# TO OBSERVE AND PROTECT: HOW NOAA PROCURES DATA FOR WEATHER FORECASTING

## HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY AND ENVIRONMENT

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED TWELFTH CONGRESS

SECOND SESSION

WEDNESDAY, MARCH 28, 2012

**Serial No. 112–73**

Printed for the use of the Committee on Science, Space, and Technology

Available via the World Wide Web: http://science.house.gov

U.S. GOVERNMENT PRINTING OFFICE

73–606PDF WASHINGTON : 2012

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov Phone: toll free (866) 512–1800; DC area (202) 512–1800
Fax: (202) 512–2104 Mail: Stop IDCC, Washington, DC 20402–0001

## COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HON. RALPH M. HALL, Texas, *Chair*

F. JAMES SENSENBRENNER, JR., Wisconsin
LAMAR S. SMITH, Texas
DANA ROHRABACHER, California
ROSCOE G. BARTLETT, Maryland
FRANK D. LUCAS, Oklahoma
JUDY BIGGERT, Illinois
W. TODD AKIN, Missouri
RANDY NEUGEBAUER, Texas
MICHAEL T. MCCAUL, Texas
PAUL C. BROUN, Georgia
SANDY ADAMS, Florida
BENJAMIN QUAYLE, Arizona
CHARLES J. "CHUCK" FLEISCHMANN, Tennessee
E. SCOTT RIGELL, Virginia
STEVEN M. PALAZZO, Mississippi
MO BROOKS, Alabama
ANDY HARRIS, Maryland
RANDY HULTGREN, Illinois
CHIP CRAVAACK, Minnesota
LARRY BUCSHON, Indiana
DAN BENISHEK, Michigan
VACANCY

EDDIE BERNICE JOHNSON, Texas
JERRY F. COSTELLO, Illinois
LYNN C. WOOLSEY, California
ZOE LOFGREN, California
BRAD MILLER, North Carolina
DANIEL LIPINSKI, Illinois
DONNA F. EDWARDS, Maryland
BEN R. LUJÁN, New Mexico
PAUL D. TONKO, New York
JERRY MCNERNEY, California
TERRI A. SEWELL, Alabama
FREDERICA S. WILSON, Florida
HANSEN CLARKE, Michigan
SUZANNE BONAMICI, Oregon
VACANCY
VACANCY
VACANCY

---

### SUBCOMMITTEE ON ENERGY AND ENVIRONMENT

HON. ANDY HARRIS, Maryland, *Chair*

DANA ROHRABACHER, California
ROSCOE G. BARTLETT, Maryland
FRANK D. LUCAS, Oklahoma
JUDY BIGGERT, Illinois
W. TODD AKIN, Missouri
RANDY NEUGEBAUER, Texas
PAUL C. BROUN, Georgia
CHARLES J. "CHUCK" FLEISCHMANN, Tennessee
RALPH M. HALL, Texas

BRAD MILLER, North Carolina
LYNN C. WOOLSEY, California
BEN R. LUJÁN, New Mexico
PAUL D. TONKO, New York
ZOE LOFGREN, California
JERRY MCNERNEY, California
EDDIE BERNICE JOHNSON, Texas

# CONTENTS

**March 28, 2012**

**Appendix II: Additional Material for the Record**

# TO OBSERVE AND PROTECT: HOW NOAA PROCURES DATA FOR WEATHER FORECASTING

**WEDNESDAY, MARCH 28, 2012**

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENERGY AND ENVIRONMENT,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
*Washington, DC.*

The Subcommittee met, pursuant to call, at 3:03 p.m., in Room 2318 of the Rayburn House Office Building, Hon. Andy Harris [Chairman of the Subcommittee] presiding.

RALPH M. HALL, TEXAS
CHAIRMAN

EDDIE BERNICE JOHNSON, TEXAS
RANKING MEMBER

U.S. HOUSE OF REPRESENTATIVES

# COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, DC 20515-6301
(202) 225-6371
www.science.house.gov

## Subcommittee on Energy & Environment

***To Observe and Protect: How NOAA Procures Data for Weather Forecasting***

Wednesday, March 28, 2012
2:00 p.m. to 4:00 p.m.
2318 Rayburn House Office Building

Witnesses

Panel I

**Ms. Mary Kicza**, Assistant Administrator, National Environmental Satellite, Data, and Information Service, NOAA

**Dr. Alexander MacDonald**, Deputy Assistant Administrator for Research Laboratories and Cooperative Institutes, Office of Oceanic and Atmospheric Research, NOAA

**Mr. John Murphy**, Chief, Programs and Plans Division, National Weather Service, NOAA

Panel II

**Mr. Eric Webster**, Vice President and Director, Weather Systems, ITT Exelis

**Dr. David Crain**, Chief Executive Officer, GeoMetWatch

**Mr. Bruce Lev**, Vice Chairman, AirDat LLC

**Dr. Berrien Moore**, Dean, University of Oklahoma College of Atmospheric and Geographic Sciences, and Director, National Weather Center

**U.S. HOUSE OF REPRESENTATIVES**
**COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY**
**SUBCOMMITTEE ON ENERGY AND ENVIRONMENT**
**HEARING CHARTER**

# *To Observe and Protect: How NOAA Procures Data for Weather Forecasting*

**Wednesday, March 28, 2012**
**2:00 p.m. to 4:00 p.m.**
**2318 Rayburn House Office Building**

## PURPOSE

On Wednesday, March 28, at 2:00 p.m. the Subcommittee Energy and Environment of the House Committee on Science, Space, and Technology Committee will hold a hearing to examine how the National Oceanic and Atmospheric Administration (NOAA) develops, evaluates, and executes plans to deliver the best and most cost effective data necessary to meet requirements for severe weather prediction and other observational needs.

## WITNESSES

### PANEL I

- **Ms. Mary Kicza,** Assistant Administrator, National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration (NOAA)
- **Dr. Alexander MacDonald**, Deputy Assistant Administrator for Research Laboratories and Cooperative Institutes, Office of Oceanic and Atmospheric Research, NOAA
- **Mr. John Murphy**, Chief, Programs and Plans Division, National Weather Service, NOAA

### PANEL II

- **Mr. Eric Webster**, Vice President and Director, Weather Systems, ITT Exelis
- **Dr. David Crain,** Chief Executive Officer, GeoMetWatch
- **Mr. Bruce Lev,** Vice Chairman, AirDat LLC
- **Dr. Berrien Moore**, Dean, University of Oklahoma College of Atmospheric and Geographic Sciences, and Director, National Weather Center

## BACKGROUND

The core mission of the National Weather Service (NWS) is to protect life and property and enhance the national economy through weather forecasts and warnings. Successful execution of this mission is primarily dependent on obtaining data necessary to generate accurate forecasts. This data is obtained through a mix of observing systems located in space (satellites), the atmosphere, on land, and in the ocean.

The FY2013 budget request for NOAA is $5.1 billion. Of this amount, $2.04 billion or 40 percent is designated for NESDIS (National Environmental Satellite, Data, and Information Service), which acquires and manages NOAA's operational satellites. Within the NESDIS budget, 84 percent, or $1.7 billion is for two satellite programs, the Joint Polar Satellite System (JPSS) and the

Geostationary Operational Environmental Satellite R-Series (GOES-R).The percentage of NOAA's budget dedicated to satellites has grown substantially in recent years. The FY09 budget request for NESDIS represented 27 percent of NOAA's total budget. Procurements of large infrastructure such as satellites have a natural ramp-up and ramp-down cycles for appropriations. However, cost over-runs, poor management, technical problems and contractor mistakes associated with recent satellite programs have exacerbated these budget pressures. As a result, the amount of resources currently designated for satellite procurement is reducing funding available for—and in some cases forcing the elimination of—other worthwhile programs at NOAA.

For example, within the NWS budget, the Administration is proposing to eliminate funding for the NOAA Profiler Network currently installed in Tornado Alley[1] and the National Mesonet Network.[2] Although both of these observing systems have been the subject of a number of reports endorsing the value of the data they generate – including the National Academies of Science – the budget request still eliminates funding for them. This action brings into question the process NOAA is using to decide the value of data from different types of observing systems.

Meeting Data Requirements

To develop data requirements for weather forecasts, NOAA has created an intra-agency group called the NOAA Observing System Council (NOSC). Led by the Assistant Secretary of Commerce for Environmental Observation and Prediction, the NOSC has members from each of the line offices in NOAA as each service uses observations to provide information and products to the public. Within this framework, NOAA employs a system called Technology, Planning, and Integration for Observation (TPIO).

The TPIO system manages three major NOAA-wide capabilities, including: Observation System Architecture, Requirements and Planning, and Data Management Architecture. Observation System Architecture (OSA) includes developing and analyzing NOAA's integrated observation architecture. OSA works with the Requirements and Planning team to assess observation requirements against current, planned, and future observational capabilities. The Requirements and Planning (RAP) team is responsible for the collection, standardization, configuration, and assessment of all NOAA observation requirements. The Data Management Architecture (DMA) team is responsible for developing and analyzing integrated data management architecture.[3]

The process further involves TPIO working with NOAA program leaders and Subject Matter Experts (SMEs) to document observing requirements and labeling these requirements as mission critical, mission optimal, or mission enhancing. Those requirements garnering a mission critical designation are considered priority-1 importance, ensuring that these are the first requirements that are satisfied.[4] Once these requirements are documented and designated, they are subject to the Government Performance and Results Act (GPRA) and other NOAA-specific performance measures and then verified again by program managers and SMEs.[5]

---

[1] The Profiler Network is a system of observing stations that measure the wind speed and direction providing a vertical profile of the atmosphere.

[2] Surface-based observing networks owned and operated by non-Federal parties.

[3] https://www.nosc.noaa.gov/tpio/main/aboutrap.html

[4] https://www.nosc.noaa.gov/tpio/main/aboutrap.html#documenting

[5] https://www.nosc.noaa.gov/tpio/main/aboutrap.html#vv

Recently, NOAA has added a new element to this process called the NOAA Observation Systems Integrated Analysis Capability (NOSIA). According to NOAA, the NOSIA is a pilot study to "examine NOAA's upper air observing portfolio and ultimately will recommend a multi-year investment strategy/road map for upper air observing systems."[6]

*Observing System Simulation Experiments*
Another method that can be used to analyze the value of weather data from observing systems is called an Observing System Simulation Experiment (OSSE). OSSEs employ computer modeling used to investigate the potential impact of planned observing systems or to test current observational and data assimilation systems. Simulated data is used as an input into a data assimilation system, which in turn, is then used as the input for weather forecasting models. Different data types, whether inferred or direct measurements (explained below), can then be compared against one another, the measurement being the utility of these data streams to weather forecasting.

According to NOAA's Earth Systems Research Laboratory (ESRL), OSSE's provide an objective and quantitative manner through which to guide optimal development of observing systems. OSSE's "could play a critical role in…identifying future observation systems and data assimilation systems for improvement."[7] Additionally, ESRL plans "to build an OSSE or OSSEs helping NOAA to evaluate all potential future observation systems for all weather applications and identify improvement of data assimilation and forecast system." To date, however, NOAA's budgetary decisions for observing systems have not been based on information gleaned from OSSEs. Rather, decisions have been made using program managers and subject matter experts. The tools for NOAA to base decisions on impartial and independent information already exist, but are not part of NOAA's standard operating procedure to utilize them.

History of Weather Observations
The value of weather observations to society has been understood for centuries. However, it was not until the advent of the telegraph in the mid-1800s that allowed such observations to be useful in the creation of weather maps. In the U.S., the first official recognition of the utility of observations was established by a Joint Congressional Resolution in 1870 and signed by President Grant. It directed the Secretary of War to collect observations and transmit such data to DC. This first national policy on weather observation became the basis of the Cooperative Observer Program (COOP), a network of civilians who take daily observation from all areas of the U.S., which was formally created in the Organic Act of 1890 that established the Weather Bureau within the Department of Agriculture.[8]

In 1926, Congress passed the Air Commerce Act and directed the Weather Bureau to perform observations, warnings, and forecasts for weather impacting the safety of civil aviation and above the oceans. Congress expanded this role in 1938 with the Flood Control Act, delegating additional authority in the areas of hydrology and water resources.

In 1940, President Franklin Roosevelt transferred the Weather Bureau from the Department of Agriculture to the Department of Commerce, recognizing that the mission of weather observations

[6] https://www.nosc.noaa.gov/tpio/
[7] http://laps.noaa.gov/met/osse.html
[8] A weather and climate observing network consisting of more than 11,000 volunteers who take observations on farms, in urban and suburban areas, National Parks, seashores, and mountaintops.

and forecasting had grown beyond its initial role of supporting just agriculture and aviation. Around the same time, observational technology was revolutionized with the introduction of the radiosonde—an instrument package usually attached to weather balloons that measures temperature, relative humidity, and wind speed.

The 1950s and 1960s were marked by improvements in observational technologies such as satellites and operational radar. The National Weather Service was incorporated into NOAA in 1970 and technological developments continued throughout the 1980s within the Federal government and also throughout the private sector and university structure. In 1992, Congress passed the Weather Service Modernization Act to provide a new framework to implement technological advances made through research.

Categories of Observational Data

There are three major components driving advances in weather forecasting: improved observational data, data assimilation, and modeling (which includes processing speed). Although data assimilation and modeling are critically important to improvements in forecasting, the hearing will focus on the procurement of observational data.

There are four general categories of observation systems: space-based remote sensing, atmospheric observations, surface observations, and ocean observations. Each of these categories play an important role in weather forecasting; no single observational system can supply all the necessary data for weather forecasts. Furthermore, not all data from the different categories are necessarily interchangeable. Atmospheric, surface, and ocean observations can include both direct measurements and passive sensing of atmospheric conditions. Space-based observations rely on a number of proxy parameters to infer atmospheric conditions. They are not direct observations, but rather the data is deduced through a series of mathematical equations based on radiated or reflected energy from the Earth.[9] NOAA uses information from over 100 observational networks. Several of these systems are highlighted below as examples of the types available.

*Space-based remote sensing*

For space-based observations, NOAA relies on two different satellite systems for weather forecasting. The Geostationary Operational Environmental Satellite (GOES) satellites sit 22,300 miles above the surface of the Earth. These satellites orbit the Earth at the same speed as the Earth's rotation, thereby allowing them to stay above the same fixed spot above the surface. GOES satellites work in tandem, with one providing observations over the eastern half of the continental U.S. and much of the Atlantic Ocean; and the second providing observations over the western half and much of the Pacific Ocean. Typically, NOAA maintains an on-orbit spare GOES satellite in the event that one of the existing operational satellites malfunctions. The on-orbit spare can be remotely maneuvered into position and begin providing observations. NOAA first began launching GOES satellites in 1975. Currently, GOES-13 covers the Eastern half of the country, and GOES-15 covers the Western half. The two most important instruments on the GOES satellites are the imager and the sounder. The imager is designed to sense radiant and solar reflected energy from the Earth. The sounder is designed to sense data that provides information about atmospheric temperature and moisture profiles, surface and cloud top temperatures, and ozone distribution.

---

[9] National Research Council. *Observing Weather and Climate From the Ground Up: A Nationwide Network of Networks*. Washington, DC. 2009.

The Polar-orbiting Operational Environmental Satellites (POES) transverse the globe from pole to pole, with each orbit being defined by the time of day they pass over the equator: early morning, late morning, and afternoon. Each polar-orbiting satellite makes approximately 14 orbits per day and is able to view per day.[10] Currently, there is one operational POES satellite, two operational Defense Meteorological Satellite Program (DMSP) satellites, and a European satellite, called the Meteorological Operational (MetOp) satellite. In order to stream-line government functions and reduce duplication, in 1993 an Executive Order brought together the Department of Defense (DoD) program and the NOAA program, and created the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program. In order to mitigate the risk of large advances in remote sensing technology, the National Aeronautics and Space Administration (NASA) was brought into the program to build the NPOESS Preparatory Project (NPP). NPP was intended to be a research satellite that would be launched in advance of the new NPOESS satellites and test the value of the data provided.

Originally designed to cost $6.5 billion for six satelites, the costs and difficulties of the NPOESS program grew substantially. In 2005, the program was subject to a Nunn-McCurdy[11] recertification and was substantially altered. By 2009, life-cycle costs of the program had grown to $14.9 billion for four satellites. A DoD-contracted Independent Review Team analyzed the program and concluded that it had an extraordinarily low probability of success.[12] In 2010, after working with NOAA, NASA, and the DoD, the Office of Science and Technology Policy (OSTP) announced that the NPOESS program would dissolve into two separate programs. NOAA and NASA would manage the Joint Polar Satellite Program (JPSS) responsible for the afternoon orbit, and DoD would manage the Defense Weather Satellite System (DWSS) responsible for the early morning orbit. The European satellite, MetOp would operate in the late morning orbit.

Given the extraordinary problems with this program, the launch schedule for NPP had slipped from May 2006 to October 2011. JPSS-1 (originally C-1 under the NPOESS program) was initially scheduled to fly in 2008. NOAA projects JPSS-1 will not launch until the first quarter of FY2017. Given these drastic shifts in schedule, NPP was re-designated an operational satellite in order to ensure working instruments in orbit when the previous POES series was retired. NOAA currently projects a near-certain data gap will occur, such that NPP will stop being operational before JPSS-1 is able to launch.

As part of the FY2013 budget request, NOAA has announced that it has capped the life-cycle costs of the JPSS program at $12.9 billion for two satellites.

