provide material for beach nourishment and coastal protection projects along the coast in response to long-term and/or storm-induced coastal erosion. The BOEM Sand and Gravel Program website states that as of 2011:

> The Bureau has conveyed rights to about 56 million yd^3 of OCS sand for 29 coastal restoration projects in 5 states. These projects have resulted in the restoration of 167 miles of the Nation's coastline, protecting billions of dollars of infrastructure as well as important ecological habitat. Some of these projects were done on an emergency basis, where immanent breaching of barrier islands was prevented by the rapid placement of OCS sand.

Grain size is a crucial variable when it comes to selecting source material for a beach nourishment project. The average grain size of source material needs to be within a certain range so that it is coarse enough to provide improved longevity (coarser nourishment material is more resistant to the cross-shore and alongshore currents that exist along the coast). However, grain size should not be too coarse for tourist areas where people prefer material that is lighter in color and finer in texture; finer sand also reduces potential impacts on beach infauna.

Due primarily to cost, over the past decades nearshore areas (within several kilometers from the coast) have been prioritized for beach nourishment projects; this has helped deplete concentrated areas of viable nearshore sand. Mining material within flood and ebb tidal deltas or along the nearshore region is not ideal since changes to the local bathymetry can have a negative impact on the tidal hydraulics of an inlet and/or the coastal processes of the nearby shoreline. As nearshore areas along the coast are depleted of material suitable for beach nourishment projects, OCS sand resources will be in greater demand.

Florida and South Carolina have contributed the results of their geotechnical investigations to BOEM's cooperative agreement program so sand sources deemed suitable for beach nourishment are identified and readily available should material be needed in the future. Figure 2.8 (in Chapter 2: Geological Oceanography) offers a graphical summary of sediment types within the South Atlantic Planning Area. The figure shows that the sediments in western portion of the South Atlantic Planning Area are comprised mostly of sand.

Trailing suction hopper dredges (TSHD), shown in Figure 13.2, are the most commonly used type of equipment in beach restoration and coastal protection projects that use OCS sand, because of the water depth, project size, oceanographic conditions, and other conditions of typical borrow sites. This type of equipment is self-supporting in that it is self-propelled and deploys the suction dredge and stores the dredged material in hoppers located in the hull of the ship. Another benefit of a TSHD is the ability to work in severe wave conditions, which is a common situation in offshore dredging projects. Typical components of a TSHD include the suction pipe, the draghead (located at the end of the suction pipe), and both the dredge pump and the hopper are located onboard the ship. Once the hoppers onboard the ship are full, TSHDs typically have options to discharge the material at the coastal project site; this includes "rainbowing," a process in which the material is dispersed through the air via an inclined pipe, pumped through a hose, or dumped through doors in the ship's hull.

Jan de Nul Group (headquartered in Luxembourg) currently maintains the largest TSHDs in the world. *Leiv Eiriksson*, one of its largest TSHDs, can dredge to a depth of 155 m and has a hopper capacity of approximately 46,000 m^3. However, due to the Jones Act, these large foreign-flagged TSHDs are not authorized to operate in US waters. In comparison, the largest TSHD owned by Great Lakes Dredge & Dock Company headquartered in the US can dredge to a depth of 33 m and has a hopper capacity of approximately 5,000 m^3.

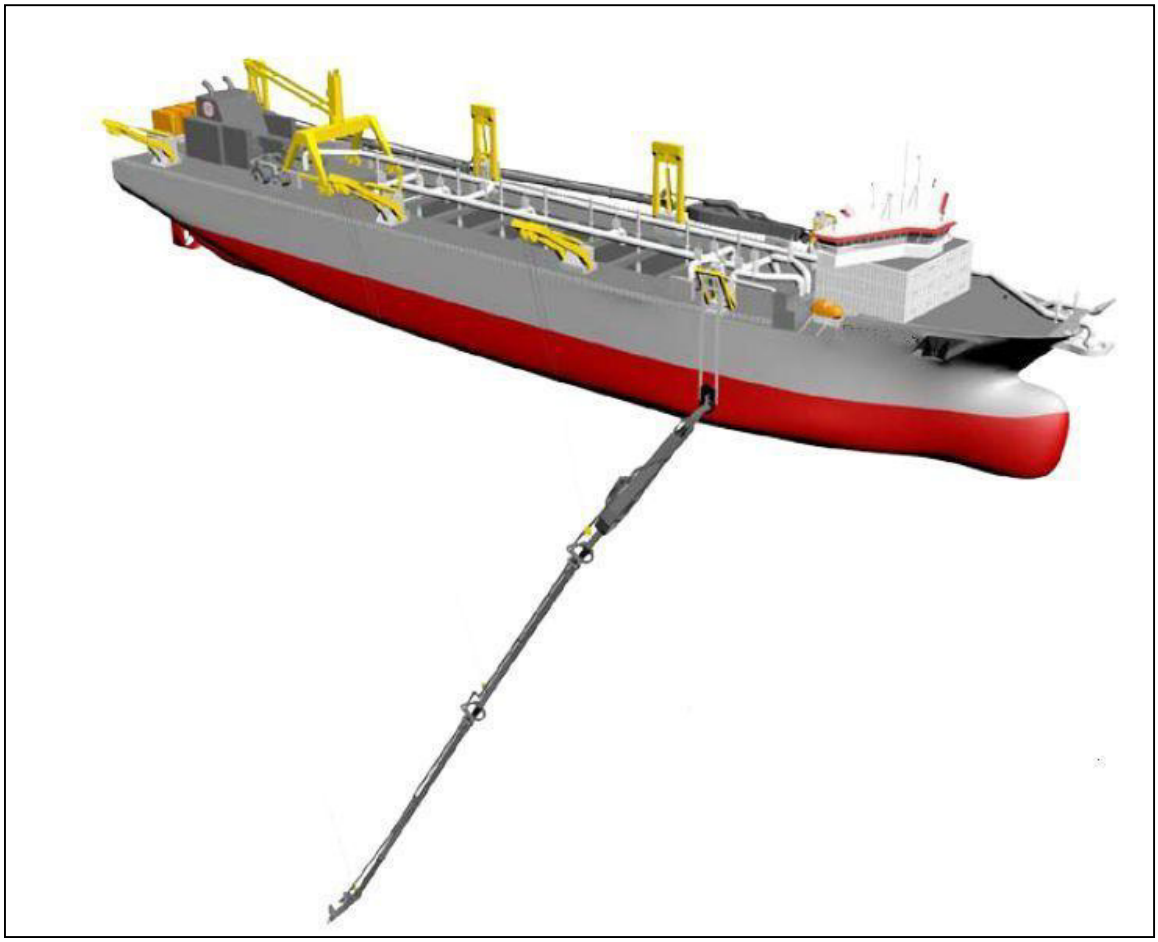

Figure 13.2 Diagram of a trailing hopper suction dredge (from The Art of Dredging, 2011).

13.4.1 Anticipated Development

When it comes to the offshore mining of sand, there are three categories of development anticipated for dredge equipment. The first category is the refinement of various components for an existing/proven dredge like a TSHD including:

- Larger and more effective dredge pumps
- Wider and more effective dragheads
- Better turbidity measures at the draghead, the hopper, and placement locations

One example of an innovative technology that will most likely be integrated into more dredges over time is the hopper dredge recirculation system. The system developed by European dredging companies recirculates overflow water from the hopper back to the draghead to help with mining material, which is again pumped back into the hopper. This closed system reduces the turbidity created by fine sediments which otherwise would flow overboard as part of the typical operations of a dredge hopper and potentially cause environmental effects. In addition to the environmental benefits of reducing turbidity and sedimentation, the recirculation system is also believed to improve the efficiency of the draghead and overall dredge operations.

The second category includes improvements in operational systems, such as drive systems, fuel-efficient power systems, and automation. Automation allows more precise dredging and avoidance of exclusion areas; more efficient dredge operations, which improve production and fuel efficiency and could lower potential turbidity effects by reducing the dredging time; and lower crew costs.

The third category of development is the creation of new technologies and types of dredges that outperform the current technology for offshore sand mining. One example of this continuing evolution was the development of TSHDs, which replaced less-efficient technologies, including the bucket ladder dredge and dipper dredge.

The RoRo Deep Dredge is a new type of dredge being developed by Damen Dredging (Figure 13.3). There are many benefits to the RoRo Deep Dredge, including:

- A flexible suction pipe that can be reeled on deck (easy to manage and does not require as much space)
- Independent hopper dredges that hold the dredged sand (allows for continuous mining if coordinated properly)
- Dredging that can reach depths over 200 m
- A less costly infrastructure is required

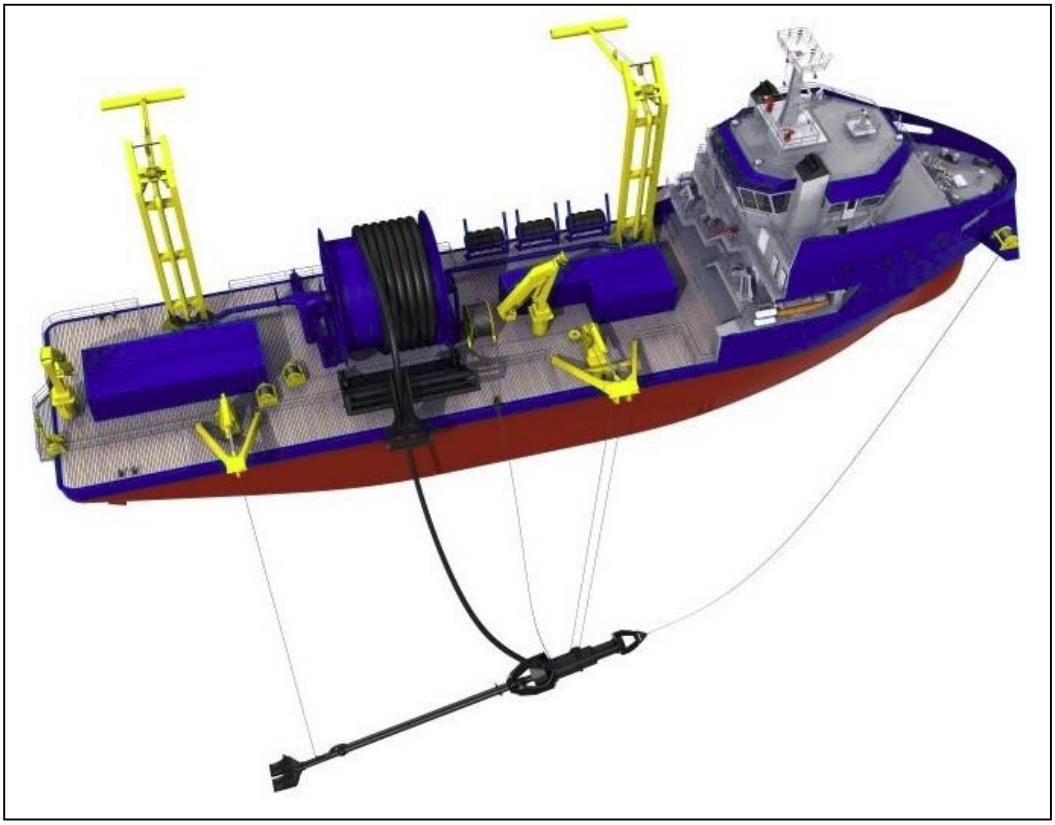

Figure 13.3 Scale model of Damen Dredging Deep Mining concept. (from Damen Dredging, 2011).

A full scale RoRo Deep Dredge is yet to be built. A scale model of the platform supply vessel and submersed excavation unit was tested successfully; the system was found to perform well at trailing speeds between 2 and 4 knots and in a significant wave climate up to 3 to 4 m in wave height. Although scale testing appears to be complete, it is not clear when the prototype will be constructed and how the full-scale model will perform.

13.4.2 Engineering Challenges

When it comes to designing dredge equipment for deeper water sand extraction, the challenge is to create a system that accounts for:

- Mining in deep water
- Transporting material long distances to shore
- Operating in heavy wave and strong current conditions
- Incorporating methods to manage turbidity
- Cost effective construction and operation (maximizing production efficiency)

Beyond the focus of the development of dredge infrastructure, it is important for engineers and scientists to also focus on the development of instrumentation and modeling software to assess if the excavation of significant quantities of material within the South Atlantic Planning Area could measurably impact the local seabed and ecosystems.

13.4.3 Research and Development Needs

There is a need to update the geological data on potential sand borrow sites within the South Atlantic Planning Area. In South Carolina, all of the sand resource studies funded by BOEM under the cooperative agreement program were conducted in the 1990s. Although these studies have identified potential sand resources, in some areas more intensive surveys are required to identify suitable sand deposits that meet grain size and depth of sediment lens criteria. In Georgia, there is no cooperative agreement program and very little data on offshore sand resources. In north Florida, BOEM has funded studies to identify potential sand resources in southern Brevard County through the cooperative agreement program.

When focusing on deep-sea dredge equipment, it is important to rigorously test new equipment to assess its ability to effectively and efficiently mine sand in deeper water and further offshore than at present, and in consideration of significant environmental issues.

Finally, there is a need to understand how mining significant quantities of sand over expansive areas and/or deep borrow pits within the South Atlantic Planning Area could impact area wave action, sediment migration, water circulation patterns, and water quality throughout the region. Numerical models should be developed that include water quality, sediment processes, and hydrodynamics (representing both currents and waves), that are calibrated to existing conditions in the area that can then be used to assess the cumulative impacts of repeated removal of sand from borrow sites, so that long-term impacts are avoided or mitigated.

13.5 RENEWABLE ENERGY

The renewable energy component of the research and development technology section of this report focuses on wind, one of the three offshore renewable energy technologies identified for review. The other two major technologies—wave and current energy sources—are not included because no offshore sites in the South Atlantic Planning Area have sufficient wave energy, ocean current, or tidal current. Sufficiently high tidal currents occur only in state waters. Therefore, only wind energy systems research and development technologies are discussed. Section 13.5.1 provides a description of the present state of the technologies used and the research and development activities, including research into the siting of such systems and anticipated technological development. Section 13.5.2 presents the engineering challenges to each type of offshore wind technology, including geologic hazards, high wind and current speeds, high water levels due to waves (short period) and events that cause storm surge, and the harsh and corrosive environmental conditions in which these offshore systems will be installed. Finally, section 13.5.3 discusses the research and development needs to move wind energy systems forward to an operational status.

13.5.1 Research and Development Activities

The nascent US offshore wind energy industry, with no wind turbines installed to date, is building on the experiences European win park operators. European offshore wind parks have been operating commercially for over a decade, and technical aspects of those operations are now being documented. Table 13.2 presents the total offshore wind power capacity worldwide in 2010, listed by country. The total installed worldwide offshore wind capacity rose to almost 3,120 MW in 2010; the majority is located in European waters, and half again as much as the total of just less than 2,000 MW in service in 2009 (WWEA, 2010).

Musial and Ram (2010) of the National Renewable Energy Laboratory (NREL) conducted one of the more comprehensive recent evaluations of the current state of offshore wind development in US waters, trends in the industry and research needs focusing on opportunities and barriers. The authors evaluated the current status of the US offshore wind industry in relation to terrestrial installations, offshore production potential, the current state of and trends in the technology, economic development, the status of the regulatory environment for siting and permitting, and the potential environmental and socio-economic impacts. NREL also developed a detailed assessment of the offshore wind power production potential (Schwartz et al., 2010). The assessment evaluated the wind resource and potential power production in all coastal states, including those on the Great Lakes, in terms of offshore areas with wind speeds greater than 7.0 m/s. The analyses were subdivided into 0.5 m/s wind resource bins to develop production estimates for each category. Additional detail will be presented below for South Carolina and Georgia (Florida was not evaluated) in the South Atlantic Planning Area.

Van Cleve and Copping (2010) of DOE compiled a list and status of twenty-one US offshore wind projects. They also evaluated wind developer experience in the pursuit of offshore wind project development that has been held back by the numerous technological challenges, uncertainties about impacts to the marine environment, siting and permitting challenges, and viewshed concerns. The study evaluated siting and project development processes, developer experience with the environmental permitting process, and the role of coastal and marine spatial planning in the development of the offshore wind industry.

Table 13.2
Total worldwide installed offshore wind capacity by country (WWEA, 2010).

Position 2010	Country	Total Offshore Capacity 2008 (MW)	Total Offshore Capacity 2009 (MW)	Added Offshore Capacity 2010 (MW)	Total Offshore Capacity 2010 (MW)	Rate of Growth 2010 (%)
1	United Kingdom	574	688	653	1341	94.9
2	Denmark	426.6	663.6	190.4	854	28.7
3	Netherlands	247	247	2	249	0.8
4	Belgium	30	30	165	195	550.0
5	Sweden	134	164	0	164	0.0
6	China	2	23	100	123	434.8
7	Germany	12	72	36.3	108.3	50.4
8	Finland	30	30	0	30	0.0
9	Ireland	25	25	0	25	0.0
10	Japan	1	1	15	16	1500.00
11	Spain	10	10	0	10	0.0
12	Norway	0	2.3	0	2.3	0.0
TOTAL		1491.6	1955.9	1161.7	3117.6	59.4

In response to a DOE request for information about the proceedings of the 20 Percent Wind Energy by 2030 Workshop, the American Wind Energy Association (AWEA) Offshore Wind Working Group developed a prioritized list of research and development needs of the offshore wind industry (AWEA, 2009). The list was ranked by need and potential impact to the offshore development process, and identified twelve specific areas for research and development. These are, in order:

1. Fundamental design evaluation for 5-to-10-MW offshore machines
2. Large-scale national offshore wind-testing facilities
3. Offshore design computer codes and methods
4. Cost-effective offshore wind foundations
5. Marine grid, power conditioning, and infrastructure development
6. Certification and standards development
7. Improved data on the offshore wind resource and development constraints
8. Offshore wind park arrays
9. Potential effect of offshore wind development on coastal tourism
10. Advanced deployment and maintenance strategies
11. Integration of large offshore power into the grid
12. Avian and marine ecology research

Since the development of the AWEA list of research and development priorities, the focus has not changed significantly; however, a new federal initiative has been developed that will focus

on and fund many of the issues identified. In early 2011, the DOE Office of Energy Efficiency and Renewable Energy and BOEM jointly presented their strategy to support the development of a world-class offshore wind industry in the US (BOEMRE and DOE, 2011). The report focused on the DOE initiative, called the Offshore Wind Innovation and Demonstration (OSWinD) program, which was designed to address the high cost and technical challenges in the development of offshore wind facilities:

> The OSWInD initiative will address these critical objectives through a suite of three focus areas–Technology Development, Market Barrier Removal, and Advanced Technology Demonstration–encompassing seven major activities: innovative turbines, marine systems engineering, computational tools and test data, resource planning, siting and permitting, complementary infrastructure, and advanced technology demonstration projects.

The OSWinD strategy objectives (BOEMRE and DOE, 2011) are further divided into activities and research areas as follows:

1. Technology Development
    - 1.1. Computational Tools and Test Data
        - 1.1.1. Performance Modeling and Validation
        - 1.1.2. Design Tools and Standards
        - 1.1.3. Field Testing
    - 1.2. Innovative Turbines
        - 1.2.1. New Turbine Concepts
        - 1.2.2. Advanced Drive Concepts
        - 1.2.3. Controls and Power Electronics
    - 1.3. Marine Systems Engineering
        - 1.3.1. Support Structures
        - 1.3.2. Balance of System
2. Market Barrier Removal
    - 2.1. Siting and Permitting
        - 2.1.1. Market Analysis and Public Acceptance
        - 2.1.2. Regulatory Processes
        - 2.1.3. Environmental Risks
        - 2.1.4. Impact on Marine Operations
    - 2.2. Complementary Infrastructure
        - 2.2.1. Manufacturing and Supply Chain Development
        - 2.2.2. Transmission Planning and Interconnect Strategy
        - 2.2.3. Optimized Infrastructure and Operations
    - 2.3. Energy Resource Planning
        - 2.3.1. Energy Resource Characterization
        - 2.3.2. Facility Design Conditions
3. Advanced Technology Demonstration

In addition to the joint DOE wind innovation program described above, BOEM is implementing a program called Smart from the Start (Salazar, 2010) to identify offshore wind energy areas

with high development and production potential and fewer potential conflicts than have been historically experienced. For these identified areas, called Wind Energy Areas, BOEM will conduct an environmental assessment to determine the potential impacts associated with lease activities, such as long-term meteorological data gathering. This approach is intended to expedite the leasing, reduce the uncertainty of the permitting process, and allow potential developers to make project financial arrangements more easily. A full Environmental Impact Statement would be performed before full site development. The Smart from the Start program will also set up communication channels to improve inter-agency coordination within the federal government through the development of the Atlantic Offshore Wind Interagency Working Group. The working group consists of officials of the cabinet level departments of Interior, Energy, Commerce, Defense, and Homeland Security, the USEPA, the Council on Environmental Quality, and other federal agencies.

As a result of the Energy Policy Act of 2005, which in part focused on the development of renewable energy resources on the OCS and the difficulties of such development, BOEM implemented the Technology Assessment and Research Program to conduct research on operational safety, engineering standards, and pollution prevention. A research study example is the Offshore Wind Energy Turbine Structural and Operating Safety Study (TRB, 2011) conducted by the National Research Council's Marine Board relating to the structural safety of offshore wind turbine systems.

BOEM has begun establishing new intergovernmental task forces concerning possible future offshore wind leasing and development in Georgia and South Carolina in 2011 and already received an application for a short-term lease for data collection off Georgia under the interim.

Currently, the focus of offshore research for wind power production is on the development of reliable foundations, towers, and turbines specifically designed for the harsher marine environment. To date, the commercial tower and turbine technology used offshore has been essentially the same as that used onshore, with some minor modifications for installation offshore.

13.5.1.1 Offshore Wind Development in the South Atlantic Planning Area

For offshore wind development in the US, deeper water depth is a more confining issue than for European development (DOE, 2009). In response, a number of studies have been performed to evaluate the total accessible offshore area in the North and Mid-Atlantic Planning Areas (Applied Technology and Management, 2007; University of Delaware, 2005) based on water depth. Several similar studies have been performed in the South Atlantic Planning Area, such as an assessment of the offshore potential for wind development for Georgia offshore areas (Southern Company, 2007), the development of offshore wind research projects in South Carolina (Kress and Bossneck, 2010), including the Palmetto Winds project (Gayes and Pietrfesa, 2009), and an offshore wind transmission study (Girgis et al., 2010). Little work has been done to develop offshore Florida resources, primarily due to the threat of high winds during hurricane season; however, a preliminary assessment of the viability of wind energy development off Florida (Smith, 2010) has been performed.

The Georgia study resulted in the identification of two potential development areas, near Tybee and Jekyll Islands, respectively, approximately 3–8 km off the coast. The study concluded that Georgia coastal waters have a relatively good wind resource (7–7.5 m/s at 50 m, based on offshore Navy platform data) and broad shallow areas (less than 30 m deep), which make potential development possible. However, the study also identified hurricane Category 3 strength winds (up to 58 m/s) as an impediment to development that uses the present state of the technology (Southern Company, 2007).

In February 2011, NREL, in coordination with AWS TruePower, released its latest predictions of the offshore wind resource for coastal states, including Georgia and South Carolina, at the 90 m height above sea level (NREL, 2011). Maps of the model-predicted, annual average offshore wind speeds for South Carolina and Georgia are shown in Figures 13.4 and Figure 13.5, respectively. The pink areas on the maps indicate wind speeds over 7.5 m/s and the dark pink areas represent wind speeds over 8.0 m/s; either is considered potentially good candidate areas for development of wind power. Although the maps extend to only approximately 90 km offshore, there are areas off South Carolina indicating winds with an annual average speed of 8.5–9 m/s (purple).

For estimations of offshore development potential, areas with wind speeds greater than 7.5 m/s must be considered in combination with limiting water depths in those offshore areas. Along the South Carolina and Georgia coasts, the water depth is less than 30 m for approximately 70 km off the coast. Currently, all of the offshore installed wind energy production capacity is supported on monopile foundations, which are typically limited to water depths less than 20 m, while some have been installed in depths up to 30 m. A number of test platforms using alternative systems, such as jacket structures, which allow installation in waters up to 60 m, have been deployed (Musial and Ram, 2010) and are being considered for commercial deployment.

For a wind resource of at least 7.5 m/s with water depths up to 30 m, Figure 13.5 shows a broad area extending up to 70 km offshore Georgia that is practically accessible for wind park development that would use commercially available technologies (monopile or jacket). In Figure 13.5, the pink area inshore of the 30 m bathymetric contour indicates the area with winds over 7.5 m/s and depths 30 m or less; this is potentially suitable for development. Given the relatively large area, approximately 12,000 km^2, it is possible that up to 60 GW could be generated, based on a uniform factor of 5 MW/km^2, and a total offshore area as estimated by NREL (Schwartz et al., 2010) and analyzed by wind speed for values greater than 7.0 m/s (Table 13.3). The Southern Alliance for Clean Energy (Wilson, 2009) also performed an analysis of the gross potential capacity for energy production from all renewable resources, including offshore wind, for eleven southern states from Mississippi to Virginia. In that study, the maximum estimated feasible capacity for development offshore Georgia was found to be 17 gigawatts (GW) with an associated energy generation potential of 53,000 GW hours annually. The significant reduction in the latter number is based on a smaller area estimate and the removal of areas considered less feasible for development based on use conflicts and development difficulty.

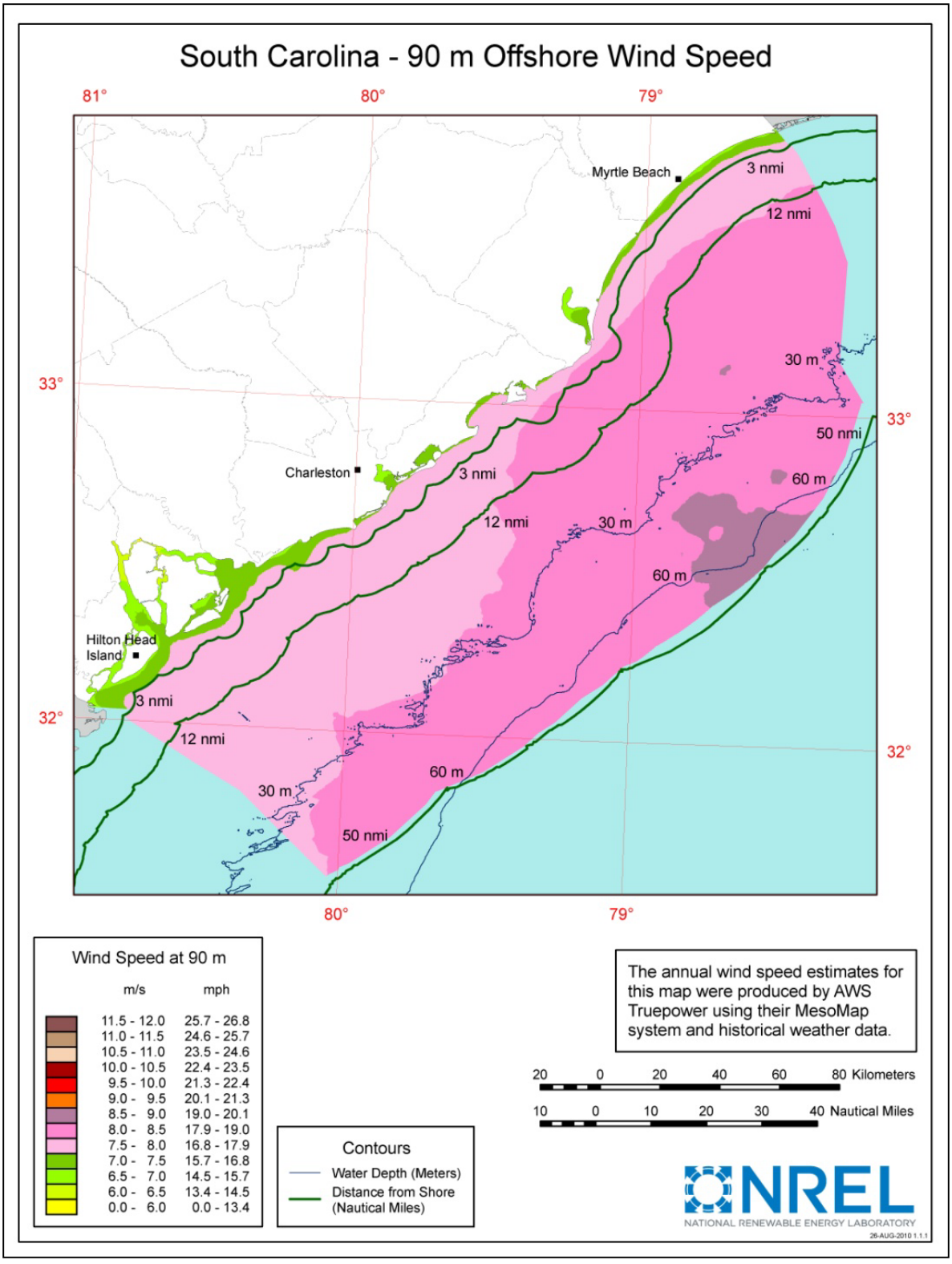

Figure 13.4 Model-predicted average annual wind speed at 90 m for waters offshore South Carolina (from Schwartz et al., 2010).

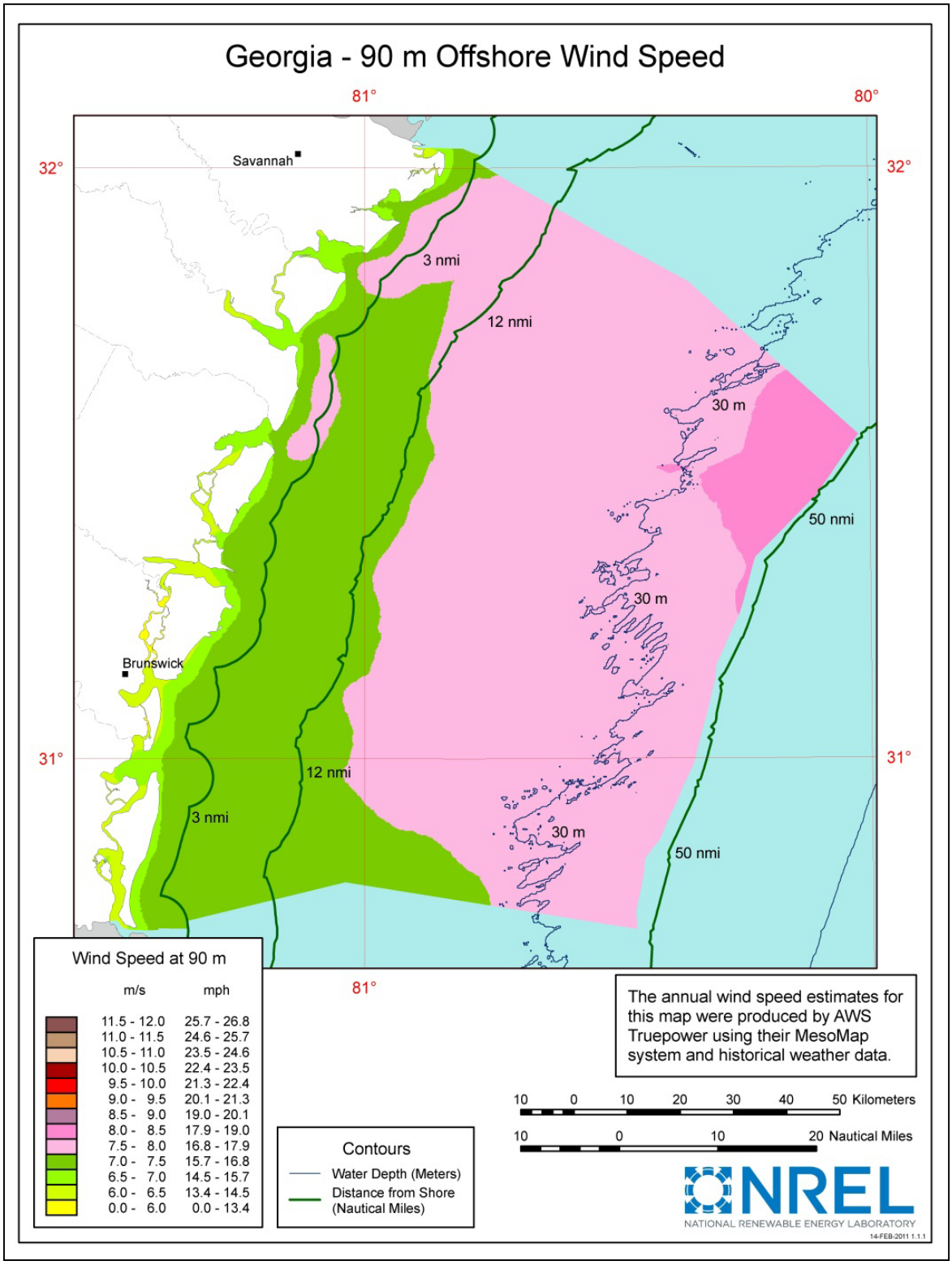

Figure 13.5 Model-predicted average annual wind speed at 90 m for waters offshore Georgia (from Schwartz et al., 2010).

Table 13.3
Offshore wind resource area and potential by wind speed interval and state within 90 km of shore (Schwartz et al., 2010).

		Wind Speed (m/s) at 90m				
State		7.0–7.5	7.5–8.0	8.0–8.5	8.5–9.0	Total >7.0
Georgia	Area (km)	3,820	7,741	523	0	12,085
	Power Potential (GW)	19.1	38.7	2.6	0	60.4
South Carolina	Area (km)	1,457	8,202	10,384	6,007	26,049
	Power Potential (GW)	7	41	52	30	130.2

The South Carolina offshore wind resource greater than 7.5 m/s with water depths less than 30 m has a somewhat larger area than offshore Georgia, primarily due to the larger area of higher wind speeds. In Figure 13.4, the dark pink color indicates areas in South Carolina that have winds over 8.0 m/s cover a much larger area compared to Georgia (Figure 13.5). Given the relatively large size of the offshore South Carolina area, 26,000 km^2 compared to 12,000 km^2 for Georgia, South Carolina has a significantly larger offshore resource. The NREL study (Schwartz et al., 2010) estimated a total potential power capacity of 130 GW for South Carolina waters (Table 13.3). In the Southern Alliance for Clean Energy (Wilson, 2009) analysis, the estimate of the maximum feasible capacity off South Carolina is 43 GW, with an associated energy generation potential of 170,000 GW hours annually (Beacham et al., 2008).

13.5.1.2 Hurricanes

Hurricane force winds are one of the greatest impediments to offshore wind energy development in the South Atlantic Planning Area. As described in section 3-2 (Chapter 3: Physical Oceanography), in the study area, any structure with an expected life up to 30 years is likely to be impacted by a Category 1 (winds up to 42.5 m/s) and/or a Category 2 (winds up to 49 m/s) storm event. It is recommended, therefore, that the design should be sufficiently strong to withstand such forcing, but statistically it may not occur. Maps of the return periods for Category 1 and Category 2 storms are shown in Figure 13.6. The return periods for areas between northern Florida and North Carolina were found to be statistically significantly longer. The values do not preclude the potential for hurricane impacts, but imply a reduced frequency. Return periods for the higher categories are comparatively longer.