*Atmospheric Observations*

Atmospheric data is measured in several ways. The oldest technology still in use is radiosondes attached to weather balloons. This instrument package measures temperature, relative humidity, and wind. The package is secured to a weather balloon and released in designated places around the country twice daily. The information provides a vertical profile of the current atmospheric

[10] Committee on Science, Space and Technology. "From NPOESS to JPSS: An Update on the Nation's Restructured Polar Weather Satellite Program". September 23, 2011. Hearing Charter Subcommittee on Investigations and Oversight and Subcommittee on Energy and Environment.

[11] The Air Force managed the acquisition of the NPOESS satellites. The program was therefore subject to Department of Defense regulations for major defense programs. When such programs exceed approved baseline costs by more than 25 percent, recertification is required by 10 U.S.C. 2433 et seq.

[12] NPOESS Independent Review Team, Final Report. June 1, 2009.

conditions. Although highly reliable in terms of data quality, the discrete temporal and spatial data points provided limit the utility of these measurements.

Doppler radar is an active observing system that measures precipitation and is vital for detecting and tracking storms of all kinds.[13] Radar wind profilers are able to provide vertical profiles of wind speed and direction up to 50,000 feet above the Earth's surface. Mainly deployed in Tornado Alley, these wind profilers have substantially increased the warning time for tornado warnings during severe outbreaks.[14]

Another method for measuring atmospheric conditions include the use of sensors on commercial aircraft. The Tropospheric Aircraft Meteorological Data Relay (TAMDAR) system measures temperature, relative humidity, winds, icing, turbulence, and position. Another method being explored for additional aerial observations is the use of unmanned aircraft systems, or drones. These drones can be flown into hurricanes or other severe storms to collect vital data without endangering human life.

*Surface Observations*

Surface measurements typically consist of temperature, relative humidity, wind, precipitation, and air pressure.[15] Although the World Meteorological Organization defines the standards for such measurements (for example, wind measurements are taken at 10 meters above land), observations for specific industries may vary. Needs for transportation, energy sector, agriculture, and air quality will all have specific measurement needs that differ from the norm. Approximately 500 surface networks operate in the U.S., owned by the Federal government, States, universities, private sector and hobbyists. Despite the large number of systems, these networks are not evenly distributed, resulting in decreased utility in rural areas.[16]

*Ocean Observations*

Integrated ocean observations formally authorized as the Integrated Ocean Observation System (IOOS) as part of P.L. 111-11. IOOS is a national-regional partnership that supports over 1,500 instruments and platforms. Measurements include water temperature, wind, waves, currents, chlorophyll, and water chemistry. Thirty-nine surface buoys and subsurface recorders measuring water pressure are used as the backbone of the Deep-ocean Assessment and Reporting of Tsunamis (DART) program. In the last few years, unmanned marine vehicles such as wave gliders have revolutionized the concept of data collection. Using wave energy, these remote platforms can be placed in stationary locations, move if necessary, and return to base for maintenance, significantly reducing ship time needed to repair stationary buoys.

Data Providers

Much of the data utilized by NOAA is obtained from observing systems owned by the Federal government. However, much data is procured from privately-owned networks, universities, and other countries. Currently, ocean, surface, and atmospheric data is obtained from public and private observation networks.

---

13 NOAA is currently research the next generation of radars to replace Doppler radars with Multiphase Array Radar (MPAR).

14 NOAA's FY13 budget request will zero out this program.

15 National Research Council. *Observing Weather and Climate From the Ground Up: A Nationwide Network of Networks.* Washington, DC. 2009.

16 National Research Council. *Observing Weather and Climate From the Ground Up: A Nationwide Network of Networks.* Washington, DC. 2009.

Space-based observations used in weather forecasting have thus far been the sole domain of government networks. NOAA uses data from satellites owned by NOAA, NASA, DoD, U.S. Geological Survey or foreign countries. In P.L. 102-555, Congress enacted the following provision:

Title VI – Prohibition of Commercialization of Weather Satellites
Sec. 601. Prohibition

> Neither the President nor any other official of the Government shall make any effort to lease, sell, or transfer to the private sector, or commercialize any portion of the weather satellite systems operated by the Department of Commerce or any successor agency.

Sec. 602. Future Considerations.

> Regardless of any change in circumstances subsequent to the enactment of this Act, even if such change makes it appear to be in the national interest to commercialize weather satellites, neither the President nor any official shall take any action prohibited by section 601 unless this title has first been repealed.

The interpretation of Title VI has led to the exclusive use of government owned satellite data. However, the language can be interpreted such that it does not prohibit the procurement of data from commercialized weather satellite systems, only the prohibition of commercializing existing weather satellite systems. The costs and problems that have plagued the NOAA weather satellite programs in the last decade indicate a new paradigm may be warranted.

Chairman HARRIS. The Subcommittee on Energy and Environment will come to order. Good afternoon. Welcome to today's hearing entitled To Observe and Protect: How NOAA Procures Data for Weather Forecasting. In front of you are packets containing the written testimony, biographies and Truth in Testimony disclosures for today's witness panel. I now recognize myself five minutes for an opening statement.

First of all, I want to thank you all for your patience while we were on the Floor voting, and I want to welcome everyone to this afternoon's hearing to gain a better understanding of the NOAA's approach to procuring data for weather forecasting.

Three weeks ago while testifying before this Subcommittee, NOAA Administrator Lubchenco spoke of the tough choices required in developing the Administration's fiscal year 2013 budget request, which, by the way, included an increase in overall funding of 3.1 percent. Each year, the budget request for satellite programs grows as a percentage of NOAA's total budget request. NOAA's "tough choices" have resulted in placing nearly all of its eggs in a single basket: satellite systems fraught with a long history of major problems. These decisions are now causing trade-offs with other valuable networks.

Today's hearing is designed to take a closer look at the NOAA process for making those tough choices when it comes to costly observing systems, including how requirements are determined, how data needs are met and how NOAA research is facilitating better analysis and technologies.

We all recognize three things about NOAA and weather forecasting in the future: First, recent severe storms have reaffirmed that we need to focus limited NOAA resources on preventing the loss of lives and property. Second, NOAA satellite programs have been plagued by schedule delays, chronic mismanagement and significant cost overruns. Third, as admitted by NOAA and confirmed by GAO experts, there will be a gap in polar-orbiting satellite data in the not-too-distant future, and Dr. Lubchenco told this Committee earlier this month that there aren't any "viable alternative options." We hope to explore this statement in further detail today.

The fiscal year 2013 budget request provides a perfect illustration of the need to take a closer look at NOAA's process. Satellite programs represent almost 40 percent of the total $5.1 billion budget request, with the result being that programs in other line offices suffer. The decision to invest so heavily in the currently planned space-based remote sensing systems comes at the expense of observing systems that would come at a small fraction of the price.

For example, NOAA has made decisions to eliminate or reduce investments in the national Profiler Network, the national Mesonet Network, and the tsunami buoy network. These decisions will affect lives and property and do not seem to be based on independent analysis.

Knowing the challenges NOAA and the Weather Service face, it is all the more important that we conduct impartial technical assessments to guarantee that the money we spend on a combination of observing systems gets us the greatest forecasting bang for our buck, and that our data procurement is based on costs and benefits, rather than subjective thinking. Rather than relying on the whims of an individual Administration or the opinions of subject matter experts divorced from fiscal realities or program managers wedded to certain systems, NOAA needs to undertake comprehensive, objective and quantitative evaluations of observing systems that incorporates cost.

There are options available to conduct more thorough analysis of these systems. For example, in a recent article, Administrator Lubchenco referred to the use of Observing System Simulation Experiments, or OSSE, as a "powerful tool," and that is her quote, a powerful tool for evaluating different combinations of observing systems to meet forecasting needs. Unfortunately, NOAA has not used this powerful tool to guide decision-making related to current weather data challenges.

The status quo can't continue. We no longer have the budgetary luxury to repeat past mistakes in our approach to procuring data for weather forecasting. NOAA needs to think beyond its current framework on the most cost-effective and efficient way to get data for weather forecasting. Technological advancements in the last two decades make it possible for more information to come from the private sector while still maintaining the level of quality assurance necessary for accurate weather forecasting. Improvements in computer processing and data assimilation allow for different combinations of data to create advanced forecasts. Such progress requires NOAA employ objective analysis to determine the best course forward.

I want to thank the witnesses for appearing before the Subcommittee, and I look forward to a constructive discussion.

[The prepared statement of Mr. Harris follows:]

PREPARED STATEMENT OF SUBCOMMITTEE CHAIRMAN ANDY HARRIS

I want to welcome everyone to this afternoon's hearing to gain a better understanding of the National Oceanic and Atmospheric Administration's approach to procuring data for weather forecasting.

Three weeks ago while testifying before this Subcommittee, NOAA Administrator Lubchenco spoke of the "tough choices" required in developing the Administration's fiscal year 2013 budget request, which, by the way, included an increase in funding of 3.1 percent. Each year, the budget request for satellite programs grows as a percentage of NOAA's total budget request. NOAA's "tough choices" have resulted in placing nearly all of its eggs in a single basket: satellite systems fraught with a long history of major problems. These decisions are causing trade-offs with other valuable networks. Today's hearing is designed to take a closer look at the NOAA process for making those tough choices when it comes to costly observing systems, including how requirements are determined, how data needs are met and how NOAA research is facilitating better analysis and technologies.

We all recognize three things about NOAA and weather forecasting in the future: First, recent severe storms have reaffirmed that we need to focus limited NOAA resources on preventing the loss of lives and property. Second, NOAA satellite programs have been plagued by schedule delays, chronic mismanagement and significant cost overruns. Third, as admitted by NOAA and confirmed by Government Accountability Office experts, there will be a gap in polar-orbiting satellite data in the not-too-distant future, and Dr. Lubchenco told this Committee earlier this month that there aren't any "viable alternative options." We hope to explore this statement in further detail today.

The FY13 budget request provides a perfect illustration of the need to take a closer look at NOAA's process. Satellite programs represent almost 40 percent of the total $5.1 billion budget request, with the result being that programs in other line offices suffer. The decision to invest so heavily in the currently planned space-based remote sensing systems comes at the expense of observing systems that would come at a small fraction of the price. For example, NOAA has made decisions to eliminate or reduce investments in the national Profiler Network, the national Mesonet Network, and the tsunami buoy network. These decisions will affect lives and property and have not seemed to have been based on independent analysis.

Knowing the challenges NOAA and the Weather Service face, it is all the more important that we conduct impartial technical assessments to guarantee that the money we spend on a combination of observing systems gets us the greatest forecasting bang for our buck, and that our data procurement is based on costs and benefits, rather than subjective thinking. Rather than relying on the whims of an individual Administration or the opinions of subject matter experts divorced from fiscal realities or program managers wedded to certain systems, NOAA needs to undertake comprehensive, objective, and quantitative evaluations of observing systems that incorporates cost.

There are options available to conduct more thorough analysis of these systems. For example, in a recent article, Administrator Lubchenco referred to the use of Observing System Simulation Experiments (OSSEs) as a "powerful tool" for evaluation different combinations of observing systems to meet forecasting needs. Unfortunately, NOAA has not used this powerful tool to guide decision-making related to current weather data challenges.

The status quo cannot continue. We no longer have the budgetary luxury to repeat past mistakes in our approach to procuring data for weather forecasting. NOAA needs to think beyond its current framework on the most cost-effective and efficient way to get data for weather forecasting. Technological advancements in the last two decades make it possible for more information to come from the private sector while still maintaining the level of quality assurance necessary for weather forecasting. Improvements in computer processing and data assimilation allow for different combinations of data to create advanced forecasts. Such progress requires NOAA employ objective analysis to determine the best course forward.

I want to thank the witnesses for appearing before the Subcommittee and I look forward to a constructive discussion.

Chairman HARRIS. The Chair now recognizes Mr. Miller, the Ranking Member, for five minutes for an opening statement.

Mr. MILLER. Thank you, Chairman Harris. I also want to welcome the witnesses today and thank them for being here to shed light on what has become a protracted problem for NOAA but one that is now marked by a new urgency.

For years the Nation's multi-billion dollar weather and climate satellite program has been the center of this committee's investigations and oversight agenda. I called the late and unlimited NPOESS program the most snake-bit program in the Federal Government at a hearing of the Investigations and Oversight Subcommittee when I chaired that subcommittee.

But despite relentless pressure from both parties to get those programs under control, they have continued to experienced costly overruns, and they almost never launch on schedule. Most of those problems, really almost all of those problems, really existed before this Administration. They were waiting on the desk when the new Administration arrived, but now it is a task of this Administration, the Obama Administration, to fix those problems. In addition to being inexcusably wasteful, the programs expose the country to a very real possibility that we will see a gap in our weather and climate forecasting abilities given the expected life of the weather satellites now flying. From the deadliest tornado in more than half-a-century to the unprecedented heat wave just this month, almost every part of the country is facing severe, life-threatening, and record-breaking weather events.

Good weather data is more important than ever. Yet, yes, satellites are expensive, but they are central to protecting life and property, and the cost of inferior systems could be far greater.

So today we are asking several questions. Is the timeframe realistic? Is the attempt to cobble together a backup system in the event that our current satellite systems fail as expected based upon their projected expected life while we are still waiting for new systems to come on line? Is all that worth the cost or should we now just rethink our reliance on satellites altogether as some now argue, perhaps out of frustration with the many problems in the satellite programs.

As stewards of the taxpayers' dollars, we have to manage these programs in the most fiscally responsible way while avoiding a reduction of the service and protection we come to expect and need. It also means we have to recognize when we can tinker and when we have to take more drastic action. Over the years, talented and innovative researchers and scientists in the public and private sector have developed a wide range of technologies and methods, weather radar, buoys, aerial data, wind profilers, atmospheric sounders that give us both depth and flexibility in anticipating the effects of weather. What I would like for us to learn today is how these and other technologies can complement the work of the satellites or if, when combined, they can give us much the same capability at less cost.

Whatever the answer, we have to be strategic in our decision, evaluating the benefits of the individual technologies while considering the cost in realistic lead time for their development. At this point, to avoid a potential weather data gap, maybe all we can do is cross our fingers and hope that the existing polar satellite lasts beyond its designed life, its expected life, and we will have more time to get the next satellite successfully launched. But that is no way to plan our Nation's strategy for advanced weather forecasting, and we have to be prepared not to be that lucky. A weather data gap could occur as early as 2016, assuming the satellite does survive the expected time, which gives us four years to develop, test and have ready any capability to mitigate the gap. These are complicated and expensive systems, and four years is not a long time for such an expensive and complicated system.

So I am interested to hear what NOAA's plans are and what the other witnesses are suggesting as realistic and cost-effective strategies for minimizing the damage of this predicament. Mr. Chairman, this should be a good hearing, one of the most important aspects of this committee's jurisdiction. Thank you for holding this hearing today and for your staff working with my staff, and I look forward to a lively and informative discussion.

[The prepared statement of Mr. Miller follows:]

PREPARED STATEMENT OF SUBCOMMITTEE RANKING MEMBER BRAD MILLER

Thank you, Chairman Harris. I also want to welcome the witnesses and thank them for being here to shed light on what has become a protracted problem for NOAA, but one that is now marked by a new urgency.

For years, the Nation's multi-billion dollar weather and climate satellite programs have been at the center of this Committee's investigations and oversight agenda. Despite relentless pressure from both sides of the aisle to get these programs under control, they continue to experience cost overruns and almost never launch on-schedule. Many of these problems existed before this Administration, but it is now the task of this Administration to fix those problems. In addition to inexcusably wasteful, the problems expose the country to a very real chance that we will see a gap in our weather and climate forecasting abilities, given the expected life of the weather satellites now flying.

From the deadliest tornado year in more than half a century, to the unprecedented heat wave this month, are facing severe, life-threatening, and record-breaking weather events across the country. Good weather data is more important than ever. Yes, satellites are expensive, but they are essential to protecting life and property, and the costs of inferior systems could be far greater.

So, today we are asking several questions. Is the time-frame realistic? Is the attempt to cobble together a backup system in the event that our current satellite-based systems fail while we wait for new systems to come online worth the cost? Or, is it simply time to rethink our reliance on satellites altogether, as some now argue.

Being stewards of the taxpayers' dollar means that we have to manage these programs in the most fiscally-responsible way while avoiding a reduction of the service and protection we have come to expect. It also means that we have to recognize when we can tinker with what we have and when more drastic action is necessary. Over the years, talented and innovative researchers and scientists in the public and private sector have developed a wide range of technologies and methods—such as weather radars, buoys, aerial data, wind profilers, and atmospheric sounders—that give us both depth and flexibility in anticipating the effects of weather. What I would like for us to learn today is how these and other technologies can complement the work of the satellites, or if, when combined, they can give us the same capability at less cost. Whatever the answer, we have to be strategic in our decisions, evaluating the benefits of the individual technologies while considering their cost and realistic lead-time for their development.

At this point, to avoid a potential weather data gap, maybe all we can do is cross our fingers and hope that the existing polar satellite lasts beyond its design life, buying us some time until the next satellite is successfully launched. But that's no way to plan our Nation's strategy for advanced weather forecasting. And we have to be prepared not to be that lucky. A weather data gap could occur as early as 2016, which gives us four years to develop, test, and have ready any capability to mitigate the gap. These are complicated and expensive systems, and four years is not a long time for such an undertaking. So I am interested to hear what NOAA's plans are, and what the other witnesses are suggesting as realistic and cost-effective strategies for minimizing the damage of this predicament.

Mr. Chairman, this should be a good hearing on one of the most important aspects of this Committee's jurisdiction. Thank you for holding this hearing today and for your staff working with my staff. I look forward to a lively and informative discussion today and with that, I yield back.