An analysis of storm category return period data and the associated wind speeds as defined by the Saffir-Simpson Hurricane Intensity Scale (Stewart, 2008; Stewart et. al., 2010) indicated that the wind speeds along the coast of the Florida-Hatteras Shelf will also be reduced. Figure 13.7 shows the predicted 50- and 100-year, 10-minute average, extreme wind speeds due to hurricanes; it clearly show a reduction in the shelf area, indicated by the yellow circles (for the 50-year return period wind speeds). In addition, the analysis (Table 13.4) evaluated the wind speeds in terms of the IEC 61400-3, offshore wind classes (IEC, 2009; Quarton, 2005), where V_{ref} is the extreme wind condition with a 50-year return period which are required to be met in the loading guidelines of the IEC 61400-3 offshore design standards (IEC, 2009).

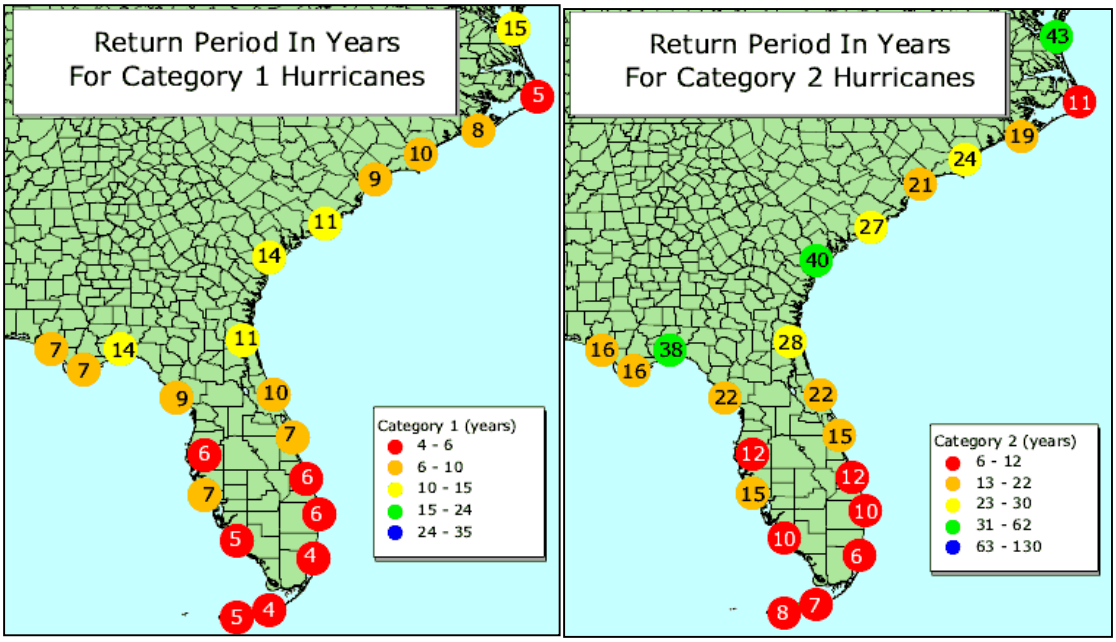

Figure 13.6 Return period in years for Category 1 and Category 2 hurricanes in the South Atlantic Planning Area (from NOAA, 2010).

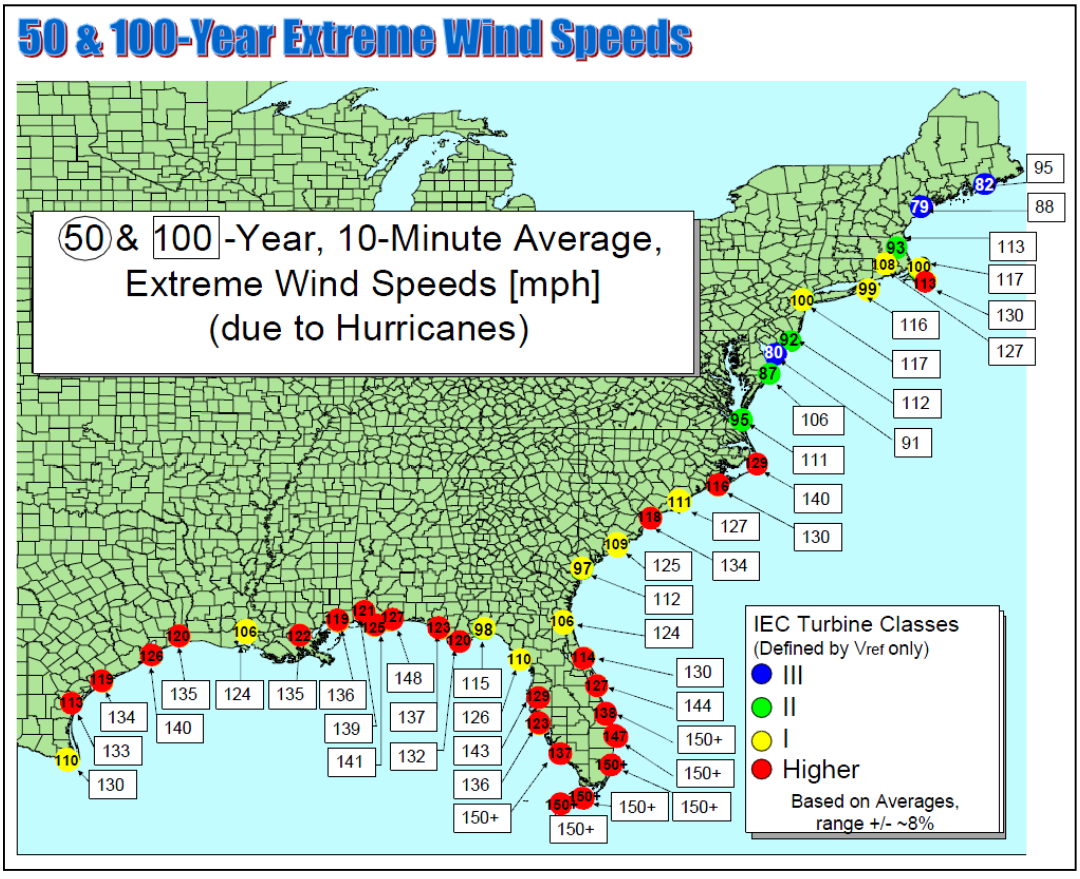

Figure 13.7 50-year and 100-year extreme wind speeds for various areas of the eastern and southern US coasts (Stewart et al., 2010).

Table 13.4
10-minute average maximum 50-year extreme wind speeds for the IEC 61400-1 and draft offshore 61400-3 wind classes.

Wind Turbine Class	I	II	III
V_{ref} [mph]	111	95	84
V_{ref} [m/s]	50	42.5	37.5

13.5.2 Exploration Research

It is very important to understand the full context in the planning of an offshore wind project, including production potential and the range of siting issues, because the marine environment is considerably more complex than onshore sites and the costs of offshore development are greater. Exploration research is, therefore, focused on better quantifying the potential resources, understanding the issues associated with siting, and reducing the uncertainties of the development process.

13.5.2.1 Resource Modeling

Modeling the national potential for onshore wind power has been conducted for many years; however, the research focus on offshore wind power is much more recent because less is known about that environment than onshore (NREL, 2011; Musial and Ram, 2010; Short and Sullivan, 2007; Musial et al., 2006). To better identify locations within a selected study area with potential natural energy resources of sufficient energy densities, a number of researchers focused on developing more detailed mesoscale and microscale meteorological modeling techniques for offshore resource assessment (DOE, 2008b; Bailey and Freedman, 2008; Giebel et al., 2007; Phillips et al., 2006). The modeling of smaller-scale processes has included the sea breeze effect (Freedman, 2009) and the influence of local topography and overland heating and cooling on the development of the boundary layer and turbulent energy production for nearshore sites (Kelley and Jonkman, 2008; Lange et al., 2004).

Discrepancies have been found between predicted and observed offshore wind park power production; the observed production loss was significantly greater for the immediately downwind turbine than predictions indicated (Barthelmie et al., 2008). New algorithms for turbine layout optimization incorporating detailed wake effects have also been developed to assist in offshore wind park design and planning and in the estimation of the power production potential for a particular site (Elkinton et al., 2008).

13.5.2.2 Project Siting

A major development area for ocean planning is site screening methodologies for identifying and evaluating the multiple and potentially conflicting uses of offshore areas (MAEOEEA, 2009; Fugate, 2008; Rodgers and Olmsted, 2008; Applied Technology and Management, 2007; Dhanju et al., 2007). In addition to the necessary wind resource assessment, the screening procedures often include collecting environmental data on bathymetry, bottom geology, wave climate, pelagic and benthic fish habitats, marine mammal feeding and migration, and avian feeding and migration. Screening procedures also include other anthropogenic uses of the potential project

area, such as shipping and transit routes, cable areas, marine fisheries, Federal Aviation Administration exclusion zones for airport approach, military uses, and a number of other site-specific exclusion areas. The product of the screening assessment allows state and Federal agencies and developers to determine the more productive and constructible sites within the planning areas.

13.5.2.3 Data Acquisition

Marine spatial planning, while not new, has received renewed focus as a result of the offshore wind energy development process (Van Cleve and Copping, 2010; CRMC, 2010; MAEOEEA, 2009). As the industry has tried to move forward, the lack of detailed data, both geophysical and biological, has highlighted the need for more extensive offshore observations. Part of the reason for the paucity of data is the expense of obtaining observations, including installation, maintenance, and cost of instrumentation. Currently, the installation of a fixed, offshore meteorological observation tower is a multimillion dollar investment. Buoy-mounted LiDAR systems that can withstand both the harsh marine environment and maintain useable signal-to-noise ratio in the constant oscillation of offshore wave conditions are now being developed. The cost is also high for photo, radar, sonar, and other systems used to detect the presence or passage of birds above the water surface and fish and mammals below. Smaller, multicomponent systems that can be attached directly to existing structures and that should reduce costs are being developed and tested.

13.5.3 Anticipated Development and Engineering Challenges

The two major environmental factors that drive the technical difficulty of offshore wind energy development are water depth and the harsh marine conditions. The latter includes high average and maximum wind speeds; significant waves, defined as the average of the one-third largest waves; extreme waves, defined as greater than twice the significant wave; ocean currents; and the corrosive salt water environment all of which serve to increase the cost of offshore development. The majority of research and development projects under way focus on engineering solutions to address these conditions.

13.5.3.1 Foundation Design

Currently, a major challenge is the limit of constructible water depth (driven primarily by the present monopile foundation technology; Figure 13.8). If this challenge is resolved, the development of a far larger offshore area would be possible (Musial and Ram, 2010; Robinson and Musial, 2006; Musial et al., 2006).

Foundation design engineering and bottom impact have been major parts of the research effort to allow development of sites in depths greater than those in which the current commercial monopile system can reliably perform. New designs include updated monopile, hybrid, tripod, jacket, semi-submersible, floating, tension line, and moored foundation systems (Schaumann and Keindorf, 2008; Musial et al., 2007; Kimon and Marcus, 2007; Achmus et al., 2007; Kleineidam and Schaumann, 2006). Figures 13.9 and 13.10 illustrate offshore foundation types under consideration.

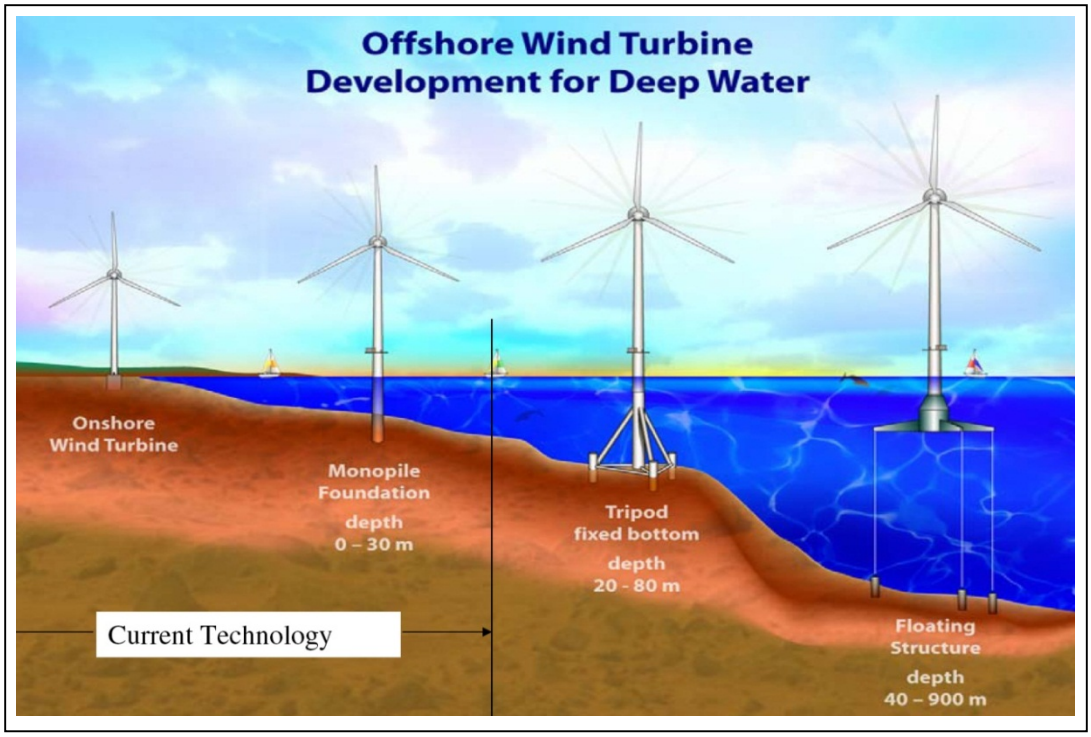

Figure 13.8 Example offshore wind turbine foundation types for a range of water depths (Robinson and Musial, 2006).

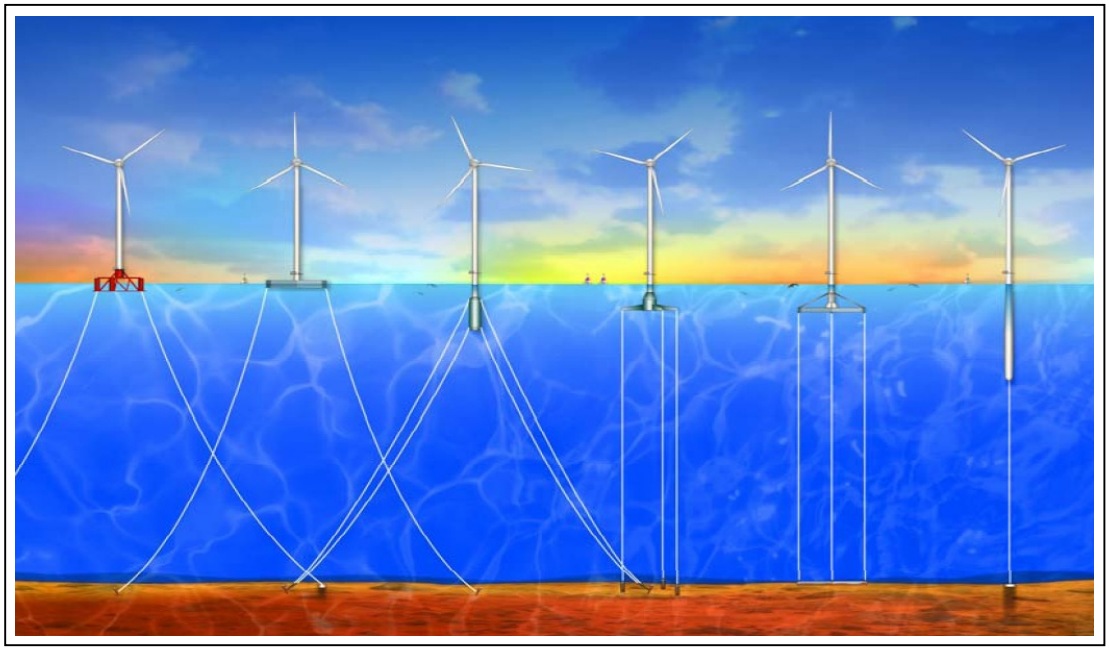

Figure 13.9 Example offshore wind turbine foundation types for transitional depths, 30–90 m (Robinson and Musial, 2006).

Figure 13.10 Example foundation types for offshore wind turbine at depths greater than 60 m (Robinson and Musial, 2006).

Building on the technological advances from the offshore oil and gas industry, a number of alternative foundation and tower designs to increase the constructible water depth are being tested. The potential extractable energy resource for a single wind turbine installation is significantly smaller than for an oil or gas platform, leading to more stringent economic constraints. A direct technology transfer is not economically feasible (i.e., using oil and gas industry platform designs directly), so new innovations are necessary.

One potential solution to the present depth constraint has important implications: the development of a floating platform foundation for the deepwater offshore areas. The advent of a floating system would dramatically increase the potential buildable area and allow for siting further offshore, thus reducing nearshore use conflicts and visibility issues. The development of a stable floating tower and turbine design has provided a potent engineering challenge and has been a major focus of research and development in this sector (Butterfield et al., 2007; Robinson and Musial, 2006). The major environmental factors that affect the floating system design are high wave climate, strong currents, and sub-bottom conditions suitable for system mooring.

13.5.3.2 Larger Systems

Development of offshore wind power is clearly more expensive per turbine installed than is development of similar-sized wind parks onshore (Black and Veatch, 2007; Fingersh et al., 2006). Several development areas—including generator, blade and tower technologies—are focused on improving the economics of offshore wind parks. The primary focus is the development of larger turbines, in the range of 5–10 MW (Robinson and Musial, 2006).

To increase the size of the wind turbine generators to the 5–10 MW range, the rotor diameter (i.e., blade length) has to increase in size. Blade design analyses for larger offshore wind turbine generators, including aero-elastic simulation codes, are being developed to assist design and evaluation of the new systems (Passon et al., 2007; Kanemoto et al., 2007). Some of the

innovations may include alternatives to conventional three-blade rotors, because these blades will have difficulties with the floating systems, because the tower may be expected to oscillate more dynamically than the fixed foundation types.

13.5.3.3 Design Standards

Until recently, design standards for wind turbines had focused on those for onshore use (IEC, 2009; Quarton, 2005). The offshore environment presents some obvious and some not-so-obvious challenges for wind turbines in that environment; an effort is being made to update and upgrade present standards for the offshore (AWEA, 2009; DOE, 2008a; IEC, 2005; 2009; Ibsen and Brincker, 2004). These challenges are discussed in the next section.

Several recent studies have been performed as part of the Technology Assessment and Research Program implemented by BOEM. At present, two well-known sets of industry standards that address offshore platform design and construction are available: the International Electrotechnical Commission (IEC, 2009) and the American Petroleum Institute (API). An assessment was performed (MMI, 2009) to develop a baseline comparison between the IEC 61400-3 design requirements for offshore wind turbines and the API RP-2A recommended practice for the design of fixed offshore platforms. The study focused on a comparison of the standards for structural reliability of systems exposed to extreme storm conditions, the appropriateness of the 50-year return frequency storm conditions by IEC, and the 100-year return frequency storms used by API. Results showed that the two methodologies generate similar levels of structural reliability.

The following two sections are associated with the research necessary for developing improved design standards that are more focused on the offshore environment.

Forces and Loads on the System

High waves and associated tower oscillations dramatically impact the turbine rotor and create complex dynamic responses in the blades. Computer models have been developed to simulate the coupled turbine blade and tower dynamic response to loading to assist in design and evaluation of new systems (Jonkman and Buhl, 2007a, b; Bir and Jonkman, 2007; Jonkman and Sclavounos, 2006; Wayman et al., 2006).

The additional forces and the dynamic action of waves and increased wind turbulence offshore reduce the expected lifetime of an offshore system. Floating wind turbine generators are more affected; this has prompted research on the engineering, modeling, and life-cycle assessment of those systems (Sclavounos, 2008; Sangyun and Kim, 2008; Shimada et al., 2007; Hong and Kim, 2004). Much of the research effort has been on wind turbine blade development and testing for systems better able to withstand the more turbulent and dynamic offshore environment (Kubo et al., 2008; Cotrell et al., 2006). The additional forces and dynamic loads acting on a floating turbine will increase the need for new materials and designs that specifically address the complex dynamic conditions. Figure 13.11 presents a schematic of the environmental forces that offshore wind turbine designs need to address.

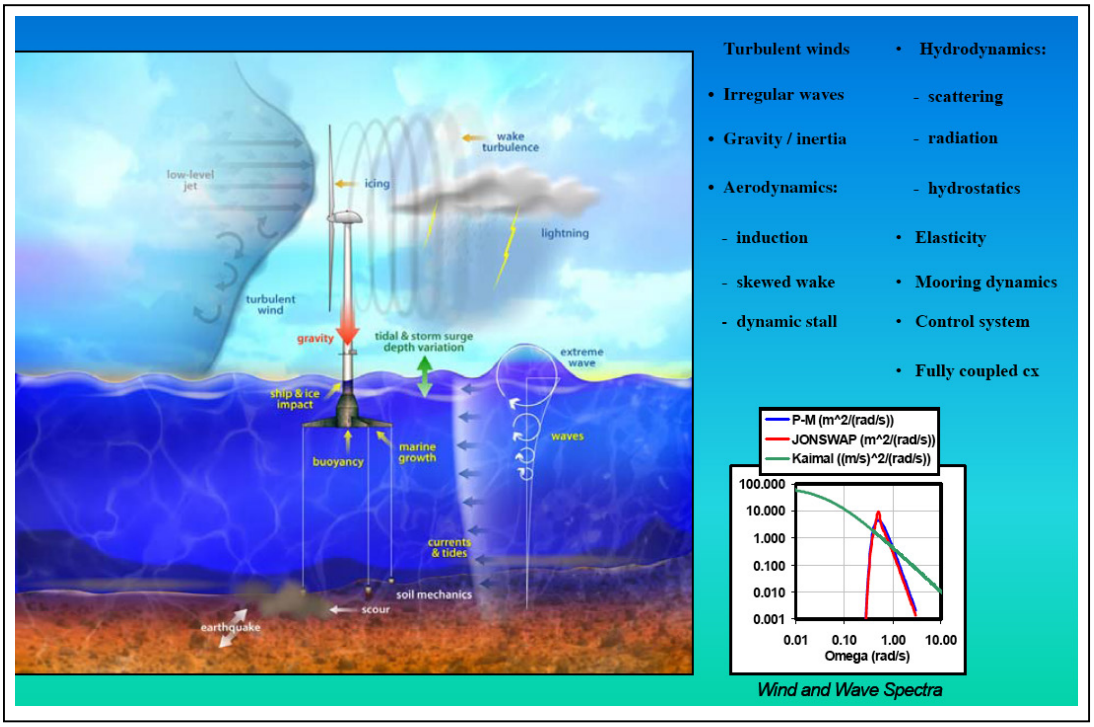

Figure 13.11 Schematic representation of the environmental aspects of the technical challenges facing the research and development of offshore wind turbines in general and specifically for floating foundations (Robinson and Musial, 2006).

Wind and wave loads also affect fixed-foundation systems, and research on foundation properties for support structures, fatigue load stress mitigation, and damage prediction modeling has progressed (Huhn and Herion, 2006; Yamashita and Sekita, 2004; Zaaijer, 2004; Henderson and Zaaijer, 2004). In addition, component materials used in the offshore systems are being refined to withstand the more dynamic and corrosive environment, including steel, fiberglass composite, carbon fiber composite, coatings, grout, and concrete (Klose et al., 2008; Lücken et al., 2007) covering all components of the system.

The coincidence of structural resonances with wind turbine dynamic forces can lead to large amplitude stresses and subsequent accelerated fatigue. For this reason, the wind turbine rotor blades and support structure are designed to avoid resonance coincidence. Peterson et.al. 2010 evaluated the impact of period of vibration requirements on the structural design of offshore wind turbines and identified and evaluated potential vulnerabilities in this design approach. They also performed a tradeoff study of potential resonance avoidance and vibration mitigation techniques for offshore wind turbines. Computational tools were developed to perform design sensitivity studies that informed the selection and analysis of alternate vibration mitigation and resonance avoidance strategies.

Some planned offshore wind parks are located in waters offshore of the northern states, where icing and the ice load on foundations can be a serious problem. Recent studies address ice load estimation and mitigation measures (Mróz et al., 2008; Barker et al., 2005). Dynamic models are

being developed to assess the loads and failure modes, along with passive and active mitigation alternatives.

System Reliability

Offshore systems are significantly more difficult to maintain than those onshore because of the logistics of transporting personnel and equipment to the towers and the harsher marine environmental conditions. This maintenance issue has prompted research to improve system reliability in areas such as the gearbox (Musial et al., 2007) and LiDAR control that enhance turbine capabilities and, thus, productivity (Harris et al., 2006).

Offshore, subsurface cable reliability and installation have received significant attention as important areas for research and development. Electrical collection and transmission from large-scale offshore wind parks are particularly vulnerable to moisture penetration in the marine environment and require specific design considerations (Green et al., 2007).

Due to the intermittent nature of the wind, power generation from multiple large offshore wind parks will have a destabilizing effect in the grid. To improve our understanding of the potential impacts to the system, and to assist in the design and evaluation of mitigation measures, power stability modeling for grid integration of large-scale intermittent power (Pinson et al., 2008; Bialasiewicz and Muljadi, 2006) and variable speed wind turbine dynamic models for grid integration studies (Behnke, 2007) are being developed and applied.

An in-depth study of wind turbine damage and critical analysis of accidents is being commissioned by the MMS (Sharples, 2011); the study will include review of safety management practices and the turbine installation, structure, equipment, and systems as a whole. The study will also highlight the need to address the issue of installation survivability in the hurricane-prone US east coast offshore waters.

13.5.4 Renewable Energy Storage Technologies

A major issue for offshore renewable energy sources is that the energy is not always produced when there is demand for it. To address the intermittent and sometimes unpredictable nature of energy production from these sources, methods for the interim storage of excess energy must be developed. Two methods have been identified, but neither is in commercial use. The first is pumped storage where the generated electricity is used to either pump water into an elevated tank or structure, or more likely, to pump water out of a tank or structure below mean sea level. In theory, the storage facilities can be located offshore (most likely) or onshore. The second method uses hydrogen (H_2) as an energy storage medium; the generated electricity is used to convert seawater via electrolysis, and the hydrogen is then stored as a gas or liquid. The generation and storage of hydrogen can be located either offshore or onshore.

Other energy storage technologies, such as batteries, flywheels, superconducting magnetic energy, compressed air, thermal, and super capacitors are theoretically possible (Denholm et al., 2010), although most have been proposed for much shorter times of discharge. None appears to have been considered for use in offshore power generation, except for powering of relatively

small or single structures such as data buoys. Therefore only pumped and hydrogen storage methods are described in more detail in the following sections.

13.5.4.1 Pumped Storage

The concept of pumped storage for renewable energy systems is identical to the approach used to balance generation with load in traditional energy systems although at different time scales. For instance, energy from fossil fuel facilities can be used during low-demand periods (i.e., late-night hours) to pump water into storage reservoirs, which can then be emptied in a hydropower mode to generate electricity via turbines from the head difference of the filled reservoir, and the resulting energy supplied to the grid during higher-demand periods.

Studies have been conducted to evaluate the ability of supplying sustainable energy from renewable sources by integration with pumped storage. One such study analyzed the ability of wind parks in Germany to supply continuous power with onshore pumped storage called a "wind and water" approach (Leonhard and Grobe, 2004). They found that such an approach, while technically feasible, would require a very large storage capacity that would be difficult to site based on topography but impossible to build based on environmental and cost reasons. Another study (Geetha et al., 2007) did not assume 100% renewable energy and found that a combination of wind, wave, and tidal currents along with distributed pumped storage could significantly reduce the need for non-renewable energy in an island environment. The authors asserted that using variable frequency transformers to control the power could keep costs competitive with non-renewable sources.

One study looked at the economics of using large offshore storage basins as part of the solution to increased energy needs over the next five decades (Lemperiere, 2008). Assuming that by the year 2050 fossil-based energy sources will contribute only 10% of the energy supply worldwide, an estimate was made that using 20% of the wind potential plus a small amount of solar photovoltaic potential would make up the difference. This approach would only work, however, if large offshore basins are used with a total capacity equal to the present capacity in hydro reservoirs. The author estimated that the basins could be used several times a week to balance the intermittency in wind and solar supply, and the costs of building these structures, along with the wind and solar facilities, would provide an economically competitive alternative. He called his "green" offshore structures, which he asserts could last for centuries, "Emerald Lakes."

Another recent study investigated the feasibility of an inverse offshore pump accumulation station which consists of an artificial island with a ring of dikes surrounding a dredged reservoir 50 m below mean sea level (de Boer et al., 2007). Power would be generated and exported during the filling of the reservoir. Using the characteristics of a site off the coast of the Netherlands, a conceptual design was developed for a 60 km^2 reservoir that would have a maximum pump/turbine power rate of 2,500 MW. It was sized to compensate for the imbalance due to wind forecast errors as well as to store wind generated energy at night.

Both the Lemperiere (2008) and de Boer et al. (2007) studies did not consider the significant environmental impacts that offshore storage reservoirs have. It is doubtful that the environmental concern present in the US would allow this type of design to be built. Finding sufficient space onshore for the storage reservoirs would also be a challenge.

13.5.4.2 Hydrogen Generation, Storage, and Transmission

The use of hydrogen as energy storage has long been recognized (Ogden, 1999) as a potential solution to the mismatch between renewable (and, to some degree, fossil and nuclear) energy production and energy demand, although it could not compete economically with natural gas turbine peaking plants. Its potential use is again being actively reconsidered due to three factors: (1) the long-term potential of renewable energy as generating costs are reduced; (2) concern about climate change and the desire to find non-carbon-based energy sources; and (3) developments in fuel cell technology that use hydrogen as a low-polluting fuel (Anderson and Leach, 2004).

Wind, wave, and current energy sources involve technologies that directly produce electricity. For this energy to be stored, the electrical energy must be converted into hydrogen. This conversion can be accomplished using electrolysis.

Electrolysis is the process of producing hydrogen and oxygen from water in an electrochemical cell. An electrolyzer immerses the two electrodes into an aqueous electrolyte, and a voltage is applied across the electrodes. The resulting migration of ions in solution results in the production of hydrogen and oxygen. Currently, the best conversion efficiency (i.e., overall system efficiency for converting electrical power to power stored as hydrogen) for commercial electrolyzers is approximately 70% (Ivy, 2004; DOE, 2005).

A recent MMS white paper (MMS, 2006) provides a useful description, summarized below, of using hydrogen for the storage and transmission of energy generated by renewable energy sources from the OCS. Hydrogen can be generated on location on a variety of scales; it can then be compressed and stored in tanks, transported in tanks or pipelines to shore, and later consumed by vehicles for power, or by industrial facilities or generating stations to produce process steam or provide electricity.

A range of approaches to using hydrogen can be used (MMS, 2006). For example, hydrogen could be produced offshore at the point of energy generation in a co-located facility, or it could be produced at an onshore location. Hydrogen production at a co-located facility would require additional construction in a marine environment and equipment capable of long-term function in an offshore setting. Additionally, if multiple power generation units were involved (such as the individual turbines found on a wind energy facility), a hydrogen production unit could be associated with each turbine or with the entire facility. In the former case, consolidation of the hydrogen would be necessary for shipment off-site; in the latter case, electrical connections between the individual turbines and the hydrogen production unit would be required.

Hydrogen production at a nearby onshore location would offer particular advantages when operated in conjunction with offshore energy sources already connected to a land-based electric power grid. In such systems, electricity from OCS sources could be diverted for use in hydrogen production when available energy on the grid from conventional sources was sufficient to meet existing power demands.

Offshore-generated hydrogen can be delivered to onshore facilities through transport as gaseous hydrogen, as liquid hydrogen, and after incorporation into a solid or liquid “hydrogen carrier”

(MMS, 2006). In the first two pathways, hydrogen would be transferred to shore-based facilities in its molecular form (H_2), either as compressed gas or as liquid, via pipeline, tanker, or a ship. The third (carrier) pathway would use materials that would transport hydrogen in a form other than free molecules, such as liquid hydrocarbons, absorbents, metal hydrides, and other hydrogen-rich compounds.

For economic reasons, hydrogen would be compressed in gaseous form for transport ashore. The actual hydrogen transport could be via a pipeline that runs between an offshore generating facility and an onshore receiving facility. Currently, approximately 1,000 km of dedicated hydrogen transmission pipelines exist in the US (DOE, 2005). Compressed hydrogen can also be transported to shore in pressurized containers loaded on ships or in specially designed tankers.

The transportation of hydrogen as a liquid in molecular form requires liquefaction, which is a well-understood but costly operation. The liquefaction process involves cooling gaseous hydrogen to below -253°C using liquid nitrogen and a series of compression and expansion steps, a very energy-intensive process. With current technologies, this process can consume one-third or more of the energy contained in the hydrogen (Freedom Care and Fuel Partnership, 2005). Once liquefied, hydrogen would need to be stored and transported at cryogenic temperatures until it is ready to be vaporized to a high-pressure gaseous form for dispensing. Present offshore cryogenic pipelines for liquefied natural gas transport are on the order of 7 km in length (WCE, 2009), so the only practical pathway from offshore would be via ship or tanker using present technology.

A hydrogen carrier is any substance that can be used to store and transport hydrogen in a chemical state other than as free hydrogen molecules. A one- or two-way carrier could be used. In a one-way carrier, hydrogen is added to the carrier at the point of initial charge and remains with the carrier until it reaches its point of use. At the point of use, the carrier/hydrogen combination is decomposed to yield hydrogen and an environmentally benign substance with no economic value. Hydrogen is used, and the remaining by-product is lost to the environment. Ammonia is an example of a one-way carrier (DOE, 2006). The by-product material is nitrogen. In a two-way system, the carrier would be charged with hydrogen at an offshore hydrogen generation station and transported back to shore. Onshore, the carrier would be stripped of its hydrogen and sent back offshore for recharging. Whether the carrier is one-way or two-way, it could be transported between the offshore generating station and an onshore facility by pipeline (if it is in a liquid or slurry state) or by ship or tanker.

13.5.4.3 Research and Development Needs

All renewable energy storage technologies require further research and development before they can be considered viable options. Pumped storage technologies required a substantial footprint, which implies significant environmental impacts to either onshore or offshore locations. Further research into the use of subsurface reservoirs, such as salt dome formations, needs to be assessed.

Hydrogen generation technology needs to be refined in order to increase process efficiency of the electrolysis process. Environmental impacts from a co-located generation facility may be too substantial to allow offshore production, so tradeoffs need to be evaluated between onshore and offshore facilities. If an offshore facility appears to have an acceptable environmental impact,

liquid hydrogen transmission requires improvements in the liquefaction process to improve efficiencies. An additional need for further research is the development and use of long distance cryogenic pipelines to transfer liquid hydrogen to shore-based storage facilities.

Another potential technology with similar longer term discharge times (at least multiple hours), such as compressed air, is problematical since it requires the use of fossil fuel to combust with the compressed air to drive a low-pressure gas turbine. Similar to the pumped storage approach, it requires the use of a suitable storage container (e.g., salt dome cavern) if its footprint needs to be minimized at offshore locations.

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CHAPTER 14: SUMMARY SYNTHESIS FOR THE SOUTH ATLANTIC PLANNING AREA

14.1 CHARACTERISTICS OF THE STUDY AREA

In October 2010, most of the Principal Investigators on this project met at the offices of Research Planning, Inc., for a two-day workshop to present their preliminary findings and work toward a multi-disciplinary synthesis of the physical and biological resources of the South Atlantic Planning Area. The results of the workshop, as well as the chapters in this report, have been used for the summary synthesis presented in this chapter.