Mr. MILLER. And I do yield back but wish to raise one minor procedural point that I do not wish to make contentious, but at an earlier hearing of this Subcommittee on hydraulic fracturing, an EPA witness arrived to testify with a slide, a PowerPoint, that had not been provided to committee staff. The majority Republicans objected to that, and Democrats supported that objection. We do need to have all the materials from the witnesses to prepare properly for these hearings. It may not look like we prepare, but we really do, or at least our staff does. And I know there are two witnesses on the second panel who have arrived today with PowerPoint presentations. Our staff has reviewed those. They are generally unobjectionable. They are unobjectionable, but it as a procedural matter, we really do need to have those in the future. And this matter today that is not a point of contention could be a contentious point at some point in the future.

So I hope we will work together to make sure that does not happen again.

Chairman HARRIS. And I want to thank the gentleman from North Carolina for bringing that to our attention, and we will work to see that it happens the way it should happen, which is that the witnesses provide everything for review prior, and we will of course share it amongst ourselves, whichever witnesses it happens to be. And thanks again to the gentleman from North Carolina for bringing it to my attention.

If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

At this time I would like to introduce our witnesses for the first panel. First witness is Ms. Mary Kicza, the Assistant Administrator of the national Environmental Satellite, Data, and Information Service at NOAA. Before coming to NOAA, Ms. Kicza was the Associate Deputy Administrator for Systems Integration at NASA.

Our next witness would be Dr. Alexander MacDonald, the Deputy Assistant Administrator for Research Laboratories and Cooperative Institutes at the Office of Oceanic and Atmospheric Research at NOAA. Dr. MacDonald served as Acting Director for the Earth System Research Laboratory and Director of the ESRL Global Systems Division during the consolidation of the Boulder Laboratories into the Earth System Research Laboratory in 2006.

The final witness on the panel, Mr. John Murphy, Chief of the Programs and Plans Division of the National Weather Service at NOAA. Mr. Murphy joined National Weather Service after serving more than 29 years with the United States Air Force as a career meteorologist.

I want to thank all of you for appearing before the Subcommittee today. I do again want to apologize for the delay, but we are not in charge of the House schedule. It is my understanding that Ms. Kicza will present one testimony on behalf of all three of the NOAA witnesses before us. However, all three of the witnesses will be available to answer the question of Members during the question-and-answer period for this panel.

As our witnesses should note, spoken testimony is limited to five minutes, after which the Members of the Committee will have five minutes each to ask questions. I now recognize Ms. Kicza to present testimony from the three witnesses on this panel.

## STATEMENT OF MS. MARY KICZA, ASSISTANT ADMINISTRATOR, NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE, NOAA; ACCOMPANIED BY DR. ALEXANDER MACDONALD, DEPUTY ASSISTANT ADMINISTRATOR FOR RESEARCH LABORATORIES AND COOPERATIVE INSTITUTES, OFFICE OF OCEANIC AND ATMOSPHERIC RESEARCH, NOAA; AND MR. JOHN MURPHY, CHIEF, PROGRAMS AND PLANS DIVISIONS, NATIONAL WEATHER SERVICE, NOAA

Ms. KICZA. Thank you. Chairman Harris, Ranking Member Miller, and Members of the Committee, thank you for the opportunity to testify today. I am Mary Kicza, Assistant Administrator for NOAA's Satellite Information Services, and this afternoon my NOAA colleagues, Dr. Sandy MacDonald, Mr. John Murphy and I will discuss how NOAA determines its observation needs to support our mission, how we identify mechanisms to fill those needs and what tools we use to optimize the appropriate mix of systems that are used to deliver the data required.

NOAA's mission to provide science, service and stewardship to the Nation is fundamentally dependent on assured access to environmental observations. Our observing requirements are derived from the needs of our research and operational programs. These observations are critical for developing forecasts and warnings that are vital to protecting life and property and promoting economic productivity.

Because no single source can provide all the data needed, NOAA integrates data from both in-situ platforms and remotely-sensed platforms such as aircraft and satellites. While acquisition of observational data is funded from all of NOAA's line and program offices, the NOAA Observing Systems Council coordinates the processes for determining the best and most cost-effective means of acquiring the data.

As a Vice-Chair of the NOSC, I participate in the ongoing assessment of NOAA's observing system portfolio and the development of recommendations made in NOAA leadership regarding capabilities needed to meet our mission. NOSC accomplishes this by ensuring that all of NOAA's observational requirements are identified, documented and prioritized; that the requirements are verified, validated and regularly updated; and that the means to acquire the data to satisfy these requirements are regularly assessed. This assessment includes a determination of whether the validated requirement for an observation can be met through existing or planned NOAA platforms or through partnering with other federal agencies, academic institutions or state or local governments. We have made extensive use of partnerships with other space agencies, both nationally and internationally to meet our requirements. These partnerships allow for mutual full and open access to data and are beneficial for all parties in terms of reducing cost and risk.

NOAA has processes to assure the availability and viability of data from commercial sources, and we routinely purchase data and services from the commercial sector. We will continue to pursue agreements with the commercial sector when it can provide data that addresses our requirements at an acceptable level of cost and risk.

NOAA regularly evaluates new observing capabilities as a way of meeting our requirements or reducing cost. Let me turn to the tools that we use to evaluate observing systems against validated requirements. NOAA uses formal technical studies called Analyses of Alternatives, or AOAs. AOAs assess the technical feasibility and maturity of various concepts and examine the cost, schedule and risk associated with implementing each concept.

NOAA also uses computer models similar to our current operational weather prediction system to estimate the impact of new observing systems or changes to existing observing systems to our operational forecasts.

One modeling tool is called Observing System Experiments or Data Denial Experiments. This involves systematically adding or denying an existing observation to a historical forecast to determine the difference that action would have caused to the forecast accuracy. Data Denial Experiments confirm that without polar orbiting satellite data for the snowmageddon snow event of February 2010, the forecast would have significantly underestimated the amount of snow and the storm's track.

Another more advanced modeling tool NOAA currently uses is called Adjoint Sensitivity Experiments. These experiments quantify the contribution of a group of existing observations to the overall reduction in forecast error. These efforts are more sophisticated in that they look at a greater number of observations to determine their impact on the forecast accuracy.

NOAA has recently expanded its use of still more sophisticated modeling tools to examining the benefit of potential future systems, systems that don't currently exist. These tools are called Observing System Simulation Experiments or OSSEs. OSSEs examine future systems to determine their relative benefit in improving future forecasts. This tool involves the use of multiple models and is used to inform decision-makers prior to investing in a completely new observing system.

Each of the modeling tools has their strengths and weaknesses, and we continue to both apply these models and refine them so as to support our investment decisions. They are used in conjunction with other programmatic information, like cost, risk and schedule to inform decisions we make in fielding existing observational capabilities or in planning for new capabilities.

In conclusion, recognizing the current austere fiscal environment we face, NOAA is working within its means using a range of tools to support its investment decisions. Thank you for the opportunity to testify, and my colleagues and I will now answer any questions you may have.

[The prepared statement of Ms. Kicza follows:]

**WRITTEN STATEMENT BY**
**MARY E. KICZA**
**ASSISTANT ADMINISTRATOR OF THE NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE AND VICE CHAIR OF THE NOAA OBSERVING SYSTEMS COUNCIL (NOSC)**
**NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION**
**U.S. DEPARTMENT OF COMMERCE**

**ON**

**TO OBSERVE AND PREDICT:**
**HOW NOAA PROCURES DATA FOR WEATHER FORECASTING**

**BEFORE**
**SUBCOMMITTEE ON ENERGY AND ENVIRONMENT**
**COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY**
**U.S. HOUSE OF REPRESENTATIVES**

**March 28, 2012**

Chairman Harris, Ranking Member Miller, and members of the Committee, thank you for your leadership and the continued support you have shown the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA). I am honored to be here as the Assistant Administrator of NOAA's National Environmental Satellite, Data, and Information Service and Vice Chair of the NOAA Observing Systems Council (NOSC) to discuss how NOAA procures data for weather forecasting and its environmental mission.

In order for NOAA to accomplish its mission, it is essential that all parts of the agency work together. That is particularly true in the area of predictive capability to protect life and property. In this arena, NOAA's National Weather Service (NWS) develops requirements for needed observations. To acquire the necessary observations, NWS works in conjunction with other parts of NOAA and non-NOAA partners that provide critical data and observations. For example, the National Environmental Satellite, Data, and Information System (NESDIS) works with the NWS to meet their requirements for satellite observations, and NOAA's Office of Oceanic and Atmospheric Research (OAR) uses current and next-generation research and technology to identify the optimal mix of observing platforms and systems that we should be exploring. My testimony will outline how the elements within NOAA work together to accomplish this goal.

NOAA's mission to provide science, service and stewardship to the nation is fundamentally dependent on observations of our environment from the surface of the sun to the bottom of the sea. These observations are the backbone of NOAA's predictive capabilities. NOAA must ensure operational weather, ocean, climate, and space weather data are available seven days a week, 24 hours a day, to address critical needs for our nation such as timely and accurate forecasts and warnings of severe weather, solar storms, and ocean events such as tsunamis and storm surges.

## NOAA's Need for Observations

Observing the environment requires integration of all available sources to include both *in-situ* and remotely-sensed data from satellites. No single observation source can stand on its own. Data from *in-situ* observation platforms are an important component, but their measurements are relatively scarce, particularly over the oceans, polar regions, or where there are increasing national security concerns. Satellite observations of the atmosphere, ocean and land provide global coverage of these critical information sources, as well as *in-situ* space weather measurements. These data facilitate the development of environmental predictions and weather forecasts and warnings that are vital to protecting life, property and promoting economic productivity of United States interests at home and abroad.

Over land, weather observations, including temperature, wind, and moisture are needed to understand current weather conditions, which may evolve and result in dangerous severe weather. Land observations of soil moisture and observed rain and snow are essential to determine the potential for flooding or drought. Radar observations detect conditions favorable for tornadoes and detect the location and amounts of precipitation that may cause flash flooding. Additionally, recognizing that our advanced technology-based economy and national security is increasingly vulnerable to space weather, solar wind and near-Earth geomagnetic and ionospheric observations are vital for the protection of our critical technology infrastructure. This infrastructure includes, but is not limited to public and private sector satellites, communication systems, aircraft navigation systems, and our electrical power grid.

Our Nation's environmental predictive capabilities are supported by four foundational pillars:

- observations;
- high performance computing,
- forecast model systems and supporting research; and
- our people, who provide forecasts and warnings to key decision makers.

By sustaining and strengthening these pillars through improved observations, computational capacity, modeling, and research, we can maintain the current forecast capabilities that our society has come to expect. Additionally, these pillars foster forecast improvements that will revolutionize the way society views and exploits environmental information across the entire spectrum, from near-term weather forecasts to long range weather and climate predictions. For example, coupled models provide improved simulations of the interaction between the ocean and atmosphere, which result in more timely and accurate predictions of tropical cyclone tracking and intensity. Timely and accurate predictions are critical to minimizing unnecessary evacuation and increasing public confidence so that affected populations will react appropriately to warnings. This, in turn, will result in reduced loss of life, assuming that potentially affected populations heed the advanced warnings of ocean surges, inland flooding, and damaging winds and tornadoes when they are issued.

Additionally, developing and acquiring higher resolution observations and models will teach us how the atmosphere behaves leading up to the formation of a tornado, and will allow us to "warn-on-forecast" and more precisely predict where flash flooding, or particularly heavy snow bands, or dust storms will occur, or even when a tornado will strike, with increased warning lead-times double or triple today's average of 12 minutes.

Environmental observations had once been the sole purview of the Federal government, owing primarily to the cost, size and complexity of the systems involved. However, weather and related observations and information services now cut a broad swath through various public, private, and academic sectors, having diverse missions and applications. NOAA attempts to collect and make use of available data from federal, state, local government funded networks, university funded, or private sector data sources, leverages data from international sources, and purchases data from commercial sources. NOAA does not unnecessarily duplicate the observing systems of others, but rather accesses and leverages the reliable and available data it needs to implement its science, service, and stewardship mission.

While acquisition of these data is funded from all of NOAA's line and program offices, coordination for determining the best means of acquiring these data is overseen by the NOAA Observing Systems Council (NOSC). The NOSC is chaired by the Assistant Secretary of Commerce for Environmental Observation & Prediction, and its vice-chairs are the Assistant Administrator for Weather Services, the Assistant Administrator for Satellites and Information Services, and the Director of the NOAA Office of Marine and Aviation Operations (OMAO). NOSC membership is comprised of a representative from each NOAA Line Office and OMAO as well as the Chief Financial Officer and the Chief Information Officer. The NOSC has established an Observing System Committee (OSC) to provide a holistic, on-going assessment and analysis of NOAA's observing system portfolio and to make recommendations to the NOSC regarding the optimal mix of capabilities to meet NOAA's mission. The NOSC and OSC are supported by the Technology, Planning, and Integration for Observations (TPIO) program. The NOSC Terms of Reference is located at https://www.nosc.noaa.gov/purpose.php.

NOAA's data activities are governed by its full and open data policy consistent with the Office of Management and Budget's (OMB's) Circular No. A-130 and the 2010 National Space Policy of the United States[1]. These policies provide the framework that allows NOAA to widely distribute its products and services to support its public safety and global environmental monitoring mission. Today's testimony provides an overview of the processes and challenges that NOAA faces in meeting its needs for observations to fulfill our mission.

## Determining Requirements

NOAA is responsible for collecting environmental information to meet its current mission requirements and determining our requirements for future data and information. Atmospheric weather and climate models of today will be transforming to an "earth system" model in the future which will involve coupling atmospheric data with ocean, land, ice and space-based data. Historically, weather and climate models incorporated only atmospheric inputs and outputs, and only recently have been integrated with ocean models to provide a more robust picture of our earth system. To the extent possible, NOAA incorporates data collected and processed from

[1] http://www.whitehouse.gov/omb/circulars_a130_a130trans4
http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf

other sources, but it is not NOAA's responsibility to collect and process data that do not fulfill our mission needs. NOAA ensures that its data are available for open and unrestricted use, and honors specific agreements to the contrary when private data sources are used.

NOAA's observation requirements are derived from the data needs of NOAA's operational and research programs. Weather forecast models require detailed information about the earth's environment including atmospheric temperature, moisture content, pressure, wind direction and wind speed, as well as ocean observations, including ocean temperature, wave height, and ocean surface winds. For river and flood forecasts, river flow data as well as soil moisture, soil temperature, rainfall, and snow depth are required. Finally, space weather prediction requires constant monitoring of the sun and the space environment, for solar flares and coronal mass ejections, and for geomagnetic and ionospheric disturbances.

## Evaluating and Validating Requirements

NOAA established the NOSC to provide a systematic assessment of NOAA's observation requirements and the range of systems available or needed to meet these requirements. This effort has included a disciplined process of documenting, validating, and assessing the relative priorities of NOAA's observing requirements. This process entails:

1. Working across NOAA units (e.g., Programs, Strategic Objectives, etc.) to identify and document, in a standardized, prioritized structure, all their observational needs to meet their mission.
2. Applying a verification and validation process to each set of Priority-1 (mission critical) observation requirements for review and endorsement by the NOSC.
3. Tracking updates to observational requirements as directed by the Programs on both an as-needed and periodic review basis.
4. Assessing the means by which observing requirements are met, including the level of requirements satisfaction, as well as gaps in observing capabilities.

The process to document NOAA's observation requirements involves close coordination with NOAA program leaders and Subject Matter Experts (SMEs) to capture information in an extensive database called the Consolidated Observation Requirement List (CORL). The following attributes are captured for each requirement: geographic coverage, vertical resolution, accuracy, sampling interval, data latency and long-term stability.

Once documented, each Program's requirements are verified and mapped to their associated Government Performance and Results Act (GPRA), NOAA performance measures and Regional Collaboration (RC) performance measures. Verification is the process by which the SMEs in a given program review, concur, and sign off on all the Priority-1 requirements that they are submitting. Verification is documented by the signing of a Program Observation Requirement Document (PORD). The PORD summarizes the programs' observation requirements and performance level required for each observation. The signatures of the program leaders on the PORD constitute verification of their observing requirements.

Once requirements are verified, each NOAA program provides documentation to support validation of each requirement and its specified attributes. Validation is important as it provides independent confirmation of the needs of the program either through the results of scientific studies, operational use, or independent review by SMEs. Both the program leadership and the NOSC support team, which includes technical staff in the TPIO, assess the applicability of the documents, prepare a summary of the validation of Priority-1 requirements, and present a summary to the NOSC for their endorsement of the validation process.

The affected line office representative to the NOSC reviews and signs the PORD, concurring that the requirements are accurately captured and meet Line Office needs. Lastly, the signatures of the NOSC co-chairs on the PORD constitute endorsement of the validation process conducted on the programs' set of observing requirements.

The validated requirements then serve as the basis for justification for acquiring NOAA observing systems to satisfy those requirements or fill gaps in observing data.

NOAA operational forecast models are one of the main drivers of its observational requirements. From a NWS perspective, these models require detailed information about the structure of the atmosphere (e.g. wind direction and speed; temperature; pressure and moisture) in order to produce a forecast. These data are acquired through three basic means:

- surface-based upper air observing systems (radiosondes);
- aircraft;
- NEXRAD radar, including dual-polarization modifications; and
- polar-orbiting and geostationary satellites.