The South Atlantic Planning Area OCS has the following characteristics, which make it unique in many ways:

Physical Environment and Resources

- There is a two-tiered physiography: an upper shelf of moderate width and depths up to 100 m, and a wide lower shelf with an average depth of 800 m (range of 400–1,200 m). The South Atlantic Planning Area can be divided into three provinces: 1) the modern coast and shoreface, 2) the upper shelf (the Florida-Hatteras Shelf), and 3) the lower shelf (the Blake Plateau).
- The Blake Escarpment and Ridge form very steep outer edges to the Blake Plateau. The Blake Escarpment is a very steep, eroded cliff, rising 3 km from water depths of 5,000 m, with an average slope of 40 degrees.
- Phosphate-manganese pavements and manganese nodules cover large areas of the Blake Plateau, forming a continuous surface except where they are cut by deep pits formed by limestone dissolution or bottom currents.
- The Florida-Hatteras Slope lacks submarine canyons and has low seismicity. There is also a lack of turbidity flows and very little evidence of slumps along the slope. Gas hydrates underlie only a very small part of the South Atlantic Planning Area, occurring only at the northeastern corner. Therefore, the area has low geohazard risks.
- Sediments on the Florida-Hatteras Shelf consist of relatively thin layers and consist primarily of arkosic to sub-arkosic fine- and medium-grained sand (thus they have low total organic carbon content). The Florida-Hatteras Shelf is considered to be relatively sediment starved; however, the Slope is muddy, representing the Holocene shoreline edge.
- Many of the rivers that drain into the area have watersheds in the coastal plain; therefore, they do not deliver much sediment to the Florida-Hatteras Shelf. Furthermore, dams on the larger Piedmont rivers (the Santee and Savannah) have reduced their sediment contributions to levels below those estimated for pre-European settlement conditions. Most of the sediments and organic matter that are transported to the coast are trapped in estuaries and adjacent salt marshes and/or transported alongshore on the inner shelf.
- Freshwater discharge to the inner shelf creates a consistent low-salinity front that minimizes mixing and sediment transport to the middle shelf, resulting in a sharp

decrease in turbidity, nutrient concentrations, and water-column production with distance from shore.

- Trace metal inputs to the shelf from rivers are low and about equal to atmospheric input. Gulf Stream intrusions and eddies are the dominant source of trace metals to the shelf (with the exception of the inner shelf).
- Submarine groundwater discharges, originating from either coastal surficial aquifers or the deeper Floridan aquifer, may be a locally important source of nutrients, though their overall extent and the importance of material cycling and input associated with the groundwater-seawater exchange are still poorly understood.
- The largest nearshore sand resources include ebb-tidal deltas in South Carolina and Georgia and offshore, mostly relict bank shoals and ridges in Florida.
- Wave climate is driven by local winds; there is very little swell (i.e., waves with periods >10 seconds).
- There is low hurricane frequency in the South Atlantic Planning Area, compared to adjacent area of south Florida and North Carolina (10–60x lower frequency); however, when hurricanes do cross the area, they mix the water column and cause re-suspension of bottom sediments.
- Circulation and hydrography in the South Atlantic Planning Area are defined by the morphology of the continental shelf, atmospheric forcing (wind climate and temperature variations), tidal processes, buoyancy fluxes introduced by the river discharges, and large-scale oceanic processes (Gulf Stream). Weather patterns dominate processes on the inner-middle shelf; meandering and eddy production by the Gulf Stream are important on the outer-middle shelf.
- Dissolved oxygen levels in the water column are near the saturation limits year round; under saturation occurs only in the deep bottom water along the continental slope and in localized nearshore areas in summer.
- Most of the shelf hydrography is marginally stable and vertically well mixed during the fall–winter, but there is strong vertical stratification on the entire shelf during the summer in response to solar heating. Bottom-water temperatures on the shelf show strong cross-shelf gradients; along-shelf gradients follow the bathymetry.
- Seasonal wind patterns generate cross-shelf currents and periods of downwelling (winter-spring) and mid-water upwelling (in summer), which result in the transport of nutrients from the Gulf Stream (which trigger plankton blooms) and larvae from the outer shelf toward the middle and, occasionally, the inner shelf.
- The Charleston Bump, a rocky outcrop ~150 km offshore at the slope edge that shoals rapidly from over 700 m to 400 m depth, deflects the Gulf Stream, creating a semi-permanent, cold, cyclonic eddy known as the Charleston Gyre. This semi-permanent upwelling supports high plankton productivity, contributes to primary and secondary production in the South Atlantic Planning Area, and supports a wide variety and high abundance of fish species.
- The Gulf Stream has a very strong influence on many biogeophysical processes of the South Atlantic Planning Area because it:

- Moderates the climate
- Sweeps sediments off the Blake Plateau
- Generates intrusions of deep water (cold, nutrient-rich) that are a major source of nutrient transport onto the shelf, and that control plankton production and dynamics on the middle and outer shelves
- Provides for the transport north of the larvae of tropical fauna, particularly those associated with hard-bottom habitats
- Generates meanders and eddies that transport larvae away from spawning grounds

Biological Environment and Resources

- There is a lack of the spring phytoplankton bloom that characterizes other areas of the US Atlantic coast. Instead, plankton production on the middle and outer shelf is controlled by upwelling-intrusion events associated with Gulf Stream frontal passages. Most intrusions are subsurface, and they generally persist for 7–21 days in summer and 2–14 days in winter. Eddies also generate intrusions that can reach the surface. In the absence of these events, nutrient concentrations are low, particularly on the middle shelf.
- There is abundant hard-bottom habitat at all depth ranges; however, little is known about life-history strategies or larval ecology of the hard-bottom community.
- The *Sargassum* community is important for fish, sea turtles, and pelagic seabirds. Many fish species, mostly during juvenile stages, take advantage of the resources (food, shelter, drifting transport, spawning, nursery) provided by *Sargassum*.
- The soft-bottom benthos are relatively depauperate because, in part, of the low organic carbon content of shelf sediments and low nutrients in the water column.
- The South Atlantic Planning Area is a distinct biogeographic province where many southern species reach their northern limit (during summer) and northern species reach their southern limit (during winter).
- The fish communities vary in composition, abundance, and diversity in space and time, and many are tightly associated with specific shelf and off-shelf zones and habitats.
- Members of the nearshore fish assemblage spawn offshore from fall through spring; while several middle-shelf species spawn across the continental shelf during spring and summer. Deepwater species spawn in areas of the shelf edge and lower shelf between spring and summer, while species inhabiting the upper continental shelf and Blake Plateau spawn on restricted deep-water areas between spring and late summer.
- Many of the commercial fish species are depleted, a result of intense fishing pressure and habitat degradation. Five Marine Protected Areas, established in 2007, were designed to protect deepwater snapper-grouper species, which are particularly hard-hit and vulnerable populations.
- Because of the hard substrate, low sediment cover, and strong flow of the moderating Gulf Stream, there are extensive areas of deep-water (>200 m) coral reefs on the Blake Plateau. Most deep coral reefs are found at depths of 370-800 m and temperatures of 5.4–12.3ºC; they are dominated by a single species of a scleractinian coral *Lophelia pertusa*. These *Lophelia* bioherms can reach heights of over 100 m.

- Deep coral ecosystems in the South Atlantic Planning Area consist of 114 known species of corals, including 57 species of scleractinians and 44 octocorals. This list will no doubt be increased as exploration and research continues.
- The bird community is dominated by nearshore and coastal species; seven species classified as nearshore seabirds nest in substantial numbers. The coastal area also supports abundant migrating and wintering nearshore seabirds and shorebirds, although detailed data on location and abundance are sparse.
- The pelagic seabird community appears to be less rich, abundant, and diverse than that in the adjacent mid-Atlantic region, particularly when compared to the area offshore of the Outer Banks of North Carolina. The pelagic seabird community is not comprised of local species but rather species that breed in more northern latitudes, more southern latitudes, and in the eastern Atlantic. Detailed data on distribution and abundance of pelagic seabirds are lacking for the study area.
- Twelve species of bats inhabit the coastal counties of the South Atlantic Planning Area, but limited data exists regarding bats' use of the offshore area.
- Five species of sea turtles occur in the area; two species (loggerhead and green) nest in significant numbers on beaches. However, little is known about the at-sea distributions of juvenile and adult sea turtles and trends of non-nesting sea turtles.
- The most common marine mammal is the bottlenose dolphin, a year-round resident that has two ecotypes: coastal and offshore forms that exhibit genetic differences and are likely distinct species.
- The only known calving grounds for the highly endangered North Atlantic right whale are off Georgia and northern Florida; this area has been designated as critical habitat for this species.
- Food-web interactions are very complex and poorly understood, as summarized below:
  - There are little data on benthic/pelagic couplings, including the role of microbial communities in nutrient remineralization.
  - Even though nutrient inputs are low, there is efficient nutrient/carbon recycling in the water column and benthos.
  - Hard-bottom communities include suspension feeders, but little is known about what they feed on.
  - Fishes exhibit high feeding plasticity, with feeding ecology influenced by species-specific energy demands, ontogenetic changes in feeding requirements, and seasonal variability of prey. Most studies on feeding ecology have focused on commercial species; information is lacking for most species.
  - Data on the foraging ecology and diets of nearshore and pelagic seabirds are sparse from the study area; therefore, the relationship between these apex predators and their prey resources (including interactions with commercial fisheries) are poorly understood.

- Current environmental threats to resources in the South Atlantic Planning Area include:
  - Freshwater diversions and droughts
  - Increased nutrient fluxes from runoff associated with coastal development
  - Hardening of the shoreline

- Habitat loss from coastal development and sea-level rise
- Invasive species
- Overfishing
- Military use

Socioeconomic Characteristics/Resources

- Population growth in coastal counties in the South Atlantic Planning Area is well above the national average, ranging from 11–17 percent over the last decade. Median household incomes are slightly lower than the US as a whole, with the exception of Florida. Employment is dominated by the professional, management, and sales sectors.
- There are several significant ports in the South Atlantic Planning Area:
  - South Carolina has two sea terminals, one in Charleston and one in Georgetown. In 2009, these ports served approximately 1,800 ships and barges.
  - Georgia has two sea terminals, one in Savannah and the other in Brunswick. In 2009, the Port of Savannah moved $52.6 billion in cargo, comprising 2.4 million TEUs.
  - The Port of Jacksonville, in Duval County, is one of Florida's five largest seaports. Collectively, the five largest seaports handled more than 100 million tons of cargo and contributed more than $47 billion to the state's economy in 2002.
- The South Atlantic Planning Area supports several commercial fisheries, the most valuable of which are shrimp and blue crab. According to the Atlantic Coastal Cooperative Statistics Program database in 2008:
  - South Carolina commercial landings totaled more than 9.6 million live pounds and were valued at approximately $18 million.
  - Georgia commercial landings totaled more than 7.7 million live pounds valued at approximately $11 million.
  - Commercial landings in the six relevant Florida counties totaled nearly 15.3 million live pounds valued at approximately $27.9 million
- Tourism is critical to the coastal economies in the South Atlantic Planning Area:
  - The South Carolina Budget and Control Board estimated that 30 million visitors generated more than $16 billion in revenue and supported more than 10 percent of employment in 2007.
  - Tourism is a growing part of the coastal economy in Georgia. Employment in tourism-related sectors made up more than 60 percent of the economic base in 2005.
  - Within the relevant Florida counties, key tourist areas include Cape Canaveral, Daytona Beach, and the city of Jacksonville. Total tourism spending for the state exceeds $70 billion and supports more than 757,000 jobs.
- Substantial recreational fishing activity takes place in the South Atlantic Planning Area:
  - In South Carolina 325,000 people engaged in saltwater fishing activities during 2,174,000 participant days and 1,574,000 trips in 2006. Targeted species include striped bass, flatfish (flounder, halibut), red drum (redfish), and sea trout (weakfish).

- In Georgia, 146,000 people engaged in saltwater fishing activities during 1,707,000 participant days and 1,103,000 trips in 2006. Targeted species for saltwater anglers focused on sea trout; nearly half of anglers identifying "anything" as a target.
- In Florida, 2.0 million people engaged in saltwater fishing activities during 23.1 million participant days and 17.6 million trips in 2006. The average trip length for saltwater anglers was 12 days. Targeted species include red drum, sea trout, mahi-mahi, and mackerel.

- Beach use has the highest participation rates among coastal recreational opportunities in the South Atlantic Planning Area:
  - The direct economic impact of beach tourism from out-of-state visitors to South Carolina was estimated to be $1.25 billion in 2006 and $1.64 billion in 2010.
  - Beach tourists spent approximately $2.8 billion on 11.2 million trips to northeast Florida in 2003.
- At present, state- or regional-level demand for renewable sources of energy, including those that might be produced offshore, is influenced in large part by Renewable Portfolio Standards (RPS), which generally require utilities to ensure that a form of renewable energy is the source for a specific percentage of retail electricity sales or generating capacity. However, the three states in the South Atlantic Planning Area are among only 14 states that do not currently have RPS requirements or an RPS Goal.
- The Georgia Institute of Technology, as part of a study of the wind power generation potential off the Georgia coast, noted but did not examine in detail several general conflicts, including viewshed effects, the ecological impacts of noise and vibrations during construction, and the need to consider the compatibility of a project with existing commercial and recreational activities. In general, literature describing socioeconomic impacts of offshore energy projects is not well developed and no additional studies specific to the South Atlantic Planning Area exist.

14.2 Seasonal Patterns in Physical and Biological Resources

Three seasonal patterns can be discerned for the South Atlantic Planning Area.

Winter/Spring

- High riverine fresh water and sediment input creates high salinity gradients along the innermost shelf.
- Shelf waters are well mixed, thus there is lower insolation.
- Wind-driven circulation in winter results in downwelling, which causes onshore surface water (and larvae) transport.
- In spring, south winds prevail, and there is a transition in nearshore waters from horizontal to vertical stratification, due to freshwater input.
- Most recruitment of new benthos occurs in the winter.
- Soft-bottom benthos abundance peaks in the late winter/early spring.

- Reef and offshore fish spawn on the middle to inner shelf; onshore currents transport larvae of estuarine-dependent fish into estuaries and nearshore waters.
- In spring, fish migration inshore and to the north.
- Migratory/wintering birds add to the avian abundance and diversity of the region.
- Right whales are present November–March in nearshore calving areas in Georgia and north Florida.

Summer

- The Gulf Stream is closer to shore, thus cold-water intrusions increase in frequency.
- Northeast (poleward) winds dominate and result in cold-water upwelling to mid-water on the middle shelf, and closer to shore in Florida and at the capes; the wind patterns are consistent.
- There can be localized low oxic conditions in nearshore waters.
- As the thermocline deepens during summer, shallow portions of the shelf warm and benthic metabolism increases.
- Phytoplankton blooms peak, followed by zooplankton blooms; many blooms are in the subsurface and cannot be detected using remote sensing techniques.
- Soft-bottom benthos decline in abundance.
- Resident, estuarine fishes spawn in the estuaries.
- Fishing pressure and recreational uses increases.
- Maximum biodiversity occurs due to recruitment of motile fish and invertebrates, including temporary tropical recruitment.
- Sea turtles nest on beaches and aggregate in nearshore waters.
- Nearshore seabirds are concentrated on nesting colonies.

Autumn

- This season is a transition period with variable winds, the water column starts to become more mixed, and intrusions are still possible (and more common in the southern part of the area) leading to phytoplankton blooms in surface waters at 0-30 m depths.
- Water temperatures start to cool.
- Soft-bottom benthos begins increasing in abundance and biomass.
- Deep-water coral spawn.
- Fish and invertebrates migrate offshore and to the south.
- There is increased fishing pressure on reef species that form spawning aggregations.
- Migratory shorebirds are common, following the coastal flyway.

14.3 ECOLOGICAL RELATIONSHIPS AND DISTRIBUTIONS

The offshore oceanic environment of the South Atlantic Planning Area is highly influenced by the Gulf Stream. This highly energetic circulation feature connects coastal oceanic environments from the Gulf of Mexico (Louisiana to Florida; Loop Current) and the southeastern US (Florida; Florida Current) to North Carolina. The strength of the Gulf Stream current prevents sediment deposition over the Blake Plateau; it is responsible for the scouring of the inner Blake Plateau that nourishes deepwater bioherms that form reefs on the western and eastern sides of the plateau. A rocky outcrop at the northern corner of the Blake Plateau, the Charleston Bump, is one of the few hard-bottom features with significant relief, which causes an offshore deflection of the Gulf Stream current forming eddies and upwelling. An important feature of the area is the formation of a cyclonic eddy called the Charleston Gyre, which moves with the Gulf Stream along the shelf edge. Over the northern section of the South Atlantic Planning Area, mid-water upwelling of Gulf Stream waters is triggered by poleward summer wind patterns.

Nutrients are relatively low in shelf waters, with the exception of events associated with high river runoff which supplies nutrients to the inner shelf, and meanders and spin-off eddies of the Gulf Stream, which supply cold, upwelled, nutrient-rich waters to the middle and outer shelf and occasionally to the inner shelf (see Figure 5.15 in Chapter 5: Plankton Communities; this diagram is still an accurate presentation of the current understanding of the hydrographic processes on the shelf of the South Atlantic Planning Area). Consequently, the Gulf Stream plays a significant role in the biological processes of the shelf. During the summer and under northward wind stress, water intrusions into the euphotic zone occupy much of the shelf and persist for several weeks. During this period, the influx of cold, nitrate-rich waters favors new primary production in waters of the continental shelf, promoting phytoplankton blooms. These blooms are also associated with the rapid increase in numbers of some zooplankton taxa, which are an important food sources for pelagic larvae of many fishes and ensure their survival as they travel from their spawning grounds. This increase in productivity also creates a more particle-rich environment that provides resources to benthic communities of the shelf. At the western edge of the Gulf Stream, patches of pelagic *Sargassum* circulate in large amounts and provide resources for many species. Invertebrate and juvenile fish species use this habitat as food, shelter, drifting transport, spawning, and nursery. In *Sargassum* patches near the Gulf Stream, post-hatchling green turtles are common, and many seabirds are particularly attracted to this prey-rich habitat. The Gulf Stream also provides unique conditions that favor the proliferation of deepwater communities. Even during winter, the shelf break is stratified due to the presence of warmer Gulf Stream waters that imposes a slight thermal stratification in the upper ocean. These stable and relatively warm bottom-water temperatures, combined with the occurrence of hard-bottom substrates on the shelf edge, support high species diversity.

In the South Atlantic Planning Area, high larvae concentrations are partially the result of their entrapment in waters of the Gulf Stream and large oceanographic features. These waters trap, transport, and disperse early life stages as they travel over spawning and into to nursery areas. Water intrusions on the middle shelf, for instance, appear to be important mechanism for transporting fish larvae into the inner shelf, particularly in northern Florida (Jacksonville to Cape Canaveral) where the shelf is considerably narrower and there seem to be semi-permanent upwellings. Offshore, the Gulf Stream also provides an important mechanism for long-distance

plankton transport along the shelf, and the Charleston Gyre retains and transports pelagic larvae of species that spawn at the shelf edge.

Bottom topography also plays an important role in defining the composition and distribution of biological resources. Hard bottoms are found from the inner to the outer shelf and the Blake Plateau. The distribution of hard bottom on the inner and middle shelf is patchy, but moderate-relief reefs are common off north Florida, South Carolina, and North Carolina. Inner-shelf reefs have high fish abundance and numbers of species during fall, and lower during winter when many tropical species move offshore or migrate south and are replaced by more temperate non-reef species. By contrast, the fish assemblage of middle-shelf reefs is more stable, given a higher persistence of warm water. Although inner-middle hard-bottom reefs support high-diversity, high-biomass sessile fauna and reef fishes, the most diverse and abundant faunal assemblages, frequently occur where sessile benthic invertebrates form structures that enhance habitat complexity (e.g., corals, sponges, reef-building polychaetes). On the outer shelf, hard bottoms are common but discontinuous across South Carolina and Georgia, and in Florida (Fort Pierce to Cape Canaveral) high-relief ridges form an almost continuous band of *Oculina* reefs or bioherms near the edge of the continental shelf. These shelf-edge reefs are important habitats for warm-water species and species found on the continental shelf, and they represent Essential Fish Habitat for deepwater reef fishes. Rugged deepwater areas on the continental slope and the Charleston Bump also provide unique environments (relatively constant water temperatures and salinity) for deepwater species. Deep-sea corals (*Lophelia* reefs) and other deep rocky reefs harbor diverse faunal communities, but the challenges associated with studying these reefs are great and their species diversity is likely higher than currently known.

The top panel in Figure 14.1 shows the relative distribution of the biological resources of the South Atlantic Planning Area across the shelf, slope, and Blake Plateau. The line for each resource is only scaled relative to itself; that is, there are no relationships inferred as to the relative abundance among different resources (or the relative position of each colored line). The bottom panel shows a bathymetric profile across the OCS at latitude 32°N, for reference. Birds are most common close to shore, relatively scarce across the shelf, and then increase somewhat in abundance at the shelf break/edge of the Gulf Stream. Sea turtles concentrate in nearshore aggredations before nesting on beaches, but little is known about their at-sea distributions. Bottlenose dolphins have two distinct ecotypes that occur in separate coastal and Gulf Stream habitats. North Atlantic right whales calve in coastal waters off Georgia and north Florida, though little is known about the spatial distribution of other marine mammals. Hard-bottom communities are extensive on the middle and outer shelf and decrease on the muddy slope, and then increase in patches on the Blake Plateau. Fish have highest abundances in estuarine and nearshore waters, then decrease across the shelf, except where they are concentrated in hard-bottom habitats; fish decrease in the Blake Plateau but occur in relatively higher concentrations in association with deep coral reef habitats. Plankton distributions across the area somewhat follow fish, with significant peaks in the middle and outer shelf and a smaller peak in the inner shelf, due to seasonal nutrient-rich intrusions, mostly in the subsurface. The soft-bottom benthic communities also peak in the middle shelf, driven by the increased food availability from plankton blooms.

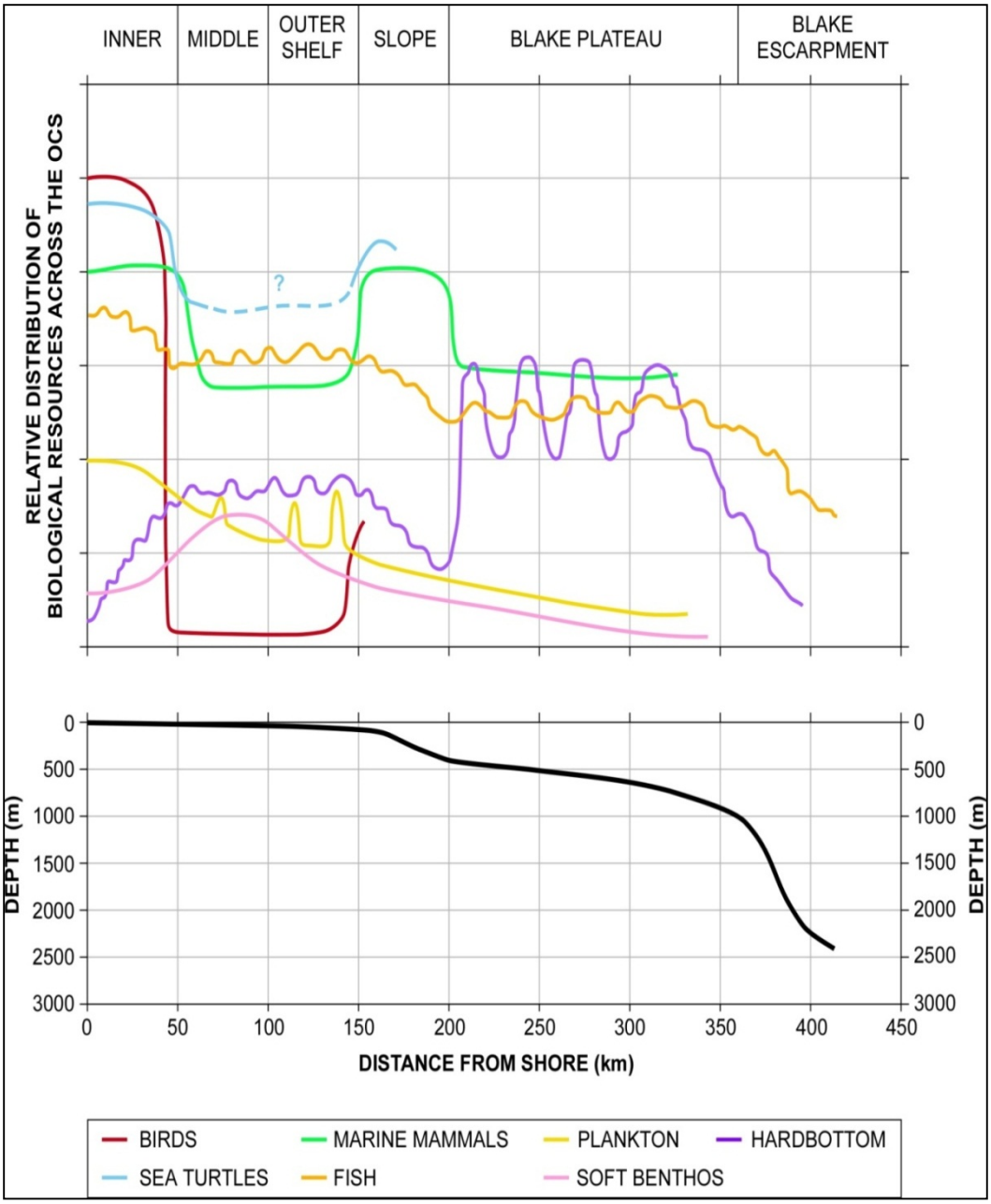

Figure 14.1 Schematic diagram showing the relative distribution of biological resources across the OCS. Each curve in the top panel shows the distribution relative only to that resource. That is, there are no relationships inferred as to the relative abundance among different resources by the position of each curve. They are positioned only to allow better visualization of each distribution. The bottom panel shows the bathymetry at latitude 32°N for reference.

14.4 SUMMARY OF DATA GAPS

Several key data and information gaps that should be addressed to better understand the resources in the South Atlantic Planning Area are summarized below.

Physical Environment

- Detailed bathymetry and acoustic seafloor mapping of the upper continental shelf, including complete delineation of hard-bottom habitats
- Information on onshore-offshore flow, submarine groundwater discharge fluxes, sediment deposition, and sedimentary bedform migration on the inner shelf
- Increased understanding of the effect of nearshore (inner shelf) coastline irregularities on large-scale oceanographic patterns
- The spatial and temporal variability of processes, such as mesoscale eddies
- The spatial and temporal characterization of chemical species (e.g., metals, radionuclides, biogenic and synthetic organic compounds), and their cross-shelf transport, cycling, and fate

Biological Environment

- Increased understanding of the coupling between the high primary/secondary production in the water to the high production of the benthos in the continental shelf; Another source of nitrogen that needs further evaluation is atmospheric nitrogen into the shelf of the South Atlantic Planning Area
- Additional information on the abundance of different phytoplankton groups on the shelf, including before, during, and after intrusions
- The lack of understanding on shelf edge or mesophotic habitats, and their biological communities
- General information on the life cycles (growth rates, reproductive cycles and seasonality, life-history parameters, mortality trends, seasonal movements, population dynamics), trophic and ecological interactions and habitat use of commercial and non-commercial fishes and invertebrates
- Additional information on the effects of underwater sound waves and electromagnetic field emissions to sensitivities of species and life stages likely fish species receptors, and on the effect of offshore wind development projects on transport and migration processes and pathways
- A systematic study of bats' use of offshore areas with emphasis on seasonal patterns and species composition, and the effect of weather (particularly wind speed), distance from shore, and landscape features
- Additional data on the foraging ecology, foraging habitat use, and diet of nearshore seabirds, and on their reproductive ecology, and temporal and spatial patterns

- At-sea surveys of pelagic seabirds throughout the annual cycle, including assessments of their composition, density, and use areas
- General understanding of the interactions between flying animals and wind energy structures in the marine environment
- Detailed information on at-sea distribution and trends of non-nesting turtles
- Studies of the hearing of sea turtles in water and their responses to sounds associated with seismic exploration and pile driving
- Little is known about food habits and trophic relationships for most marine mammals in this region, and little is known on the winter occurrence of several migratory species

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Appendices for Chapter 7

Appendix 7-A1 Life Histories of Selected Species

Although this review focuses on all fish resources, there is much more information for managed species than for non-managed species (e.g., anchovies, gobies, toadfish) and, therefore, most of the information presented below relates to managed species. Detailed species descriptions from studies specific to the study area of this synthesis are also provided. *Note:* Not all available literature was reviewed.

Snapper Grouper Complex

Sea Basses and Groupers (Serranidae)

Gag

Gag (*Mycteroperca microlepis*) is a demersal serranid that inhabits the continental shelf and shelf edge (Sedberry et al., 2001; 2006). The circulation patterns influenced by the Charleston Bump and the temperature regimes modulated by the warm waters of the Gulf Stream have been linked to the timing of gag spawning aggregations (Sedberry et al., 2001). This species spawns once a year during winter and early spring off the west coast of Florida (Collins et al., 1987) and the Carolinas. Large spawning aggregations occur near offshore hydrographic features, allowing early life stages to avoid predation, while ensuring the removal of larvae from reefs and their retention in highly productive and environmentally favorable areas (Sedberry et al., 2001; 2006). Gag's recruitment success is strongly influenced by the presence of high nutrients at the edge of the shelf, and the occurrence of large gyres that transport larvae from shelf spawning grounds to estuarine nursery habitats (Sedberry et al., 2001).

This species is a protogynous hermaphrodite (i.e., individual fish transition from reproductively active females to reproductively active males at a certain age and/or size). The younger size classes of the population are dominated by females (100%; total body lengths ≤700 mm), while older fish are predominantly males (60%), with female to male sex transition starting at age 5 and at lengths 750-950 mm (Collins et al., 1987). Along the southeastern US size and age at first maturity is reached at 50.8 cm total length (TL) and 2 years, respectively, and 50% of gag females are sexually mature at 62.2 cm and 3 years (Harris and Collins, 2000; McGovern et al., 1998a). Gag's maximum reported size, weight, and age are 145 cm TL, 36.5 kg, and 26 years (Harris and Collins, 2000; Heemstra and Randall, 1993). Adults are solitary or can form aggregations of 5 to 50 individuals, particularly during the spawning season (SAFMC, 2009). Gag juveniles are considered estuarine dependent (Keener et al., 1988; Ross and Moser, 1995). Post-larval stages enter South Carolina estuaries between April and May at 43 days old (range 33-66 days) and approximate length of 15 mm TL (range 9-20 mm TL) (Keener et al., 1988) where they occupy oyster shell rubble before moving offshore between September and October. Minimum estimates of post larval gag entering an inlet in South Carolina over a 10-week period were in the order of 294,000-900,970 individuals, with most individuals occupying the upper 3 m of the water column (Keener et al., 1988).

A tag and recapture study of 3,876 individuals along the South Atlantic, but primarily off South Carolina (81%), found movement beyond 150 km (up to 1,767 km) from the tagging location during a ~366 day migration period (McGovern et al., 2005). High movement (~209- 219 km from the tagging location) was typical of gag tagged at depths of 20-40 m, while deeper tagged specimens (40-80 m) were relatively sedentary (~9-85 km from the tagging location). This study

also revealed new information regarding this species: 1) mortality ranges from 14% at 15 m depth to 95% at 95 m depth; 2) fish length is related to depth, with larger individuals (794-853 mm TL) occurring at depths >35 m; and 3) a relatively low percentage (3.6%) of tagged individuals were male, with the highest percentage of males occurring at depths >55m (typically >8.4% males across several depth intervals). Another important finding was that the mean length of tagged individuals and depth of capture were greatest during February-April (coinciding with the spawning season) and least during May-July, indicating that commercial fishermen target spawning aggregations. Gag are vulnerable to overfishing since they are long-lived, late to mature, change sex, and aggregate to spawn. The estimated natural mortality rate is 0.15/year (SAFMC, 2009).

Red grouper

Red grouper (*Epinephelus morio*) are found primarily towards the northern portion of the South Atlantic Bight on reefs of the middle and outer shelf at depths ranging from 5 to 300 m. Specimens from the Carolinas range in length and age from 315-851 mm TL and from 2-20 years, respectively, with 50% maturity reached at age 2.4 (487 mm TL) and 50% transition reached at age 7.2 (690 mm TL) (Burgos et al., 2007). This species is a protogynous hermaphrodite, with females commonly found in the 1-10 year age class (315-739 mm TL; 87%), but predominantly in the 3-6 year age class (1 M:6.6 F sex ratio) and <660 mm length. Transitional individuals are found at ages 3-10 (455-744 mm TL), while males are common in the 3-20 year age class (509-851 mm TL) (Burgos et al., 2007).

Spawning appears to be restricted to depths >40-90 m, with a protracted spawning season (~115 d) occurring in late winter and spring (February- June, peak in April) (Burgos et al., 2007; Sedberry et al., 2006). Estimates of spawning frequency indicated a total of 13 spawning events per season of 8.8 days in duration (Burgos et al., 2007). The pelagic larval stage inhabits open waters, while juveniles–which appear to be estuarine dependent (see Ross and Moser, 1995)–are found on estuarine grass beds, inshore hard bottom habitats and rock formations where they prey on demersal crustaceans (Burgos et al., 2007; Jory and Iversen, 1989). Immature red grouper off the Carolinas are common in shallow waters (<40 m), with females apparently undergoing annual migrations between inshore reefs and deeper water spawning locations (>40 m). Transitional individuals and males, on the other hand, are permanent residents of offshore reefs (>40 m) (Burgos et al., 2007). Red groupers are most common in areas with salinities ranging from 30 to 35, requiring optimum salinities of at least 32 to ensure egg flotation. Genetic analyses indicate that overfishing has not reduced the population enough to induce inbreeding (Zatcoff et al., 2004). Although the maximum reported age for this species is 25 years (Heemstra and Randall, 1993), in waters of the Southeast Atlantic red grouper live for at least 20 years (McGovern et al., 2002c; Burgos et al., 2007). The natural mortality rate of red grouper is estimated to be 0.20/year (Potts and Brennan, 2001).

Scamp

Scamp (*Mycteroperca phenax*) is a demersal grouper found at depths between 40-100 m often associated with low-relief, live/hard-bottom habitats of the middle and outer shelf, shipwrecks, and rock outcroppings (Manooch et al., 1998a). Scamp appears to prefer habitats characterized by structural complexity (e.g., *Oculina* and other reefs) that provide the necessary shelter to avoid predation by larger species. When present on reefs of the continental shelf (70-100 m) and

water temperatures above 8ºC, this species is dominant and abundant, reaching several hundred individuals per hectare (Gilmore and Jones, 1992). In the South Atlantic Bight, individuals range in age from 1-30 years, with a median age of 5 years (Harris et al., 2002).