Satellite data are particularly critical for gathering global atmospheric data, as well as collecting measurements over the oceans and other data sparse areas. On a global scale, integrated, (otherwise known as coupled) atmosphere-ocean forecast systems provide improved weather forecasts by adding the interaction between ocean and atmosphere. This also results in more accurate predictions of tropical cyclone behavior and the development of major storm systems, such as those that can produce devastating tornado outbreaks and disruptive winter weather. On smaller and shorter timescales, very high resolution observations and forecast systems, together with high performance computing, can provide the type of short-term severe weather predictions that will allow for more precise forecasts -- to the neighborhood or wind farm scale, for example. Data from radars are used along with satellites to support NOAA's warning programs in advance of severe weather systems.

Observational requirements are also derived from NOAA's mission responsibilities for oceans and climate. NOAA is an international leader in the use of moored buoys, floats, drifters, and other systems that are used to understand and predict the physical ocean. These include observations of the biochemistry of the ocean, including changing acidity and other ocean chemistry, as well as observations of the chemical and aerosol constituents of the atmosphere. NOAA maintains a global chemistry monitoring network for atmospheric constituents including greenhouse gases, aerosols, ozone, and other important substances.

Finally, detailed information necessary to produce a space weather forecast comes from the space environment. These measurements: solar wind, solar radiation, and magnetic field are observed by operational polar-orbiting and geostationary satellites, and a research satellite at the Lagrange-1 point. From these platforms, NOAA is able to derive data to support space weather monitoring, and forecasts and warnings.

## Requirements Assignment to Observing Systems

The validation of all of NOAA's observational requirements is an on-going process. Once validated, observing requirements can be assessed against existing or planned observing systems. If gaps are identified where no observing systems collect or measure the required observation data, NOAA pursues meeting these un-met requirements – either through the development of its own observing system(s) or acquiring it by other means, including partnering for or leveraging data from other federal agencies, foreign governments, state and local governments, academic and private assets; as well as purchasing data from commercial sources.

When NOAA plans and develops an observing system it documents the requirements the system must achieve in a Level One Requirements Document (L1RD). Level I requirements are the highest priority mission requirements derived from the CORL. These requirements form the basis for generating the lower level, system/component requirements documents (e.g., Level II requirements documents). The L1RD includes information on which CORL observation requirements the planned system will be capable of measuring to the performance level required. L1RDs are approved by the NOSC.

NOAA regularly evaluates new observing capabilities for their potential to improve its mission capabilities or decrease its costs. For example, it is currently evaluating Phased Array Radar, Unmanned Aircraft Systems, and Autonomous Underwater Vehicles to determine the extent to which technologies can meet NOAA's observation requirements.

## Requirements Validation for Satellite Data

The requirements for NOAA's next generation geostationary and polar orbiting environmental satellites are primarily associated with providing continuity of the capability currently being provided from by NOAA's existing, on-orbit satellite systems, the Geostationary Operational Environmental Satellites (GOES) and Polar-orbiting Operational Environmental Satellites (POES). The next generation satellites will include technology upgrades, since the technology currently being flown on legacy GOES and POES satellites is largely from the 1980s. Lastly, the next generation geostationary (GOES-R) and polar-orbiting (Joint Polar Satellite System or JPSS) satellites will include technological enhancements which have been demonstrated on a number of research platforms. For example, instruments on JPSS are being developed based on demonstrated successes on the NASA Earth Observing System (EOS) satellites, as well as the Suomi National Polar-orbiting Partnership (Suomi NPP) satellite.

*GOES-R requirement process* - Initial GOES-R observation requirements were set forth in the 1999 NWS Operational Requirements Document for future geostationary satellites. The requirements within this document were gathered and prioritized through collaboration with

NWS Headquarters, NWS Regions, National Centers for Environmental Prediction, and the nation-wide network of NWS Forecast Offices. The GOES-R Level 1 Requirements Document (L1RD) was signed by NOAA leadership in June 2007. The L1RD has been updated periodically as changes were made to the GOES-R Program.

*NPOESS/JPSS requirements process* - U.S. operational polar-orbiting observation requirements originated with the NPOESS program (the predecessor to JPSS), where the observing requirements were documented in the Integrated Operational Requirements Document (IORD). This document was approved by each member of the NPOESS Tri-agency partnership (NOAA, DOD, and NASA). After NPOESS was restructured, NOAA initiated the JPSS Program to meet NOAA's polar-orbiting observation requirements in the afternoon orbit. The observation requirements for JPSS are documented in the JPSS Preliminary L1RD that was signed in September 2011. These requirements were vetted through a cross-NOAA team to ensure any unnecessary carry over from NPOESS was removed. The JPSS Final L1RD will be signed once the Program is baselined[2].

*L1 (Lagrange point) requirements* – NASA's Advanced Composition Explorer (ACE) satellite, which was launched on August 25, 1997, is the sole provider of real-time, in-situ solar wind data timely enough to provide early warning of pending and potentially damaging solar activity. Based on a multi-agency study by the Administration, directed by the Office of Science and Technology Policy, the Deep Space Climate Observatory (DSCOVR) was selected as a follow-on mission to ACE. DSCOVR is a partnership among NASA, NOAA, and DoD which will ensure the continuity of critical real time solar wind measurements. The DSCOVR L1RD has been drafted and is currently in the signature cycle. The spacecraft is being refurbished and is expected to launch in 2014.

*Space-based ocean altimetry* -- NOAA is procuring Jason-3, a satellite radar altimeter jointly with EUMETSAT, France's Centre National d'Etudes Spatiales (CNES), and NASA. Jason-3 will be an operational follow-on satellite to Topex/Poseidon, launched in 1992; Jason-1, launched in December 2001; and Jason-2, launched in June 2008. NOAA has been using Jason data to support its operational oceanography mission, surface wave forecasting and evaluation, and hurricane intensity forecasting. These Jason data are also being used in large scale oceanic models to track the onset, duration, and intensity of seasonal climate events such as El Nino and La Nina. These data are also being used in models that are currently tracking the marine debris from the Tohoku earthquake and tsunami (March, 2011).

## Optimizing NOAA's Observing System Portfolio

NOAA has also developed an inventory of its observing systems capabilities, which are summarized in Observing System Summary reports[3]. This inventory includes system capabilities, system points of contact, system owners, system descriptions, numbers of sensors/systems deployed, and a detailed lists of system/sensor performance for the various environmental parameters that the systems measure.

[2] P.L 112-55 requires a JPSS baseline by the 4Q FY2013.
[3] https://www.nosc.noaa.gov/OSC/oss.php

NOAA is evaluating individual systems against validated observing requirements; NOAA also evaluates the relative effectiveness of the suite of NOAA observing systems in meeting its observation requirements. To address this portfolio perspective, NOAA applies a number of software tools that provide both a graphical and analytical framework to help decision makers select the best portfolio (combination) of observing systems based on considerations such as cost and operational benefit. The process of capturing information about NOAA's observing requirements and systems is called the NOAA Observation Systems Integrated Analysis (NOSIA) capability. The NOSIA process uses a portfolio optimization tool, the MITRE Portfolio Analysis Machine (PALMA ™)[4] as a cornerstone to this framework. Before beginning the acquisition and development of new satellite observing systems, NOAA often conducts an analysis of alternatives (AoA) to investigate potentially lower cost approaches to the government developed systems.

In addition to these prioritization tools, NOAA uses numerical forecast systems, similar to NWS' current operational weather prediction system, to estimate the impact of observing system options. These approaches include withholding existing observations from assimilation into weather prediction models and observing the magnitude of the degradation in predictions. Atmospheric, oceanic, and/or earth system models can also be used to simulate observations that would be produced by new or modified observing systems and to estimate the impact of those observations on our predictive capability.

One technique, called "adjoint sensitivity experiments" shows the amount of forecast error reduction contributed by each observation in a predictive model. A second technique, called an Observing System Experiments (OSE), or "data denial experiment," involves systematically adding or denying an existing observation to a control forecast to determine the differences that induces in the forecast accuracy. NOAA conducted a series of OSEs to demonstrate the possible impact of the loss of polar-orbiting satellite observations to the "Snowmageddon" event in February 2010.

NOAA is also exploring expansion of quantitative observation assessments for future observing systems. These assessment tools, including Observing System Simulation Experiments (OSSEs) may provide a way to evaluate observing systems that yields optimization of both systems and savings in the future. OSSEs use multiple models to estimate the benefits of a hypothetical (either new or modified) observing system. They use simulated observations (instead of real observations) and are designed to measure the impact of adding future instruments to current observing systems. If a future instrument requires new data assimilation, i.e. algorithms or techniques that do not currently exist, NOAA may not be able to fully assess the impacts of the instrument using the OSSE, the OSSE may underestimate or overestimate the impact.

Adjoint sensitivity experiments and Observing System Experiments are two critical tools providing decision makers with an understanding of the impact of existing observing systems and data streams on NOAA's mission service areas. OSSEs can provide decision makers with an understanding of proposed observing systems by simulating the impact of what might be built. In

---

[4] PALMA is a trademark of the MITRE Corporation.

this way, the benefits of an observing system or type of observation can be estimated before it is designed, built, and launched into orbit.

NOAA employs these types of simulations to determine the viability of new data and information from proposed new instruments. This information can assist decision makers with trade-offs in instrument or orbital configurations and methods of assimilating a new type of observing system can be determined. These data impact experiments can identify an optimal configuration for a future observing network and help recognize weaknesses in the processing or assimilation of the observations.

Because of the challenges posed with observing the environment, it is often necessary to test, evaluate, and compare different types of instruments or observations to determine which one alone or in combination with others is best suited to meet a particular set of observational requirements. A specific case involves examining the Gulf Stream IV (GIV), which provides data about the atmosphere in large circulations, such as hurricanes and winter storms. In a "data denial experiment," comparing computer models with and without these data that would have been obtained from a GIV, determined there is a 20 percent improvement in hurricane track forecasts when the data are available. These types of studies are important to quantify improvements from new or existing data sources..

Testing the efficacy of observing systems through data denial experiments and simulating measurements that proposed new observing systems will provide allows NOAA to make the decisions necessary to optimize its observing system portfolio. The resulting benefits include:

- Gaining a well-defined quantitative foundation for the design and acquisition of observing systems;
- Developing a quantitative understanding of the impacts of existing observing systems; and
- Delineating between the impacts of new observing systems and an alternative mix of current systems.

### Maximizing Cost Effectiveness for Observations

NOAA develops an observation acquisition plan through its annual programming and budgeting process known as the Strategic Execution and Evaluation (SEE). The SEE is the process NOAA uses to ensure linkage between NOAA's strategic vision and its programs, budget development, and annual operating plans. The SEE process ties strategy, planning, programming, and budgeting together to determine the best allocation of resources, given performance of existing and planned programs against mission requirements. As part of choosing the appropriate solution, the SEE process involves the NOSC evaluation of possible approaches to meeting NOAA's observing requirements. The NOSC, in offering input to the SEE process, uses the suite of analysis tools mentioned above.

NOAA is continually evaluating new observing capabilities for their potential to improve its mission capabilities or decrease costs while still providing equivalent capabilities. For example, it is currently evaluating Phased Array Radar, Unmanned Aircraft Systems, and Autonomous

Underwater Vehicles to determine how these technologies could fit into the total set of observing capacity.

## Leveraging Data from non-NOAA Observations Systems

Even with these robust quantitative assessments and prioritization mechanisms feeding NOAA's planning and programming process, maintaining NOAA's observational capability is an on-going challenge. NOAA continues to pursue agreements with owners and operators of local/regional observing networks, whenever possible and cost effective, to create and leverage a national "network of networks." NOAA's assets are foundational and provide the backbone for a network of local/regional observing capabilities.

NOAA is moving from the era when it was the only entity able to sustain observations and maintain the national networks, to one where NOAA will benefit from leveraging and being integrated into other's capabilities. NOAA's expertise will focus on enhancing value of the data and information, maximizing the exploitation of this data in making operational forecasts and warnings and ensuring data are valid, rather than being the only source of data. For example, NOAA is working with the renewable energy community to obtain mesoscale data that will be used in NWS computer forecast systems to provide more accurate and timely weather forecasts that can be used by both NWS forecasters and private sector forecasters.

NOAA has made extensive use of its partnerships with other space agencies, both nationally and internationally. These partnerships allow for mutual full and open access to data from spacecraft, and include a range of partnership options, including reciprocal hosting of instruments on each others' satellite platforms, as well as partnerships where each agency is responsible for specific elements of the satellite system. These arrangements have proven extremely beneficial for all parties since costs and development burdens are shared.

The commercial sector is already significantly involved with NOAA's satellite acquisition activities. Through contracts, NOAA leverages the expertise of the commercial sector to develop concepts and to build spacecraft, instruments, and ground systems for the government. NOAA has a continuing process to assess the availability and viability of data from commercial sources, and routinely purchases space-based scientific data from the commercial sector. NOAA will pursue potential agreements with the commercial sector when it can provide data that addresses NOAA's requirements at a reasonable cost to the taxpayer. Some of the key considerations the commercial sector must demonstrate include:

- Ability to provide sustained and uninterrupted observations to meet operational requirements,
- Compliance with NOAA's data policy for full and open exchange and distribution of data,
- Demonstrated technical feasibility to acquire and deliver the observations and data in a reliable and timely manner, and
- Affordability of operations and cost-effectiveness to the Government.

## Conclusion

NOAA will continue to use all available data to ensure the best possible forecasts and warnings for the protection of the public. NOAA will further expand the public-private partnerships to collect weather related data whenever possible, however, recognizing that a foundational set of observations are a critical national asset required to protect life and property. NOAA will explore and leverage all opportunities, while operating in a cost-effective manner.

Chairman HARRIS. Thank you. I want to thank the witnesses for being available for the questioning today, reminding Members the committee rules limit questioning to five minutes. The Chair at this point will open the first round of questions for this panel, and I recognize myself for five minutes.

The question I guess, whoever thinks they are best suited to answer, you know, the testimony as well as past testimony of GAO has indicated that even if the joint polar satellite system is fully funded, there will be a data gap from polar orbiting satellites for potentially several years. A few weeks ago the Administrator as I said testified that we don't believe there are any viable options to obtaining the data necessary for weather forecasting. Is this statement a subjective opinion or is it based in objective fact? Has NOAA actually undertaken a quantitative analytical study and they concluded there is no viable alternative to mitigate the expected data gap or is this just the, again, kind of a subjective feeling? What alternatives were evaluated and deemed not to be viable alternatives? So specifically, what was looked at? Ms. Kicza, maybe you can comment on that.

Ms. KICZA. Sure. What I would like to do is talk about the gap first, and then I will talk about the tools we use to evaluate the gap itself. And it is an objective statement on the part of the Administrator.

So the concern about the gap is the time between the end of an NPP mission, the current orbiting satellite, and the onset of the JPSS–1 experiment. The NPP has a contractual design life of five years that launched in late 2011. The end of the five-year design life will be 2016.

The JPSS–1 satellite is scheduled to launch not earlier than second quarter of fiscal year 2017. So it is a small physical gap in terms of when two satellites are on orbit, but the concern we have is that we need overlap of the measurements. We want to cross-calibrate between the measurements on NPP, on the instruments on NPP and the instruments on JPSS–1. Depending on the complexity of the instrument, it takes different amounts of time to fully calibrate the instruments. Some instruments can be calibrated within six months. Other instruments may take 12 months or longer to calibrate. So we want overlap of those instruments.

In terms of the capabilities that NPP represents, it provides a continuity of the capability we are currently utilizing now to support our weather forecasts. That includes both our current polar satellites, the POESS series of satellites as well as the NASA capability that is afforded by the EOS platforms. So NPP provides continuity of that. JPSS will provide continuity beyond NPP.

When we look at the implications of denying capability from an on-orbit forecast—that is the Data Denial Experiments I referred to earlier—that is what we have looked at in terms of saying there will be a gap based on the time it takes to calibrate and the relative contribution of those instruments to the weather forecast.

Chairman HARRIS. Well, let me just clear something up for you. If one of the satellites is going off-line potentially in 2016 and the other one not coming on until 2017, there will be no overlap. I mean, how do you calibrate a satellite that is not functioning?

Ms. KICZA. When we talk about the contracted life, that is what is written in the contract specification, we will see how this spacecraft performs. It may last longer. The spacecraft itself may last longer than the contracted for performance, but we can't plan on that.

Chairman HARRIS. So if it doesn't, then there is no overlap at all in order to calibrate one against the other?

Ms. KICZA. Then we fall back on any other assets that are available, and we already have agreements in place with our European counterparts for the mid-morning orbit. We back each other up so that if we lose capability in the afternoon orbit, we can continue to pull in data from the European's mid-morning orbit.

Additionally, we will have any other assets that may be available so the NPP satellite is one of the assets that are there. Older POESS satellites, portions of those satellites and instrument capability may continue to operate on line. We keep those in orbit and continue to nurse those as they get older.

So we will take advantage of whatever assets we have at that timeframe.

Chairman HARRIS. But it is possible that there may be nothing to calibrate them against directly?

Ms. KICZA. There is a possibility that there would be nothing to calibrate them against in that orbit other than in-situ measurements that we take from the ground.

Chairman HARRIS. Okay. Thank you. Dr. MacDonald, where are some of the areas of research and technology development that could enhance our ability to protect against severe weather, and how much would they cost to undertake?

Dr. MACDONALD. Congressman, there are several new, exciting areas of research that we have been working on. One of them is that we know our models are crucial, and there is a really exciting advance in our ability to do modeling using these new kinds of computers based on graphics processor units. So we are working hard on that research. NOAA has been funding for several years the unmanned aircraft program looking at how we can really address the severe weather prediction and other capabilities using this new type of technology that we have learned so much about.

We also are putting in new capability with our radars. For example, the radar system is being upgraded, and we are putting in what is called dual polarization and we have a group that studies that and tries to improve our severe weather prediction in that way.

So we have a lot of tools. And as Mary Kicza mentioned, we are also looking at ways of looking at our observing systems using all these tools that she mentioned.

Chairman HARRIS. Now, the budget and just one brief and then I will turn it over to the Ranking Member, the weather research is flat at about $69 million in the budget, but the climate research actually increases and is three times as much. Given the budgetary constraint, I mean, are there opportunities that we can't investigate fully because of budgetary constraints?

Dr. MACDONALD. I think we, at my level, work as hard as we can with the funds we are provided, and that is what we are doing.

Chairman HARRIS. Okay. Thank you very much. Mr. Miller?

Mr. MILLER. Thank you, Mr. Chairman. Ms. Kicza, I understand NOAA's infrastructure does make it possible to collect various data using technologies other than satellites, radar, data buoys, wind profilers, all I mentioned in my opening statement, on the ground and also other surface observing systems. How important are all those technologies in comparison to the capabilities that we now have with satellites and how do the capability of satellites and those other technologies depend upon each other? Can they operate independently or do they really need to act in concert, work in concert?

Ms. KICZA. They do need to act in concert. It is not one or the other, it is actually both. They complement one another. If you look at today's weather forecast modeling capabilities, satellites on the whole contribute about 94 percent of the input into our weather forecasting models. The in-situ contribute the additional 6 percent.

Of the satellites, the polar orbiters, contribute about 84 percent, the geostationary, about ten percent. But both are important to the overall forecast models.

Mr. MILLER. Okay. Mr. MacDonald, Mr. Murphy, either of you have anything to add?

Mr. MURPHY. Thank you, Mr. Miller. I would just like to add that the in-situ, like Ms. Kicza says, they are complementary. There is the modeling aspect of it, but then there is also the forecasting aspect on the ground to put out weather forecasting warnings. And the in-situ observations play a key part in the forecasting of our tornado warnings and such.

Mr. MILLER. Okay. I also have a question about the 2013 budget proposal request from the Administration, and given extreme weather events that almost every state and almost every district has experienced this year, including my district, there was a tornado that resulted in the death of several children. And there have been extreme weather events all over the country. Particularly given that we are looking at the possibility of a gap in our weather forecasting, I have to ask about the criteria in making the decisions on what to cut, and it seems that the proposal does cut some of these other systems that do complement, that do need to work with our satellite. Even assuming that the satellite proves to have a longer useful life than we project, and even assuming that the Europeans will be able to continue to provide us data, it seems like those other systems are all the more important, but the proposal would cut the wind profile, the Mesonet Network. Ms. Kicza, how did the Administration make that decision to propose cutting those systems and what will that do to our forecasting ability, given all the other uncertainty about the satellites?

Ms. KICZA. I am going to start, and then I am going to ask Mr. Murphy to augment what I have to say. When NOAA looks at its observing capabilities, it looks at the entire portfolio and the relative contribution that each element of that observational portfolio contributes. As I had indicated earlier, the satellites represent a huge contribution to our weather forecasting capabilities. But systematically we look at the overall portfolio, and through these types of experimental simulation tools I have mentioned previously, we understand the relative contribution of each of those capabilities and use that information, combined with our situation in terms of programmatic cost, risk and schedule to make the determinations that we make in coming forward with budget recommendations.

I will offer Mr. Murphy any additional comments.

Mr. MURPHY. Yes. Mr. Miller, as Ms. Kicza had pointed out, we look very carefully at the portfolio, and we basically categorize our observation systems in two ways. They are not critical to the functions we need to perform, or they are supplementary. That doesn't mean that they don't add value. It just means that they are critical to our ability to put out our forecast and warnings.

In the case of Mesonet and the profilers, we see those as gap-fillers between our RAOBs and our regular reporting fixed-ground sites. The primary tool that we use to issue our warnings is the Doppler radar. Dr. MacDonald mentioned the dual polarization upgrade. What that allows us to do is see greater fidelity and get better understanding of storm structure, and that is allowing us, we believe, to increase our lead times and lower our false alarm rates. So that is how we are accounting for that.

Mr. MILLER. I know that in addition to the government weather forecasting efforts, there are a good many universities, researchers, others in the private sector at businesses that do rely upon the data that you all collect and generate. Were they consulted in the decision to cut the budgets for those weather forecasting tools?

Mr. MURPHY. Mr. Miller, I don't believe they were consulted. Our mandate is to collect the data to provide our services for life and property and protect the infrastructure of the nation. We do share the information freely with our commercial partners in academia and so forth, but we don't collect the data for them necessarily.

Mr. MILLER. Mr. Murphy, was your office consulted in the preparation of that budget request?

Mr. MURPHY. I participated in the exercise that Ms. Kicza pointed out that the NOSC conducted where we looked at all the observation systems, and we prioritized all our observation systems. And that was again validated by the NOSC.

Mr. MILLER. Okay. My time is expired.

Chairman HARRIS. The Chairman of the Committee, Mr. Hall, is recognized for five minutes.

Chairman HALL. Thank you, Mr. Chairman. Last week, Ambassador Lubchenco testified to the Appropriations Committee she convened a group to evaluate sources of environmental data and examine how NOAA can best utilize observing assets at the cheapest price. Ms. Kicza, when will this analysis be complete?

Ms. KICZA. I think that Dr. Lubchenco was referring to the fact that under the NOAA Science Advisory Board we convened a satellite task force or working group to examine with us lower cost approaches to both fielding the space segments and the ground segments.

Chairman HALL. I don't really know what she was thinking, but I am told that NOAA failed to conduct such an analysis before submitting a budget request, and that should have made a significant decision regarding these systems.

Ms. KICZA. I am sorry. I am referring to the task force that she was referring to, and that will be reporting to the NOAA Science Advisory Board in July.

In terms of making the budget recommendations for the fiscal year 2013 budget, she consulted with all of her line organizations as well as took the recommendations of the NOAA Observing System Council into account in formulating that budget.

Chairman HALL. She did conduct the analysis, though, before submitting a budget request, right?

Ms. KICZA. Absolutely, yes.

Chairman HALL. Do you know why? Do you have any idea why she did, why she shouldn't have?

Ms. KICZA. For each budget cycle and development, there is a structured process of consultation.

Chairman HALL. Will this analysis incorporate objective quantitative evaluations and comparisons of observing systems on the basis of c-o-s-t, cost?

Ms. KICZA. Yes, the ongoing analysis that NOAA employs to determine its observational requirements and its funding recommendations, its investment recommendations, employs all of the tools that I previously mentioned.

Chairman HALL. Let us talk about commercial options for providing weather data. At least nine other U.S. built commercial satellites are launched every year. I think that is a fairly close estimate. The reliability of these satellites is pretty well-established. If the government has weather missions, it could be included on these satellites to the benefit of all parties. It seems to me that would be a cost-effective option. Is that unreasonable?

Ms. KICZA. No, sir, it is not.

Chairman HALL. In the past NOAA has considered this and other commercial options. That might not work for all of NOAA's missions, but the potential benefits and cost savings seems too great to pass up.

Ms. KICZA. Yes, sir, and when we look at alternatives to meeting our operational observational requirements, we do consider all sources. We do in fact purchase commercial data now to augment our forecasting activities. Each of our analysis of alternatives generally does include commercial options as well. When we make a decision, it is based on both the technical maturity and feasibility of the option as well as the cost and the risk.

Chairman HALL. Can you tell me why NOAA is not pursuing commercial payload options to get necessary weather data?

Ms. KICZA. As I had said, we do currently employ commercial services and options for purchase of data, and we explore options in nearly every exercise that we go through before making a determination.

Chairman HALL. Well, my time is about up. Let me ask you, will you provide with the committee a summary in writing of NOAA's analysis and efforts to consider these commercially held options?

Ms. KICZA. Yes, sir. I will be happy to do so.

Chairman HALL. Thank you. I yield back, Mr. Chairman.

Chairman HARRIS. Thank you very much. The Chair recognizes the gentleman from Maryland, Mr. Bartlett.

Mr. BARTLETT. Thank you. Our military obviously has an acute need for accurate weather forecasting. It is my understanding that because of budget constraints that we are cancelling or proposing to abort a troubled weather satellite program in the Department of Defense.

Can you tell us how what NOAA does relates to what DOD does in the collecting of data for weather forecasting, how you share this information to minimize cost? And are there assets that NOAA has that could fill the gap that will be there because the Pentagon is aborting this troubled weather satellite program?

Ms. KICZA. Yes, sir. Let me talk for a minute about my understanding of the situation. In the fiscal year 2012 budget appropriations, DOD was instructed to terminate the contracts associated with the DWSS, Defense Weather Satellite System. At the same time they were given funds to explore the next system in the wake of that. That is being conducted. They are currently in the process of reevaluating the requirements and conducting an analysis of alternatives. We are working in conjunction with them.

For the weather satellite system, there are three orbits that are of interest, and there have been traditional roles in who handles each orbit now. The military handles the early morning orbit. We rely on our partners, EUMETSAT, for the mid-morning orbit and NOAA in partnership with NASA covers the afternoon orbit. All of the information from these orbits is available to all of the partners and as used in their weather prediction systems. The predominant orbit for our weather prediction is our orbit. When I say our, the United States is the afternoon orbit, and that is made available to the DOD as they do their weather predictions.

I will ask Mr. Murphy to augment.

Mr. MURPHY. I would just add that the DOD also has two spacecraft in the barn, so to speak. Their DMSP program has F–19 and F–20, so they will fly that out into the 20s which allows them the time to do the analysis of alternatives. So they will be flying that morning orbit for a bit longer. So this is not a crisis.

We do share data back and forth. We collaborate in many forms, both in modeling and in sharing data.

Mr. BARTLETT. Does DOD not have satellites in polar orbit?

Mr. MURPHY. The DWSS, that was a polar orbiter. They do not have geostationary.

Mr. BARTLETT. I thought it was the polar orbiting satellites that were compromising your forecasting?

Ms. KICZA. The DOD flies in the early morning orbit. Their current satellite series is called the Defense Meteorological Satellite Program, the DMSP series of satellites. Those are currently operational, and in fact, NOAA on a reimbursable basis operates those satellites for DOD from our NOAA satellite operations facility. What Mr. Murphy had indicated is that they still have two on the ground, so they have got time before they introduce their next generation and they are in an analysis of alternatives mode right now for that is next generation capability.

Mr. BARTLETT. So you will not have lost all of your polar orbiting satellites with this gap?

Ms. KICZA. No, sir, we will not. We will still have the DOD early morning orbit, EUMETSAT, the European satellite is covering the mid-morning orbit. Our concern is about the gap for a period of time, the potential gap, for a period of time between the NPP satellite, which we launched last October and which is operating successfully on orbit now, and the first of the JPSS satellites which is scheduled to launch in early 2017.

Mr. BARTLETT. So we still have considerable data from polar orbits but not all we would like? Is that where we are?

Ms. KICZA. We currently have a robust constellation in orbit. We are concerned about the longevity of that constellation in the 2016, 2017 timeframe.

Mr. BARTLETT. Thank you, Mr. Chairman. I yield back.

Chairman HARRIS. Thank you, and I have one other brief question, so I am going to yield myself 2 minutes, then I will yield the Ranking Member.

Mr. Murphy, I have a question for you. With regards to severe weather prioritization, the ones that a lot of average Americans are worried about, the types of weather events that cause loss of life, are polar orbiting satellites versus earth-based measuring devices the best approach to improve forecasting for those events? Because again, in the context, you know, the budget kind of emphasized everything on these polar orbiting satellites, but are they really the best way versus earth-based?

Mr. MURPHY. Mr. Chairman, as Ms. Kicza pointed out, the JPSS or the polar orbiters provide the bulk of the forecast model input. So where that is important is in the longer range, 2- to 5-day period. So they give us the ability to forecast that there is going to be a severe weather outbreak in Missouri in several days. That allows emergency managers and local officials to prepare.

In terms of the warnings, that is when you really have to depend on the in-situ or our primary tool which I mentioned was the dual pole or the Doppler radar to issue our warnings.

Chairman HARRIS. And that is not obviously not polar satellite based. Those are Earth-based.

Mr. MURPHY. That is ground.

Chairman HARRIS. So in essence, if we want to maintain the zero to two ay warning, then what we really need, we have to make sure that our insight to techniques are state of the art?

Mr. MURPHY. Yes, sir.

Chairman HARRIS. Okay, thank you. And I will yield two minutes to the Ranking Member.

Mr. MILLER. Thank you. A further question about the ground observation platforms as you referred to them in your testimony, the in-situ. The in-situ observation platforms are scarce in polar and ocean environments, I assume, because they require being in a fixed place, and the oceans and the ice in the polar regions will not sit still for us. So is it possible or cost-effective to actually have more in-situ observation platforms in polar regions and oceans or are those problems inseparable? I can't hear you.

Ms. KICZA. I said I will start and I will let Mr. Murphy augment. The beauty of the satellite observations are that they are global, so I guess literally you could do it but physically it is nearly impossible to have the coverage with in-situ buoys, and they, in and of themselves, require a lot of maintenance and upkeep. So that presents a problem in and of itself. But they are important in terms of their in-situ capabilities. So as I said, they supplement, they augment, they are complementary. Mr. Murphy, would you like to——

Mr. MILLER. But they are not a replacement?

Ms. KICZA. They do not replace.

Mr. MURPHY. Yes, and we pretty much depend on whoever owns the territory to pretty much take care of the in-situ observation. In the case of oceans, NOAA is looking at unmanned water gliders, as they are called, to take ocean and potentially some atmospheric observations in lieu of the buoys that are a maintenance challenge. So I think we are doing what we can and what is practical in very remote and hard-to-get-to places.

Ms. KICZA. And I will offer one additional comment. There are a number of buoys, and it is an international activity. The Argo has on the order of 3,000 I believe. So it is not a small number of buoys that are internationally shared, and the satellites again provide the bent pipe communications path for retrieving that data and then sending it down to where it needs to go.

Mr. MILLER. My time has expired.

Chairman HALL. [Presiding] The gentleman's time has expired. Anybody else want to be heard? I want to thank the panel for the very valuable testimony and the Members for their questions. The Members of the Committee may have additional questions for you. I would ask you to respond to those in writing in a reasonable time. We would like to have them in about two weeks if we could.

Let me note that the committee has not received NOAA's written responses to follow-up questions asked of NOAA's Deputy Administrator, Kathy Sullivan, after last September's hearing on polar satellites. These questions were sent more than five months ago. The delay is unacceptable, and we expect each of the three witnesses here today to deliver a timely response to these questions. Are you able to do that?

Ms. KICZA. Yes, sir.

Chairman HALL. I am going to recognize you for five minutes. I am ready to go. They say no. Witnesses are excused. May we have the second panel? The witnesses are excused, and we thank you very much for your time. We will move to our second panel.

Are you gentlemen ready to proceed? The first witness on our second panel is Mr. Eric Webster, Vice President and Director of Weather Systems, ITT Exelis. Mr. Webster directly oversees Exelis weather and climate satellite instrument business unit which includes instruments for NOVA, NASA, geostationary and polar orbiting programs, NASA Earth Science and international customers.

Our next witness is Dr. David Crain, Chief Executive Officer of GeoMetWatch. Prior to his work with GeoMetWatch, Dr. Crain was a Senior Program Manager at Space Dynamics Laboratory where he oversaw the sensor development activity.

Our third witness, Mr. Bruce Lev, Vice Chairman of AirDat LLC. Prior to this, he was Vice Chairman and Director of USCO Logistics, which the business was sold to Global Freight, formerly Kuehne & Nagle in 2001.

Our final witness, our last witness, is Dr. Berrien Moore, Dean of the University of Oklahoma College of Atmospheric and Geographic Sciences and the Director, National Weather Center. Prior to joining the University of Oklahoma, Dr. Moore served as Executive Director of Climate Central, a non-profit organization based in Princeton, New Jersey, and Palo Alto, California.

As our witnesses should know, spoken testimony is limited to five minutes, after which the Members of the Committee have five minutes each to ask questions. I now recognize our first witness, Mr. Webster, to present his testimony.

**STATEMENT OF MR. ERIC WEBSTER, VICE PRESIDENT, DIRECTOR, WEATHER SYSTEMS, ITT EXELIS**

Mr. WEBSTER. Good afternoon, Chairman Hall, Ranking Member Miller and staff, my name is Eric Webster, and I manage the weather system business at ITT Exelis. I appreciate your leadership and efforts to examine how NOAA procures data for weather forecasting.

This is sort of a homecoming for me, Mr. Chairman, as I was privileged to be a staffer on this committee for five years under Chairman Boehlert and help lead the examinations into NOAA's weather satellite programs. I then served in the George W. Bush administration as NOAA's Head of Congressional Affairs and the Senior Policy Advisor on weather satellites.

During that time, the committee conducted 12 NOAA satellite oversight hearings, and I still have the scars to prove it.

My position at ITT Exelis has brought me full circle as now I actually oversee the building of next generation instruments for both GOES–R and the JPSS programs.

There are two major types of instruments flying in space in two different orbits. To generalize, it is the imagers on geostationary satellites flying 22,300 miles above the earth, staring at the United States and taking pictures of clouds, water vapor and gathering other information on the surface which are critical to near-term severe weather forecasting.

The pictures that you see on TV or the internet of hurricanes usually come from the imagers on geostationary satellites. The sounding instruments on polar satellites fly about 520 miles above the earth from pole to pole, taking three-dimensional pictures of the atmospheric column from space to near surface. Understanding the atmospheric column is important because it where weather is created, it gets mixed, it moves and it evolves. As was stated earlier, these measurements are crucial to global weather models and for our two to five day forecasts. So our ability to know several days in advance of a potential tornado or a large snow event is mostly because of polar sounders.