Scamp is a long-lived (>21 years), slow-growing, and protogynous hermaphrodite species that spawns from February to August (peak March to May) (Matheson et al., 1986; Sedberry et al., 2006). Spawning grounds are found along shelf-edge reefs off northern Florida, Georgia, and South Carolina at depths between 33-93 m and water temperatures from 15.6-24 °C (Sedberry et al., 2006). Females spawn from February to July (peak March to May) during the late afternoon and evening, and around new moon and full moon (Harris et al., 2002). During the 106-day spawning period, females spawn every 2.5 days for a total of 42 times. Annual fecundity ranges from 1,313,000 to 10,503,200 oocytes in females of lengths between 445-712 mm TL (Harris et al., 2002). Scamp spawning sites and timing overlaps with that of gag (Gilmore and Jones, 1992). The length and age at female maturation in waters of the South Atlantic Bight are 30-35 cm TL and 1 year, with length and age at 50% maturity reported at 35 cm TL and 1.28 years, respectively (Harris et al., 2002). Sex transition occurs primarily between August and November at various lengths and ages (401-850 mm TL and 2-16 years), with most changes occurring at lengths between 502-750 mm TL and at ages between 5-9 (Harris et al., 2002). Genetic analyses of fish collected between 1991 and 2001 indicated that overfishing has not reduced the population enough to induce inbreeding (Zatcoff et al., 2004). The natural mortality rate of scamp is estimated to be 0.15/year (Potts and Brennan, 2001).

Red and rock hind

Red hind (*Epinephelus guttatus*) and rock hind (*E. adscensionis*) are uncommon in waters of the South Atlantic Planning Area, but inhabit coral reefs and rocky substrates at depths of 122 m (Potts and Manooch, 1995). Red hind and rock hind have estimated longevities of 11 (491 mm TL) and 12 years (467 mm TL), respectively, and experience fast growth rates during the first 2 years. These species appear to be shorter-lived and have faster growth rates than specimens from tropical waters (Potts and Manooch, 1995). Rock hind females in spawning condition (hydrated oocytes or postovulatory follicles) have been collected off South Carolina from May through August, and red hind are believed to spawn during the summer off the southeastern US (MARMAP unpublished data).

Snowy grouper

Snowy grouper (*Epinephelus niveatus*) are typically found on shelf-edge and upper-slope reefs (60->185 m depth) off the Carolinas in waters with temperatures from 16-29 °C (Matheson and Huntsman, 1984; SAFMC, 1998a; Sedberry et al., 2006). Juveniles are found in inshore waters (~35 m) and occasionally in estuaries, which may represent important nursery habitats (Matheson and Huntsman, 1984; Heemstra and Randall, 1993; Williams and Carmichael, 2009), as well as in shelf-edge rocky habitats. Adults are highly territorial and prefer irregular habitats of boulders and limestone ridges mixed with sand, broken shells, and rock fragments (SAFMC, 1998a).

This species is a protogynous hermaphrodite that spawns between April and September on the upper continental slope (176-232 m depth) north of Cape Canaveral (SAFMC, 1998a; Wyanski et al., 2000). Numerous spawning locations have been identified off the coast of South Carolina

at depths of 187-302 m (Sedberry et al., 2006). Matheson and Huntsman (1984) reported individuals of this species off the Carolinas as old as 17 years (958 mm), with recruitment to the fishery occurring between 6-9 years. Although the maximum age reported by Wyanski et al. (2000) was 29 years for fish collected off North Carolina and South Carolina, radiocarbon techniques indicate that snow grouper may live for as long as 40 years (Harris, South Carolina Department of Natural Resources, pers. comm.).

Yellowedge grouper

Yellowedge grouper (*Epinephelus flavolimbatus*) is a demersal species found primarily on reefs of the shelf-edge and upper-slope reefs off of the Carolinas at depths of 31-205 m. Spawning occurs between August and September at depths of 160-194 m and at temperatures of about 15 °C (Sedberry et al., 2006). Maximum reported size is 114 cm TL (male) and 18.6 kg, with 50% of fishes maturing at 56.9 cm, and 50% of females transforming into males by 81 cm TL (see SAFMC, 2009).

Warsaw grouper

Adult Warsaw grouper (*Epinephelus nigritus*) are found on irregular benthic habitats (steep cliffs, rocky ledges, and drop-offs) at depths of from 76-219 m, while juveniles are found closer to shore around jetties or shallow reefs (SAFMC 1983; SAFMC 1998a). Maximum reported size is 230 cm (TL) and 263 kg (Heemstra and Randall, 1993; SAFMC, 2009), and the oldest specimen was 41 years old (Manooch and Mason, 1987). Natural mortality rate is estimated to range from 0.05 to 0.12 (SEDAR, 2004). Although the reproductive biology and life history of this species are relatively unknown in waters of the South Atlantic Planning Area, this species is known to spawn from August to October in the Gulf of Mexico (Peter Hood, NOAA Fisheries, pers. comm.).

Goliath grouper

Goliath grouper (*Epinephelus itajara*) occur infrequently along the southeastern US from Cape Lookout, North Carolina to the Florida Keys (Williams and Carmichael, 2009). This species is found on live-bottom and mud substrates of shallow and inshore waters as deep as 100 m (Heemstra and Randall, 1993). Juveniles are found in mangrove areas and brackish estuaries (Williams and Carmichael, 2009). Goliath grouper form spawning aggregations containing the largest and oldest individuals in the population, as well as individuals traveling distances as great as 100 km (Coleman et al., 2000; Williams and Carmichael, 2009). Spawning occurs off the southwest Florida coast from July to September, but has not been documented elsewhere in this region.

Speckled hind

Speckled hind (*Epinephelus drummondhayi*) are commonly found at depths of 28-114 m (Matheson and Huntsman, 1984; Sedberry et al., 2006), though others have found this species in waters as deep as 400 m (Bullock and Smith, 1991). Adults are found on ledges and hard-bottom, while juveniles are found in similar habitats at shallower waters (Heemstra and Randall, 1993). This species has been reported to live up to 15 years (861 mm TL) off the Carolinas, with recruitment to the fishery occurring at 6 and 7 years (Matheson and Huntsman, 1984). Speckled hind is a protogynous hermaphrodite with females reaching 50% and 100% maturity at 497 mm TL and 500-549 mm TL, respectively, and males reaching 50% and 100% maturity at 710 mm

TL and 800-849 mm TL, respectively (SEDAR, 2004). The estimated age at transition from female to male is 8-12 years (SAFMC, 2009). Relatively little is known regarding the reproductive biology of this species in the South Atlantic Planning Area. However, spawning aggregations have been found between July and September off South Carolina (Sedberry et al., 2006).

Black sea bass

Black sea bass (*Centropristis striata*) are distributed from Massachusetts to the Gulf of Mexico, with one distinct population found throughout the South Atlantic Bight (between south of Cape Hatteras and the Gulf of Mexico) (Steimle et al., 1999). Although this species is highly migratory in the northern end of their distribution, in the South Atlantic Bight they are practically non-migratory (Mercer, 1989) and exhibit strong habitat fidelity (Low and Waltz, 1991; McGovern et al., 2002a; Sedberry et al., 1998). Tagging studies from 1974 to 1992 in South Carolina reported a mean distance of 1.76 km between the tagging and recapture locations, and all but one individual were recaptured in the vicinity of the tagging site (Davy, 1994). This species is a conspicuous year-round resident of inshore (20-60 m), hard-bottom habitats, co-occurring with tropical reef fishes, such as snappers, groupers, porgies, and grunts (Mercer, 1989; Edwards et al., 2008b). Juveniles occur in estuarine environments around jetties, piers, wrecks, and shell bottoms (Mercer, 1989).

The black sea bass is a protogynous hermaphrodite that spawns primarily on rocky reefs of the middle shelf (15-56 m depth) (Sedberry et al., 2006). This species is an indeterminate spawner recruiting new eggs throughout the spawning season, with spawning occurring every 3.4 days (27 times) during the ~92 day spawning season (SEDAR, 2003a). Female fecundity ranges from 17,000 (2 year old and 108 mm SL) to 1,050,000 eggs (438 mm SL; Wenner et al., 1986). Their pelagic larval stage is relatively short (between 20 and 35 days post-hatch) before becoming demersal or moving to nearshore estuarine habitats (Edwards et al., 2008; Mercer, 1989). Larvae spawned in shallower areas of the shelf (15-25 m depth) have a higher success rate than larvae spawned further offshore, as the latter areas are influenced by offshore/northward wind conditions (Ekman transport) reducing the ability to find suitable settlement habitat (Edwards et al., 2008). Mature females are found in the 1-8 age range, with 100% mature gonads at >3 years. Females dominate the smaller length classes <219 mm SL (M:F sex rations 1:1.22 to 1:8.5), while males dominated lengths >220 mm SL (M:F sex ratios 1:0.55 to 1: 0.02) (Wenner et al., 1986). The overall sex ratio in the South Atlantic Bight is M:F 1:1.71 (Wenner et al., 1986). Individuals of this species have been reported to live at least 10 years (SEDAR, 2003a). The natural mortality rate of this species is estimated at 0.3/year (SEDAR Update #1, 2005).

Black grouper

In the South Atlantic Bight, black grouper (*Mycteroperca bonaci*) occur from North Carolina to Florida, with higher frequency of occurrence in southern Florida (Crabtree and Bullock, 1998). Juveniles are associated with sub-aquatic vegetation and oyster reefs in shallow estuarine waters of North and South Carolina, while adults are found over hard bottom at depths of 30-40 m (Keener et al., 1988; Ross and Moser, 1995; Williams and Carmichael, 2009). This species spawns year round in waters <100 m deep, with peak of spawning females occurring between January and March (Crabtree and Bullock, 1998; Williams and Carmichael, 2009).

Bank sea bass

Bank sea bass (*Centropristis ocyurus*) have a broad distribution across the continental shelf and are found in deeper waters (at the shelf edge) than the black sea bass (1-146 m). Spawning females are found in waters off South Carolina at depths of 27-57 m between October and May, though the spawning peak occurs between February and April (Sedberry et al., 2006). Unpublished MARMAP reports indicated that bank sea bass experience female to male sexual transitions over a wide range of sizes, most frequently between 12.5-17.4 cm TL.

There is limited life-history information specific to the study area for the following species: graysby (*Cephalopholis cruentata*); coney, (*C. fulva*); yellowfin grouper (*Mycteroperca venenosa*); yellowmouth grouper (*M. interstitialis*); tiger grouper (*M. tigris*); goliath grouper (*Epinephelus itajara*); Nassau grouper (*E. striatus*); misty grouper (*E. mystacinus*); and rock sea bass (*Centropristis philadelphica*).

Wreckfish (Polyprionidae)

The only known population (stock) of wreckfish (*Polyprion americanus*) in the western North Atlantic is found on the Blake Plateau–including the continental slope at the Charleston Bump (44-653 m)–and in the Straits of Florida (Sedberry et al., 2001). Ross and Quattrini (2007; 2009) and Reed et al. (2006) also reported wreckfish on the Plateau's deep-coral reefs. Spawning may occur almost exclusively at the Charleston Bump from November to May (peak February to March) (Sedberry et al., 2001; 2006), although spawning has also been documented on the Blake Plateau between December and March (Vaughan et al., 2001). Eggs, larvae, and juveniles of wreckfish are pelagic, and pelagic juveniles (<60 cm length) are found in surface waters of the Gulf Stream and waters further offshore often associated with floating structures (Sedberry et al., 1996; 1999; 2001). Wreckfish are long-lived (31 years at 1.46 m TL and 47 kg) and exhibit slow growth rates particularly after assuming a demersal existence (Sedberry et al., 1996; 1999). Genetic work (Sedberry et al., 1996; Ball et al., 2000) indicates that the North Atlantic wreckfish (Blake Plateau, Bermuda, Azores, Madeira, and Majorca) constitute a single stock with genetic flow maintained across the North Atlantic by drifting pelagic juveniles, and possibly by migratory adults (Sedberry et al., 1996; 1999).

Snappers (Lutjanidae)

Yellowtail snapper

Adult yellowtail snappers (*Ocyurus chrysurus*) are typically found over sandy or hard-bottom areas near deep reefs at depths of 10-70 m (Bester, 2005). Juveniles are found in shallow estuaries, on and around shallow reef areas, and near jetties and pilings at water temperatures ranging from 24-30^{o}C (Wallace, 1977). During the summer, adult yellowtail snapper occupy a broader area extending as far north as Massachusetts (Bortone and Williams, 1986). Garcia et al. (2003) collected 1,528 yellowtail snapper from central Florida (north of Cape Canaveral) to south Florida (Dry Tortugas) and found that specimens ranged in age between 1-13 years and in length between 220-561 mm FL. Yellowtail snapper grows fast up to the age of 3 (280 mm FL), and recruit into the commercial and headboat fishery at the ages of 2 and 3, respectively. Since 1983 fishing regulations imposing minimum size limits have positively impacted the recruitment of this species to fisheries (Garcia et al., 2003).

Gray snapper

Gray snappers (*Lutjanus griseus*) are demersal and found in coastal and offshore waters associated with reefs, rocky outcroppings, and ledges (Bortone and Williams, 1986; Miller and Richards, 1980). Juvenile gray snappers prefer shallower inshore areas (including estuaries), soft- and sand-bottom areas. Both adults and juveniles have been found in freshwater systems of south Florida, indicating a broad salinity tolerance (Bortone and Williams, 1986). Adults occur in waters at depths ≤180 m, and during summer they occupy a broader area extending as far north as Massachusetts (Bortone and Williams, 1986). The oldest reported specimen was 24 years and 760 mm in length (Burton, 2001). Because of the distribution of gray snapper, most landings in the South Atlantic occur in Florida. Individuals recruit to fisheries between ages 5-8 in north Florida, with headboat length frequencies ranging from 400-424 mm TL, and commercial length frequencies ranging from 550-574 mm TL (Burton, 2001)

Mutton snapper

Adult mutton snapper (*Lutjanus analis*) are typically associated with deep hard bottoms, whereas juveniles prefer shallower estuarine habitats and habitats (soft bottom and vegetated areas) closer to shore (Allen, 1985; Bortone and Williams, 1986; Lindeman et al., 2000). During summer, adults occupy a broader area extending as far north as Massachusetts (Bortone and Williams, 1986). The southeast US stock of mutton snapper is considered a single stock (SEDAR, 2008c) centered off southern Florida and the Florida Keys where this species is more abundant (Williams and Carmichael, 2009). Spawning aggregations occur in spring and summer in waters outside the study area of this synthesis (Williams and Carmichael, 2009). The natural mortality rate of this species is estimated at 0.11/year (SEDAR, 2008c).

Lane snappers

Adult lane snapper (*Lutjanus synagris*) are demersal fish found on a variety of habitats (4-132 m depth), but are most commonly found on reefs and vegetated sandy bottoms in shallow inshore waters including estuaries (Bester and Murray, 2005). In Florida, lane snapper are also found on seagrass beds and offshore waters to depths of 400 m (Bester and Murray, 2005). Juveniles prefer protected inshore areas and are often found in low salinity waters (≤15; Bester and Murray, 2005), while adults are typically found in waters at temperatures of 15-28^{o}C and high salinities (≥30). During the summer, adults occupy a broader area extending as far north as North Carolina (Bortone and Williams, 1986). Lane snapper form large aggregations, particularly during the spawning season (Allen, 1985), which occur between late spring and late summer in waters outside the South Atlantic Planning Area.

Vermilion snapper

Vermilion snapper (*Rhomboplites aurorubens)* occur in shelf and upper-slope waters of the South Atlantic Bight at depths of 14-183 m, and occupy inshore live-bottom, shelf-edge, rock rubble, and rock outcrop areas (Grimes, 1979; Sedberry et al., 2006). This species is not believed to exhibit extensive movement (SEDAR, 2003b). In waters off South Carolina and Florida, the proportion of males in the population is smaller than that of females (37-47%) (Bagley et al., 1999; Grimes and Huntsman, 1980). Sexual maturation is attained at ages 3-4, or 186-324 mm TL (Grimes and Huntsman, 1980). This species has a prolonged spawning season from April through September (Grimes, 1979; Grimes and Huntsman, 1980; Cuellar et al., 1996), spawning

every 5-5.5 days for a total of 27-35 events per spawning season (Cuellar et al., 1996; Mikell et al., 2007). Spawning has been reported at depths of 18-97 m and at temperatures of 16-28 °C (Grimes and Huntsman, 1980; Sedberry et al., 2006). Throughout the spawning season, fecundity shows a bell-shape distribution with low levels in May (54,100 oocytes, ovary-free body weight range 109-194 g), increasing gradually through August (118,500 oocytes, ovary-free body weight range 108-442 g) and decreasing towards the end of the spawning season (58,200 oocytes, ovary-free body weight range 106-238 g) (Cuellar et al., 1996). Fecundity of first spawners (3-4 years old and 205-275 mm TL) ranges between 17,000-42,000 eggs, with older females (age 5-10 and <530 mm TL) spawning earlier and longer with each reproductive season (~1.5 million eggs) (Grimes and Huntsman, 1980). This strategy allows them to maximize their reproductive biomass by balancing the costs associated with somatic and gonadal growth (Grimes and Huntsman, 1980). This species is an indeterminate spawner, which indicates that annual fecundity is not pre-determined as oocytes are continually produced during the spawning season (SEDAR, 2007a). The spawning stock, measured by total egg production, increased from the mid 1960s years to a peak in 2000 and steadily declined to the late 1970s levels; by contrast recruitment has been consistently low and appears to be highly variable over time (1964-2007) (SEDAR, 2007a). High genetic flow and lack of genetic differentiation across specimens collected throughout its distribution range (South Atlantic Bight and Gulf of Mexico) suggests the existence of a single genetic stock (Bagley et al., 1999). SEDAR (2003b; 2008e) recommends natural mortality rates between 0.2/year and 0.3/year.

Red snapper

Red snapper (*Lutjanus campechanus*) are found in relatively warm waters (17-29^{o}C) of the continental shelf at 10-190 m depth (Parker, 1990; Manooch and Potts, 1997b; Parker and Mays, 1998). Eggs and larvae are found offshore, while juveniles and adults are reef or structure dependent (Navy, 2009), with juveniles occupying shallower waters than the adults. Adults are found typically over high relief bottoms, on hard limestone/gravel substrates and on deep reefs. This species does not undergo seasonal migrations and appears to exhibit high site fidelity (Navy, 2009). Although red snapper inhabiting waters off the southeastern states typically range in age between 1-15 years, specimens of this species have been recorded to live up to 25 years (955 mm TL; Manooch and Potts, 1997b). Fishery-independent and fishery-dependent samples documented ages ranging from 1-22 (mean 3.1 years) and 1-45 years (mean 4.2 years), respectively (White and Palmer, 2004). Information collected through commercial, headboat, and recreational fishing (Manooch et al., 1998c) and from fishery-independent and fishery-dependent samples (White and Palmer, 2004) indicate that the sex ratios of this species are 1:1, and that female sexual maturity schedule varies according to age: 0% at age -1-2, 30% at age 3, 74% at age 4 and 100% at age ≥5 (Manooch et al., 1998c). Similar sex ratios (M:F 1:0.94) were also found in more recent records (2000-2006) (SEDAR, 2008a). Red snapper males reach sexual maturity at age 1 (200 mm TL) with all males mature by age 3 (378 mm TL), while females mature at age 2 (287 mm TL) with all females mature by age 4 (435 mm TL; White and Palmer, 2004). The length at 50% maturity is estimated at 378 mm TL (1.62 years) for females and 223 mm TL (age not estimated) for males (White and Palmer, 2004). Spawning occurs from June to September (peak season) in waters of the middle- to outer-shelf at depths of 24-67 m, and temperatures of 18-27.6 °C (Sedberry et al., 2006; White and Palmer, 2004). Most female red snapper in waters of the South Atlantic Bight are in spawning condition from May through October (peak June to September), while males are spawning condition year round (peak May-

September) (White and Palmer, 2004). Studies showed that 93% percent of 1,597 tagged red snapper were recaptured within 2 km of the tagging site, indicating limited movement of this species in the Atlantic (SEDAR, 2008a). Adult and sub-adult annual natural mortality rates are estimated at 0.25 (SEDAR, 2008a).

There is limited life-history information specific to the study area for the following species: blackfin snapper (*Lutjanus buccanella*); cubera snapper (*L. cyanopterus*); dog snapper (*L. jocu*); silk snapper (*L. vivanus*) schoolmaster (*L. apodus*); mahogany snapper (*L. mahogoni*); black snapper (*Apsilus dentatus*); and queen snapper (*Etelis oculatus*).

Porgies (Sparidae)

Red porgy

Red porgy (*Pagrus pagrus*) is a species with a wide distribution in the Atlantic, but with distinct genetic markers that differentiate the eastern North Atlantic population (North Carolina to the eastern Gulf of Mexico) from other populations (Ball et al., 2007). Red porgy is a resident species of the Carolinas lacking long-range migrations and extensive local movements; this demersal species is commonly associated with reefs of the middle and outer shelf and found over irregular and low profile hard-bottom at depths of 18-183 m (Parker, 1990; Sedberry et al., 2006). Eggs and early-stage larvae are pelagic, while older larvae are demersal and settle on offshore reefs (SEDAR, 2006b). Red porgy are protogynous hermaphrodites, exhibiting slow growth rates and a lifespan >15 years (Vaughan et al., 1992). Spawning occurs at depths of 26-57 m from September through May (peak November-March) at bottom temperatures of 16-22ºC (Sedberry et al., 2006). Females are believed to be indeterminate spawners, producing and releasing approximately 55 batches of new eggs per spawning season (Daniel, 2003). Recent surveys found a much greater percentage of males in smaller size classes compared to those of the early 1980s (Daniel, 2003). Fisheries data (North Carolina to Florida) showed age and length ranges of 1-18 years and 176-733 mm TL, respectively (Potts and Manooch, 2002). The estimated the natural mortality rate for this species is 0.225/year (SEDAR, 2002).

Knobbed porgy

Knobbed porgy (*Calamus nodosus*) are restricted to reefs of the mid and outer shelf off the Carolinas and Georgia at depths of 21-155 m. Spawning occurs between February and July (peak April to May) almost exclusively on outer shelf reefs at depths of 45-60 m over a narrow temperature range (20-22.7 °C) (Sedberry et al., 2006). Earlier work in the late 1970s (Horvath et al., 1990) documented a longevity of 17 years (460 mm TL), with specimens of ages 6-10 and 11-16 growing at an average 13 and 12 mm per year, respectively, a much slower rate than other reef species. This study also reported that sex ratio at size and age (F:M, 1.5:1) were indicative of a protogynous hermaphrodite species. Females were predominant (88% of all fish) at lengths <441 mm TL, while males were predominant (72% of all fish) at >441 mm TL lengths. Sex change occurs at lengths between 300-500 mm TL.

Scup

Scup (*Stenotomus chrysops*) is a demersal species found over a variety of habitats (sandy bottoms to reefs in the inner to middle shelf), with apparent differences in distribution with ontogenetic changes. This species has a more northern distribution than the longspine porgy (*S. caprinus*; S.W. Ross, pers. comm.). This species is often confused with longspine porgy (S.W. Ross, pers. comm.), and numerous studies in the 1980s referred to this species as the southern porgy (*S. aculeatus*). However, *S. chrysops* and *S. aculeatus* are not considered separate species by the American Fisheries Society. Habitat preferences and diet resemble that of black sea bass.

Whitebone porgy

Whitebone porgy (*Calamus leucosteus*) is commonly found on and around sponge-coral reef and live-bottom habitats at depths of 9-110 m, and occasionally over the sandy bottom of the open shelf (Waltz et al., 1982). Surveys in the late 1970s showed increased abundance of whitebone porgy in deeper (>19 m) warmer offshore waters of the South Atlantic Bight compared to inshore densities during winter, with variable vertical and horizontal distribution during the remaining seasons (Waltz et al., 1982). This protogynous hermaphrodite species spawns from April to August (peak May), and has a fecundity ranging from 30,400-1,587,400 eggs, which is positively correlated with female length and weight (Waltz et al., 1982).

There is limited life-history information specific to the study area for the following species: jolthead porgy (*Calamus bajonado*); saucereye porgy (*C. calamus*); grass porgy (*C.s arctifrons*); and longspine porgy (*Stenotomus caprinus*).

Grunts (Haemulidae)

White grunt

White grunt (*Haemulon plumieri*) is a demersal species found on reefs from the inner shelf to the outer shelf, primarily towards the northern portion of the South Atlantic Bight. Major spawning occurs between April and June at depths of 22-51 m and in waters warmer than most members of the snapper-grouper complex (20-27 °C) (Sedberry et al., 2006). Analyses of white grunt samples from 1972 to 1975 found specimens as old as 13 years (589 mm TL), and a higher frequency of older males (ages 10-13) than females (ages 4-9) (Manooch, 1976). A similar study (Padgett, 1997) found white grunt off North and South Carolina as old as 27 years (459 mm TL), though most specimens (95%) were between ages 1 and 8. The same study found 50%, 88%, and 100% female maturity at ages 1, 2, and 3-4, respectively, with females in spawning condition between March-September (peak May-June). By contrasts, males were in spawning condition year round (peak March-June). A study by Potts and Manooch (2001) suggested that white grunt along the southeastern US belong to two very distinct stocks: the stock from offshore hard-bottom habitats off the Carolinas, and the stock from shallow waters off southeastern Florida. This study showed that this species not only has an uneven distribution along the southeastern US, but also that specimens off the Carolinas grow faster and are larger (1-13 years and 173-512 mm TL) than those of the southern stock (2-15 years and 192-360 mm TL).

Tomtate

The tomtate (*Haemulon aurolineatum*) is an abundant demersal fish in the South Atlantic Bight, occurring as one of the most abundant (by number and weight) fishes on hard-bottom habitats

and sponge-coral habitats at depths of 9-55m (Manooch and Barans, 1982; Sedberry, 1985). The highest density of tomtate has been reported on high-relief, shelf-edge habitats (Schobernd and Sedberry, 2009). Though found across the continental shelf, tomtate is most common in offshore areas during winter at bottom temperatures in the 10-28.1ºC range (Manooch and Barans, 1982). Juveniles (≤148 mm TL) are found in the same areas as the adults and in warmer waters during fall and winter. Both juveniles and adults appear to be more common towards the north end of the South Atlantic Bight (Manooch and Barans, 1982). Compared to other fish species, tomtate grows fast (103 mm at age 1, to 281 at age 9), has a relatively short life span (9 years), and has a high natural mortality rate (59% per year, ages ≥4; instantaneous mortality rates 0.67-1.04). Spawning occurs on middle and outer-shelf reefs at depths from 15-54 m and at bottom temperatures of 20-28 °C between May and July (Sedberry et al., 2006).

There is limited life-history information specific to the study area for the following species: black margate (*Anisotremus surinamensis*); porkfish (*A. virginicus*); margate (*Haemulon album*); sailor's choice (*H. parra*); bluestriped grunt (*H. sciurus*); french grunt (*H. flavolineatum*); cottonwick (*H. melanurum*); spanish grunt (*H. macrostomum*); and smallmouth grunt (*H. chrysargeryum*).

Jacks (Carangidae)

Greater amberjack

Sub-adult and adult greater amberjack (*Seriola dumerili*) are pelagic fish found on rock outcrops, wrecks (Manooch and Potts, 1997a), on reefs of the middle and outer shelf, and upper slope at depths of 15-216 m (Sedberry et al., 2006). Juveniles and adults form schools and are associated with floating plants or debris in oceanic and offshore waters (Williams and Carmichael, 2009; Casazza and Ross, 2008).

Recreational and commercial fishery data from Cape Lookout, North Carolina, to Key West, Florida revealed clear sexual dimorphism and larger size at age of females than males (Harris et al., 2007). Size at 50% maturity was 644 mm FL (95% CI=610-666) for males, and 733 mm FL (95% CI=719-745) for females (1.3 years; 95% CI=0.7-1.7). Spawning occurs between April and May at depths of 45-122 m, and at water temperatures of 24 °C (Sedberry et al., 2006). Estimates of potential annual fecundity ranged from 18,271,400 to 59,032,800 oocytes for 930-1,296-mm specimens, and from 25,472,100 to 47,194,300 oocytes for ages 3-7, with spawning occurring off south Florida and the Florida Keys (Harris et al., 2007). Estimates of spawning frequency off South Florida indicate that females spawn approximately 14 times over a 73 day spawning season (February-May) (SEDAR, 2008b).

Individuals of this species tagged off South Carolina have been recaptured off Georgia, east Florida, Florida Keys, west Florida, Cancun Mexico, Cuba, and the Bahamas, with extensive movements possibly linked to spawning activity (MARMAP, unpublished data). Tagging data also indicates the presence of a resident group of greater amberjack off Florida and a migratory group moving southward during the spawning season (see SEDAR, 2008b). Greater amberjack has been reported to live at least 17 years (Manooch and Potts, 1997a). Reported mean lengths and age at capture of the greater amberjack (*Seriola dumerili*) in the southeast were 366, 873, 1207, 1471, and 1552 mm TL for ages 1, 5, 10, 15, and 17 respectively, with recruitment to

fisheries at age 8 (Manooch and Potts, 1997a). The estimated natural mortality rate for this species is 0.23/year (SEDAR, 2008b).

Blue runner

Blue runner (*Caranx crysos*) is a schooling fish frequently found proximity to reef habitats and attracted to artificial reefs and FADs (Arendt et al., 2009; Rountree, 1990). Scarce information exists regarding its distribution and habitat utilization in the South Atlantic Planning Area. One report indicated high frequency of blue runner between July and September (Arendt et al., 2009) and high association of juveniles with floating *Sargassum* (SAFMC, 2009).

There is limited life-history information specific to the study area for the following species: Crevalle jack (*Caranx hippos*); bar jack (*C. ruber*); yellow jack (*C. bartholomaei*); almaco jack (*Seriola rivoliana*); banded rudderfish (*S. zonata*); and lesser amberjack (*S. fasciata*).

Tilefishes (Malacanthidae)

Tilefish

The demersal golden tilefish (*Lopholatilus chamaeleonticeps*) is the largest and longest-lived tilefish species (Malacanthidae) inhabiting restricted areas of the outer continental shelf at depths typically >250 m (range 100-400 m) and relatively warm water temperatures (9-14 °C) (Freeman and Turner, 1977; Harris and Grossman, 1985). Catch rates off the continental slope indicate a strong association of this species with silt-clay substrates, allowing the construction and maintenance of stable burrows (Grossman et al., 1985). Off South Carolina and Georgia, tilefish flourishes over steeply sloping green mud bottom at 180-300 m and bottom water temperatures of 7.5-16 °C, and they have average sizes larger than that of areas with higher exploitation rates (Middle Atlantic and Gulf of Mexico) (Low et al., 1983). Off central east Florida this species occurs at depths of 150-290 m, water temperatures of 8.6-15.4 °C, and over soft-bottoms where densities can reach 2.91-8.10 burrows per 1,000 m^2 (Able et al., 1993). These burrows provide protection from shark predation and habitat for a variety of organisms (decapod crustaceans and fishes *Anthias woodsi* and *Laemonema barbatulum*) (Able et al., 1987; 1993). Grimes et al. (1988) further suggested that male tilefish construct burrows as reproductive territories. Dominant large males may actively spawn when burrows are occupied with females, while smaller but yet mature satellite males with unoccupied burrows do not spawn. Smaller subordinate males with small testes often do not fertilize the eggs produced by females, suggesting that the removal of large dominant males may impair the reproductive success of this population, or reduce the spawning prospects for ripe females (Grimes and Turner, 1999).

Spawning occurs between March and July at 190-300 m depths and 10-15 °C water temperatures (Sedberry et al., 2006). Female tilefish are fractional spawners releasing small batches of eggs once every 4 days or 38 times over a 135 day spawning season (Grimes et al., 1988; Palmer et al., 2004); female of lengths between 53 and 91 cm produce between 195,000 and 10,000,000 eggs, with a mean fecundity of 2,280,000 eggs (Grimes et al., 1988). The fecundity of females off Georgia have been reported to range from 850,000 (57 cm TL, 2.0 kg, 8 years) to 8,500,000 eggs (90 cm TL, 8.9 kg, 20 years) (Erickson and Grossman, 1986).

Katz et al. (1983) suggested on the basis of morphometric (gill raker numbers) and electrophoretic (genetic variation of proteins) similarities that this species in the South Atlantic Bight and Gulf of Mexico should be considered a separate stock from the fish occurring off North Carolina. Tagging studies indicate that this species is non-migratory and adults move <2 km over one year period (Grimes et al., 1983). Tilefish have been reported to live up to 33 years with males experiencing faster growth (887 mm standard length at age 33) rates than females (775 mm standard length at age 32) (Harris and Grossman, 1985), which may explain higher fishing mortality of adult males (Grimes and Turner, 1999). Radiocarbon aging indicates that tilefish can live up to 50 years (Harris, South Carolina Department of Natural Resources, pers. comm.). Both sexes reach sexual maturity at age 5 (Grimes and Turner, 1999), and males recruit to the fishery at age 12 (606 mm length) while females recruit at age 10 (525 mm length). Documented skewed sex ratios (different from 1:1) across fish lengths are likely the result of differential growth and mortality rates between the sexes, and not due to protogynous hermaphroditism (Erickson and Grossman, 1986; Harris and Grossman, 1985). Their relatively slow growth rates, unique life history, restricted habitat, and behavior makes them particularly sensitive to overfishing (Harris and Grossman, 1985; Grimes and Turner, 1999). A recent assessment estimated the natural mortality rate of tilefish at 0.07/year (SEDAR, 2004).

Blueline tilefish

Blueline tilefish (*Caulolatilus microps*) are found almost exclusively on reefs of the shelf edge and upper slope off South Carolina at depths of 46-256 m. Tilefish of the genus *Caulolatilus* (*C. microps* and possibly *C. cyanops*) construct burrows in soft sediments off Cape Canaveral at depths of 91-150 m and bottom water temperatures of 14-18ºC (Able et al., 1987). These burrows provide protection from shark predation and habitat for a variety of organisms (decapod crustaceans and fishes *A. woodsi* and *L. barbatulum*) (Able et al., 1987; 1993).

The major spawning period is thought to occur between March and September at temperatures from 9-16 °C (Sedberry et al., 2006), with development of ovaries starting as early as February (Ross and Merriner, 1983). Multimodal size distributions of ova and continuous production of spermatozoa in testes indicate that this species is a multiple spawner (Ross and Merriner, 1983). Estimated fecundity ranges from 210,000 (412 mm TL and 820 g) to 3,220,000 (736 mm TL and 4,850 g) eggs per female, and is strongly correlated with body weight (Ross and Merriner, 1983). There is no conclusive evidence indicating that this species is a protogynous hermaphrodite. Although transitional gonads or testes with residual oocytes have been observed in juveniles, adults with transitional gonads have not been reported (Ross and Merriner, 1983). Blueline tilefish exhibit sexual differences in growth rates and longevity, with males living longer and growing larger than females. For instance, tilefish samples from the mid to late 1970s showed that males represented 87% of the fishes with lengths >700 mm, 83% of fishes between the ages of 10-15, and the average male was 66 mm longer than the average female (male: 593 mm; female: 527 mm; Ross and Huntsman, 1982). By contrast, females appeared to be heavier at size than males possibly because of higher gonadal weight. A similar study reported that females are more common in the 500-600 mm TL range, and ages 3-7, while males were predominant above 600 mm TL and ages 10-15 (Ross and Merriner, 1983). The oldest reported blueline tilefish was 15 years old, and the largest was 780 mm TL (5.6 kg; Ross and Huntsman, 1982). Blueline tilefish recruit to recreational fishing at age 6, and fishes collected of South Carolina (609 mm) were larger than those off North Carolina (554 mm) (Ross and Huntsman, 1982). A recent

assessment estimated natural mortality rate of blueline tilefish between of 0.04 and 0.17/year (SEDAR, 2004).

There is limited life-history information specific to the study area for the following species: sand tilefish (*Malacanthus plumieri*).