Our engineers and workers in Ft. Wayne, Indiana, have an impressive record of building every imager and every sounder for NOAA's legacy polar satellite programs since the 1970s, including the next generation polar sounding instrument flying today on NPP and for the JPSS program.

Our folks have also built every imager and every sounder for NOAA's geostationary program since the 1990s, including the advanced imager for GOES–R. That is a total of more than 50 instruments without one major systems failure. So if you will, we are the Cal Ripkens of the space-based sensors, when he was still at his prime.

As such, we also have some experience with the contracting process. Requirements for observation systems should be driven by scientific tools and experiments to maximize capabilities and overall effectiveness. These tools, with proper oversight and funding, can help prioritize unmet needs. However, they will not fix many of the problems in the actual design and procurement of observing systems. In the case of GOES–R, systems requirements were determined over a course of a three-year formulation phase involving industry teams and review team of NASA and NOAA representatives. All the parties went through an iterative process whereby industry did cost and performance trades and presented the results back to NASA and NOAA.

For the GOES–R imager, the process works as requirements remain stable, and we are in production on the first flight unit expected to be delivered next year. But it took $100 million just in formulation studies and ten years to get here.

For the GOES–R sounder, the situation was different. Requirements were never really solidified, and too many competing priorities were being asked of one instrument. The cost and development of the instrument and the cost and to assimilate the data into user products kept growing. Thus, the decision was made to cancel the geo-sounder instrument, and at the time I believe it was the right decision.

NOAA and NASA must find ways to reduce the overall systems cost as the current GOES–R and JPSS programs are likely unsustainable. GOES–R is $8 billion for two satellites, sensors, ground systems and operations. The imager, which is a significant increase in technological capability, is less than ten percent of the total program cost. The JPSS program is $13 billion for two main satellites, sensors, ground systems and operations. While amortizing out to the mid-2020s can lessen the sting of the total price tag, these costs are having a tremendous effect on NOAA's missions today and probably assuring no new observing systems, especially from space, can be acquired.

In summary, space-based sensors are critical to weather forecasting, both for global weather models and severe warnings. NOAA should increase its use of scientific tools to determine requirements, but more than ever, hard choices have to be made. NOAA must examine different procurement models for space-based sensors such as fixed price or modifying existing instruments to meet requirements at lower costs and lower risks. Given the difficulties in turning these requirements into actual observing systems, NOAA will also have to rely more on commercial capabilities into the future to improve weather forecasts, whether it is advanced geo-sounders from space or Mesonets from the ground.

Thank you, Mr. Chairman, for the opportunity to testify.

[The prepared statement of Mr. Webster follows:]

WRITTEN STATEMENT BY
ERIC WEBSTER
VICE PRESIDENT AND DIRECTOR
WEATHER SYSTEMS
ITT EXELIS, GEOSPATIAL DIVISION

HEARING ENTITLED
TO OBSERVE AND PROTECT: HOW NOAA PROCURES DATA
FOR WEATHER FORECASTING

BEFORE THE
U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY
SUBCOMMITTEE ON ENERGY AND ENVIRONMENT

MARCH 28, 2012

Good afternoon Chairman Harris, Ranking Member Miller, and members of the Committee, my name is Eric Webster, and I am the Vice President and Director of Weather Systems at ITT Exelis. I appreciate your leadership and efforts to examine how NOAA procures data for weather forecasting, and I appreciate the opportunity to testify.

This is a sort of homecoming for me, as I was privileged to be a staffer on this Subcommittee for five years from 2001 to 2005 under Chairman Sherwood Boehlert and led examinations into NOAA's weather satellite programs. I then served in the George W. Bush Administration as NOAA's head of Congressional Affairs and a senior policy advisor on weather satellites. During that time, the Committee conducted 12 NOAA satellite oversight hearings. My position at ITT Exelis has brought me full circle, as I now oversee the building of next generation instruments for GOES-R and JPSS. So my advice to the staff is to be careful as you never know where you might end up.

People often joke about endeavors being not as hard as "rocket science." But our engineers will tell you the design and manufacture of these highly sensitive instruments - which must survive the extreme forces of a rocket launch, the harsh environment of space, have the sensitivity to tell variation of sea surface temperature to a tenth of a degree from 22,300 miles away, and work 24/7 for several years – is much more difficult than rocket science.

While I have played a role in this discussion for more than 10 years, this is the first time the broader scientific and technical processes that drives decision making for requirements and eventual procurement have been brought to the forefront. If done properly, this process leads to an optimal combination of systems and data that ultimately helps forecasters save lives. So I commend the Committee for taking a more holistic view of the situation beyond the normal inquiries into the cost and schedule difficulties of the major programs.

Why are these weather observations and forecasts so important? The government, many industries, and our citizens rely daily on these forecasts for military operations, for logistics and transportation flow, for agriculture, for normal quality of life, and for warnings to save lives and property. In fact, the weather affects more than one-third of our nation's GDP.

We often forget the U.S. has the most natural hazards and severe weather on the globe ranging from tornadoes, hurricanes, hail, damaging winds, winter storms, floods, wildfires, extreme temperatures, poor air quality to drought. To measure, monitor and forecast the weather, NOAA uses more than 100 different observing systems (such as satellites, radars, radiosondes, data from air planes, ocean buoys, soil moisture sensors, and a network of 11,000 volunteers with small weather stations in their backyards). NOAA also utilizes data and information from commercial and international observing systems to help augment its resources. To the public and through its accurate forecasts, it is a seamless effort, but behind the scenes it is a large undertaking and NOAA deserves credit for making it work.

However, the cost and maintenance of NOAA systems adds up to billions of dollars a year with nearly $2 billion a year just in satellite costs. Given the fiscal constraints and budgetary crisis we are facing, and the need to continue to improve our capabilities to save lives and livelihoods, NOAA must constantly examine and re-examine its priorities for observing systems to provide the best value for the taxpayers' investment.

While observations are critical and tend to receive much of the attention, it is important to note observations alone do not make the forecast. The observations must be broken down into useable information through data assimilation. This requires very sophisticated models run on supercomputers and then exported to computer workstations for forecasters, who in turn must effectively translate and communicate the information. Finally, it is an understanding public whose responsibility it is to take action based on the information. Each part of this system is important and must work in concert. If not, the most advanced and expensive observing systems would not improve the forecast or save lives. In fact, I often wonder if providing shelters for people living in mobile homes in the Southeast U.S. would save more lives than new satellite instruments or radars – but that is probably the subject for another hearing.

I was asked to describe the types of data generated by space-based sensors and the importance of such data in weather forecasting, including the role of this data within the context of the current mix of observing systems.

There are two major orbits for weather satellites, one is called a polar low-earth orbit and the other is geostationary orbit. Polar satellites fly about 520 miles above the earth in a pattern from pole to pole and, as the earth rotates, the satellites gather global data, roughly seeing the same spot twice a day. They circle the globe about every 90 minutes. These satellites are critical to provide data and measurements used in global weather forecast models and critical for two to seven day forecasts. Polar satellites can be thought of as forecasting satellites. These satellites also provide the only visible imagery of high latitude regions such as Alaska, where geostationary satellites are effective due to the curvature of the earth.

Geostationary satellites fly about 22,300 miles above the earth and constantly stare at the United States from Atlantic Ocean to Pacific Ocean from a fixed location relative to earth. These satellites are critical for monitoring severe weather, such as hurricanes and tornadoes, and providing real-time data on weather parameters for the U.S. Geostationary satellites can be thought of as now-casting.

While there are many types of space-based sensors, it is imagers and sounders that provide the majority of the data and information used for weather models and by forecasters. Imagers, true to their name, take pictures and gather information at a specific spot on the surface of the land, ocean, or ice. They also take pictures and measurements of clouds and their movements, as well as water vapor transport which is invisible to the naked eye, all critical to severe weather forecasts. When you see the pictures of hurricanes on television or the Internet, they come from space-based imagers. Imager capability is measured in how small area they can see, how quickly they can scan to the next spot, and how many channels or bands it has to measure different chemical compositions making up temperature, moisture, pressure, wind and other attributes such as volcanic ash, hot spots for fires, etc.

Sounders work technically in a similar way to imagers, but instead of taking pictures of the surface, they are taking 3-D pictures of the atmospheric column from space to near surface. Their performance is measured by the number of different slices of the atmospheric column they produce and the sensitivity to differentiate chemical compositions of temperature, moisture, pressure, wind, etc. The atmosphere is where the weather is created, mixed, moves, and evolves. If imagers are our sight, sounders are our feeling, our hearing, our tasting and our smelling of the atmosphere. Thus, these measurements are particularly important for the creation of weather forecast models.

In general, weather observing systems measure the same or similar parameters of temperature, moisture, pressure, wind, etc., regardless of if it is a space-based sensor, radiosone/weather balloon, aircraft sensor, radar, ocean buoy or small weather station at your local elementary school. The difference is in the breadth of coverage, the latency or timing of the data, its sensitivities, and its biases.

No one observing system can meet all the requirements. Data from each system plays an important role in the development of weather forecast models and in warnings of severe weather. They complement each other and fill in the gaps and limitations of the others – or, as they say in NOAA, they act as a network of networks. Most of these other systems can even be more sensitive than spaced-based sensors because they are much closer to the observation, but they cannot provide the sheer breadth, abundance and consistency of coverage. It is difficult to judge relative importance of each capability – but I understand doing so is one of the goals of this hearing.

Global weather forecast models are critical to initialize the whole forecasting process and rely mostly on data from polar sounders because of the global reach (remember 70 percent of the earth is covered by ocean, with few in-situ measurements) and their ability to measure the atmospheric columns – where the weather is being created. The National Weather Service has been able to forecast the likelihood of severe weather and potential tornadoes in specific areas of the country days in advance mostly because of polar sounders. After global forecast models are created, the National Weather Service then creates regional models and finally localized forecasts that are higher in resolution and thus more sensitive to particular conditions and small features that may be smoothed out by the global models.

Similarly geostationary imagers are critical for visualization of large movements of clouds, storms, and other features that drive weather in the U.S. They are especially crucial for monitoring hurricanes and ocean storms. However, forecasters rely much more on radar, radiosondes, local weather stations and other data sets for specific short-term forecasts and local warnings. There are exciting commercial capabilities in the use mesonets and lidar to measure the boundary layer and wind which can further improve forecasts, especially at a hyper-localized level.

I did want to briefly mention a related and important topic known as space weather. NOAA is also responsible for space weather forecasts. Space weather consists of charged particles, radiation, winds and "storms" ejected from the sun, which can quickly reach the earth and have a significant negative impact on satellite operations, the power grid, airline communications over the poles, and GPS signals (which control banking transactions and other critical IT functions). Radiation from solar storms can also harm the astronauts on the space station if not properly warned in advance. Satellite instruments are the best way to measure the different types and parameters of space weather. In fact, no other observing systems have the capability to provide the necessary measurements to allow for analysis and forecasting. Both geostationary and polar satellites carry instruments measuring space weather.

As the next generation weather satellite systems GOES-R and JPSS come on-line and the data is fully assimilated into models, there will be significant improvements in weather forecasting. These next generation space-based sensors will provide more information, be more accurate, and provide the data much more quickly than ever before. Further studies and research should then be conducted to reevaluate the relative importance of the new systems in the global forecasts models.

The larger question is if we can afford the tremendous costs of these satellites, which touches on the next question I was asked to address regarding the current process by which space-based observing systems are designed and procured to meet data requirement of the National Weather Service, including any processes that evaluate and prioritize these requirements.

NOAA's requirements process for spaced-based observing systems seems to be the same as for all NOAA observing systems. Requirements are first developed by operational users or researchers within NOAA and the scientific community. The requirements must be supported, vetted and approved by program leadership, and then senior officials within the supportive line-office. Once verified, requirements are presented to NOAA's Observing System Council (NOSC) for further validation and prioritization.

Recently, there have been discussions about the use of simulations and experiments to help prioritize requirements and study the impact of observing systems on forecast models and forecast accuracy itself. One type, Observing System Simulations Experiments (OSSEs), use model simulations of "nature" and simulations of new or modified observing systems to gauge their impact on forecasting. These experiments are highly theoretical and could be biased toward the creator's desires. They also require tremendous computation power and thus are expensive, but do allow for experiments where no observing system exists.

Observing Systems Experiments (OSEs) add or subtract data from an existing observation used in a specific forecast, such as the demonstrations NOAA conducted for the large snowstorms in February 2010. In this example, NOAA subtracted data from polar instruments to show the negative impact to the forecast. The results showed a significant underestimate in the amount of snowfall for the event. Another tool just starting to be used in the U.S. is called "adjoint experiment." This technique measures the amount of forecast error reduction accumulated by each observation based on global forecast model. European researchers using this technique recently affirmed the importance of polar sounders as the most important observation for global forecast models.

I do believe more extensive use of these tools can help NOAA make better assessments of observational needs, as well as compare existing, modified and potentially new observing systems. However, each has its strengths and weaknesses and requires additional expenditures, especially in the case of OSSEs, and will not fix many of the problems in the actual design and procurement of these systems.

Assuming requirements are finalized, and the decision is made for a space-based capability built by the U.S. government to meet the requirements, the next step is for NOAA's satellite division to work with NASA as the procurement agency to take the requirements and turn them into instrument specifications.

At ITT Exelis, our team in Fort Wayne, Indiana, has decades of experience with the difficulties in transitioning the requirements and user needs into actual space-based sensors providing data for use in models and products. ITT Exelis has built every imager and every sounder for NOAA's polar program (POES) since the 1970s, including the next generation CrIS sounder flying on NPP and scheduled for the JPSS program. We have also built all the imagers and sounders for NOAA's geostationary program (GOES) since early 1990s, including ABI imager for the GOES-R program.

In naming and prioritizing requirements, the factors most benefiting the end data products must be balanced against what is technically possible, than the benefit has to be quantified, and compared to the cost impact on the system to be designed - a standard cost/benefit trade. What makes it so complex in the case of space-based observing systems is that very few, if any, organizations or individuals really understand the entire value chain. NOAA understands the benefits to the users, NASA understands how to translate the user characteristics into hardware specifications, and industry understands the cost of implementing those specifications at the system level.

The process must also include the broader budget discussion within NOAA's budget assumptions and then approval within NOAA, the Department of Commerce, the Office of Management and Budget and ultimately with Congress.

In the case of GOES-R, system requirements were determined over the course of a two to three year "formulation phase," involving three industry teams and a review team consisting of combined NASA and NOAA representatives. NASA took an initial set of NOAA requirements, translated them into instrument level specifications, then all of the parties went through an iterative process whereby industry did cost and performance trades, and presented the results back to the NASA/NOAA review team. NOAA was the interface with the users, and NASA bridged the gap with industry. In this way, the instrument level requirements were tweaked and finalized. In the final phase of formulation the three industry teams competed for the most efficient, highest performing design. Throughout the process, NASA was able to modify requirements according to feedback from NOAA regarding the relative benefit, and from industry regarding the cost to implement.

This approach takes time and money. NOAA, with the help of NASA, spent more than $100 million on the GOES-R imager (ABI) and GOES-R sounder (HES) formulation phases, and the entire process took four to five years. The approach seems to have worked well for the GOES-R imager ABI as the requirements have been stable and ITT Exelis is in production on the first flight unit expected to be delivered early next year. But, it has taken nearly 12 years to get to this point.

For the GOES-R advanced sounder (HES), the requirements never really solidified properly, as too many priorities were collected into one system (sounding, coastal monitoring, and a backup for ABI). The requirements were still unstable in the final days of the formulation; the cost of developing the combined system along with the costs to assimilate the data into user products were not solidified and kept growing; and NOAA, NASA, the Department of Commerce, OMB and Congress were all still reeling from the cost and technical problems on the NPOESS program. Thus the decision was made not to go forward with an advanced sounder for GOES-R. At that time, I believe it was the right decision.

For the next generation polar program, which began as NPOESS and is now the JPSS program, similar requirements definitions were made and prioritized nearly 15 years ago, except the Department of Defense, NOAA and NASA all played a role, which made it even more difficult and challenging to transfer the requirements into actual space instruments. For example, the polar imager (VIIRS) requirements were expanded to include functions and capabilities of other instruments (low light and ocean color), causing technical challenges that persist today. The original requirements for the advanced sounder (CrIS) we are building demanded a very compact instrument making the design especially complicated. This requirement turned out to be more stringent than was necessary. All these debates, changes, and back and forth regarding the specific requirements and the end user needs, negatively impact the ability of industry to meet cost, schedule and performance, and increase the overall risk to the programs.

There are many significant pressures on this process beyond the technical experts at NOAA, NASA and in industry. There are continual technology advancements, and there are procurement officials, budget managers, oversight teams, NESDIS/NOAA leadership, continued review by NOAA's NOSC, NASA leadership, OSTP, OMB, GAO and you here in Congress all playing a significant role in how these requirements become reality in observing systems. So even if the requirements process worked flawlessly, there are many other important factors built into the system, which make it hard to turn requirements into actual observing systems. NOAA will likely face a gap in critical polar coverage because of our collective inability to turn the requirements into observing systems

In conclusion, I was asked to provide recommendations on how best to evaluate the most cost-effective and diverse combination of observing systems to meet the National Weather Service's forecasting needs.

I do believe NOAA and the National Weather Service are doing a pretty good job under very difficult circumstances. They are using a combination of U.S. government owned systems, commercial systems and international capabilities to put together a network of networks providing increasingly better forecasts and understanding into earth systems. But many unmet requirements and areas for improvement remain.