Triggerfishes (Balistidae)

Gray triggerfish

Gray triggerfish (*Balistes capriscus*) are broadly distributed across the continental shelf at depths of 13-128 m and typically found on hard-bottom habitats (Sedberry and Van Dolah, 1984; Sedberry et al., 2006) except during the early stages when they occupy pelagic habitats and are often associated with *Sargassum* (Dooley, 1972). Gray triggerfish can live up to 10 years, and males and females occur in similar numbers (Moore, 2001). Spawning occurs on offshore reefs of the middle shelf to shelf edge at depths of 20-75 m from May to August (peak June-July) at temperatures of 19-27°C (Moore, 2001; Sedberry et al., 2006). Gray triggerfish as well as other balistids spawn on cleared substrate depression or nests. Males are larger than females of similar age, and both sexes are larger offshore (Moore, 2001). The estimated natural mortality rate of gray triggerfish is 0.30/year (Potts and Brennan, 2001).

There is limited life-history information specific to the study area for the following species: ocean triggerfish (*Canthidermis sufflamen*); and queen triggerfish (*Balistes vetula*).

Wrasses (Labridae)

The following species have limited life-history information specific to the study area: hogfish (*Lachnolaimus maximus*); and puddingwife (*Halichoeres radiatus*).

Spadefishes (Eppiphidae)

Atlantic spadefish

Atlantic spadefish inhabit the inner to middle shelf, and form large schools over high-relief reefs and artificial reefs (Grimes et al., 1982; Hayse, 1990). This species spawns off South Carolina between May and August (peak May), with females spawning several times during the spawning season (Hayse, 1990). Larvae are highly abundant between June and August in coastal waters (salinities 26.7-31.3) when water temperatures reach ~28ºC. Older age classes are also abundant in coastal and nearshore areas during summer and fall, with increased offshore abundance during winter, presumably due to seasonal migrations though the overwintering areas of adults are not currently known (Hayse, 1990). Atlantic spadefish are gonochorists, with female and male sexually maturity reached at age 1. Adults can be as old as 8 years (Hayse, 1990).

COASTAL MIGRATORY PELAGICS

Coastal migratory pelagics (king mackerel, Spanish mackerel, dolphin, cobia, and cero) share several adaptations. These species are fast-swimmers, prey on schooling fish, feed voraciously,

exhibit fast growth rates and early maturation, and spawn over several months (National Marine Fisheries Service, 2009a).

Cobia

Cobia (*Rachycentron canadum*) are large pelagic fish distributed in tropical and subtropical waters and are commonly associated with floating structures (artificial reefs, pilings, platforms, anchored boats, *Sargassum*) or large animals (sharks, turtles, and rays) (Shaffer and Nakamura, 1987). Larvae are found in estuarine, nearshore, and offshore habitats, between the water surface and down to 300 m depth, and have been collected off Charleston, SC (24-36 hours post-hatch), indicating that spawning occurs in open waters (Burns et al., 1998). Juveniles are known to utilize resources from estuaries in South Carolina during the summer (sizes of 42-129 mm TL) and early fall (260->400 mm TL) (Hammond, 2001). Adult cobia are more common in warm waters (20-30ºC) and follow the typical south-north seasonal migrations. In the South Atlantic Bight, adult cobia spend a few weeks inshore, moving offshore to spawn and then returning to inshore waters prior to their southward migration (Burns et al., 1998). Their abundance increases on coastal artificial reefs and shallower nearshore waters of the Carolinas (Port Royal and St. Helena Sound) in early April, dropping sharply by July and completely absent by the end of September. However, a recent survey suggested that high occurrence of cobia on offshore reefs in July may indicate that, during the summer, some portion of the cobia population moves offshore rather than migrating northward (Arendt et al., 2009). A two-decade tagging study (1974-1992) in South Carolina reported a mean of 237 km between tagging and recapture locations and documented one case of cobia migrating into the Gulf of Mexico (Davy, 1994).

Histological analysis shows that in waters of the southeastern states gonadal development occurs from April to May, indicating the onset of the reproductive season (April to September) (Brown-Peterson et al., 2001). Batch fecundity ranges from 212,500 eggs in August to 637,000 eggs in September (average 377,000 eggs), and relative fecundity during the spawning season–calculated by two different methods–varies between 29.1 and 53.1 eggs/g ovary-free body weight, with cobia spawning once every 4-5 days (36 times during the spawning season) (Brown-Peterson et al., 2001). Other observations indicate that the reproductive season of females is shorter (6 months) than that of males (10 months), and that the estimated total fecundity ranges between 15,000,000 and 90,000,000 eggs per reproductive season (Burns et al., 1998). The work by Burns et al. (1998) suggested that off the Carolinas: 1) females range in size from 941-1,381 mm FL (mean: 1,158 mm) and in weight from 48-188 kg (mean: 99 kg), while males range in size from 801-1,130 mm FL (mean: 951 mm) and in weight from 29-198 kg (mean: 60 kg); 2) cobia live longer (13+ years females; 9+ years males) and grow slower than cobia in other ranges of its distribution; and 3) females appear to double the abundance of males. Cobia are opportunistic carnivores feeding near the bottom on crabs, shrimp, squid, and benthic fish or at the water surface on fish (Shaffer and Nakamura, 1987).

King mackerel

King mackerel (*Scomberomorus cavalla*) are important pelagic species with a broad distribution range over the continental shelf including inshore habitats, typically at depths up to 200 m. This species is highly abundant during spring and fall in waters off South Carolina and Georgia, with a population skewed towards females (57-76%) (Trent et al., 1983). However, this species

appears to be much more abundant (all age classes) in waters off north and southwest Florida (Trent et al., 1983).

These highly fecund fish have a protracted spawning season from May to October (Godcharles and Murphy, 1986). Eggs and larvae are pelagic over depths of 30-180 m with optimum growth in salinities >30 (Godcharles and Murphy, 1986). A study of juvenile king mackerel in waters off central Florida reported growth rates ranging of 0.54-1.33 mm/d in 3-15 day old individuals (length 2.9-13 mm SL) (Devries et al., 1990). Females live longer than males and grow faster after the age of two (Godcharles and Murphy, 1986).

Ontogenetic changes influence spatial distribution and diet. Juveniles generally live in shallow (<9 m depth) nearshore waters and prey on small pelagic fish, while larger age classes move farther offshore to the edge of the continental shelf and prey on larger pelagic fish and squid (Godcharles and Murphy, 1986). Williams and Godcharles (1984) identified two migratory stocks: the Atlantic stock (North of Volusia/Flagler County line, Florida) and a Gulf of Mexico stock. Analysis of migratory patterns based on capture/release found that fish likely return to the area of release within a five-year period (Sutter et al., 1991). King mackerel tagged in South Carolina migrate south during spring and summer to spawning locations and return between late summer (June and August) and early fall (October and November), traveling more than 100 km from the tagging location. Tagging records from 1974 to 1992 indicated a mean travel distance of 268 km (range 10-722 km) (Davy, 1994). Overall, this stock has a high fidelity to areas within the South Atlantic Bight (Sutter et al., 1991). The estimated the annual natural mortality rate of king mackerel in the South Atlantic is 0.15 (SEDAR, 2009a).

Spanish mackerel

Spanish mackerel (*Scomberomorus maculates*) undergo seasonal latitudinal migrations (SAFMC, 1983). This species has a protracted spawning season starting in April off the Carolinas and continuing through September farther north (Godcharles and Murphy, 1986). Collins and Wenner (1988) reported that 79% of king and 91% of Spanish mackerel caught in multiple trawl nets samplings (1980-1982, 1985-1986) were found at depths <9 m, and that most king and Spanish mackerel found in shrimp trawls were juveniles (10-22 cm and 10-30 cm fork length, respectively). The fact that most fish are caught between July and October indicates that spawning of these two species occurs between May and September. Spawning occurs in waters of the inner continental shelf at depths between 12-34 m (Godcharles and Murphy, 1986; SAFMC, 1983). The eggs of Spanish mackerel are pelagic and are found in relatively shallow waters (<50 m depth) along the inner continental shelf during the spring and summer (Godcharles and Murphy, 1986). Observations on the seasonal occurrence and distribution of larval Spanish mackerel in the northern Gulf of Mexico and the South Atlantic Bight suggest that they are restricted to high salinity (28-37), warm (20-32 °C) waters of the middle and inner continental shelf (9-84 m depth) (Godcharles and Murphy, 1986; Peters and Schmidt, 1997), particularly between May and September (SAFMC, 1983). Juveniles utilize diverse nursery grounds ranging from low salinity estuaries to high salinity nearshore waters (Godcharles and Murphy, 1986). A study of juvenile Spanish mackerel in waters off central Florida reported growth rates ranging from 0.64-2.26 mm/day in individuals between 3-15 days old (length 2.8-22 mm SL; Devries et al., 1990). Peters and Schmidt (1997) reported a mean absolute growth rate of 2.4 mm/day consistent with growth rates observed in other scombrids during the first few months

of life. Adults are surface feeders, form large schools, and often frequent nearshore coastal waters, tidal estuaries, and bays (SAFMC, 1983). Sexual maturity is reached at age 1 (351-375 mm FL) for males and at age 2 (451-475 mm FL) for females. The latter reach 50% maturity at 0.54 years (95% CI=0.45-0.64) (Schmidt et al., 1993). The majority of the Spanish mackerel population is found in Florida waters, and the Atlantic stock is currently managed as a single unit (Mid-Atlantic region, North Carolina-Virginia border to Dade/Monroe County, Florida) separate from that of the Gulf of Mexico (SEDAR, 2008d). The recommended annual natural mortality rate of Spanish mackerel in the South Atlantic is 0.35 (SEDAR, 2008d).

There is limited life-history information specific to the study area for the following species: little tunny (*Euthynnus alletteratus*); and cero (*Scomberomorus regalis*).

Dolphin and Wahoo

Dolphin

Dolphin (*Coryphaena hippurus*) are predatory oceanic fish that are limited to waters with high salinities (32-35). Spawning is poorly documented. Dolphin larvae grow rapidly and reach maturity within 1 year of hatching. Larvae and juveniles thrive in high salinities and are rare in estuarine and coastal waters. Young dolphin are most common at depths >180 m, and adults are most common between 40 and 200 m, although they can occur as deep as 1,800 m. Dolphin are abundant off North Carolina and South Carolina from May through July and off Florida from April through June. Feeding of juvenile dolphin was documented by Casazza (2009) and their distributions in surface waters were studied by Casazza and Ross (2008).

Wahoo

Adult wahoo (*Acanthocybium solandri*) are pelagic and commonly found near *Sargassum* (Manooch and Hogarth, 1983). Little is known regarding the spatial and temporal distribution of eggs and larvae in the South Atlantic. However, critical habitat for this species encompasses waters of the Gulf Stream, Charleston Gyre, Florida Current, and pelagic *Sargassum* (SAFMC, 2009). Wahoo are abundant off North and South Carolina during the spring and summer, and off Florida year-round (SAFMC, 1998b).

HIGHLY MIGRATORY SPECIES

Some or all age classes of highly migratory species occur in waters of the South Atlantic Bight. Species-specific information is provided when available.

Tuna

Atlantic bluefin tuna

Atlantic bluefin tuna (*Thunnus thynnus*) are found in coastal, shallow continental shelf and offshore waters of the South Atlantic Bight throughout winter, migrating north in the spring and south in the fall with movements largely regulated by water temperature (SAFMC, 2009). Tagging studies have documented the highly migratory behavior (foraging and spawning) and trans-oceanic movement of this species in the Atlantic, and have confirmed the presence of one

spawning area along the continental slope (200-3,000 m depth) of the northern Gulf of Mexico (Block et al., 2005 and references herein). Although larvae have been collected near the shelf edge and over the Blake Plateau (from Florida to North Carolina), their presence was attributed to advection from spawning grounds to the Gulf Stream and not to the presence of spawning grounds in the area (McGowan and Richards, 1989).

Swordfish

Swordfish

Eggs of swordfish (*Xiphias gladius*) are pelagic, buoyant, and common in offshore waters year round but most commonly between April and November, whereas larvae are common at temperatures of 24-29 °C with high densities occurring between Florida and Cape Hatteras, North Carolina (see Navy, 2009). Larvae distribution may indicate that spawning occurs throughout the year off the southeastern US. Larvae collected in waters of the South Atlantic Bight have two distinct growth patterns (~0.3 mm/d and ~6 mm/d at <13 mm and 13-115 mm preserved standard length, PSL), consistent with changes in mouth morphology (structure of the alimentary canal and jaws) (Govoni et al., 2003). The diet of the smaller larvae (<8 mm PSL) is limited to copepods (primarily *Corycaeus*), intermediate size larvae (9-11 mm SL) have a more broad diet consisting of copepods and chaetognaths, while the larger larvae (>11 mm SL) eat exclusively neustonic fish larvae (Govoni et al., 2003). Adults are primarily oceanic and are found at depths of 200-600 m (Navy, 2009). Tagging of adults from the Charleston Bump indicated that some fish remain in the proximity of this site, likely attracted to its topographic relief (>100 m steep scarps at depths of 375 -700 m) and the thermal fronts generated by deflection of the Gulf Stream. Most individuals are not residents of this site and are frequently associated with high relief areas and the Gulf Stream front (Sedberry et al., 2004b).

Large Coastal Sharks

Blacktip shark

Blacktip shark (*Carcharhinus limbatus*) are widely distributed in shallow waters (<30m depth), but are most abundant during the summer off South Carolina, Georgia, and Florida (Castro, 1993). Female dispersal abilities and seasonal migrations support the presence of natal philopatry, with females selecting their place of birth as pupping and nursery areas (SEDAR, 2006c). Blacktip sharks give birth in inshore nursery grounds and estuarine waters (muddy substrates or seagrass beds at 2-4 m depths) of the Carolinas, Georgia and Florida during late spring to early summer (April to June) following a 10-11 month gestation period (Castro, 1993). Juveniles and adults are common in shallow waters until late September, decreasing in numbers during the fall (Castro, 1993). The blacktip shark is one of the most frequently caught sharks in waters off the South Atlantic Bight (Trent et al., 1997). Median size and age-at-maturity in the South Atlantic Bight are 126.6 cm FL and 6.7 years for females, and 116.7 cm FL and 5.0 years for males, respectively (SEDAR, 2006c). Genetic markers suggest the existence of two stocks: an Atlantic stock (Delaware to the Straits of Florida) and a Gulf of Mexico (Florida Keys throughout the Gulf of Mexico) (SEDAR, 2006c).

Dusky sharks

Dusky sharks (*Carcharhinus obscurus*) are a coastal and pelagic species occurring from the surf zone to offshore waters and from surface waters to depths of 400 m. Major nursery areas have been identified in coastal waters of South Carolina where they give birth from April to May. Dusky sharks move out to cooler waters in early summer (Castro, 1993).

Sandbar shark

Sandbar shark (*Carcharhinus plumbeus*) are a bottom-dwelling species found in temperate to tropical waters of the continental shelf and in deep waters of the shelf break over soft substrates (Castro, 1993; Navy, 2009). This species segregates by sex, with females dominating shallow nursery areas from South Carolina to Cape Canaveral. Mature males, on the other hand, are uncommon in inshore waters during the summer, but occur occasionally in late fall (Castro, 1993). Neonates and juveniles are common in shallow estuarine and coastal waters through late September before moving offshore (<137 m) during winter. There is one sandbar shark stock, extending from Cape Cod and into the Gulf of Mexico (SEDAR, 2006c).

Spinner shark

Spinner shark (*Carcharhinus brevipinna*) nursery grounds are known to occur in waters of South Carolina (Castro, 1993). Neonates and juveniles are often found in estuarine waters during the summer. The absence of adult females in these waters indicates that parturition occurs at depths >5 m, or that females enter shallow waters only to briefly deliver their pups (Castro, 1993).

Smooth dogfish

Smooth dogfish (*Mustelus canis*) give birth off South Carolina between April and May prior to their northward migration (Castro, 1993). This species is most common in the spring throughout the region (except Florida), and the average lengths for females and males are 88.1 cm (range 34-120 cm) and 79.5 cm (range 38-116 cm), respectively (Boylan, 2006). An increase in this species' abundance in waters of the South Atlantic Bight has been noted since 2001 (SEAMAP, 2005).

Small Coastal Sharks

Bonnethead shark

Bonnethead sharks (*Sphyrna tiburo*) inhabit shallow coastal waters and are typically associated with sandy or muddy substrates. Nursery grounds are found in estuaries of South Carolina, Georgia, and Florida (Castro, 1993). This species migrates to inshore areas of the Carolinas and Georgia during the summer and off Florida from spring through fall. Bonnethead sharks are most common in the spring in waters of the southernmost portion of the South Atlantic Bight (Boylan, 2006). Mating occurs in waters off the coast of Florida during spring and fall (Castro, 1993). The average length of females and males are 50.5 cm (range 32-120 cm) and 52.7 cm (range 31-101 cm), respectively (Boylan, 2006).

Atlantic sharpnose shark

Atlantic sharpnose sharks (*Rhizoprionodon terraenovae*) are a demersal species and a common year-round coastal resident along the South Atlantic Bight (Boylan, 2006; Loefer and Sedberry, 2003). This species is most abundant in shallow (<10 m deep) warm-temperate to subtropical waters of the continental shelf, and inhabits waters from inshore areas to the continental shelf

(Castro, 1993). The mean estimated age in waters of the southeast ranges from 1-10 years (45-79 cm precaudal length, [PCL]) for females and 1-9 years (45-75 cm PCL) for males, with a 11+ years maximum reported age (83 cm PCL) (Loefer and Sedberry, 2003). More recent assessments (Boylan, 2006) also reported average lengths of 43 cm (range 27-108 cm) for females and 45 cm (range 28-102 cm) for males. Both sexes reach sexual maturity at age 3 (59-61 cm PCL for females and 60-615 cm PCL for males) (Loefer and Sedberry, 2003).

This species reproduces annually with mating occurring between late spring and early summer, followed by an offshore migration of females during their 11 month gestation period (Castro, 1993; Loefer and Sedberry, 2003). Females migrate inshore to give birth in shallow areas (<9 m deep) from North Carolina to central Florida (Castro, 1993), where pups (litter size range is 1-8, mean: 4) are born from mid-May to early June (Loefer and Sedberry, 2003). Many nursery areas occur in estuarine habitats of South Carolina (Castro, 1993).

Two defined stocks of Atlantic sharpnose shark are believed to exist: an Atlantic stock (North Carolina to the Straits of Florida and a Gulf of Mexico stock (Florida Keys throughout the Gulf of Mexico) (SEDAR, 2007b). Although sharks from these two regions are not genetically different, these non-mixing groups differ substantially in life-history parameters (SEDAR, 2007b). Atlantic sharpnose sharks are one of the most frequent sharks caught in waters off northern Florida (Trent et al., 1997).

Blacknose shark

Blacknose sharks (*Carcharhinus acronotus*) are commonly found in coastal and offshore waters of the South Atlantic Bight. Fifty percent of the male and female blacknose sharks reach maturity at fork lengths (FL) of 896 and 964 mm, respectively, equivalent to ages of 4.3 and 4.5, respectively (Driggers et al., 2004). Data from specimens off South Carolina showed that mature males have fully developed testes and genital ducts during late spring, and that females have enlarged oviducal glands and uterine eggs between June and July–indicating that fertilization occurs during this latter period (Driggers et al., 2004). Females reproduce biennially and give birth to an average 3.3 pups per litter between May and June, following a gestation period of ~11 months. Nursery areas occur in shallow waters of South Carolina, where pups, juveniles, and adult females are abundant during the summer (Castro, 1993), and the presence of non-migratory individuals off Florida suggest the presence of nursery areas in the region (Navy, 2009). Blacknose sharks are one of the most frequent sharks caught in waters off the South Atlantic Bight (Trent et al., 1997).

Finetooth shark

Finetooth sharks (*Carcharhinus isodon*) of all age classes are common in shallow estuarine and coastal waters of South Carolina between May and September. Finetooth give birth off the Carolinas between May and June, with juveniles entering nursery areas in South Carolina in the spring (Castro, 1993). The maximum observed ages in the South Atlantic, based on vertebral band counts, were 10.3 years for male sharks and 12.3 years for female sharks. Females give birth to an average of 4 pups per year (SEDAR, 2007b).

The following "Highly Migratory Species" have limited life-history information specific to the study area: Atlantic bigeye tuna (*Thunnus obesus*); yellowfin tuna (*T. albacares*); great

hammerhead shark (*Sphyrna mokarran*); scalloped hammerhead shark (*S. lewini*); tiger shark (*Galeocerdo cuvier*); bigeye sand tiger shark (*Odontaspis noronhai*); nurse shark (*Ginglymostoma cirratum*); lemon shark (*Negaprion brevirostris*); longfin mako shark (*Isurus paucus*); sand tiger shark (*Carcharias taurus*); white shark (*Carcharodon carcharias*); bignose shark (*Carcharhinus altimus*); bull shark (*C. leucas*); night shark (*C. signatus*); oceanic whitetip shark (*C. longimanus*); and sand silky shark (*C. falciformis*).

OTHER MIGRATORY SPECIES

Blue marlin

Blue marlin (*Makaira nigricans*) are an epipelagic and oceanic species typically inhabiting deep waters at temperature of 22-31 °C (see Navy, 2009). Blue marlin are solitary and undergo migrations (trans-equatorial and trans-Atlantic) in response to fluctuations in sea surface water temperatures. In the South Atlantic high densities occur from January to April with peak occurring off Florida between May and June (Navy, 2009).

Bluefish

Bluefish (*Pomatomus saltatrix*) are migratory coastal pelagics abundant in estuarine and shallow waters of the continental shelf and found in offshore habitats at temperatures above 13ºC (Navy, 2009; Oliver et al., 1989). High concentrations of bluefish larvae occur along the South Atlantic Bight particularly near the edge of the continental shelf off South Carolina and in waters of the Gulf Stream (Hare and Cowen, 1996; Kendall and Walford, 1979), primarily at 17-26 °C and 35-38 (Kendall and Walford, 1979). Juveniles, on the other hand, are rather scarce in open waters indicating high dependency of estuarine and nearshore habitats at least during their first summer (Kendall and Walford, 1979). Juvenile recruitment to estuaries is largely controlled by the dynamics of the Gulf Stream's water mass–the presence of warm-core ring streamer activity (i.e., large anticyclonic eddies) and dissipation of the thermal barrier of the surface shelf-slope temperature front (Hare and Cowen, 1996).

Two morphometrically different stocks have been identified along the Atlantic coast: one stock spawns during the summer in the Middle Atlantic, while the other spawns during the spring at the margin of the Gulf Stream in the South Atlantic (Oliver et al., 1989). Bluefish are multiple spawners with indeterminate fecundity and asynchronous oocyte development (Robillard et al., 2008). Females are sexually mature at 1.90 years and 480 mm TL, and have fecundities ranging from 114,513 to 920,746 eggs (mean 402,247 eggs) (Robillard et al., 2008). Large spawning areas occur between South Carolina and Florida at 20-26ºC and 35-38 salinities, with high spring concentration of larvae in nearshore waters of Charleston, SC and in the upper 6 m of waters of the outer edge of the continental shelf (Oliver et al., 1989). Large larvae concentrations off South Carolina indicate the presence of spring-spawning aggregations near the western edge of the Gulf Stream, consistent with a northward migration of adults from their wintering grounds (Kendall and Walford, 1979). High inter-annual variations in spawning in the South Atlantic Bight are largely explained by several concurrent factors: temperature, salinity, photoperiod, and food for the adults (Kendall and Walford, 1979). McBride et al. (1993) documented spring-spawned bluefish in waters of Breech Inlet, SC (age 51-62 days and 40-58 mm FL) between April and June, and in waters of North Inlet, SC (age 92±12 days and 113±7 mm FL) in July; and summer-spawned bluefish (<150-170 mm FL) in shelf waters in October. The latter group is

believed to be cohort spawned in waters of the Middle Atlantic Bight. Another study (Murt and Juanes, 2009) identified three clear cohorts recruiting to estuaries and nearshore waters of northern Florida: the spring-spawned cohort hatching in April; the summer-spawned hatching in August; and fall-spawned cohort hatching in October. Of these three cohorts, the fall-spawned is the only cohort known to recruit to estuarine and nearshore waters during winter, a cohort that has not been documented in the Middle Atlantic Bight (Murt and Juanes, 2009). This study also documented young-of-the-year growth rates ranging between 1.35-1.52 mm/day, through growth rates of juveniles vary considerably across years, cohorts and locations.

Juveniles and adults move north of the South Atlantic Bight towards the warmer months (spring and summer) where they concentrate in the northern portions of the Middle Atlantic. Their southern migration to overwinter grounds in waters off the Florida coast is triggered when water temperatures drop below 15 °C (Murt and Juanes, 2009; Oliver et al., 1989). Consistently, tagging studies in South Carolina between 1974 and 1992 indicated a mean travel distance of 194 km (range 0-639 km) between tagging and recapture locations, with northern recaptures occurring during summer and fall, and southern recaptures occurring during winter (Davy, 1994). Specimens from the South Atlantic (n=852) collected in the early 1980s were ≤4 years old and ≤600 mm long (Barger, 1990).

There is limited life-history information specific to the study area for the following species: longbill spearfish (*Tetrapturus pfluegeri*); white marlin (*T. albidus*); and sailfish (*Istiophorus platypterus*).

OTHER SPECIES

Smalltooth sawfish

Smalltooth sawfish (*Pristis pectinata*) live in shallow subtropical-tropical inshore and marine waters. Early life stages are most common in shallow waters (~1 m deep), while adults are most common in deeper waters (>70-122 m depth) (Navy, 2009). Recent reports suggest that northern migrations from Florida waters are no longer occurring as supported by low-to-no encounters off Georgia and South Carolina (National Marine Fisheries Service, 2006; Navy, 2009).

Red drum

Red drum (*Sciaenops ocellatus*) are estuarine-dependent, being found in marine nearshore and estuarine habitats on sandy bottoms, with a distribution ranging from Massachusetts to Florida (Vaughan, 1992). Larvae and juveniles are found on the bottom of intertidal and estuarine waters, while late juveniles prefer deeper waters (Vaughan, 1992). Although most of its life cycle is spent in estuarine and coastal waters, sexually mature adults undergo seasonal inshore movements and occupy deeper waters of the surf zone and nearshore live/hard-bottom and artificial reefs (40-70 m deep) (SAFMC, 1998a; Vaughan, 1992). Females mature at age 4 and represent ~61% of the population (Vaughan, 1992). Tagging studies from 1974 to 1992 in South Carolina indicated that adults and most small red drum did not travel far from the tagging location (mean distance 0.74 km), except for a few small red drum which moved as far as 333 km (Davy, 1994). The same study reported growth rates of 3.2 cm a month during the first year.

Menhaden

Atlantic menhaden (*Brevoortia tyrannus*) are an estuarine-dependent species that takes seasonal migrations along the coast (Vaughan, 1992). During summer adults are most common in the northern South Atlantic Bight (Dryfoos et al., 1973), while in the fall they migrate south and disperse throughout the Bight. Early winter marks the northern migration to spawning grounds off the shelf of the northern South Atlantic Bight, where spawning occurs between December and January (Lewis et al., 1987). Checkley et al. (1988) documented that menhaden have evolved to reproduce under physical conditions (winter storms, offshore upwelling, and strong cross-shelf circulation) that ensure the survival, rapid development (abundant food sources and warm temperatures), and shoreward transport of eggs and larvae to estuarine nursery areas. The high fecundity and low parental care explain the presence of undeveloped-hatched larvae, which require food-rich waters to survive because of their inability to move in search of food (Rogers and Van Den Avyle, 1983). The average age of larvae immigrating into South Atlantic Bight estuaries is about 60 days (range 40-100 days) (Warlen, 1994). Juveniles (29-42 mm) are frequent between June and September in estuarine habitats with salinities of 0.5-16.8, and water temperature of 28.4-30.8 °C (Dahlberg, 1972). Though Atlantic menhaden live up to 10 years, most fish caught are age ≤3 (National Marine Fisheries Service, 2009a). This species has experienced steady declines in recruitment most likely due to environmental pressures (e.g., increased predation, degraded water quality) (National Marine Fisheries Service, 2009a)

Round scad

Round scad (*Decapterus punctatus*) are one of the most abundant pelagic species in waters of the South Atlantic Bight (<55 m depth) during summer and fall, but restricted to deeper (28-110 m) and warmer (>15 °C) waters during the rest of the year (Hales, 1987). This species shows segregation of age classes in the water column, with larger occurrence of juveniles in shallow waters (19-27 m) and increased dominance of adults in deeper waters (<110 m). Both male and female reach sexual maturity at around 150 days and fork length of 110 mm, with ripe individuals occurring between March and August. Adult inshore migration occurs during the spawning season. Annual female fecundity is variable and ranges between 6,200 and 51,000 eggs per female (Hales, 1987).

Sand perch

Sand perch (*Decapterus formosum*) are widely distributed in high salinity (35-36) waters of the continental shelf at <60 m depths (range 9-84 m), and they are found on offshore snapper and grouper banks of Florida (Sedberry et al., 2006). Specimens collected in the South Atlantic range in ages between 0 and 8 years (mean 2.3 years), with minimum age at maturity of 12 months for ovarian tissue and 5 months for testicular tissue (Bubley and Pashuk, 2010). The gonads of this species contain simultaneously ovarian and testicular tissues (simultaneous hermaphrodite) separated by a thin basement membrane, releasing mature sperm and eggs through separate ducts (Bubley and Pashuk, 2010). Spawning events last 2 days for a maximum of 168 events per year, with spawning females found between March and January (peak May) at depths of 17-47 m and bottom temperatures of 14-28.5 °C (Sedberry et al., 2006; Bubley and Pashuk, 2010). Sand perch do not undergo large-scale migrations, but juveniles and adults leave inshore waters in winter returning in spring.

Blackbelly rosefish

Blackbelly rosefish (*Helicolenus dactylopterus*) are found between 38 and 686 m over hard bottom. Off the Carolinas this species occupies the continental slope intermingling habitats occupied by snowy grouper, tilefishes, and wreckfish (White et al., 1998), and has been found associated with deep-sea corals (Ross and Quattrini 2007, 2009). White et al. (1998) reported a longevity range of 7-30 years (165-412 mm TL), with mean age of 16 years (~296 mm TL). Their reproductive strategy appears to be intermediate between oviparity and viviparity (zygoparous). This species undergoes delayed fertilization 1-3 months post insemination (from July to December, with peak between September and November), followed by extrusion of embryos in a gelatinous matrix (from December and April, with peak between February and March). Males appear to be more abundant than females (1 M:0.6 F sex ratio) at lengths >250 mm TL, with slight increase in female abundance from September to October, corresponding to the male spawning peak. Spawning of blackbelly rosefish occurs at depths of 229-238 m between December and April (peak January-April) (Sedberry et al., 2006)

Barrelfish

The barrelfish (*Hyperoglyphe perciformis*) are a deep-water species (>200 m) often caught as by-catch of the deep-water wreckfish in the vicinity of the Charleston Bump (Filer and Sedberry, 2008). By-catch specimens collected in waters off South Carolina and Georgia in 1995, 1997, and 2001-2006 indicated that the barrelfish has a life-history characteristic of deep-water fishes– long life span, slow growth, and high age at maturity (Filer and Sedberry, 2008). Analysis of over 800 specimens showed that age classes in waters around the Charleston Bump range between 5 to 85 years (mode 12 years). Histological samples suggested that females spawn from September to May (peak November to January), while males spawn year round (peak September to April). In these samples, the estimates mean of age at 50% female maturity was 6 years (95% CI: 4-7 years; 660 mm LF).

Diadromous species

Diadromous species play important ecological roles (trophic interactions, energy and nutrient export across habitats) throughout their distribution range (Greene et al., 2009). American shad, blueback herring, and hickory shad spend most of their lives in nearshore waters of the Atlantic Ocean, arriving to freshwater spawning grounds from Florida to South Carolina between late winter and early spring. Early juveniles migrate from freshwater to brackish waters, gradually moving, with growth, to higher salinity habitats (Greene et al., 2009). Other important anadromous species include striped bass and Atlantic sturgeon. Striped bass undergoes seasonal spawning migrations from marine waters to freshwater portions of estuaries and tributaries. Early life stages (0-2 years) inhabit the same areas of spawning adults, while older juveniles are found in higher salinity areas (estuaries and the nearshore) (Greene et al., 2009). The Atlantic sturgeon is common in coastal waters and less frequent in shelf waters at depths up to 50 m (Van Den Avyle, 1984). Adults utilize a wide range of coastal habitats including freshwater, brackish, estuarine, and nearshore waters. They spawn in rivers with large coastal migrations occurring in February (Van Den Avyle, 1984). The eggs are demersal and adhere to hard surfaces, while the juveniles prefer tidally influenced nursery areas (1-5) characterized by hard sand or shell substrates. Immature adults move out to sea where they can live up to 25 years. Information on their distribution at sea, habitat preferences, and diet are largely unknown (Van Den Avyle, 1984). However, the Atlantic sturgeon is thought to reduce competition by feeding

opportunistically while avoiding predation with the development of a strong armor (Van Den Avyle, 1984). A valid stock assessment for this species is urgently needed as part of its management process, as the Atlantic sturgeon is currently considered for listing under the Endangered Species Act (Collins, 2010). A catadromous species found in waters of the South Atlantic Bight is the American eel, a species thought to spawn in the Sargasso Sea between winter and spring. Its larvae metamorphose into glass eels in open waters while drifting towards the continental shelf. Its metamorphosis (from glass eels to the elver life stage to the silver phase) continues in brackish and freshwater habitats where they spend most of their life before migrating offshore for a single spawning event. This species is believed to comprise one panmictic population (Greene et al., 2009).

APPENDIX 7-A2 TROPHIC INTERACTIONS OF SELECTED SPECIES

The paragraphs below focus primarily on species inhabiting the study area whose feeding ecology have been reported. *Note:* Not all available literature was reviewed.

Gag

Gag undergo clear ontogenetic changes in diet from planktonic to piscivorous with changes in feeding morphology (Mullaney, 1994; Mullaney and Gale, 1996). Small fish (<20 mm) eat predominantly neritic calanoid copepods and gammaridean amphipods, shifting to a larger prey (decapods and fish) with growth. Juveniles feed primarily on crustaceans and begin to consume fishes when they reach about 25 mm in length (Bullock and Smith, 1991; Mullaney, 1994; Ross and Moser, 1995). This shift in prey selection, and a dominance of larger prey, is the result of increased mouth size, number of gill rakers, and tooth morphology (Mullaney and Gale, 1996). Adult gag feed on fishes but also crabs, shrimps, and cephalopods (Heemstra and Randall, 1993), and often forage in small groups far from the reef ledge (Bullock and Smith, 1991).

Black sea bass

The diet of black sea bass is comprised of 220 species, where the main food prey consists of motile epifaunal amphipods (caprellids and tube dwellers) and decapods (brachyurans), and fishes (Sedberry, 1988). This carnivorous bottom-feeder exhibits changes in feeding preferences (i.e., prey size and occurrence of fish increase with size) with ontogeny (Sedberry, 1988). Small fish eat a larger proportion of small crustaceans (mainly amphipods but also mysids, isopods, small decapods), while large fish feed on decapods (primarily brachyurans) and fishes (Mercer, 1989; Sedberry, 1988). Black sea bass (50->250 mm SL; n=313) collected from live-bottom reefs on the continental shelf fed exclusively on these reefs and were highly dependent on the feeding resources available within these habitats (Sedberry, 1988). However they preyed on organisms not frequently consumed by other demersal predator species. Their diet overlaps with southern porgy and to a lesser degree with the diet of pinfish and sheepshead (Sedberry, 1988).

Tomtate

The tomtate has a diverse diet comprised of about 120 species, but largely dominated by polychaetes and amphipods (Sedberry, 1985). Prey item composition varies according to the age class, with smaller individuals (1-100 mm SL) consuming small crustaceans (copepods) as well as fishes and decapods, medium size individuals (101-150 mm SL) consuming mostly amphipods and polychaetes, and larger individuals (151-200 mm SL) consuming mollusks

(pelecypods) and fish-like invertebrates (cephalochordates). Although this species is highly abundant on hard-bottom habitats, its diet is not restricted to this habitat, as much of its prey is comprised of pelagic species (e.g., brachyuran, crustacean larvae, copepods) and benthic invertebrates from soft sediments (e.g., polychaetes, bivalves). The diet composition of tomtate suggests an active nocturnal feeding outside hard-bottom and reef habitats (Sedberry, 1985; SCWMRD and GDNR, 1984).

Vermilion snapper

The diet of vermilion snapper includes 115-199 prey species and is largely dominated by small pelagic and epibenthic fauna (Grimes, 1979; SCWMRD and GDNR, 1982; Sedberry and Cuellar, 1993). Ontogenetic changes in diet have been documented in this species (Grimes, 1979; Sedberry and Cuellar, 1993), with smaller fish preying predominantly on small crustaceans (hyperiid and caprellid amphipods, copepods, and decapods), and larger fish ingesting prey of larger size (crustaceans, Spanish sardine, squid, and cumaceans). For example, small individuals (100 mm TL) feed on copepods (67% by volume) and nematodes (10% by volume), intermediate juveniles (100-175 mm TL) feed mostly on fish scales (68% by volume) and copepods (14% by volume), while juveniles (100-175 mm TL) feed on larger pelagic prey (gastropods 9% by volume and cephalopods 9% by volume; Grimes, 1979). Changes in diet also vary by season, depth, and time of day (Grimes, 1979). For instance, decapods (e.g., *Leptochela papulata* and *Lucifer faxoni*) comprised over 90% (by volume) of the winter diet, while fishes were the dominant prey during the rest of the year (SCWMRD and GDNR, 1982). Vermilion snapper do not depend on reef habitats for food, providing an important pathway for transporting energy and nutrients between reefs and the water surface (Sedberry and Cuellar, 1993).

Red porgy

The diet of the red porgy, regardless of life stage, is dominated by obligate benthic fauna and organisms living near the bottom. Small juveniles (46-64 mm TL) feed exclusively on small crustaceans (amphipods, copepods, isopods), as well as on stomatopods, and annelids; larger juveniles (130-162 mm TL) and adults feed on larger prey, predominantly on crustaceans (crabs), mollusks, and echinoderms, with fish (e.g., lined seahorse *Hippocampus erectus* and pipefish *Syngnathus* spp.) comprising a smaller fraction of their diet (Manooch, 1977). However, others (SCWMRD and GDNR, 1982) reported that fishes (e.g., round scad, Spanish sardine) comprise >75% (by volume) of the red porgy's diet. These discrepancies in reported prey, as well as changes in the seasonal composition of their diet, likely reflect the spatial and temporal occurrence of the prey (Manooch, 1977). The feeding strategy of red porgy (i.e., fast feeding, prey sorting, and strong crushing teeth) added to its opportunistic feeding probably contributes to its successful occurrence on the outer continental shelf (Manooch, 1977).

Southern porgy

The diet of southern porgy is mainly comprised of amphipods (corophoid *Erichthonius brasiliensis* and the caprellids *Phtisica marina* and *Caprella equilibra*) and polychaetes (~30 species), although decapods, copepods, and chaetognaths are also frequent prey items (SCWMRD and GDNR, 1982, 1984). Even though this species forages extensively on sand bottom, its diet is not dominated by sand-bottom organisms. The diet composition of this species varies greatly with seasonal changes in the abundance of prey (SCWMRD and GDNR, 1982), and it overlaps that of tomtate.

Whitebone porgy

The diet of the whitebone porgy overlaps that of sheepshead and red porgy. They feed primarily on pagurid decapods (*Pagurus* spp., *Dardanus* spp., *Paguristes* spp., *Pylopagurus* spp.) and on a small hard-shelled gastropod *Aspidosiphon gosnoldi*, as well as on sipunculids. Other important diet consisted of polychaetes, pelecypods, barnacles, and fishes (Sedberry, 1989). Diets seem to change slightly with increased size, which is unusual for sparid fishes. For example, larger whitebone porgy ingested fishes of larger size and in larger proportions than younger fish. Seasonal variations in diet composition seem to reflect prey availability, though decapods and gastropods were a frequent prey item throughout the year (Sedberry, 1989). Whitebone porgy appears to be a selective feeder as it forages on invertebrate characteristic of sand bottom substrates, suggesting that this species does not forage directly on the hard-bottom reefs where it inhabits (Sedberry, 1989).

Greater and almaco amberjack

The greater amberjack (397-1,386 mm TL) and almaco jack (276-1,094 mm TL) are large predators that feed primarily on fish inhabiting the open ocean or reefs (75-85% of their diet), although cephalopods (Loliginidae and Octopodidae) and crustaceans are also important. Families of fish important in their diet (by frequency) include Clupeidae (25%), Bothidae (8%), Serranidae (5%), Balistidae (4%), and Sparidae (4%) for greater amberjack, and Serranidae (8.5%), Synodontidae (4%), Scombridae (4%), and Balistidae (4%) for almaco jack (Manooch and Haimovici, 1983).

Wreckfish

Stomach contents of wreckfish indicated that squid (northern shortfin squid *Illex illecebrosus*) contributes up to 47% of their prey items (65% of the stomachs), followed by fishes (longnose lancetfish *Alepisaurus ferox,* snipe eel *Avocettina infans,* gulper eel *Eurypharynx pelecanoides*, and fangtooth *Anoplogaster cornuta*) which contributed 42% of their prey items (57% of the stomachs) (Weaver and Sedberry, 2001). Other less common prey items also includes golden crab (*Chaceon fenneri*), the bathyl swimming crab (*Bathynectes longispina*), and small sharks (black dogfish *Centroscyllium fabricii* and lantern sharks *Etmopterus* spp.) (Weaver and Sedberry, 2001). A more recent study (Goldman and Sedberry, 2011) also highlighted the importance of cephalopods and teleosts in the diet of wreckfish (>95% of the diet), and documented high frequency of cephalopods in fall, and high numbers of teleosts in spring. Variations in the occurrence of prey items throughout the seasons reflect the opportunistic feeding behavior of this species (Goldman and Sedberry, 2011).

Grey tilefish

Grey tilefish (*Caulolatilus microps*) are members of the shelf-edge demersal fish community, typically found at depths >65 m. Of the 34 invertebrate families found in specimens (400 and 780 mm TL) of North and South Carolina at 65-236 m depths, decapod crustaceans were the most common prey item (78.1% of the intestines and 60% of the stomachs) (Ross, 1982). Important decapod crustaceans included portunids (e.g., *Portunus spinicarpus*), callapids, and porcellanids. Natantian decapods were also frequent in their diet, occurring frequently in intestines (41.5%), while shrimp and fish appeared in high frequencies in stomachs. Fish identified in their diet included members of the Bothidae family (e.g., *Gymnothorax* spp.,

Synodus spp., and *Porichthys porosissimus*), as well as moray eels and lizard fish. Other prey items included, in order of importance, echinoderms (holothurians, echinoids, stelleroids), polychaetes (families Eunicidae and Sabellaridae), ascideans, molluscs (gastropods and bivalves), stomatopods, and sipunculids. Ontogenetic differences in diet were observed only in prey fish (17.6% for 400-500 mm TL to 37.5% for 700+ mm TL), but not with decapods crustaceans. This species co-occurs with species occupying a similar trophic level, such as snowy grouper and tilefish (Low, 2000).

Spanish and King mackerel

The large eyes of scombrids, even during the larval stage, suggest that they are visual predators. Light cycles strongly influence predatory behavior (e.g., dial vertical migrations) and detection, along with fluctuations in temperature (see Peters and Schmidt, 1997). Spanish mackerel and other species of *Scomberomorus* are known to feed on ichthyoplankton during the larval stage and are almost completely piscivorous as juveniles. King mackerels feed on a variety of small schooling pelagic fishes. Important food items include members of the clupeids (anchovies), carangids (round scad, blue runner, and Atlantic bumper), sciaenids, trichiurids, exocoetids, engraulids, and scombrids for the 100-150 mm FL size range (Saloman and Naughton, 1983). Of these fishes, clupeids were the only important family in the diet of King mackerel (0-1,599 mm FL; n=6,977) from shelf areas between North Carolina and Florida (Saloman and Naughton, 1983).

Dolphin

Manooch et al. (1984) analyzed the stomach contents of 2,219 dolphin ranging in lengths from 250 to 1,530 mm FL. Fishes were the most common (77.6 % of the stomachs), followed by miscellaneous items (plant material, plastics; 50.6 % of the stomachs) and invertebrates (27.5 % of the stomachs). The fish diet included a total of 34 families and 55 species of all age classes, with a high frequency of juvenile balistids (32% of the stomachs) of at least seven species. Carangids were the second most common group of fishes (10% of the stomachs), which included 14 genera (*Caranx, Chloroscombrus*, *Decapterus*, *Hemicaranx*, *Setar*, *Selene*, *Seriola*, *Trachinotus*, and *Uraspis*). Invertebrates were more important in the diet of smaller dolphins, while fish were the dominant diet in larger individuals. Manooch et al. (1984) stated that changes in diet diversity differed across seasons and area of collection, indicating food availability differences, and that the presence of several young-of-year found in 1.6% of the stomachs indicated cannibalism. *Sargassum* is also a relatively frequent food item in intestine tracts, suggesting certain level of dependency and active foraging behavior of this species on fauna associated with this habitat (Manooch et al., 1984; Casazza, 2009). Juveniles, for instance, were found to feed on fish (primarily *Decapterus* spp.) and copepods (primarily *Pontella atlantica*) (Casazza, 2009).

Wahoo

Stomach content analysis of 885 wahoo collected between 1965 and 1981 found that the diet of nearly half of these specimens was largely comprised of pelagic fish (92% of prey items) (Manooch and Hogarth, 1983). The most common fishes included fast-swimming members of the Scombridae (23%), Diodontidae (13%), Exocoetidae (7%) and Clupeidae (8%) families, as well as families associated with *Sargassum*. Representative species included round herring (*Etrumeus teres*), Atlantic flyingfish (*Cypselurus melanurus*) and frigate mackerel (*Auxis*

thazard), juvenile carangids and balistids, butterfish (*Peprilus triacanthus*), and porcupinefish (*Diodon hystrix*). Squid (*Loligo* spp.) was the only invertebrate relatively frequent in stomach contents (9% of stomachs). Wahoo consumed large offshore epipelagic fish, and prey size did not change with the size of wahoo. Unlike several sympatric species, wahoo did not eat small items, nor did they feed as readily at the surface.

Little tunny

Little tunny (172 to 885 mm FL; n=2,124) collected from waters of the southeastern US and the Gulf of Mexico have a diet composition that varies with size, season and sampling location (Manooch et al., 1985). Fishes are the most important prey items (66.9 % of the stomachs; 23 species), followed by invertebrates (30.5 % of the stomachs; e.g., squid, stomatopods, penaeids). Little tunny feed primarily on mid-water and pelagic species, mostly c1upeids (e.g., *Brevoortia patronus* and *Sardinella aurita*), engraulids (e.g., *Anchoa mitchilli* and *Anchoa hepsetus*), and carangids (e.g., *Caranx, Chloroscombrus, Decapterus,* and *Seriola*), although many juveniles (Synodontidae, Batrachoidae, Chaetodontidae, Pomacentridae, Triglidae, Bothidae, Balistidae, Tetraodontidae, and Diodontidae) are also part of their diet. Fish are the predominant diet in larger tunny (≥500 mm FL), while invertebrates are a more important prey in smaller fish (<500 mm FL). Fish are a more predominant diet item during summer and fall, while invertebrates are more common in winter.

Bluefish

Larvae and juveniles of bluefish feed primarily on invertebrates (eggs and copepods), while adults are visual predators feeding during daylight on fish (e.g., anchovies, menhaden, scup, flounder, sheepshead, red drum) (Oliver et al., 1989). A more recent study found that the winter and summer diet of young-of-the-year (50-80 mm FL) was almost entirely comprised of fish (94-100% of prey) (Murt and Juanes, 2005).

APPENDIX 7-A3 CURRENT STATUS OF SELECTED SPECIES

The paragraphs below focus primarily on species inhabiting the study area whose status have been reported. *Note:* Not all available literature was reviewed.

Mutton snapper

In the 1980s and 1990 mutton snapper reached low fish abundance, biomass, and spawning stock biomass levels that since have increased steadily to 6,140, 9,570, 7,150 metric tons, respectively, in 2006, (SEDAR, 2008c). Stock assessments indicated that by 2006 the stock was not overfished, but that there was a moderate probability that the stock could be overfished (SEDAR, 2008c). Increases in the recreational fishing mortality rate adds to the concern regarding the status of the stock.

Vermilion snapper

Vermilion snapper (*Rhomboplites aurorubens*) is one of the most important finfish species of the fisheries in Georgia and South Carolina (Manooch et al., 1998b). Analysis of 1979-1993 fish data from the South Atlantic Bight found declines in both age and total length at sexual maturity indicative of increased fishing pressure (i.e., selective removal and removal of superior genotypes) (Zhao and McGovern, 1997). Between 1979-1981 and 1985-1987, the median total length at maturity decreased from 160 mm to 151 mm in females, and from 145 mm to 140 mm in males. By contrast, the percentage of mature males at age 1 increased from 63.6% to 100% in males, and from 48.6% to ~98% in females. Manooch et al. (1998b) also examined commercial, recreational, and headboat fisheries records (1986-1996) from south of Cape Hatteras, North Carolina to the Florida Keys and found that commercial and headboat fishery in the Carolinas consistently recorded the largest contribution (70% and 81-88%, respectively) of the total vermilion snapper landing (average 538 and 147 metric tons/year, respectively). Between 1992 and 1996, commercial landings decreased by nearly half (from 640 to 344 metric tons). However, the mean size landed did not change drastically within the 1986-1996 period. They also found that 80% of the specimens caught in commercial, headboat, and recreational fishing were females. Data from the 1990s suggested that the vermilion snapper stock was in a less than desirable condition, but that it appeared to be responding to management regulations (Manooch et al., 1998b). However, a more recent study found low number of recruits indicative of poor recruitment (Harris and Machowski, 2004). The current SEDAR assessment for vermilion snapper states that the stock was undergoing overfishing, but that there was a high level of uncertainty in the overfished condition as the stock recruitment relationship was poorly defined (SEDAR, 2003b; 2008e). Continuing overfishing at the current rates would lead to a stock currently at, or approaching overfishing (SEDAR, 2007a). Studies also have shown high discard rates of this species in fisheries that co-occur with other targeted species, and 48% immediate release mortality (Stephen and Harris, 2010).

Tilefish

Prior to the 1980s, the tilefish population in the South Atlantic Bight was virtually unexploited (Harris and Grossman, 1985). In 1982, fishing removed 37% of the population (Hightower and Grossman, 1989; Harris et al., 2001; Low et al., 1983), and over a few years, this population shifted from a virgin to an exploited population. Data on annual exploitation in the late 1980s revealed an estimated commercial catch slightly below the annual maximum sustainable yield for the population off South Carolina and Georgia (Low et al., 1983), suggesting unsustainable

fishing practices. Between 1980 and 1985 tilefish landings were on average 35 times higher than those between 1858 and 1979, except for 1982 when landings were 87 times higher (Harris et al., 2001). Fishery data off South Carolina and Georgia showed a decline in independent catch per unit effort from 6.2 fish/100 hooks in 1983 to 2.4 fish/100 hooks in 1986, as well as a 28 cm decrease in the mean total length of tilefish from 1977 to 1985 (Barans and Stender, 1993). A study on the status of this species off South Carolina and Georgia estimated a stock size of 200-600 metric tons, which is below the recommended level (400-800 metric tons) that would support an annual harvest of 50 tons (Hightower and Grossman, 1989). The tilefish population shows symptoms of severe overfishing: 1) skewed sex ratios favoring smaller females (1:1 M:F in 1980-1987 vs. 1:1.34 M:F in 1996-1998); 2) decreased length at age (11% of specimens >900 mm TL in 1980-1987 vs. 2.5% of specimens >900 mm TL in 1996-1998; or from 720 mm to 625 mm between the two periods); 3) decreased mean age (from 8.8 years in 1980-1986 to 8.2 years in 1996-1998 ; and 4) reduced landings (1,600 metric tons in 1982 vs. <400 metric tons after 1995) (Harris et al., 2001; Palmer et al., 2004). These changes, particularly those impacting females, suggest a potential reduction of the reproductive potential of the population. High risk of tilefish overfishing results from inherent biological characteristics of this species: long lived, slow growing, delayed age at sexual maturity, and shelter-dependent, therefore relatively sedentary behavior (Hightower and Grossman, 1989; Harris et al., 2001). This species is non-migratory (Freeman and Turner, 1977) further suggesting that recruitment from resident adults can be compromised by overfishing this age class. The current assessment indicated that the stock was not overfished but overfishing was occurring (SEDAR, 2004).

Tomtate

Tomtate are abundant in trawl catches over low relief, live-bottom habitats (Manooch and Barans, 1982). Standing crop estimates of the tomtate between Cape Fear and Cape Canaveral ranged between 1,730 (summer 1974) and 12,878 metric tons (winter 1976) (Manooch and Barans, 1982). Trap catches of this species increased between 1983 and 1996 in the South Atlantic Bight, which are indicative of the decline of known predators (Arendt et al., 2009). This species is discarded in fisheries that co-occur with other targeted species (e.g., vermilion snapper) and experience high immediate release mortality (72%) (Stephen and Harris, 2010).

Red drum

Red drum is one of the most common species in recreational fishing. Coastal catches from recreational fishing (Florida to North Carolina) have decreased steadily from a peak average of 988 metric tons in 1984 to 232 metric tons in 1990. The same pattern was observed in commercial landings, which decreased from a peak average of 192 metric tons in 1984 to 85 metric tons in 1990. The Atlantic population (Florida to North Carolina) may be overfished, and recruitment to the adult population may be limited by high subadult fishing mortality (ages 1-4) (Vaughan, 1992) currently estimated to range between 10-30% (Latour et al., 2001). These effects may be further compounded by a high catch and release rate (75% of total catches between 2000 and 2005), which may lead to an additional 2-10% increase in subadult mortality (Vecchio and Wenner, 2007). Current management strategies have banned red drum fishing within Federal waters to allow for increase abundance in the adult population (National Marine Fisheries Service, 2009a). The red drum stock in the South Atlantic region is likely not experiencing overfishing (SEDAR, 2009b).

Wreckfish

When wreckfish were first discovered, commercial monthly landings increased from 4 metric tons in 1987 up to 100 metric tons three years later (Sedberry et al., 1999). Data from the Blake Plateau (1991-1998) indicated that South Carolina and Florida contributed to 51% and 42%, respectively, of the total fish landed (Vaughan et al., 2001). Recruitment steady declined from 1988 to 1994 (~30,000-60,000 to <10,000 recruits at age 7, respectively), but increased slightly afterwards (<20,000 recruits at age 7 in 1998) (Vaughan et al., 2001). This population experienced a decline in the stock biomass (weight of the population at ages +7) from its high values in 1988-1989 (5,670-8,165 metric tons – based on annual catch estimates) to its lowest values in 1997 (<1,134 metric tons – based on annual catch estimates) (Vaughan et al., 2001). Because of the global distribution of this species and complex life history over a wide geographic area, this species may require international management plans (Sedberry et al., 1999).

Red porgy

Red porgy (*Pagrus pagrus*) are much more abundant in South Carolina catches than in Georgia and Florida (Vaughan et al., 1992). A 20-year analysis of red porgy from the South Atlantic Bight showed that changes in life-history measures (e.g., reduced size at age and maturity; female to male transition at smaller sizes; reduced recruitment) may be the result of a resource overexploitation, which selectively removed individuals predisposed towards rapid growth and larger size (Harris and McGovern, 1997). Earlier studies found a decline in the population size (ages 1-10) from its peak in the mid-1970s (2,600 metric tons) to a minimum in 1986 (600 metric tons), a decrease in the spawning stock between these two periods (from 1,500 metric tons in 1977 to 500 metric tons in 1986), and a greater contribution of younger age classes to fishing landings (Vaughan et al., 1992). These trends provided earlier warning signals regarding the status of this population in the Carolinas. Despite decreases in population estimates and reduced length over time, Harris and Machowski (2004) found slight increases in abundance of small fish of the red porgy in the South Atlantic Bight, indicative of improved recruitment rates. However, this species continues to be discarded in substantial numbers in fisheries that co-occur with other targeted species (e.g., vermilion snapper), and experience high immediate release mortality (82%) (Stephen and Harris, 2010). The current SEDAR assessment for red porgy indicated that the stock was overfished, but overfishing was not occurring (SEDAR, 2002). An update of this assessment (SEDAR, 2006b), indicated that the spawning stock biomass increased from 41% in 2001 to 66% in 2006, and that the population is showing a positive rebuilding trend. The South Atlantic Council established a maximum allowable rebuilding time of 18 years, starting with the implementation of a no harvest emergency rule in September of 1999 (64 FR 48324) until December 31, 2017 (SAFMC, 2000).

Red grouper

The red grouper fishery has been managed as two separate stock units (Atlantic and Gulf of Mexico) on the bases of size, age structure, and growth rate differences between the two areas (SEDAR, 2010). Red grouper are commonly caught off North Carolina, northern South Carolina, and southern Florida, but are relatively rare between southern South Carolina and northern Florida (McGovern et al., 2002b). Landings between North Carolina and Florida increased from 1983 to 1995 reaching a peak of 94 metric tons, with Florida dominating the catch through the 1980s, and North Carolina through the 1990s (McGovern et al., 2002b). The southeast stock of red grouper is currently overfished and experiencing overfishing (SEDAR, 2010).

Snowy grouper

The snowy grouper (*Epinephelus niveatus*), a protogynous hermaphrodite species common in waters of the Carolinas, have also shown indications of overfishing (Wyanski et al., 2000). Evidences include an increase in size at age since the 1980s (possibly resulting from a density-dependent response to high fishing), an increase in frequency of individuals in the 1-6 age range (primarily immature females) in catches during the mid 1990s, a decline in number of males over a three decade period (1970-1980s=7-23% and 1990s=1%), and a decrease in the mean fish length (1980s=65-80 cm and mid-1990s=50-60 cm) (Wyanski et al., 2000). The current SEDAR assessment for snowy grouper indicated that the population was overfished and experiencing overfishing. In the absence of fishing it would take 13 years to rebuild the spawning stock biomass to produce the maximum sustainable yield. Under this assessment the maximum rebuilding time is 34 years (SEDAR, 2004).

Gag

Gag (*Mycteroperca microlepis*), another protogynous hermaphrodite and one of the most important commercial species, have also showed changes in life-history parameters indicative of increased fishing pressures (Harris and Collins, 2000). A comparison of gag samples collected in 1976-1982 and 1994-1995 across the South Atlantic Bight showed a significant reduction in the median age (1976-1982=7 years, 1994-1995=5 years), the number of individuals aged >10 years (1976-1982=17%, 1994-1995=%), the age at 50% maturity (1976-1982=3.8 years, 1994-1995=2.8 years), and a higher percentage of younger gag in the 1994-1995 period. Gag is likely sensitive to overfishing because it is more sedentary with increasing depth, and it forms large spawning aggregations (Gilmore and Jones, 1992; McGovern et al., 2005) exclusively on shelf-edge reefs (45-128 m) (McGovern et al., 1998a), which are areas heavily used for commercial and recreational fishing. Gilmore and Jones (1992) suggested that males are selectively removed from the population by fisherman during spawning because of their large size. McGovern et al. (1998a) also reported a reduced proportion of males in the South Atlantic Bight from 19.6% of the entire population in the early 1980s to 5.5% in the mid 1990s. These findings were confirmed by a more recent study (McGovern et al., 2005). Removal of males, which would translate into sperm limitation, in combination with reduced total fecundity caused by fewer large females, younger age at maturity, and younger mean age of the population, could result in significant reduction in reproductive capacity and lower recruitment, having large consequences on population fitness (Harris and Collins, 2000). In fact, an analysis of microsatellite variation in DNA samples from gag collected between North Carolina and Florida found reduced genetic frequency and heterozygosity deficiencies potentially indicative of population inbreeding resulting from declining population numbers and sex ratios skewed towards females (Chapman et al., 1999). Recent stock assessments of this population indicated that the spawning stock biomass declined from 6,622 metric tons in 1962 to 1,814 metric tons in 1990, with a positive rebound in 2004 and 2005 (3,175 and 3,357 metric tons, respectively) (SEDAR, 2006a). However, this stock is considered to be experiencing overfishing and approaching an overfishing condition (SEDAR, 2006a).

Black sea bass

Unlike other protogynous hermaphrodites, increased fishing pressure on the black sea bass up to the early 1990s had only minor effects on population characteristics (e.g., total length) (Vaughan et al., 1995). This apparent lack of impacts on population parameters relative to other sympatric reef species could be the result of males not being limited and a faster age at maturation (1 year) (Vaughan et al., 1995). The black sea bass population is currently managed as three separate stocks: Mid-Atlantic, South Atlantic, and Gulf of Mexico. Earlier estimates of black sea bass on reefs along the South Atlantic Bight reported relatively high densities (18.7 fish/ha, Sedberry and Van Dolah, 1984; 51 fish/ha, Powles and Barans, 1980; 70 fish/ha, Parker, 1990; 14-125 fish/ha, Wenner et al., 1986); however, the stock of this population has been in decline since the mid 1980s. Wenner et al. (1986) reported a ~89% and ~61% decline in abundance between 1981 and 1983, and between 1982 and 1983 at two reefs in the South Atlantic Bight, which were also reflected in the decrease of fish biomass. Stock assessments (1996, 2003, and 2005) by the South Atlantic Fishery Management Council also indicated that the black sea bass has been overfished. Recent analysis have further determined that recruitment has declined by 55% of the early 1980s levels, and that by 1995 modeled mature biomass has decline by 30% compared to 1978, remaining low through 2002 (SEDAR, 2003a). Model estimates indicate that fishing mortality needs to decrease by 87% (range 50-90%) of current levels to allow the recovery of the stock in 18 years (range 10-25 years; SEDAR, 2003a). An updated assessment (SEDAR Update #1, 2005) found that the black sea bass stock was overfished and overfishing was occurring. However, the biomass stock could be rebuilt to equilibrium conditions in 5 years at an instantaneous rate of fishing mortality of 0 (SEDAR Update #1, 2005). Unintended effects of current management regulations on this species include elevated discard rates in fisheries that co-occur with other targeted species (e.g., vermilion snapper), as well as moderate immediate release mortality (66%) (Stephen and Harris, 2010).

Red snapper

Commercial landings of red snapper along the east coast from North Carolina to Florida averaged 272 metric tons between 1951 and 1985, and declined to 83 metric tons between 1986 and 1995 (Manooch et al., 1998c). Both mean size and weights have generally increased since 1985 in commercial, headboat, and recreational fishing. In the late 1990s Manooch et al. (1998c) suggested that the red snapper stock was in a less than desirable condition, but that it appeared to be responding to imposed management regulations. Stock assessments reported a sharp decline of total biomass and spawning biomass during the 1950s and 1960s, continuing declines during the 1970s, and stable but low levels since 1980 (SEDAR, 2008a). The same analysis indicated that fish of age 10 and above are practically non-existent in the population. The stock of red snapper has been overfished since 1960, and overfishing is currently occurring. In an effort to reduce overfishing, recent regulations have prohibited the possession of red snapper in state and federal waters of the South Atlantic. However, this species is currently listed as unknown in terms of an overfished status (SEDAR, 2008a), and a stock assessment is underway to determine the status of the population. Other issues faced by this species include elevated discard rates in substantial numbers in fisheries that co-occur with other targeted species (e.g., vermilion snapper), and high immediate release mortality (>90%) (Stephen and Harris, 2010).

Greater amberjack

Greater amberjack have been managed as two separate units: the Atlantic and Gulf stocks (SEDAR, 2008b). Commercial and recreational fishing mortality increased from the 1980s through the mid-1990s, and steadily declined the 1990s to 2006. Stock assessments indicate that in 2006 the South Atlantic stock of greater amberjack was not overfished and was not experiencing overfishing (SEDAR, 2008b). Unintended effects of current management regulations on this species include substantial discard rates in fisheries that co-occur with other targeted species (e.g., vermilion snapper), and high immediate release mortality (>90%) (Stephen and Harris, 2010).

Scamp

An analysis of scamp (*Mycteroperca phenax*) data between 1986 and 1996 indicated that landings increased in the mid 1990s, and that minimum size limits positively influenced age-at-entry to the fisheries (e.g., recruitment age and age at entry to fisheries were 5 and 1 for the 1992-1996 period) (Manooch et al., 1998a). Harris et al. (2002) compared scamp collected from North Carolina to Cape Canaveral between two periods (1979-1989 and 1990-1997) and found that the median age, size at maturity, and age at maturity remained stable, but that the median length decreased by 40 mm TL. During the 1990s, the percent of scamp age ≥10 declined by 10% (17% in 1979-1989; 7% in 1990-1997), the proportion of males >500 mm TL in fisheries declined by 13% (34% in 1979-1989; 21% in 1990-1997), and mature scamp were significantly smaller (594 vs. 557 mm TL) and younger (5.6 vs. 4.9 yrs). Harris et al. (2002) concluded that reduced males in the population and reduced fecundity combined with increased fishing pressures can drive this population to unsustainable levels. This species is discarded in substantial numbers in fisheries that co-occur with other targeted species (e.g., vermilion snapper), and experience high immediate release mortality (>90%) (Stephen and Harris, 2010).

Highly Migratory Species

Two species of large coastal sharks (sandbar and blacktip sharks) have steadily declined since the early 1980s and are currently overfished, though improvements have been made since 1998 (National Marine Fisheries Service, 2009a). A recent assessment indicated that the stock of sandbar sharks was overfished, overfishing is occurring, and the target year to rebuild the stock was estimated to be 2070 (SEDAR, 2006c). By contrast, no reliable estimates of stock status for the Atlantic blacktip shark are available given the absence of reliable estimates of abundance, biomass, and exploitation rates (SEDAR, 2006c). A significant portion of small coastal shark (Atlantic sharpnose, bonnethead, blacknose, and finetooth sharks) catches between 1972 and 2005 was comprised of Atlantic sharpnose. However, stock assessment of Atlantic sharpnose and bonnethead sharks concluded that these stocks were not overfished nor was overfishing occurring (National Marine Fisheries Service, 2009a). By contrast, stock assessments of blacknose and finetooth sharks are ambiguous, thus cautious management has been recommended (National Marine Fisheries Service, 2009a). Nevertheless, assessments for blacknose sharks have indicated that the stock was overfished and that overfishing was occurring (SEDAR, 2007b).

Coastal migratory pelagics

Because of their broad distribution, coastal migratory pelagics (king mackerel, Spanish mackerel, dolphin, cobia, and cero) are co-managed by the South Atlantic Fishery Management Council and the Gulf of Mexico Fishery Management Council under the Coastal Migratory Pelagic

Resources Fishery Management Plan. Though not currently overfished, coastal migratory pelagics in the South Atlantic are being harvested near or at their maximum sustainable yield (National Marine Fisheries Service, 2009a).

Two stocks of Spanish and king mackerel stocks have been identified: the Gulf of Mexico and the Atlantic stocks (Sutter et al., 1991; National Marine Fisheries Service, 2009a; SEDAR, 2009a), with substantial mixing of the two stocks of king mackerel during winter (National Marine Fisheries Service, 2009a). Significant landings of king mackerel occur south of the study area (Cape Canaveral to Palm Beach). The South Atlantic king mackerel stock declined from its peak of 4,749 metric tons in 1982 to a low of 2,560 metric tons in 2002, consistent with a decreased of 45% in the spawning stock biomass since 1981 (SEDAR, 2009a). More recent estimates indicate a significant improvement of the stock, with landings reaching 2,600 tons in 2006 from its minimum numbers in 2002 (National Marine Fisheries Service, 2009a). In recent years, most of the commercial catch of Spanish mackerel (>70%) has been landed off Florida, and assessments indicate that this stock is considered to be at or near its full maximum fishery potential (National Marine Fisheries Service, 2009a). Current stock assessments indicate that South Atlantic stock of Spanish mackerel is not overfished (SEDAR, 2008d).

Annual yields of cobia in the US Atlantic ranged from 13 to 700 tons between 1981 and 2006 (National Marine Fisheries Service, 2009a). In waters of South Carolina, cobia represents a relatively small proportion of the commercial landings, falling below 10,000 pounds annually. This indicates that the fishery in South Carolina may have little impact on the cobia population (Hammond, 2001). However, the status of the cobia stock in the South Atlantic is currently unknown (Hammond, 2001; National Marine Fisheries Service, 2009a).

APPENDIX 7-B1: MISCELLANEOUS TABLES

Table 7-B1.1
Fish species associated with nearshore hard-bottom habitats in central and southeast Florida.