NOAA should increase its use of OSSEs, OSEs and adjoint experiments with proper oversight and funding. These tools can help to prioritize unmet needs and identify more cost-effective and perhaps technically superior solutions to existing observations systems. I believe a reexamination of an advanced geostationary sounder, requirements for a polar imager, and new technologies to measure 3-D winds are warranted.

NOAA and NASA must find ways to reduce costs, as the current GOES-R and JPSS programs are likely unsustainable. GOES-R is $8 billion for two satellites, sensors, ground systems and operations. For example, of the total program cost, the imager, which is the most advanced ever designed and built, is less than 10 percent. JPSS is $13 billion for two satellites, sensors, ground systems and operations. While amortizing out to the mid-2020s can lessen the sting of the total price tag, these costs are having a tremendous effect on the rest of NOAA's mission today and nearly assuring no new observing systems, especially from space can be acquired.

NOAA should examine different procurement models such as fixed price, modifying existing instruments (rather than building new) to meet requirements at lower costs and risks, and the potential to buy more data from commercial observations and networks.

In summary, space-based sensors are critical to weather forecasting both for global weather models and severe warnings. Requirements for observation systems should be driven by scientific tools and experiments to maximize capabilities and overall effectiveness to produce actionable data to protect lives and livelihoods. However, it is exceedingly difficult to turn the requirements into actual observing systems. Finally, the cost of NOAA's main satellite programs are likely unsustainable given our fiscal situation. More than ever, hard choices need to be made and new ways of doing business must be explored, such as relying more on commercial capabilities for unmet needs.

Chairman HALL. Mr. Webster, thank you. And did anybody ever tell you that you kind of took on some of Mr. Boehlert's expressions?

Mr. WEBSTER. No, sir, but I appreciate the compliment. Thank you.

Chairman HALL. You know, he was a Republican Chairman and I was the Ranking Democrat then.

Mr. WEBSTER. Yes, sir.

Chairman HALL. The book on us was that I kept him from saving all the whales and hugging trees, and he kept me from dribbling on cemeteries.

Mr. WEBSTER. Yes, sir. That is true.

Chairman HALL. He was a good guy, hard working. Dr. Crain, I will recognize you now for five minutes.

## STATEMENT OF DR. DAVID CRAIN OF ERIC WEBSTER DAVID CRAIN, CHIEF EXECUTIVE OFFICER, GEOMETWATCH

Dr. CRAIN. Thank you, Mr. Chairman, and Members of the Committee and the senior member for inviting me to testify today. I am honored to discuss the role of geostationary advanced sounding and how commercial approaches can help NOAA meet the country's observational needs.

Today's budget and the programmatic challenges faced by NOAA's satellite programs present a perfect opportunity to implement commercial alternatives as a means to provide essential data needed to improve severe weather forecasting. A commercial approach, building on critical government technology investments that have already been made, combined with private industry and experienced universities, provides an affordable means for NOAA to protect lives at a price the Nation can afford. Commercial capabilities can complement existing and future NOAA systems to provide the best value solution.

One way in which these private-sector capabilities can be quantified and assessed is through the use of observing system simulation experiments, as you have heard in previous testimony. We encourage NOAA to carry out OSSE experiments to validate the system that I will discuss today.

[Slide]

Dr. CRAIN. If you look at slide 1 just for background, our current operational weather systems rely on technology developed over 30 years ago. The current POES, DMSP and GOES satellites were developed in the '80s and '90s. Part of the rationale for both the JPSS, NPOESS and GOES–R programs was to implement new technology that would dramatically improve the capability to forecast and predict severe weather. Not just continue with the old, implement new important technology.

One of the key technology improvements on both systems was hyperspectral sounding. The role of sounders on both LEO and GEO platforms is to produce the vertical profiles of atmospheric water vapor, temperature and pressure. Hyperspectral sounders dramatically increase the vertical resolution accuracy of these profiles over previous sounders. These profiles are the essential data products needed for every forecast. In fact, Dr. Kathy Sullivan in previous testimony before this committee stated that sounding data are the essential lifeblood of weather forecasting.

For this and other reasons, the advanced hyperspectral sounder was identified as a primary mission in the process described by Eric when the GOES–R program was authorized. And when it was authorized, it was originally slated to have two primary instruments, an advanced imager and an advanced sounder. The roles of the two instruments are complementary but different. The imager tells you what the weather is going to be now, the sounder tells you what the weather is going to be 6 hours from now.

Severe weather events that have occurred over the last several years really underscore the benefits of the advanced geostationary sounder, and they include extending warning times from minutes to hours for tornados and thunderstorms avoiding many of the 500 deaths we had in the 2011 season; improve hurricane track and the intensity forecast; avoiding unnecessary evacuations like we had with Irene and Rita; improve the routing of aircraft, significantly reducing weather delays for passengers, allowing the airlines to manage their fuel and routing more efficiently. All of these are goals of the next-gen FAA system.

All of these benefits can be reliably delivered by an advanced sounder and geostationary orbit. Unfortunately, due to the reasons that Eric described and for budgetary reasons and other satellites, the advanced sounder was cancelled on GOES–R, and NOAA did assess some alternatives to restore the capability which included flying a full capability sounder, flying a reduced legacy-like sounder, flying no sounder at all and letting the European weather agency develop an advanced sounder in purchasing either the data or the sounder from the Europeans.

Compared to these options, we feel a commercial approach can provide the needed data years earlier and with minimal cost and risk. In 2010, GeoMetWatch applied for and received a commercial remote sensing license from the Department of Commerce to operate six hyperspectral imaging sounders. The GeoMetWatch sounder will equal or exceed NOAA's requirements and when flown over the United States will restore the full benefits of the GOES–R sounding mission. This sounder will provide continuous coverage for severe weather and vastly improve our ability to predict tornados, hurricane landfall and intensification. And as mentioned before by others, these benefits can now be evaluated through a use of OSSEs which NOAA can do.

Mr. Chairman, we at GeoMetWatch are excited about the future of weather technology and the role of the private sector to dramatically improve the ability of NOAA and the weather service to predict severe weather in the United States. We encourage NOAA to promptly undertake OSSE experiments to validate the advantages of the geostationary system we have described, and we would also encourage the committee to consider legislation to clarify the authorities of NOAA and clarify their ability to acquire meteorological data and confirm the private sector's critical role in improving severe weather forecasting while saving lives and strengthening our economy. Thank you, and I welcome your questions.

[The prepared statement of Dr. Crain follows:]

**WRITTEN STATEMENT BY**
**Dr. David Crain**
**President and CEO of GeoMetWatch**
**COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY**
**U.S. HOUSE OF REPRESENTATIVES**
**SUBCOMMITTEE ON ENERGY AND ENVIRONMENT**
**TO OBSERVE AND PREDICT;**
**HOW NOAA PROCURES DATA FOR WEATHER FORECASTING**
**MARCH 28, 2012**

Thank you, Mr. Chairman and committee members, for inviting me to speak today.

Once upon a time in America, we were leaders in space. The United States won the race to the moon and invented many things we take for granted that have a space connection. The US invented the weather satellite, the communication satellite, GPS and from the 1960's to present day, the majority of earth observation satellites have been flown by the US. But things are changing. Our research satellite programs are almost universally over-budget and behind schedule. Our infrastructure and operational weather satellites are aging and the next generation programs in all areas have been dramatically cut back to the point that even our current capability to adequately monitor and predict severe weather over the United States is threatened to the point that we must rely on satellite missions flown by Europe and China to meet our basic weather observation requirements. We once flew a constellation of Polar Orbiting weather satellites in 3 separate orbit planes to provide comprehensive global coverage. In the JPSS era, we will fly only one, reducing coverage by $2/3^{rds}$.

Moreover, we now critically rely on Eumetsat's METOP program for critical observations that predict weather over the United States. In the near future, we may have to rely on China's FY-3 Series of LEO orbiters to provide data in orbits currently flown by DMSP. Today, we still operate a robust fleet of Geostationary GOES weather satellites. We have been so generous with our GOES satellites, that we routinely reposition them for use by other countries (though still to our benefit). We have always maintained a spare GOES satellite in-orbit ready to take over for the operational East or West GOES in the case of a premature failure. This capability is now in immediate jeopardy. As the GAO has been warning about for years, there is a looming gap in the GOES fleet, which in addition to the reduced polar coverage puts the entire US space-based operational weather capability at risk. Prior to GOES-R launch, the US will be at risk of having only a single operational GOES spacecraft; after GOES-R launch there will be no spare spacecraft on orbit until GOES-S. A launch or premature orbit failure of GOES 15, GOES-R or GOES-S could lead to significant coverage gap beginning as soon as 2015 and lasting for several years.

But America remains a resourceful country, an entrepreneurial country. The Communication Satellite sector, once an exclusive sovereign government domain, is now in the vast majority of cases *commercial.* Over 250 commercial communication satellites are in operation today. Many of these sell critical communication bandwidth to our government at a fraction of the cost of a dedicated government operated system. GeoEye and DigitialGlobe have revolutionized and transformed the way high resolution imagery is collected and distributed with a capability that once was only obtainable at costs orders of magnitude higher and with significant risk to the government customer.

In the same way, I am convinced we can remedy the potential gap in our weather observation system and restore critical new observations that have been de-manifested from our future programs. When the GOES-R program was authorized, it was originally slated to carry both an advanced Imager and an advanced Sounder. The roles of the two instruments are complementary, with the Imager most sensitive to clouds and surface regions and the sounder most sensitive to water vapor and able to determine high resolution vertical profiles of the atmosphere and 3-D wind profiles continuously. In the words of a former GOES-R deputy program manager, "The Imager tells you what the weather is NOW and the Sounder tells you what the weather will be 6 hours from now." NOAA's own cost benefit analysis has shown that the benefit from each sensor is about 50% of the total program value.

When the Advanced Sounder (HES) was canceled on GOES-R, this benefit was lost while the total program cost has increased above the original authorization. There have been efforts to restore a "legacy sounding" capability using the Advanced Imager (ABI) alone, but even the GOES-R lead scientists conclude that this capability is not as good as the current sounder and cannot meet any of the Advanced Sounder requirements. This shortfall has been recognized by many groups in the US and internationally who have consistently advocated for a restoration of this capability.

Given the current fiscal environment, but also because of the precedent of successful commercial alternatives in other areas, GeoMetWatch (GMW) has made efforts to license and fly a commercial Advanced Sounder. GeoMetWatch applied for and was granted a commercial remote sensing license to operate up to Six Geostationary Hyperspectral Imaging Sounders in 2010. This license was issued by the US Department of Commerce and signed by the Assistant Administrator of NOAA/NESDIS. The planned capability of the GeoMetWatch sounder equals or exceeds the sounding requirements of the original HES mission, and if flown over the US would restore the full benefits of the GOES-R mission. A GeoMetWatch mission can provide redundancy and risk mitigation for a premature failure of any future GOES. A GeoMetWatch Sounder over the US also provides continuous coverage for severe weather forecasting and hurricane track and intensification. This continuous coverage over the US provides from 24 – 1300 times more sounder coverage of a given region than NPP or JPSS.

GeoMetWatch anticipates its first launch in late 2015 / early 2016 to cover the Asia Pacific region. We selected this location because of the customer commitments we have received to purchase the data when available.

And with commitment (even conditional) to purchase data in the US Sector, GMW can have a satellite ready in the 2015/2016 timeframe.

**Why GEO Hyperspectral Sounding?**

The benefits of Geostationary Weather observation are well documented. The primary benefit of a geostationary system (vs. a Polar orbiting Leo system) is the persistent and continual observation capability of a Geo System. This is especially significant for severe weather. A Geostationary system over the United Stated can continually observe evolving severe weather with NO gaps in coverage. In the case of a Geo Hyperspectral Sounder, continuous observations of the entire 3-D structure of the atmosphere BEFORE, during and after severe weather systems form is possible. The types of observations that a hyperspectral sounder can do are unique in that the conditions that can form future severe weather are possible to observe HOURS before any other technology, including Radar.

A GEO system has the additional advantage over a hyper spectral sounder in LEO orbit, in that the coverage is continuous. For example: If we examine a Midwest region of the United States, say Missouri, a GEO System can observe a region's full 3-D atmospheric structure each hour or half hour at 4km ground resolution. If severe weather emerges, then individual regions of 1000km x 1000km can be monitored every 1-5 minutes. Rapidly evolving weather can be monitored in a 512km x 512km region every 12 seconds. In contrast, a LEO System will take a snapshot of the 3-D structure of the atmosphere each time it flies over. In the case of a JPSS-like satellite, the revisit time for a single geographic location, such as our Midwest example, is only about once every 6 hours or less. This means that reliance on a LEO only system can lead to significant gaps in coverage and ability to warn for emerging severe weather. Additionally, the current JPSS/NPP sounder only makes observations with a 10-12km ground resolution.

In the case of our Midwest example, a GEO system can make as many as 6, 12, 72, 600, 1300 observations for every single LEO system observation. This can have tremendous impact on the ability to forecast and provide warnings for severe weather.

Additionally, because of the persistent nature of the GEO system, better and enhanced observations can be made like 3-D winds and improved vertical atmosphere profiles in cloudy regions.

For aviation applications, the ability to make more observations in regions of severe weather, enable more efficient and safer routing of air traffic through these regions, result in more efficient routing, fuel savings and minimization of passenger delays. Indeed these are key aspects of the NextGen FAA's 4-D weather cube initiative. Without a GEO Hyper spectral Sounder, there will be no capability to fully populate a CONUS and GLOBAL 4-D weather cube, except to use simulated data.

**Why Commercial?**

Commercial remote sensing has been part of US Space Policy for decades. In the case of the Commercial Hyper spectral Sounder, our company explicitly applied for and received a remote sensing license from the Department of Commerce after the HES mission was canceled from GOES-R. Our system is licensed to supply global observations of GEO Hyper spectral Sounding and Imaging products. These observations (which produce gridded high horizontal and vertical resolution atmospheric profiles) remain an ongoing requirement of the National Weather Service (NWS) and are critical inputs into the NextGen FAA and Warn on Forecast programs.

There is precedent for the NWS to purchase commercial data. National Lightning Detection Network (NLDN) data is purchased now on a commercial data-buy basis and is a component of the national capability to forecast and provide warnings for severe weather. Other data types are also purchased now, such as *in situ* weather data from commercial aircraft and other sources.

Additionally, a commercial system provides a means for a significant number of high-paying technical jobs that would not otherwise exist and a global commercial system represents a significant economic export, with resulting revenue and tax returns having direct economic benefit in the United States.

**Background (NOAA Satellite Program and Geo Advanced Sounding)**

Historically, NOAA has developed, procured and operated a fleet of Geosynchronous/Geostationary (GEO) and Polar Low Earth Orbit (LEO) spacecraft for purposes of providing space-based weather observations. These observations provide essential data to the NWS and other agencies that enable severe weather forecasting, hurricane tracking, intensification and landfall prediction, short, medium and long-range numerical weather prediction (NWP), now-casting and forecasts for aviation weather. These data also contribute to global monitoring of pollution, climate change and earth science.

The requirements of these systems have historically been developed and vetted through academic and research entities both in the United States and Internationally. Coordinating bodies such as the World Meteorological Organization (WMO), GCOS, GSICS, ITOVS as well as national organizations like the National Academy of Sciences (NAS), American Meteorological Society (AMS), National Weather Association (NWA) and others attempt to coordinate the utilization of current and future systems to maximize the ability of these systems to improve global weather forecasting. All of the agencies listed above have explicitly endorsed or recommended Hyperspectral Geostationary Sounding as a technology to dramatically improve global weather forecast capability. The reason this capability is so important is that it is the only technology capable of providing high vertical resolution atmospheric profiles with both high spatial and high time resolution. A single or even several LEO weather satellites, such as NPP and JPSS, cannot meet either of these requirements.

This was the rationale for the specification of an Advanced GEO Sounder in the original authorization of the GOES-R mission. This requirement for high vertical resolution atmospheric profiles was to be provided by the Hyperspectral Environmental Suite (HES), which was demanifested from GOES-R in 2006 and from all future missions in the GOES-R series in 2011. Both NOAA and 3rd Party Cost-benefit studies indicated that half or more of the total benefit of the GOES-R mission is derived from the HES sounding mission. This has been noted several times by the GAO in official reports in 2007, 2008, 2009, 2010 and 2011.

*The cancelation of HES and the continual requirement by the NWS for high vertical resolution atmospheric profiles was the original impetus for the founding of GeoMetWatch.*

**Background (Commercial Remote Sensing)**

The US Commercial Remote Sensing Act 2003 provides for the licensing of commercial remote sensing systems. An advantage of this act is that Foreign Sales are allowed with few restrictions (there are no ITAR issues for data). This allows American companies to compete with technology that is restricted for export. Most commercial licensee's sell services using a Fee-for-Service Data model. GeoEye and DigitalGlobe currently do this for Space-Based Imagery. GeoMetWatch will do this for licensed weather data products. The act also offers some beneficial implicit and explicit protections.

It is also consistent with the US Space Policy's intent to promote commercial options which meet Operational and Observation requirements to the maximum extent. Other advantages and benefits include:

- Meets government requirements with commercial solutions
- Grows Domestic Earth Observation Capability

- Strong International Demand for Data
- ITAR Neutral Business Model
- Lower Cost and Risk
- High Value US Jobs and International Exports

**Commercialization of Weather Satellite Functions**

The 1992 Land Remote Sensing Policy Act prohibits the Department of Commerce from commercializing weather satellite systems. Section 5671 of the bill states:

> *"Neither the President nor any other official of the Government shall make any effort to lease, sell, or transfer to the private sector, or commercialize, any portion of the weather satellite systems operated by the Department of Commerce or any successor agency."*

Recently, many commercial space companies have presented different ideas and concepts for providing environmental data to meet US government requirements. Some of these concepts include hosting Government Furnished Equipment (GFE), such as environmental instruments or sensors on commercial satellites, as well as selling commercial environmental data to the US government requirements.