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Ginglymostomatidae	*Ginglymostoma cirratum*	X						X	X							X	X	X
Carcharhinidae	*Carcharhinus brevipinna*		X						X						X			X
	Carcharhinus leucas		X						X						X			X
	Carcharhinus limbatus		X						X						X			X
	Carcharhinus plumbeus		X						X						X			X
Sphyrnidae	*Sphyrna mokarran*		X						X						X			X
Rhinobatidae	*Rhinobatos lentiginosus*		X					X							X			X
Dasyatidae	*Dasyatis americana*		X					X							X			X
Myliobatidae	*Aetobatus narinari*		X					X							X			X
Urolophidae	*Urobatis jamaicensis*	X						X						X				X
Mobulidae	*Manta birostris*		X			X									X			
Elopidae	*Megalops atlanticus*		X						X						X			X
Muranenidae	*Echidna catenata*	X						X						X		X	X	X
	Enchelycore carychroa	X												X				X
	Gymnothorax funebris	X							X					X		X	X	X
	Gymnothorax moringa	X							X				X			X	X	X
	Gymnothorax vicinus	X							X					X		X	X	X
	Muraena miliaris	X							X				X			X	X	X
Ophichthidae	*Ahlia egmontis*	X							X				X			X	X	X
	Myrichthys breviceps	X							X					X				X
	Myrichthys ocellatus	X							X					X				X
Clupeidae	*Harengula clupeola*		X			X						X				X	X	X
	Harengula humeralis		X			X						X				X	X	X

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Clupeidae	*Harengula jaguana*		X			X						X				X	X	X
	Opisthonema oglinum		X			X						X				X	X	X
	Sardinella aurita		X			X					X					X	X	X
Engraulidae	*Anchoa cubana*		X			X					X					X	X	X
	Anchoa hepsetus		X			X					X					X	X	X
	Anchoa lyolepis		X			X					X					X	X	X
Synodontidae	*Synodus foetens*	X		X					X			X				X	X	X
	Synodus intermedius	X							X				X			X	X	X
Gobiesocidae	*Gobiesox strumosus*	X						?		X						X	X	X
Atherinidae	*Membras martinica*		X			X					X					X	X	X
	Menidia peninsulae		X			X					X					X	X	X
Belonidae	*Tylosurus crocodilus*	X							X				X	X	X			X
Hemiramphidae	*Hemiramphus brasiliensis*		X			X					X							X
	Hyporhamphus unifasciatus		X			X					X							X
Holocentridae	*Holocentrus adscensionis*	X		X					X		X	X				X	X	X
	Holocentrus rufus	X						X				X						X
	Myripristis jacobus	X		X					X		X	X						X
Aulostomidae	*Aulostomus maculatus*			X					X				X	X	X			X
Fistulariidae	*Fistularia tabacaria*			X					X						X			X
Syngnathidae	*Cosmocampus albirostris*	X						X			X					X	X	X
	Cosmocampus elucens	X						X			X					X	X	X
	Scorpaena grandicornis	X							X	X	X	X				X	X	X
Scorpaenidae	*Scorpaena plumieri*	X							X	X	X	X				X	X	X
Triglidae	*Prionotus scitulus*	X							X			X						X
Dactylopteridae	*Dactylopterus volitans*		X					X						X				X

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Centropomidae	*Centropomus undecimalis*		X						X				X	X				X
Serranidae	*Centropristis striata*			X					X	X	X	X				X	X	X
	Cephalopholis fulva			X					X	X	X	X					X	
	Cephalopholis cruentata			X					X	X	X	X					X	
	Diplectrum formosum			X					X	X	X	X						X
	Epinephelus adscensionis			X					X	X	X	X					X	
	Epinephelus itajara	X							X	X	X	X				X	X	X
	Epinephelus morio	X							X	X	X	X				X	X	X
	Hypoplectrus puella	X						X		X								X
	Hypoplectrus unicolor	X						X		X								X
	Mycteroperca bonaci			X					X					X				X
	Mycteroperca microlepis			X					X					X				X
	Mycteroperca phenax			X					X					X				X
	Rypticus maculatus							X										
	Rypticus saponaceus							X										
	Rypticus subbifrenatus							X										
	Serranus baldwini	X							X	X	X					X	X	X
	Serranus subligarius	X							X	X	X					X	X	X
	Serranus tigrinus	X		X					X	X	X					X	X	X
Apogonidae	*Apogon binotatus*	X				X				X	X					X	X	X
	Apogon maculatus	X				X				X	X					X	X	X
	Apogon pseudomaculatus	X				X				X	X					X	X	X
	Apogon townsendi	X				X				X	X					X	X	X
	Astrapogon puncticulatus	X							X	X	X					X	X	X
	Astrapogon stellatus	X							X	X	X					X	X	X

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Apogonidae	*Phaeoptyx conklini*	X				X				X	X					X	X	X
Carangidae	*Caranx bartholomaei*		X	X					X	X	X	X	X					X
	Caranx crysos		X	X					X	X	X	X						X
	Caranx hippos		X	X					X	X	X	X						X
	Caranx latus		X	X					X	X	X	X						X
	Caranx ruber		X	X					X	X	X	X						X
	Chloroscombrus chrysurus		X			X				X	X							X
	Decapterus punctatus		X	X		X				X	X	X						X
	Elagatis bipinnulata		X						X			X						X
	Oligoplites saurus		X						X		X	X						X
	Selar crumenophthalmus		X	X		X				X	X	X						X
	Selene setapinnis		X					X	X		X	X						X
	Selene vomer		X					X	X		X	X						X
	Seriola dumerili		X	X					X			X	X					
	Seriola rivoliana		X	X					X			X	X					
	Trachinotus carolinus		X	X				X	X			X						X
	Trachinotus falcatus		X	X				X				X						X
	Trachinotus goodei							X	X			X						X
Lutjanidae	*Lutjanus apodus*			X					X	X	X	X						X
	Lutjanus analis			X					X	X	X	X	X					X
	Lutjanus griseus		X	X					X	X	X	X						X
	Lutjanus jocu		X						X		X	X						X
	Lutjanus mahogoni			X					X	X	X	X				X	X	
	Lutjanus synagris			X					X	X	X	X				X	X	
	Ocyurus chrysurus			X					X	X	X					X	X	
	Rhomboplites aurorubens			X					X	X	X					X	X	

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Lobotidae	*Lobotes surinamensis*								X	X	X					X	X	X
Gerreidae	*Eucinostomus argenteus*			X				X		X	X					X	X	X
	Eucinostomus gula			X				X		X	X					X	X	X
	Eucinostomus jonesii			X				X		X	X							X
	Eucinostomus lefroyi			X				X		X								X
	Eucinostomus melanopterus			X				X		X	X							X
	Gerres cinereus	X						X		X	X	X				X	X	X
Haemulidae	*Anisotremus surinamensis*			X				X		X	X	X				X	X	X
	Anisotremus virginicus			X				X		X	X	X						X
	Haemulon album		X					X		X	X	X					X	
	Haemulon aurolineatum			X				X		X	X	X				X	X	X
	Haemulon carbonarium			X				X		X	X	X						X
	Haemulon chrysargyreum			X		X		X		X	X	X						X
	Haemulon flavolineatum			X				X		X	X	X						X
	Haemulon macrostomum			X				X		X	X	X						X
	Haemulon melanurum			X				X		X	X	X					X	
	Haemulon parra			X				X		X	X	X				X	X	X
	Haemulon plumierii			X				X		X	X	X				X	X	X
	Haemulon sciurus			X				X		X	X	X						X
	Haemulon striatum		X			X				X	X							X
	Orthopristis chrysoptera			X				X		X	X	X						X
Sparidae	*Archosargus probatocephalus*		X					X					X					X
	Archosargus rhomboidalis		X					X			X	X						X
	Calamus bajonado		X					X			X	X						X
	Calamus calamus	X		X				X			X	X	X					X
	Calamus penna	X		X				X			X	X	X					X

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Sparidae	*Diplodus argenteus*	X		X	X	X		X		X	X	X	X			X	X	X
	Diplodus holbrooki	X		X	X	X		X		X	X	X	X			X	X	X
	Lagodon rhomboides		X					X				X						X
Polynemidae	*Polydactylus virginicus*							X										
Sciaenidae	*Bairdiella sanctaeluciae*	X		X				X		X	X	X				X	X	X
	Cynoscion nebulosus		X					X	X			X						X
	Equetus acuminatus	X		X				X								X	X	X
	Equetus umbrosus	X		X				X								X	X	X
	Sciaenops ocellatus		X					X	X			X	X					X
	Odontoscion dentex	X		X				X								X	X	X
	Umbrina coroides	X						X								X	X	X
Mullidae	*Mulloidichthys martinicus*	X						X			X	X						X
	Pseudupeneus maculatus	X						X			X	X						X
Pempheridae	*Pempheris schomburgkii*	X				X				X	X					X	X	X
Kyphosidae	*Kyphosus sectatrix/incisor*			X	X						X	X	X					X
Ephippidae	*Chaetodipterus faber*		X	X				X				X	X			X	X	X
Chaetodontidae	*Chaetodon capistratus*	X						X		X	X					X	X	
	Chaetodon ocellatus	X		X				X								X	X	X
	Chaetodon sedentarius	X						X		X	X					X	X	
	Chaetodon striatus	X		X				X								X	X	X
Pomacanthidae	*Holacanthus bermudensis*	X		X				X		X	X	X	X			X	X	
	Holacanthus ciliaris	X		X				X		X	X	X	X			X	X	
	Pomacanthus arcuatus	X		X				X		X	X	X	X			X	X	
	Pomacanthus paru	X		X				X		X	X	X	X			X	X	
Pomacentridae	*Abudefduf saxatilis*	X		X				X		X	X	X				X	X	X

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Pomacentridae	*Abudefduf taurus*	X		X				X		X	X	X				X	X	X
	Microspathodon chrysurus			X	X					X	X					X	X	
	Stegastes adustus	X		X	X					X	X					X	X	X
	Stegastes diencaeus	X		X	X					X	X					X	X	X
	Stegastes leucostictus	X		X	X					X	X					X	X	X
	Stegastes partitus	X		X	X	X				X	X					X	X	
	Stegastes planifrons				X					X	X					X	X	
	Stegastes variabilis	X			X					X	X					X	X	X
Opistognathidae	*Opistognathus aurifrons*	X				X					X					X	X	X
	Opistognathus macrognathus	X				X					X					X	X	X
	Opistognathus whitehursti	X				X					X					X	X	X
Mugilidae	*Mugil cephalus*		X				X					X						X
	Mugil curema		X				X					X						X
Labridae	*Bodianus rufus*	X		X				X		X	X					X	X	
	Doratonotus megalepis			X				X		X	X							X
	Halichoeres bivittatus	X		X				X		X	X					X	X	X
	Halichoeres cyanocephalus			X				X		X	X							X
	Halichoeres garnoti			X				X		X	X					X	X	
	Halichoeres maculipinna	X		X				X		X	X					X	X	X
	Halichoeres poeyi	X		X				X		X	X					X	X	X
	Halichoeres radiatus	X		X				X		X	X					X	X	
	Lachnolaimus maximus		X					X				X						X
	Thalassoma bifasciatum	X		X				X		X	X					X	X	X
	Xyrichtys martinicensis	X		X				X		X	X					X	X	X
	Xyrichtys splendens	X		X				X		X	X					X	X	X

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Scaridae	*Cryptotomus roseus*				X													
	Scarus coelestinus	X			X					X	X	X	X			X	X	
	Scarus coeruleus	X			X					X	X	X	X			X	X	
	Scarus guacamaia	X			X					X	X	X	X			X	X	
	Scarus iseri	X		X	X					X	X					X	X	
	Scarus taeniopterus	X		X	X					X	X					X	X	
	Scarus vetula	X			X					X	X	X	X			X	X	
	Sparisoma atomarium	X			X					X	X					X	X	
	Sparisoma aurofrenatum	X		X	X					X	X					X	X	X
	Sparisoma chrysopterum	X		X	X					X	X					X	X	
	Sparisoma radians	X			X					X	X					X	X	X
	Sparisoma rubripinne	X			X					X	X	X	X			X	X	X
	Sparisoma viride	X			X					X	X	X	X			X	X	X
Uranoscopidae	*Astroscopus y-graecum*	X							X				X			X	X	X
Tripterygiidae	*Enneanectes pectoralis*	X						X		X	X							
Labrisomidae	*Labrisomus bucciferus*	X							X	X	X					X	X	X
	Labrisomus gobio	X							X	X	X					X	X	X
	Labrisomus kalisherae	X							X	X	X					X	X	X
	Labrisomus nuchipinnis	X							X	X	X	X				X	X	X
	Malacoctenus aurolineatus	X						X		X	X					X	X	X
	Malacoctenus macropus	X						X		X	X					X	X	X
	Malacoctenus triangulatus	X						X								X	X	X
	Paraclinus fasciatus							X										
	Paraclinus marmoratus							X										
	Paraclinus nigripinnis							X										
	Starksia ocellata							X										

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Chaenopsidae	*Acanthemblemaria aspera*	X				X				X	X					X	X	X
	Acanthemblemaria spinosa	X				X				X	X					X	X	X
	Emblemaria pandionis	X				X				X	X					X	X	X
Dactyloscopidae	*Dactyloscopus crossotus*							X										
	Platygillellus rubrocinctus							X										
Blenniidae	*Entomacrodus nigricans*				X													
	Hypleurochilus bermudensis	X			X					X	X					X	X	X
	Ophioblennius macclurei				X													
	Parablennius marmoreus	X			X					X	X					X	X	X
	Scartella cristata	X			X					X	X					X	X	X
Callionymidae	*Paradiplogrammus bairdi*	X						X		X	X					X	X	X
Eleotridae	*Erotelis smaragdus*							X										
Gobiidae	*Coryphopterus dicrus*	X						X		X	X					X	X	X
	Coryphopterus eidolon	X						X		X	X					X	X	X
	Coryphopterus glaucofraenum	X						X		X	X					X	X	X
	Coryphopterus personatus	X						X		X	X					X	X	X
	Ctenogobius saepepallens							X		X	X					X	X	X
	Elacatinus macrodon							X		X	X					X	X	X
	Elacatinus oceanops	X						X		X	X					X	X	X
	Gnatholepis thompsoni	X						X		X	X					X	X	X
	Gobiosoma grosvenori							X										
	Microgobius carri					X				X	X					X	X	X
	Nes longus							X		X	X					X	X	X
	Priolepis hipoliti							X										

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Ptereleotridae	*Ptereleotris calliurus*					X												
	Ptereleotris helenae					X												
Acanthuridae	*Acanthurus bahianus*	X		X	X					X	X	X	X			X	X	X
	Acanthurus chirurgus	X		X	X					X	X	X	X			X	X	X
	Acanthurus coeruleus	X		X	X					X	X	X	X			X	X	X
Sphyraenidae	*Sphyraena barracuda*	X		X					X		X	X	X	X	X			X
	Sphyraena guachancho	X		X					X		X	X				X	X	X
	Sphyraena picudilla	X		X					X		X	X				X	X	X
Pomatomidae	*Pomatomus saltatrix*		X						X					X				X
	Scomberomorus maculatus		X										X	X				X
Scombridae	*Scomberomorus regalis*		X						X				X	X				X
Bothidae	*Bothus lunatus*	X						X			X	X	X			X	X	X
Balistidae	*Balistes capriscus*	X		X				X			X	X	X					X
	Balistes vetula			X				X			X	X						X
	Canthidermis sufflamen	X		X				X			X	X	X					X
Filefishes	*Aluterus schoepfii*	X		X				X			X	X	X					X
	Aluterus scriptus	X		X				X			X	X	X					X
	Cantherhines macrocerus	X		X				X										X
	Cantherhines pullus	X		X				X										X
	Monacanthus tuckeri	X		X				X			X	X				X	X	X
	Stephanolepis hispidus	X		X				X										X
Ostraciidae	*Acanthostracion polygonia*	X						X			X							X

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.1 Fish species associated with nearshore hard-bottom habitats in central/southeast Florida (continued).

Family	Species	Association			Trophic Guild					Size Class (mm)						Life Stage		
		Resident	Transient	Ontogenic	Herbivore	Planktivore	Detritivore	Invertivore	Piscivore	<2	2-10	10-25	25-50	50-100	>100	Newly settled	Juvenile	Adult
Ptereleotridae	*Ptereleotris calliurus*					X												
	Acanthostracion quadricornis	X		X				X								X	X	X
	Lactophrys bicaudalis	X						X		X						X	X	X
	Lactophrys trigonus	X		X				X								X	X	X
	Lactophrys triqueter	X						X		X						X	X	X
Tetraodontidae	*Canthigaster rostrata*	X						X		X	X					X	X	X
	Sphoeroides spengleri	X						X			X					X	X	X
	Sphoeroides testudineus	X						X			X	X						X
Diodontidae	*Chilomycterus schoepfii*	X						X			X							X
	Diodon holocanthus	X						X			X	X						X
	Diodon hystrix	X						X			X	X						X

Modified from Continental Shelf Associates (2009). See citation for details.

Table 7-B1.2
Fish associated with Lophelia and *Oculina* deep-water reefs on the Blake Plateau.

Family	Scientific name	Common name	Distrib. range (m)	*Lophelia* reefs				*Oculina* reefs
				Stetson	Savannah	Jacksonville	Florida	Florida
Acropomatidae	*Synagrops spp.* ●		678	X				
Apogonidae	*Apogon pseudomaculatus*	Twospot cardinalfish	70-100					X
Batrachoididae	*Opsanus pardus*	Leopard toadfish	70-100					X
Berycidae	***Beryx decadactylus***	Red bream	287-671	X				
Bythitidae	*Bellottia apoda* ●		629			X		
	Bythites gerdae ●		383-687			X		
Carangidae	*Caranx crysos*	Blue runner	70-100					X
	Caranx hippos	Crevalle jack	70-100					X
	Decapterus punctatus	Round scad	70-100					X
	Seriola dumerili	Greater amberjack	70-187					X
	Seriola rivoliana	Almaco jack	70-179					X
Carcharhinidae	*Galeocerdo cuvieri*	Tiger shark	70-100					X
Chaetodontidae	*Chaetodon ocellatus*	Spotfin butterflyfish	70-100					X
	Chaetodon sedentarius	Reef butterflyfish	70-100					X
	Prognathodes aya	Bank butterflyfish	70-179					X
Chaunacidae	*Chaunax* sp.	Sea toads	526-628	X				
	*Chaunax stigmaeus**		>70	X	X		X	X
	Chimaera monstrosa ●		506-528		X			
Chimaeridae	*Hydrolagus* sp.	Spotted ratfish	714-762				X	
Clupeidae	*Sardinella aurita*	Spanish sardine	70-100					X
Congridae	***Conger oceanicus***	Conger eel	296-519		X			
Etmopteridae	*Etmopterus* sp.	Lantern shark	550-550		X			
Gobiidae	*Lythrypnus nesiotes*	Island goby	70-100					X
	Lythrypnus spilus	Bluegold goby	70-100					X
Haemulidae	*Haemulon aurolineatum*	Tomtate	70-100					X
Holocentridae	*Corniger spinosus*	Spinycheek soldierfish	70-100					X
	Holocentrus adscensionis	Squirrelfish	70-100					X

Modified from Reed et al. (2006). Reported by Caruso et al. (2007) * and Ross and Quattrini (2007)●. In bold: Prime reef species tightly associated with deep corals (Ross and Quattrini, 2009)

Table 7-B1.2 Fish associated with Lophelia and *Oculina* deep-water reefs on the Blake Plateau (continued).

Family	Scientific name	Common name	Distrib. range (m)	*Lophelia* reefs				*Oculina* reefs
				Stetson	Savannah	Jacksonville	Florida	Florida
Labridae	*Bodianus pulchellus*	Spotfin hogfish	70-100					X
	Halichoeres bathyphilus	Greenband wrasse	70-100					X
	Halichoeres bivittatus	Slippery dick	70-100					X
	Halichoeres caudalis	Painted wrasse	70-100					X
Lophiidae	*Lophius* sp.	Goosefish	750-750				X	
	*Lophiodes beroe**●		70-721	X	X		X	X
	*Lophiodes monodi**		>70	X	X		X	X
	Lophius cf. americanus ●		311-507		X			
Lutjanidae	*Lutjanus campechanus*	Red snapper	70-100					X
	Lutjanus griseus	Gray snapper	70-100					X
	Lutjanus synagris	Lane snapper	70-100					X
	Rhomboplites aurorubens	Vermilion snapper	70-100					X
Macrouridae	*Nezumia* sp.	Grenadier	322-752	X			X	
	Nezumia sclerorhynchus ●	Roughtip grenadier	373-770	X	X	X	X	
Mobulidae	*Manta birostris*	Giant manta	70-100					X
Molidae	*Mola mola*	Ocean sunfish	70-180					X
Moridae	*Laemonema barbatulum*	Shortbeard codling	521-521		X			
	Laemonema melanurum	Codling	186-770	X			X	
Muraenidae	*Gymnothorax miliaris*	Goldentail moray	70-100					X
	Gymnothorax nigromarginatus	Blackedge moray	70-100					X
Myctophidae	*Myctophidae*	Lanternfish	296-500				X	
Myxinidae	*Myxine glutinosa*	Hagfish	628-757		X		X	
Nettastomatidae	*Nettenchelys exoria*●		374-748	X				
Phycidae	*Phycis sp.*	Hake	557-767	X				
Pomacentridae	*Chromis enchrysura*	Yellowtail reeffish	70-100					X
	Chromis scotti	Purple reeffish	70-100					X
Polyprionidae	*Polyprion americanus*	Wreckfish	283-693				X	

Modified from Reed et al. (2006). Reported by Caruso et al. (2007) * and Ross and Quattrini (2007)●. In bold: Prime reef species tightly associated with deep corals (Ross and Quattrini, 2009)

Table 7-B1.2 Fish associated with Lophelia and *Oculina* deep-water reefs on the Blake Plateau (continued).

Family	Scientific name	Common name	Distrib. range (m)	*Lophelia* reefs				*Oculina* reefs
				Stetson	Savannah	Jacksonville	Florida	Florida
Pomacanthidae	*Holacanthus bermudensis*	Blue angelfish	70-100					X
	Pomacanthus arcuatus	Gray angelfish	70-100					X
	Pomacanthus paru	French angelfish	70-100					X
	Stegastes variabilis	Cocoa damselfish	70-100					X
Priacanthidae	*Priacanthus arenatus*	Bigeye	70-100					X
	Pristigenys alta	Short bigeye	70-100					X
Rajidae	*Dactylobatus armatus*		671				X	
	Raja sp.	Skate	339-738	X	X		X	
Sciaenidae	*Equetus lanceolatus*	Jacknife fish	70-100					X
	Pareques iwamotoi	Blackbar drum	70-100					X
	Pareques umbrosus	Cubbyu	70-100					X
Scombridae	*Acanthocybium solandri*	Wahoo	70-100					X
	Euthynnus alletteratus	Little tunny	70-100					X
	Scomberomorus cavalla	King mackeral	70-100					X
	Scomberomorus maculatus	Spanish mackeral	70-100					X
Scorpaenidae	*Helicolenus dactylopterus* ●	Blackbelly rosefish	179-754	X	X	X	X	
	Idiastion kyphos ●		374-570	X	X			
	Neomarinthe hemingwayi	Spinycheek scorpionfish	70-100					X
	Scorpaena brasiliensis	Barbfish	70-100					X
	Scorpaena dispar	Hunchback scorpionfish	70-100					X
	Scorpaenidae	Scorpionfish	186-752	X			X	
	Trachyscorpia cristulata ●	Atlantic thornyhead	375-769	X	X	X	X	
Scyliorhinidae	*Scyliorhinus retifer*	Chain digfish	517-517		X			
Serranidae	*Centropristis ocyurus*	Bank sea bass	70-100					X
	Centropristis philadelphica	Rock sea bass	70-100					X
	Centropristis striata	Black sea bass	70-100					X
	Diplectrum formosum	Sand perch	70-100					X

Modified from Reed et al. (2006). Reported by Caruso et al. (2007) * and Ross and Quattrini (2007)●. In bold: Prime reef species tightly associated with deep corals (Ross and Quattrini, 2009)

Table 7-B1.2 Fish associated with Lophelia and *Oculina* deep-water reefs on the Blake Plateau (continued).

Family	Scientific name	Common name	Distrib. range (m)	*Lophelia* reefs				*Oculina* reefs
				Stetson	Savannah	Jacksonville	Florida	Florida
Serranidae	*Epinephelus adscensionis*	Rock hind	70-100					X
	Epinephelus drummondhayi	Speckled hind	70-100					X
	Epinephelus itajara	Goliath grouper	70-100					X
	Epinephelus morio	Red grouper	70-100					X
	Epinephelus nigritus	Warsaw grouper	70-198					X
	Epinephelus niveatus	Snowy grouper	70-308					X
	Hemanthias vivanus	Red barbier	70-191					X
	Liopropoma eukrines	Wrasse basslet	70-100					X
	Mycteroperca bonaci	Black grouper	70-100					X
	Mycteroperca microlepis	Gag	70-100					X
	Mycteroperca phenax	Scamp	70-100					X
	Plectranthias garrupellus	Apricot bass	70-172					X
	Pronotogrammus martinicensis	Roughtongue bass	70-212					X
	Rypticus maculatus	Spotted soapfish	70-100					X
	Rypticus saponaceus	Greater soapfish	70-100					X
	Serranus phoebe	Tattler	70-100					X
	Serranus subligarius	Belted sandfish	70-100					X
Sparidae	*Archosargus probatocephalus*	Sheepshead	70-100					X
	Pagrus pagrus	Red porgy	70-100					X
Sphyrnidae	*Sphyrna lewini*	Scalloped hammerhead	70-100					X
Squalidae	*Squalus cubensis*	Dogfish	507-525		X			
	Squalus sp.	Dogfish	501-529		X			

Modified from Reed et al. (2006). Reported by Caruso et al. (2007) * and Ross and Quattrini (2007)●. In bold: Prime reef species tightly associated with deep corals (Ross and Quattrini, 2009)

Table 7-B1.2 Fish associated with Lophelia and *Oculina* deep-water reefs on the Blake Plateau (continued).

Family	Scientific name	Common name	Distrib. range (m)	*Lophelia* reefs				*Oculina* reefs
				Stetson	Savannah	Jacksonville	Florida	Florida
Synaphobranchidae	*Dysommina rugosa*		368-525		X			
Synaphobranchidae?	*Synaphobranchidae?*	Cutthroat eel	632-770	X			X	
Torpedinidae	*Torpedo nobiliana*	Atlantic torpedo	530-530		X			
Trachichthyidae	***Hoplostethus occidentalis***	Roughy	650-650	X				
Triakidae	Triakidae	Dogfish	586-586				X	
Xiphiidae	*Xiphias gladius*	Swordfish	518-518		X			

Modified from Reed et al. (2006). Reported by Caruso et al. (2007) * and Ross and Quattrini (2007)●. In bold: Prime reef species tightly associated with deep corals (Ross and Quattrini, 2009)

Table 7-B1.3A
Fish species and age classes associated with Sargassum from the North Atlantic and Gulf of Mexico.

Species	Common name	Egg	Larvae	Juvenile	Adult
*Abudefduf saxatilis*****	sergeant major		X	X	
Acanthocybium solandri	wahoo			X	X
Acanthurus randalli	gulf surgeonfish			X	
Acanthurus sp.	surgeonfish		X		
*Aluterus heudelotii***	dotterel filefish		X	X	
*Aluterus monoceros***	unicorn filefish		X	X	
*Aluterus schoepfii***	orange filefish		X	X	
*Aluterus scriptus*****	scrawled filefish		X	X	
Apogon maculatus	flamefish		X		
Ariomma sp.	driftfish		X		
Auxis thazard	frigate mackerel			X	X
*Balistes capriscus*****	gray triggerfish			X	X
Balistes vetula	queen triggerfish			X	
Bodianus pulchellus	spotfin hogfish			X	
Bothus sp.	flounder		X		
*Cantherhines macrocerus***	whitespotted filefish			X	
*Cantherhines pullus*****	orangespotted filefish			X	X
*Cantherhines sufflamen***	ocean triggerfish			X	
*Canthidermis maculata***	rough triggerfish			X	
*Carcharhinus falciformis**	silky shark				X
Carcharhinus limbatus	blacktip shark				X
Carcharhinus longimanus	oceanic whitetip shark				X
Centrolophus sp.	ruff			X	
Chaetodon ocellatus	spotfin butterflyfish			X	
Chaetodon striatus	banded butterflyfish			X	
Chilomycterus antennatus	bridled burrfish			X	
Chilomycterus schoepfii	striped burrfish			X	
Cubiceps pauciradiatus	bigeye cigarfish			X	
Cyclopsetta fimbriata	spotfin flounder		X		
Cypselurus furcatus	spotfin flyingfish	X	X	X	X
Cypselurus melanurus	Atlantic flyingfish	X	X	X	X
Dactylopterus volitans	flying gurnard		X	X	
*Diodon holocanthus***	ballonfish			X	
*Diodon hystrix***	porcupinefish			X	
Epinephelus inermis	marbled grouper			X	
Euthynnus alletteratus	little tunny				X
*Exocoetus obtusirostris**	oceanic two-wing flyingfish			X	
Fistularia tabacaria	bluespotted cornetfish			X	

Modified from SAFMC (2002). See citation for details. In blue, species identified in *Sargassum* from Cape Fear to Cape Hatteras, North Carolina (Casazza and Ross, 2008). *Sargassum* fish association based on Dooley (1972): *coincidental, **moderate, ***seasonal, and ****close

Table 7-B1.3A Fish species and age classes associated with Sargassum from the North Atlantic and Gulf of Mexico (continued).

Species	Common name	Egg	Larvae	Juvenile	Adult
*Hemiramphus balao****	balao			X	
Hemiramphus brasiliensis	ballyhoo			X	
Hippocampus reidi	longsnout seahorse			X	
Hippocampus erectus	lined seahorse			X	
*Hirundichthys affinis***	fourwing flyingfish	X	X	X	X
*Histrio histrio*****	*Sargassum*fish		X	X	X
Hyperoglyphe bythites	black driftfish			X	
Hyperoglyphe perciformis	barrelfish			X	
Hyporhamphus unifasciatus	silverstripe halfbeak		X	X	
Hypsoblennius hentzi	feather blenny		X		
Istiophorus platypterus	sailfish		X	X	
Katsuwonus pelamis	skipjack tuna				X
Kyphosus incisor	yellow chub		X	X	
*Kyphosus sectatrix*****	Bermuda chub		X	X	
Lactophrys sp.	cowfish		X		
*Macroramphosus scolopax**	longspine snipefish			X	
Makaira nigricans	blue marlin		X	X	X
Microgobius sp.	goby		X		
Microphis brachyurus	opossum pipefish			X	
Mola sp.	mola			X	
*Monacanthus ciliatus*****	fringed filefish			X	
Monacanthus hispidus	planehead filefish			X	
Monacanthus setifer	pygmy filefish			X	
*Monacanthus tuckeri***	slender filefish			X	
Mugil cephalus	striped mullet		X		
*Mugil curema****	white mullet		X		
Mullus auratus	red goatfish		X	X	
Pagrus pagrus	red porgy		X	X	
Parablennius marmoreus	seaweed blenny		X		
*Paraexocoetus brachypterus**	sailfin flyingfish	X	X	X	X
Peprilus triacanthus	butterfish		X	X	
Polydactylus virginicus	barbu			X	
Priacanthus arenatus	bigeye			X	
Pristigenys alta	short bigeye		X	X	
Prognichthys gibbifrons	bluntnose flyingfish	X	X	X	X
*Psenes cyanophrys*****	freckled driftfish			X	
Sardinella aurita	Spanish sardine			X	
*Scomber japonicus****	chub mackerel			X	
Scomberomorus cavalla	king mackerel				X

Modified from SAFMC (2002). See citation for details. In blue, species identified in Sargassum from Cape Fear to Cape Hatteras, North Carolina (Casazza and Ross, 2008). Sargassum fish association based on Dooley (1972): *coincidental, **moderate, ***seasonal, and ****close

Table 7-B1.3A Fish species and age classes associated with Sargassum from the North Atlantic and Gulf of Mexico (continued).

Species	Common name	Egg	Larvae	Juvenile	Adult
*Sphoeroides maculatus**	northern puffer		X		
*Sphoeroides spengleri**	bandtail puffer		X		
Sphyraena borealis	northern sennet		X	X	
Syngnathus caribbaeus	Caribbean pipefish			X	
*Syngnathus floridae****	dusky pipefish			X	
Syngnathus fuscus	northern pipefish			X	
*Syngnathus louisianae**	chain pipefish			X	
Syngnathus scovelli	gulf pipefish			X	
Syngnathus springeri	bull pipefish			X	
Tetrapturus albidus	white marlin		X	X	X
Thalassoma bifasciatum	bluehead			X	
Thunnus albacares	yellowfin tuna			X	X
Thunnus atlanticus	blackfin tuna				X
*Tylosurus acus***	agujon		X	X	
Unidentified	moray		X		
Unidentified	lightfish		X		
Unidentified	lanternfish		X		
Unidentified	scorpionfish		X		
Unidentified	goatfish		X		
Unidentified	parrotfish		X		
Unidentified	stargazer		X		
Unidentified	snake mackerel		X		
Unidentified	puffer		X		
Urophycis chuss	red hake		X	X	
Urophycis earlli	Carolina hake		X	X	
Urophycis floridana	southern hake		X	X	
Urophycis regia	spotted hake		X	X	
*Xanthichthys ringens***	*Sargassum* triggerfish			X	
*Xiphias gladius**	swordfish		X	X	

Modified from SAFMC (2002). See citation for details. In blue, species identified in Sargassum from Cape Fear to Cape Hatteras, North Carolina (Casazza and Ross, 2008). Sargassum fish association based on Dooley (1972): *coincidental, **moderate, ***seasonal, and ****close

Table 7-B1.3B
Species identified by Casazza and Ross (2008) not reported in SAFMC (2002).

Species		
Ablennes hians	*Coryphaena hippurus*****	*Myctophum selenops*
Ahlia egmontis	*Cyclothone* sp.	*Myctophum* sp.
Argyrapelecus aculeatus	*Cypselurus comatus*	*Oxyporhamphus micropterus*
Bryx dunckeri	*Decapterus punctatus*****	*Paraexocoetus occidentalis*
*Caranx bartholomaei*****	*Decapterus* sp.	*Platybelone argalus*
*Caranx crysos*****	*Diaphus dumerilii*	*Pseudupeneus maculatus*
Caranx lugubris	*Echeneis naucrates*	*Remora osteochir*
*Caranx ruber*****	*Elagatis bipinnulata***	*Selar crumenophthalmus*****
Caranx sp.	*Euloptorhamphus velox*	*Selene setapinnis*
Cheilopogon cyanopterus	*Kyphosus* sp.	*Seriola dumerili*****
Cheilopogon exsiliens	*Lagocephalus lagocephalus*	*Seriola fasciata***
Cheilopogon furcatus	*Lobotes surinamensis*****	*Seriola rivoliana*****
Cheilopogon melanurus	*Monacanthus* sp.	*Seriola* sp.
Cheilopogon sp.	*Mulloidichthys martinicus*	*Seriola zonata***
Chilomycterus sp.	*Myctophum affine*	*Synagrops bellus*
Clupea harengus	*Myctophum obtusirostre*	*Tylosurus crocodilus*
Coryphaena equiselis	*Myctophum punctatum*	*Tylosurus* sp.

Modified from SAFMC (2002). See citation for details. In blue, species identified in *Sargassum* from Cape Fear to Cape Hatteras, North Carolina (Casazza and Ross, 2008). *Sargassum* fish association based on Dooley (1972): *coincidental, **moderate, ***seasonal, and ****close.

Table 7-B1.4
Families of fish larvae associated with inshore and offshore waters of the Gulf Stream during winter. Modified from Govoni and Spach (1999).

Inshore	Offshore	Inshore/offshore		
Anguillidae	Acropomaridae	Acanthuridae	Gempylidae	Ophidiidae
Antennariidae	Aulopidae	Apogonidae	Gobiidae	Paralepltidae
Holocentridae	Balistidae	Ariommatidae	Gonostromatidae	Phosichthydae
Lophiidae	Carapidae	Blenniidae	Haemulidae	Priacanthidae
Macrorhamphosidae	Centrolophidae	Bothidae	Howellidae	Scaridae
Moridae	Ceratiidae	Bregmacerotidae	Labridae	Sciaenidae
Mugilidae	Chaetodontidae	Calliomydae	Malacanthidae	Scorpaenidae
Scombridae	Dactylopteridae	Caproidae	Merlucciidae	Serranidae
Soleidae	Elopidae	Carangidae	Monacanthidae	Sparidae
Synodontidae	Evermannellidae	Chiasmodontidae	Moringuidae	Sphyraenidae
Trachichthyidae	Melanocetidae	Clupeidae	Mullidae	Stomateidae
	Percophidae	Congridae	Muraenidae	Stromiidae
	Pomacentridae	Coryphaenidae	Myctophidae	Syngnathidae
	Tetragonunidae	Cynoglossidae	Nomeidae	Tetraodontidae
	Trachipteridae	Engraulidae	Notosudidae	Triglidae
	Trichiuridae	Gadidae	Ophichthidae	Uranoscopidae

Table 7-B1.5
Trophic guilds, defined as degree of piscivory, of nearshore and shelf fishes of the South Atlantic Bight. Modified from Marancik and Hare (2007).

Family	Species	Size (mm)	Trophic guild						
			Benthic/structure browser	Benthic/demersal piscivores	Pelagic piscivores	Structure-associated piscivores	Benthic/demersal carnivore	Structure-associated carnivore	Benthic invertebrate consumer
Sparidae	*Archosargus probatocephalus*	<300->410 SL	X						
Sparidae	*Diplodus holbrooki*	60–160 SL	X						
Triglidae	*Prionotus alatus*	47.8–156.5 SL		X					
Coryphaenidae	*Coryphaena hippurus*	250–1,530			X				
Scombridae	*Euthynnus alletteratus*	172–885 FL			X				
Scombridae	*Katsuwonus pelamis*	220–810 FL			X				
Pomatomidae	*Pomatomus saltatrix*	0–999 FL			X				
Scombridae	*Scomberomorus cavalla*	2.9–1,599 FL			X				
Scombridae	*Scomberomorus maculatus*	2.8–749 FL			X				
Scombridae	*Thunnus albacares*	400–1550 FL			X				
Scombridae	*Thunnus atlanticus*	<500–1100 FL			X				
Carangidae	*Decapterus punctatus*	46–151 SL				X			
Muraenidae	*Gymnothorax vicinus*	403–947 TL				X			
Lutjanidae	*Lutjanus analis*	210–460				X			
Lutjanidae	*Rhomboplites aurorubens*	1->175 SL				X			
Carangidae	*Seriola dumerili*	397–1,386 TL				X			
Carangidae	*Seriola rivoliana*	276–1,094 TL				X			
Triglidae	*Bellator militaris*	28.1–108.2 SL					X		
Sparidae	*Calamus leucosteus*	<1250->272 SL					X		
Sciaenidae	*Cynoscion regalis*	0–4 TL					X		
Sciaenidae	*Larimus fasciatus*	19–182 SL					X		
Paralichthyidae	*Paralichthys dentatus*	100–700 TL					X		
Paralichthyidae	*Paralichthys lethostigma*	100–300 TL					X		
Triglidae	*Prionotus martis*	50.1–168.0 SL					X		
Triglidae	*Prionotus ophryas*	63.0–188.5 SL					X		
Triglidae	*Prionotus roseus*	67.4–183.0 SL					X		
Triglidae	*Prionotus rubio*	107.0–221.5 SL					X		
Triglidae	*Prionotus scitulus*	26.3–156.5 SL					X		
Triglidae	*Prionotus tribulus*	57.5–211.0 SL					X		
Sciaenidae	*Sciaenops ocellatus*	250–932 SL					X		
Mullidae	*Upeneus parvus*	73–150					X		
Malacanthidae	*Caulolatilus microps*	400–780 TL						X	
Serranidae	*Centropristis philadelphica*	<75-224 SL						X	
Serranidae	*Centropristis striata*	50->250 SL						X	
Lutjanidae	*Duarte and*	105–335 SL						X	
Serranidae	*Epinephelus niveatus*	335–1,100 TL						X	

Table 7-B1.5 Trophic guilds, defined as degree of piscivory, of nearshore and shelf fishes of the South Atlantic Bight. Modified from Marancik and Hare (2007) (continued).

Family	Species	Size (mm)	Trophic guild						
			Benthic/structure browser	Benthic/demersal piscivores	Pelagic piscivores	Structure-associated piscivores	Benthic/demersal carnivore	Structure-associated carnivore	Benthic invertebrate consumer
Muraenidae	*Gymnothorax moringa*	379–808 TL						X	
Haemulidae	*Haemulon aurolineatum*	1–200 SL						X	
Lutjanidae	*Lutjanus griseus*	71.2–151.1 SL						X	
Lutjanidae	*Lutjanus synagris*	63.7–86.5 SL						X	
Serranidae	*Mycteroperca microlepis*	10–200 SL						X	
Sparidae	*Pagrus pagrus*	46–625 TL						X	
Rachycentridae	*Rachycentron canadum*	390–1,420 FL						X	
Serranidae	*Serranus subligarius*	20–90 SL						X	
Sparidae	*Lagodon rhomboides*	123–159 SL							X

Table 7-B1.6
Analysis of the risk of fishing on commercial species based on stock productivity and susceptibility.

Attribute\ Species				Grouper																
			Red drum	Gag	Red grouper	Scamp	Black grouper	Rock hind	Red hind	Graysby	Yellowfin grouper	Coney	Yellowmouth grouper	Tiger grouper	Nassau grouper	Snowy grouper	Yellowedge grouper	Warsaw grouper	Speckled hind	Misty grouper	Wreckfish
Productivity	Age at maturity		M	M	M	M	H	H	H	M	?	?	M	H	H	H	H	H	M	?	?
	Size at maturity		H	H	M	M	H	L	L	L	H	L	M	M	M	M	M	H	M	H	H
	Maximum age		H	H	M	M	H	M	M	M	M	M	M	M	M	M	H	H	M	?	H
	Maximum size		M	M	M	M	M	M	M	L	M	L	M	M	M	M	M	H	M	H	H
	Fecundity		L	L	L	L	L	?	L	?	L	L	?	?	?	?	?	?	?	?	L
	Reproductive strategy		L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	Trophic level		H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	?	H	H
Susceptibility	Availability	Global distribution	H	H	H	H	H	H	H	H	M	H	M	M	M	M	M	M	H	H	M
		Behavior	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	?	H
	Encounterability	Habitat	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
		Bathymetry	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
	Selectivity	Size at maturity	M	H	M	M	H	L	L	L	H	L	M	M	M	M	M	H	M	H	H
		Maximum size	M	M	M	M	H	M	M	L	M	L	M	M	M	M	M	H	M	H	H
		Desirability	M	H	H	H	L	L	H	L	L	L	L	L	L	H	L	L	L	L	L
	Post Capture Mortality		M	H	H	H	H	H	H	M	H	H	H	H	H	H	H	H	H	H	H
Risk Ranking			H	H	H	H	H	H	H	M	H	M	H	H	H	H	H	H	H	H	H

Species in red: overfished/overfishing occurring. L=low, M=Moderate, H=High,?=unknown. Age at maturity: L=>4 years, M=2-4 years, H=<2 years; Size at maturity: L=>50 cm, M=30-50 cm, H=<30 cm; Maximum age: L=>30 years, M=10-30 years, H=<10 years; Maximum size: L=>150 cm, M=60-150 cm, H=<60 cm; Fecundity: L=<1,000 eggs per year, M=1,000-20,000 eggs per year, H=>20,000 eggs per year; Reproductive strategy: L=Live bearer, M=Demersal egg layer, H=Broadcast spawner; Trophic level: L=>3.5, M=2.5-3.5, H=<2.5. Source: http://www.mragamericas.com/.

Table 7-B1.6 Analysis of the risk of fishing on commercial species based on stock productivity and susceptibility (continued).

Attribute\ Species			Snapper													Tilefish			Wrasses	
			Queen snapper	Gray snapper	Mutton snapper	Lane snapper	Cubera snapper	Dog snapper	Schoolmaster	Mahogony snapper	Vermilion snapper	Red snapper	Silk snapper	Black snapper	Blackfin snapper	Tilefish	Blueline tilefish	Sand tilefish	Hogfish	Puddingwife
Productivity	Age at maturity		L	M	M	L	?	H	?	?	M	L	H	L	?	H	M	?	?	?
	Size at maturity		M	L	M	L	?	M	M	?	L	L	M	M	L	M	M	?	L	?
	Maximum age		L	M	H	M	?	M	?	?	M	H	?	?	?	H	H	?	M	?
	Maximum size		M	M	M	M	H	M	M	L	M	M	M	M	M	M	M	M	M	L
	Fecundity		?	L	L	L	?	?	?	?	L	L	?	?	?	L	L	?	L	?
	Reproductive strategy		L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	Trophic level		H	H	H	H	H	M	H	H	H	H	H	H	H	M	H	M	H	M
Susceptibility	Availability	Global distribution	H	H	H	M	H	H	H	H	M	M	M	H	M	H	H	M	H	M
		Behavior	M	H	H	H	H	H	H	H	H	H	H	H	H	H	H	M	H	H
	Encounterability	Habitat	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
		Bathymetry	M	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
	Selectivity	Size at maturity	M	L	M	L	?	M	M	?	L	L	M	M	L	M	M	?	?	?
		Maximum size	M	M	M	M	H	M	M	L	M	M	M	M	M	M	M	M	M	L
		Desirability	L	H	L	L	L	L	L	L	H	H	L	L	L	H	M	L	H	L
	Post Capture Mortality		H	H	H	H	H	H	H	H	H	H	H	M	H	H	H	H	H	M
Risk Ranking			M	H	H	M	H	H	H	H	M	M	H	H	H	H	H	H	H	M

Species in red: overfished/overfishing occurring. L=low, M=Moderate, H=High,?=unknown. Age at maturity: L=>4 years, M=2-4 years, H=<2 years; Size at maturity: L=>50 cm, M=30-50 cm, H=<30 cm; Maximum age: L=>30 years, M=10-30 years, H=<10 years; Maximum size: L=>150 cm, M=60-150 cm, H=<60 cm; Fecundity: L=<1,000 eggs per year, M=1,000-20,000 eggs per year, H=>20,000 eggs per year; Reproductive strategy: L=Live bearer, M=Demersal egg layer, H=Broadcast spawner; Trophic level: L=>3.5, M=2.5-3.5, H=<2.5. Source: http://www.mragamericas.com/.

Table 7-B1.6 Analysis of the risk of fishing on commercial species based on stock productivity and susceptibility (continued).

Attribute\ Species			Jacks								Grunts										
			Greater Amberjack	Crevalle Jack	Blue Runner	Almaco Jack	Banded Rudderfish	Bar Jack	Lesser Amberjack	Yellow Jack	White grunt	Porkfish	Margate	Black Margate	Tomtate	Bluestriped grunt	French grunt	Spanish grunt	Cottonwick grunt	Sailors choice	Smallmouth grunt
Productivity	Age at maturity		L	M	?	?	?	?	?	?	L	?	M	?	?	M	M	?	?	?	?
	Size at maturity		H	H	L	H	?	L	?	L	L	?	H	?	L	L	L	?	L	?	L
	Maximum age		M	M	M	?	?	?	?	?	M	?	?	?	L	M	?	?	?	?	?
	Maximum size		H	M	M	H	M	M	M	M	L	L	M	M	L	L	L	L	L	L	M
	Fecundity		L	?	?	?	?	?	?	?	M	?	L	?	L	L	L	?	?	?	L
	Reproductive strategy		L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	Trophic level		H	M	H	H	H	H	H	H	H	M	M	M	M	M	M	M	M	M	M
Susceptibility	Availability	Global distribution	L	L	M	L	M	H	H	H	M	M	M	M	M	M	M	M	M	M	M
		Behavior	H	H	H	M	M	H	M	M	H	H	H	?	H	H	H	M	H	H	H
	Encounterability	Habitat	L	L	L	L	L	H	H	L	H	H	H	H	H	H	H	H	H	H	H
		Bathymetry	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
	Selectivity	Size at maturity	H	H	L	H	?	L	?	L	L	?	H	?	L	L	L	?	L	?	L
		Maximum size	H	M	M	H	M	M	M	M	L	L	M	M	L	L	L	L	L	L	M
		Desirability	L	L	M	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	Post Capture Mortality		H	H	H	M	M	H	M	H	H	H	H	H	H	H	H	H	H	H	M
Risk Ranking			M	M	M	H	H	H	H	M	M	H	M	H	L	L	M	H	M	H	M

Species in red: overfished/overfishing occurring. L=low, M=Moderate, H=High,?=unknown. Age at maturity: L=>4 years, M=2-4 years, H=<2 years; Size at maturity: L=>50 cm, M=30-50 cm, H=<30 cm; Maximum age: L=>30 years, M=10-30 years, H=<10 years; Maximum size: L=>150 cm, M=60-150 cm, H=<60 cm; Fecundity: L=<1,000 eggs per year, M=1,000-20,000 eggs per year, H=>20,000 eggs per year; Reproductive strategy: L=Live bearer, M=Demersal egg layer, H=Broadcast spawner; Trophic level: L=>3.5, M=2.5-3.5, H=<2.5. Source: http://www.mragamericas.com/.

Table 7-B1.6 Analysis of the risk of fishing on commercial species based on stock productivity and susceptibility (continued).

Attribute\ Species			Triggerfish and Spadefish				Porgies									Sea basses		
			Gray triggerfish	Ocean triggerfish	Queen triggerfish	Atlantic spadefish	Red porgy	Grass porgy	Jolthead porgy	Saucereye porgy	Whitebone porgy	Knobbed porgy	Longspine porgy	Sheepshead	Scup	Black Sea Bass	Bank Sea Bass	Rock Sea Bass
Productivity	Age at maturity		L	?	?	L	M	?	M	?	?	H	?	L	M	L	M	?
	Size at maturity		L	L	L	L	L	?	L	?	?	L	?	?	L	L	?	?
	Maximum age		M	?	M	L	M	?	M	?	M	M	L	M	M	M	L	?
	Maximum size		L	M	M	M	M	L	M	L	L	L	L	M	L	M	L	L
	Fecundity		L	L	M	L	L	?	?	?	?	?	?	M	M	L	M	?
	Reproductive strategy		M	M	M	L	L	L	L	L	L	L	L	L	L	L	L	L
	Trophic level		M	M	M	M	H	M	M	M	H	?	M	H	H	H	?	?
Susceptibility	Availability	Global distribution	M	H	M	M	M	H	H	H	H	H	H	M	M	M	M	M
		Behavior	M	M	H	H	H	H	H	H	H	H	?	M	H	H	H	H
	Encounterability	Habitat	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
		Bathymetry	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
	Selectivity	Size at maturity	L	L	L	L	L	?	L	?	?	L	?	?	L	L	?	?
		Maximum size	L	M	M	M	M	L	M	L	L	L	L	M	L	M	L	L
		Desirability	L	L	L	L	M	L	L	L	L	L	L	L	L	H	L	L
	Post Capture Mortality		M	H	H	M	H	H	H	H	H	H	H	H	H	H	H	M
Risk Ranking			L	M	M	L	M	H	H	H	H	M	H	M	M	M	M	H

Species in red: overfished/overfishing occurring. L=low, M=Moderate, H=High,?=unknown. Age at maturity: L=>4 years, M=2-4 years, H=<2 years; Size at maturity: L=>50 cm, M=30-50 cm, H=<30 cm; Maximum age: L=>30 years, M=10-30 years, H=<10 years; Maximum size: L=>150 cm, M=60-150 cm, H=<60 cm; Fecundity: L=<1,000 eggs per year, M=1,000-20,000 eggs per year, H=>20,000 eggs per year; Reproductive strategy: L=Live bearer, M=Demersal egg layer, H=Broadcast spawner; Trophic level: L=>3.5, M=2.5-3.5, H=<2.5. Source: http://www.mragamericas.com/

APPENDIX FOR CHAPTER 8:

MARINE AND COASTAL BIRDS AND BATS

APPENDIX 8-A1: CONSERVATION STATUS OF MARINE AND COASTAL BIRDS IN THE SOUTH ATLANTIC PLANNING AREA

Name		Taxonomy	Conservation Status									
			SAB	NatureServe/TNC					State/Federal Status			
Common Name	Scientific Name	Order	Breeder	Global Status	State Status			IUCN Red List Status	U.S. ESA Status/USFWS BCC	Legal Status		
					FL	GA	SC			SC	GA	FL
LOONS & GREBES												
Arctic Loon	*Gavia arctica*	Gaviiformes	N	G5				LC				
Common Loon	*Gavia immer*	Gaviiformes	N	G5				LC				
Red-throated Loon	*Gavia stellata*	Gaviiformes	N	G5	SNRN	S4	SNRN	LC	BCC (BCR 27)			
Western Grebe	*Aechmophorus occidentalis*	Podicipediformes	N	G5				LC				
Horned Grebe	*Podiceps auritus*	Podicipediformes	N	G5	SNRN	S5	SNRN, SNRM	LC				
Red-necked Grebe	*Podiceps grisegena*	Podicipediformes	N	G5		S4	SNA	LC				
Eared Grebe	*Podiceps nigricollis*	Podicipediformes	N	G5	SNA		SNA	LC				
Least Grebe	*Tachybaptus dominicus*	Podicipediformes	N	G5				LC				
ALBATROSSES, PETRELS, STORM-PETRELS												
Yellow-nosed Albatross	*Thalassarche chlororhynchos*	Procellariiformes	N					NT				
Black-browed Albatross	*Thalassarche melanophris*	Procellariiformes	N					EN				
Herald Petrel	*Pterodroma arminjoniana*	Procellariiformes	N	G4				LC				
Trindade Petrel	*Pterodroma arminjoniana*	Procellariiformes	N					VU				
Bermuda Petrel/Cahow	*Pterodroma cahow*	Procellariiformes	N	G1				EN	LE			
Jamaica Petrel	*Pterodroma caribbaea*	Procellariiformes	N					CR				
Fea's Petrel	*Pterodroma feae*	Procellariiformes	N	G1G2				NT				
Black-capped Petrel	*Pterodroma hasitata*	Procellariiformes	N	G1	SNRN	SNRN		EN	BCC (BCR 27,31)			
Zino's Petrel	*Pterodroma madeira*	Procellariiformes	N					EN				

Name		Taxonomy	Conservation Status									
			SAB	NatureServe/TNC				State/Federal Status				
Common Name	Scientific Name	Order	Breeder	Global Status	State Status			IUCN Red List Status	U.S. ESA Status/USFWS BCC	Legal Status		
					FL	GA	SC			SC	GA	FL
Soft-plumaged Petrel	*Pterodroma mollis*	Procellariiformes	N					LC				
Bulwer's Petrel	*Bulweria bulwerii*	Procellariiformes	N	G4				LC				
Little Shearwater	*Puffinus assimilis*	Procellariiformes	N					LC				
Greater Shearwater	*Puffinus gravis*	Procellariiformes	N	G5	SNRN	SNRN		LC				
Sooty Shearwater	*Puffinus griseus*	Procellariiformes	N	G5	SNA	SNRN		NT				
Audubon's Shearwater	*Puffinus lherminieri*	Procellariiformes	N	G4G5	SNRN	SNRN		LC	BCC (BCR 27,31)			
Manx Shearwater	*Puffinus puffinus*	Procellariiformes	N	G5		SNRN		LC				
Cory's Shearwater	*Calonectris diomedea*	Procellariiformes	N	G5	SNRN	SNRN	SNRN	LC				
Northern Fulmar	*Fulmarus glacialis*	Procellariiformes	N	G5				LC				
Black-bellied Storm-Petrel	*Fregetta tropica*	Procellariiformes	N	GNR				LC				
European Storm-Petrel	*Hydrbates pelagicus*	Procellariiformes	N					LC				
Wilson's Storm-Petrel	*Oceanites oceanicus*	Procellariiformes	N	G5	SNRN	SNRN		LC				
Band-rumped Storm-Petrel	*Oceanodroma castro*	Procellariiformes	N	G3	SNA	SNRN	SNA	LC				
Leach's Storm-Petrel	*Oceanodroma leucorhoa*	Procellariiformes	N	G5	SNA		SNA	LC				
Swinhoe's Storm-Petrel	*Oceanodroma monorhis*	Procellariiformes	N					LC				
White-faced Storm-Petrel	*Pelagodroma marina*	Procellariiformes	N	G5				LC				
PELICANS & ALLIES												
Brown Pelican	*Pelecanus occidentalis*	Pelecaniformes	Y	G4	S3	S2	S1S2	LC				
Eastern Brown Pelican	*Pelecanus occidentalis carolinensis*	Pelecaniformes	Y	G4TU	SNR	SNRN	SNR	LC		SC		SSC (1)
Magnificent Frigatebird	*Fregata magnificens*	Pelecaniformes	N	G5	S1	SNRN		LC	BCC (BCR 31)			
Northern Gannet	*Morus bassanus*	Pelecaniformes	N	G5	SNRN	S4		LC				
American White Pelican	*Pelecanus erythrorhynchos*	Pelecaniformes	N	G4	SNRN	SNRN		LC				
Red-billed Tropicbird	*Phaethon aethereus*	Pelecaniformes	N	G5		SNRN		LC				

Name		Taxonomy	Conservation Status									
			SAB Breeder	NatureServe/TNC				State/Federal Status				
Common Name	Scientific Name	Order		Global Status	State Status			IUCN Red List Status	U.S. ESA Status/US FWS BCC	Legal Status		
					FL	GA	SC			SC	GA	FL
PELICANS & ALLIES												
White-tailed Tropicbird	*Phaethon lepturus*	Pelecaniformes	N	G5	SNA	SNRN		LC				
Masked Booby	*Sula dactylatra*	Pelecaniformes	N	G5	SNR			LC				
Brown Booby	*Sula leucogaster*	Pelecaniformes	N	G5	SNR			LC	BCC (BCR 31)			
Red-footed Booby	*Sula sula*	Pelecaniformes	N	G5				LC				
Double-crested Cormorant	*Phalacrocorax auritus*	Pelecaniformes	Y	G5	SNR	S5	SNRB, SNRN	LC				
WADERS												
American Bittern	*Botaurus lentiginosus*	Ciconiiformes	N (BCC 2008)	G4	SNRN	S3?	SNRN	LC	BCC (BCR 27,31)			
Least Bittern	*Ixobrychus exilis*	Ciconiiformes	Y	G5	S4	S4	SNRB, SNRN	LC	BCC (BCR 27,31)			
Great Blue Heron	*Ardea herodias*	Ciconiiformes	Y	G5	SNR	S4	SNRB, SNRN	LC				
Great Egret	*Ardea alba*	Ciconiiformes	Y	G5	S4	S4	SNRB, SNRN	LC				
Snowy Egret	*Egretta thula*	Ciconiiformes	Y	G5	S3	S4	SNRB, SNRN	LC				SSC (1)
Little Blue Heron	*Egretta caerulea*	Ciconiiformes	Y	G5	S4	S4	SNRB, SNRN	LC		SC		SSC (1,4)
Tricolored Heron	*Egretta tricolor*	Ciconiiformes	Y	G5	S4	S4	SNRB, SNRN	LC				SSC (1,4)
Cattle Egret	*Bubulcus ibis*	Ciconiiformes	Y	G5	SNR	S5	SNRB, SNRN	LC				
Green Heron	*Butorides virescens*	Ciconiiformes	Y	G5	SNR	S5	SNRB, SNRN	LC				
Reddish Egret	*Egretta rufescens*	Ciconiiformes	Y	G4	S2	S4		NT	BCC (BCR 31)			SSC (1,4)
Yellow-crowned Night-Heron	*Nyctanassa violacea*	Ciconiiformes	Y	G5	S3	S3S4	SNRB, SNRN	LC				

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					FL	GA	SC			SC	GA	FL
WADERS												
Black-crowned Night-Heron	*Nycticorax nycticorax*	Ciconiiformes	Y	G5	S3	S4	SNRB, SNRN	LC				
White Ibis	*Eudocitnus albus*	Ciconiiformes	Y	G5	S4	S4	SNR	LC				SSC (2)
Glossy Ibis	*Plegadis falcinellus*	Ciconiiformes	Y	G5	S3	S2	SHB, SNRN	LC		SC		
Roseate Spoonbill	*Platalea ajaja*	Ciconiiformes	Y	G5	S2			LC	BCC (BCR 27,31)			SSC (1,4)
Wood Stork	*Mycteria americana*	Ciconiiformes	Y	G4	S2	S2	S1S2	LC	E	E	E	E
WATERFOWL												
Harlequin Duck	*Histrionicus histrionicus*	Anseriformes	N	G4				LC				
White-winged Scoter	*Melanitta fusca*	Anseriformes	N	G5	SNA	S4	SNRN	LC				
Black Scoter	*Melanitta nigra*	Anseriformes	N	G5	SNRN	S5	SNRN	LC				
Surf Scoter	*Melanitta perspicillata*	Anseriformes	N	G5	SNRN	S4	SNRN	LC				
Common Merganser	*Mergus merganser*	Anseriformes	N	G5		S4	SNRN	LC				
Common Eider	*Somateria mollissima*	Anseriformes	N	G5			SNA	LC				
King Eider	*Somateria spectabilis*	Anseriformes	N	G5				LC				

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					FL	GA	SC			SC	GA	FL
SHOREBIRDS												
Black-bellied Plover	*Pluvialis squatarola*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC				
American Golden-Plover	*Pluvialis dominica*	Charadriiformes	N	G5	SNA	SNRN	SNA	LC				
Semipalmated Plover	*Charadrius semipalmatus*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC				
Wilson's Plover	*Charadrius wilsonia*	Charadriiformes	Y	G5	S2	S2	S3?	LC	BCC (BCR 27,31)	T	T	
Piping Plover	*Charadrius melodus*	Charadriiformes	N	G3	S2	S1	SNRN	VU	LE, LT		T	T
Snowy Plover	*Charadrius alexandrinus*	Charadriiformes	N	G4	S1			LC	BCC (BCR 27,31)©			T
Southeastern Snowy Plover	*Charadrius alexandrinus tenuirostris*	Charadriiformes	N	G4T3Q	S1							
American Avocet	*Recurvirostra americana*	Charadriiformes	Y	G5	S2	S3	SNRN	LC				
Lesser Yellowlegs	*Tringa flavipes*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC	BCC (BCR 31)			
Greater Yellowlegs	*Tringa melanoleuca*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC				
Willet	*Tringa semipalmata*	Charadriiformes	Y	G5	SNR	S5	SNR	LC				
Spotted Sandpiper	*Actitis macularius*	Charadriiformes	Y	G5	SNRN	S4	S4	LC				
Solitary Sandpiper	*Tringa solitaria*	Charadriiformes	N	G5	SNA	SNRN	SNA	LC	BCC (BCR 27,31)			
Semipalmated Sandpiper	*Calidris pusilla*	Charadriiformes	N	G5	SNRM	SNRN	SNA	LC	BCC (BCR 27,31)			
Sharp-tailed Sandpiper	*Calidris acuminata*	Charadriiformes	N	G5				LC				
Baird's Sandpiper	*Calidris bairdii*	Charadriiformes	N	G5			SNA	LC				
Curlew Sandpiper	*Calidris ferruginea*	Charadriiformes	N	G5?				LC				

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					FL	GA	SC			SC	GA	FL
SHOREBIRDS												
White-rumped Sandpiper	*Calidris fuscicollis*	Charadriiformes	N	G5	SNA	SNRN	SNA	LC				
Stilt Sandpiper	*Calidris himantopus*	Charadriiformes	N	G5	SNRM	SNRN	SNA	LC				
Purple Sandpiper	*Calidris maritima*	Charadriiformes	N	G5	SNRN	S4		LC				
Western Sandpiper	*Calidris mauri*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC				
Pectoral Sandpiper	*Calidris melanotos*	Charadriiformes	N	G5	SNRM	SNRN	SNA	LC				
Least Sandpiper	*Calidris minutilla*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC				
Rock Sandpiper	*Calidris ptilocnemis*	Charadriiformes	N	G5				LC				
Buff-breasted Sandpiper	*Tryngites subruficollis*	Charadriiformes	N	G4	SNA	SNRN	SNA	NT	BCC (BCR 27,31)			
Red-necked Stint	*Calidris ruficollis*	Charadriiformes	N	G5				LC				
Broad-billed Sandpiper	*Limicola falcinellus*	Charadriiformes	N	G5				LC				
Whimbrel	*Numenius phaeopus*	Charadriiformes	N	G5	SNRN	S4	SNRN	LC	BCC (BCR 27,31)			
Long-billed Curlew	*Numenius americanus*	Charadriiformes	N	G5	SNA	S3	SNA	NT	BCC (BCR 27,31)			
Eskimo Curlew	*Numenius borealis*	Charadriiformes	N	GH			SX	CR	LE			
Ruddy Turnstone	*Arenaria interpres*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC				
Dunlin	*Calidris alpina*	Charadriiformes	N	G5	SNRN	G5	SNRN	LC				
Red Knot	*Calidris canutus*	Charadriiformes	N	G4	SNRN	S3	SNRN	LC	BCC (BCR 27,31)(a)		R	
Sanderling	*Calidris alba*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC				
Short-billed Dowitcher	*Limnodromus griseus*	Charadriiformes	N	G5	SNRN	S4	SNRN	LC	BCC (BCR 27,31)			

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					FL	GA	SC			SC	GA	FL
SHOREBIRDS												
Long-billed Dowitcher	*Limnodromus scolopaceus*	Charadriiformes	N	G5	SNRN	S4	SNRN	LC				
Marbled Godwit	*Limosa fedoa*	Charadriiformes	N	G5	SNRN	S3	SNRN	LC	BCC (BCR 27,31)			
Hudsonian Godwit	*Limosa haemastica*	Charadriiformes	N	G4				LC				
Bar-tailed Godwit	*Limosa lapponica*	Charadriiformes	N	G5				LC				
Red Phalarope	*Phalaropus fulicarius*	Charadriiformes	N	G5	SNRN	SNRN	SNR	LC				
Red-necked Phalarope	*Phalaropus lobatus*	Charadriiformes	N	G4G5	SNRN	SNRN	SNR	LC				
Wilson's Phalarope	*Phalaropus tricolor*	Charadriiformes	N	G5	SNA	SNRN	SNA	LC				
American Oystercatcher	*Haematopus palliatus*	Charadriiformes	Y	G5	S2	S2	SNR	LC	BCC (BCR 27,31)		R	SSC (1,2)
TERNS & GULLS												
Sooty Tern	*Onychoprion fuscatus*	Charadriiformes	Y	G5	S1		SNR	LC				
Gull-billed Tern	*Gelochelidon nilotica*	Charadriiformes	Y	G5	S2	S1	SNR	LC	BCC (BCR 27)		T	
Least Tern	*Sterna antillarum*	Charadriiformes	Y	G4	S3	S3	S3	LC	BCC (BCR 27,31)©	T	R	T
Roseate Tern	*Sterna dougallii*	Charadriiformes	Y	G4	S1			LC				T
Roseate Tern	*Sterna dougallii dougallii*	Charadriiformes	Y	G4T3	S1		SNR	LC	LE, LT			
Forster's Tern	*Sterna forsteri*	Charadriiformes	Y	G5	SNRN	S5	SNRN	LC				
Common Tern	*Sterna hirundo*	Charadriiformes	Y	G5	SNR	SNRN	S3?	LC				
Arctic Tern	*Sterna paradisaea*	Charadriiformes	N	G5	SNA			LC				
Royal Tern	*Thalasseus maximus*	Charadriiformes	Y	G5	S3	S5	SNRB, SNRN	LC				

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SHOREBIRDS												
Sandwich Tern	*Thalasseus sandvicensis*	Charadriiformes	Y	G5	S2	S4	SNR	LC	BCC (BCR 27)			
Black Tern	*Childonias niger*	Charadriiformes	N	G4	SNA	S3	SNA	LC				
Bridled Tern	*Onychoprion anaethetus*	Charadriiformes	N	G5	SNRN	SNRN		LC				
Black Noddy	*Anous minutus*	Charadriiformes	N	G5	SNA			LC				
Brown Noddy	*Anous stolidus*	Charadriiformes	N	G5	S1			LC				
Black Skimmer	*Rynchops niger*	Charadriiformes	Y	G5	S3	S1	S2	LC	BCC (BCR 27,31)		R	SSC (1)
Bonaparte's Gull	*Chroicocephalus philadelphia*	Charadriiformes	N	G5	SNRN	S3	SNRN	LC				
Common Gull	*Larus canus*	Charadriiformes	N	G5								
Ring-billed Gull	*Larus delawarensis*	Charadriiformes	N	G5	SNRN	S5	SNRN	LC				
Lesser Black-backed Gull	*Larus fuscus*	Charadriiformes	N	G5	SNA	SNRN	SNA	LC				
Great Black-backed Gull	*Larus marinus*	Charadriiformes	Y	G5	SNRN	S3	SNRN	LC				
Herring Gull	*Larus argentatus*	Charadriiformes	Y	G5	SNRN	S5	SNRN	LC				
Iceland Gull	*Larus glaucoides*	Charadriiformes	N	G5				LC				
Glaucous Gull	*Larus hyperboreus*	Charadriiformes	N	G5	SNA		SNA	LC				
Little Gull	*Larus minutus*	Charadriiformes	N	G5				LC				
Black-headed Gull	*Larus ridibundus*	Charadriiformes	N	G5				LC				
Thayer's Gull	*Larus thayeri*	Charadriiformes	N	G5				LC				
Franklin's Gull	*Leucophaeus pipixcan*	Charadriiformes	N	G4G5	SNA			LC				
Laughing Gull	*Leucophaeus atricilla*	Charadriiformes	Y	G5	SNR	S5	SNR	LC				
Ivory Gull	*Pagophila eburnea*	Charadriiformes	N	G5				NT				
Sabine's Gull	*Xema sabini*	Charadriiformes	N	G5				LC				
Ross's Gull	*Rhodostethia rosea*	Charadriiformes	N	G3G4				LC				

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SHOREBIRDS													
Black-legged Kittiwake	*Rissa tridactyla*	Charadriiformes	N	G5	SNRN	SNRN	SNRN	LC					
Long-tailed Jaeger	*Stercorarius longicaudus*	Charadriiformes	N	G5	SNA			LC					
Parasitic Jaeger	*Stercorarius parasiticus*	Charadriiformes	N	G5	SNRN	SNRN	SNA	LC					
Pomarine Jaeger	*Stercorarius pomarinus*	Charadriiformes	N	G5	SNRN	SNRN	SNA	LC					
South Polar Skua	*Catharacta maccormicki*	Charadriiformes	N	G5				LC					
Great Skua	*Catharacta skua*	Charadriiformes	N	G4G5				LC					
ALCIDS													
Razorbill	*Alca torda*	Charadriiformes	N	G5				LC					
Dovekie	*Alle alle*	Charadriiformes	N	G5									
Black Guillemot	*Cepphus grylle*	Charadriiformes	N	G5				LC					
Atlantic Puffin	*Fratercula arctica*	Charadriiformes	N	G5				LC					
CommonMurre	*Uria aalge*	Charadriiformes	N	G5				LC					
Thick-billed Murre	*Uria lomvia*	Charadriiformes	N	G5				LC					

Global Status

G1 = critically imperiled
G2 = imperiled
G3 = vulnerable
G4 = apparently secure
G5 = secure
GNR = unranked

G#G#/S#S#	**Range Rank**—A numeric range rank (e.g., G2G3, G1G3) is used to indicate the range of uncertainty about the exact status of a taxon or ecosystem type. Ranges cannot skip more than two ranks (e.g., GU should be used rather than G1G4)
SU	**Unrankable**—Currently unrankable due to lack of information or due to substantially conflicting information about status or trends.
SNR	**Unranked**—National or subnational conservation status not yet assessed
SNA	Not Applicable —A conservation status rank is not applicable because the species or ecosystem is not a suitable target for conservation activities
S#?	**Inexact Numeric Rank**—Denotes inexact numeric rank. This designation should not be used with any of the variant national or subnational conservation status ranks or NX, SX, NH, or SH
B	**Breeding**—Conservation status refers to the breeding population of the species in the nation or state/province
N	**Nonbreeding**—Conservation status refers to the non-breeding population of the species in the nation or state/province
M	**Migrant**—Migrant species occurring regularly on migration at particular staging areas or concentration spots where the species might warrant conservation attention. Conservation status refers to the aggregating transient population of the species in the na
U.S. ESA Status/USFWS BCC	(BCC) Bird of Conservation Concern, (BCR) Bird Conservation Region, (a) ESA candidate, (b) non-listed subspecies or population of Threatened or Endangered

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island communities.

The Bureau of Ocean Energy Management Mission

The Bureau of Ocean Energy Management (BOEM) promotes energy independence, environmental protection, and economic development through responsible, science-based management of offshore conventional and renewable energy.