One of the first tasks that we performed in exploring the license requirements for our system was to seek clarification of the 1992 law. Specifically, we asked NOAA General Counsel if and under what conditions licensing of a weather system was possible. Additionally, we had many discussions with the NOAA Commercial Remote Sensing Group, the entity responsible for the issuing of commercial remote sensing licenses.

What we were told is that the intent and the wording of the law explicitly prohibit the commercialization of any portion of the existing or future government-owned or government-operated weather satellite systems.

The intent was to prohibit transfer to the private sector the infrastructure that had been paid for and operated by the US Government, via lease, sale or transfer. Furthermore, a capability which is part of an ongoing Program of Record would be prohibited from receiving a license.

Thus, any *government system* -- currently funded and/or under development for future operational use -- cannot be licensed under the Commercial Remote Sensing Act.

This would mean that most of the commercial options that could make use of GFE (Government Furnished Equipment) equipment or allow for an operational gap-filler satellite on a commercial basis and that benefit from the use of the government-funded JPSS or POES ground systems are, by definition, not subject to commercial licensing.

What CAN be licensed, however, are capabilities or functions that meet a stated government requirement AND for which NOAA has specifically and unequivocally has stated that they would not fly as a program of record. The best example of this capability is the GEO Hyperspectral Sounder, which was originally part of the HES mission on GOES-R and was canceled in 2006 and officially removed from all satellites in the GOES-R series in 2011 (see Mary Kicza testimony to the National Academy Panel Review, April 2011).

These criteria having been met; a private company (GeoMetWatch) applied for and was granted by the Department of Commerce a commercial license to fly the GEO Hyperspectral Sounder in October of 2010.

The issuance of this license by the Department of Commerce reflects the Administration's commercial space policy that encourages the development of innovative, sustainable and affordable options to meet critical mission requirements that government otherwise cannot achieve.

The protections offered in the Commercial Remote Sensing Act incentivize private industry to invest and offer these services to both government and private customers. These protections state that a licensed system, that meets government requirements, should be preferentially procured by the US Government and, further, that the US Government will not compete against this licensed capability.

There is abundant precedence for this commercialization model of the US Government contracting with the private sector to meet critical program requirements. Both GEOEYE and DigitialGlobe are excellent examples. The reason the NextView program exists is because both of these companies have demonstrated a licensed capability to meet US Government space-based imaging requirements and because of this, the US Government cannot develop systems that directly infringe on this licensed capability (i.e. NRO BASIC program, canceled in part due to this issue).

**Specific Questions from the Invitation letter:**

1. **Describe the types of data available from commercial sources.**

The licensed capability of the GeoMetWatch system will provide calibrated and geolocated (Level 1b data in NASA/NOAA nomenclature) Top of Atmosphere (TOA) radiances which are specified to exceed the original HES and NASA GIFTS sensor requirements and to meet or exceed the Eumetsat MTG Sounding requirement. By incorporating both the technology and algorithm requirements of the original mission, GMW can offer data that will meet all observational requirements for the original HES sounding mission, with the added capability of being able to serve as a backup or primary GEO imaging system. This imaging capability does not meet the full Advanced Imaging capability of the GOES-R mission, but it exceeds the imaging capability of the current GOES Imagers. For customers who desire advanced data products, such as gridded vertical profiles of atmospheric parameters, 3-D Water vapor winds, aviation products and other specified derived products, GMW will provide these additional products in near real time.

The GeoMetWatch system will be a global system of 5 or 6 sounders and all of the data will be available to GMW subscribers. The availability of data, not just over the US, but from around the world will enable improved long range weather forecasts and mitigate any future loss of data from either US Government LEO or GEO missions.

2. **How can this data supplement Government owned data?**

Since Hyperspectral Sounding Data was part of the original mission spec for GOES-R, addition of this data will help restore the full mission capability originally authorized for this program. In addition, since the GMW system is flown on separate commercial spacecraft, there is significant risk mitigation for a GOES-R launch delay or failure. The GMW Sounder also provides the ability to provide emergency Imaging capability in the case of a premature loss of the GOES-R Imager. As noted above, the global imaging and sounding data available from the GeoMetWatch system will also supplement the data coming from the existing fleet of LEO (POES, DMSP, NPP and JPSS) and provide alternative Imaging and sounding data at non-polar latitudes globally in the event of a Gap or premature failure of these missions.

In addition, because of the importance of global, gridded high vertical resolution atmosphere profiles in other US Government programs, such as in the FAA's NextGen 4-D data cube and NWS Warn on Forecast initiative, GMW is the only capability to provide directly observed data (vs. synthetic data) that meet the resolution and timing requirements. Availability of this data will dramatically improve the ability to accurately compute and provide the decision aid data products needed for these programs.

Another benefit of Geostationary Hyperspectral Sounding is to complement existing and future NASA and other agencies' Earth Observation Missions. Over half of the NASA Decadal Survey missions garner some benefit from the availability of Hyperspectral Sounding Data. Having continuous, high time, high spatial and high vertical atmospheric profiles, in addition to the other Sounder data products, provided the ability for other remote sensing missions to produce better science and extend their missions in various ways.

**3. What processes exist to evaluate and prioritize procurement of data?**

NOAA has in the past, used Cost Benefit Analysis to gauge the economic benefit of various programs. Both the original CBA for GOES-R in 2003 and a follow-on study in 2007 identified significant economic benefit from having both a Hyperspectral Sounder and Advanced Imager on the GOES-R mission. Table 60 (from page 96) from this study is shown below.

Table 60. Allocation of Benefits by Instrument

| | Benefit Portion | | Present Value of Benefits ($M) | | |
|---|---|---|---|---|---|
| **Case Study** | **HES** | **ABI** | **HES** | **ABI** | **Total** |
| Aviation | | | | | |
| Avoidable weather-related delays | 100% | | $504 | | $504 |
| Volcanic ash plumes | | 100% | | $265 | 265 |
| Energy | | | | | |
| Electricity | 50% | 50% | 1,256 | 1,256 | 2,512 |
| Natural gas transmission | 50% | 50% | 10 | 10 | 19 |
| Natural gas utilities | 50% | 50% | 16 | 16 | 32 |
| Irrigated agriculture | 50% | 50% | 545 | 545 | 1,090 |
| Recreational boating | | 100% | | 141 | 141 |
| Total | | | $2,331 | $2,232 | $4,563 |
| Portion of benefits | | | 51% | 49% | |

*from: "An Investigation of the Economic and Social Value of Selected NOAA Data and Products for Geostationary Operational Environmental Satellites (GOES), submitted by CENTREC Consulting LLC, Feb. 2007"*

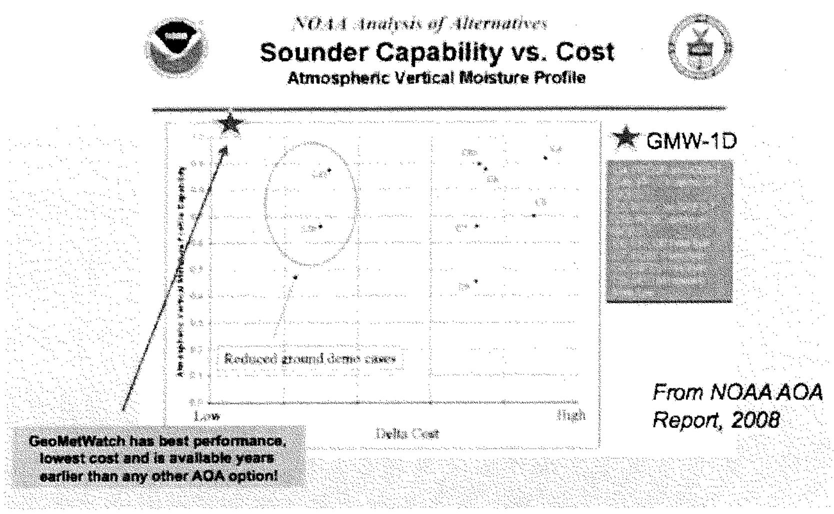
Every other Economic benefit study that I have seen has shown similar or great benefit due to Geostationary Hyperspectral Sounding. In Eumetsat's analysis of mission priorities for the MeteoSat Third Generation Mission (MTG), Hyperspectral GEO Sounding was the highest ranked requirement. There is extensive documentation of how the MTG requirements are determined on the *Eumetsat* website.

Given the clear economic benefit of these data, I cannot rationally explain why other demanifested missions have higher priority than GEO Sounding at NOAA. Another type of analysis performed by NOAA NESDIS after HES that was canceled was an Analysis of Alternatives (AOA). This study evaluated a reduced capability sounding mission as an alternative to HES. This study concluded that there was no reasonable option for adding Advanced Sounding Capability to GOES-R that would satisfy requirements given the price and risk profiles mandated by the study.

It is significant to note, that in the AOA, the most capable option identified sufficient to meet mission requirements was the NASA GIFTS mission. However, the estimated price in implement that option was estimated to be $600M-$1100M. This was the implementation cost, and the cost to fly a GIFTS mission as an operational alternative to HES.

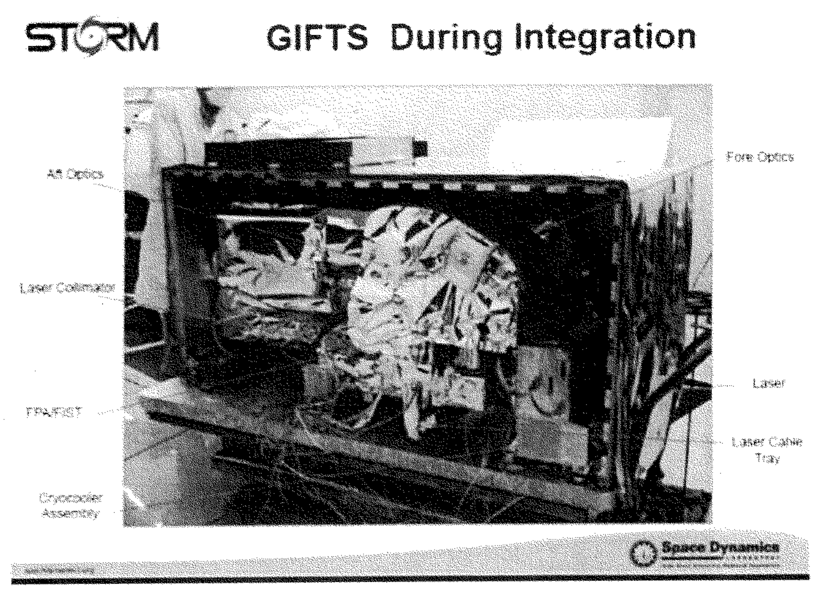
I will note that the GeoMetWatch Mission utilizes an improved GIFTS design and there is ZERO development and implementation cost, so that in the methodology of the AOA, a commercial GIFTS would appear to be a recommendable option. This is what GeoMetWatch offers.

Below is the summary figure from the AOA report, C8 represents a GIFTS sensor, the Red Star represents a commercial version. The vertical axis represents performance relative to the original HES vertical atmospheric profile requirements. The horizontal requirement represents relative cost. The GMW-1D mission is the lowest cost option and is specified to exceed the performance of all options studied.




**4. Current Status of commercial sources.**

GeoMetWatch represents a real capability. We have a functional hardware prototype and the entire ground segment architecture and data products have been developed. GeoMetWatch leverages over $300M of previous NASA and NOAA investment through our partners at Utah State University and University of Wisconsin at Madison. This technology is now available for commercial use because the predecessor programs under which they were developed have been canceled. The primary legacy program for the GMW Commercial Sounder is the NASA GIFTS mission. GeoMetWatch has funded a commercial version of the GIFTS sensor, called STORM. GeoMetWatch has Space Dynamics Laboratory of the Utah State University Research Foundation under contract as a preferred sensor provider and has exclusive agreements with SSEC of the University of Wisconsin at Madison to develop and provide the software needed to produce GeoMetWatch Weather products. GeoMetWatch is in the process of completing hosting and contractual agreements to fly our first mission over Asia-Pacific region (110E). This mission has been enabled by customer commitments to purchase the GMW data and develop data centers for utilization and dissemination of the data in the region. The total customer commitments expressed through US Export Import bank Letters of Interest and MOU agreements is in excess of $200M USD/ year for the Asia region. GMW has a small window to implement a US sounder in the 2015 to 2016 timeframe, but that option will expire by the summer of 2012. Later options to fly over the US will then be available in 2017-2020. GMW can prioritize a US mission with a customer commitment for the US longitude sector. Projected locations will be in the proximity of 130 W and 70 W longitude. GMW has provisional agreements with operators in the US Sector and we plan to use the same bus and sensor configuration for a US mission as for the 110E mission.




The above figure shows the current Hardware unit of the GIFTS sensor, which is the STORM prototype.

## STORM Top-Level GIFTS / STORM Comparison

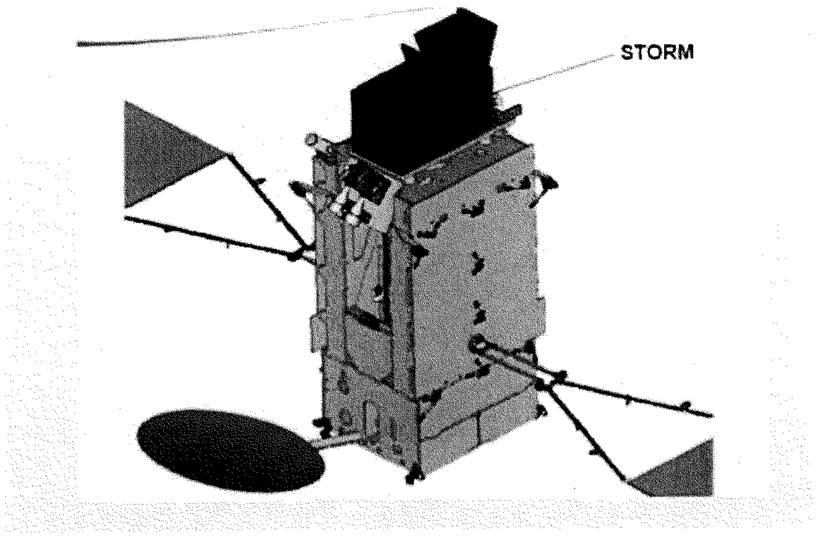
| Parameter | GIFTS | STORM |
|---|---|---|
| Spectral Bands | LW: ≤685 $cm^{-1}$ to ≥1130 $cm^{-1}$<br>SMW: ≤1650 $cm^{-1}$ to ≥2250 $cm^{-1}$<br>VIS: ≥0.725 µm to ≤0.875 µm | same |
| Spectral Resolution | 7 resolutions in range 0.6 - 36.7 $cm^{-1}$ | 0.6, 1.2, and 9.6 $cm^{-1}$ |
| FPA Field-of-view (FOV) | 14.3 mrad (0.82°) | same |
| Field-of-regard (FOR) | ≥0.306 rad (17.53°)<br>(pointing mirror design: 0.450 rad) | same |
| IR FPA format | 128 X 128 pixels, 60 µm pixel pitch | same |
| Noise equivalent spectral radiance (NESR) goal | LW: ≤0.4 mW/($m^2$-sr-$cm^{-1}$)<br>SMW: ≤0.06 mW/($m^2$-sr-$cm^{-1}$) | same |
| Calibration accuracy goal | ≤ 1K (3σ) | same |
| Data Rate | Max: 70 – 80 Mb/sec<br>Nom: 58 – 73 Mb/sec | same |
| Mass* | 200 kg | 300 kg |
| Volume | 1.8 X 1.0 X 1.4 $m^3$ | same |
| Power* | 535 W | 550 W avg, 650 W peak |
| Thermal Rejection * | Design assumed yaw-flip | ≥400 W @ 0 °C |

* Mass, power, and thermal rejection change due to expected no-yaw-flip operations

Space Dynamics

The above figure shows a comparison between the NASA GIFTS sensor and GMW STORM.

# Bus Configuration




The above figure shows the current hosting configuration of the STORM sensor on the TAS bus.

GeoMetWatch will start a full Sensor contract in 2012 and anticipates additional contracts to other US companies later this year

5. **Barriers that prevent a commercial option.**

The biggest impediment in the US region is the lack of a customer commitment. GMW is willing to enter into provisional or conditional commitments to provide data, but without an identified customer, we cannot finance a commercial option.

On a related note, commercial providers continue to lack on advocate within the US government. This role was formally held by the Director of the Office of Space Commercialization, but that position is currently unfilled. We need an advocate.

**6. How other countries evaluate mission requirements and role of new technologies.**

Eumetsat has a comprehensive process to first identify requirements and then identify the technology needed to implement these requirements. The historical role of ESA is to fund the development of these technologies to the point where they are considered mature and ready for implementation. Then Eumetsat funds this implementation. Up until the new technology is proven and ready, the previous generation technology continues in operation, even to the point of flying both new and old technology on the same mission. The advantage of this methodology is that program risk and gaps associated with the development of new technology is minimized, along with the impact of having no data at all. Eumetsat's analog in the US is NOAA and ESA's analog is NASA. The US has deviated from this path in recent decades by attempting to both develop and implement new technology as the same time. In my view this has been one of the principal causes of cost overruns and schedule delays on the NPOESS and JPSS programs and has contributed to the cancellation of HES on GOES-R.

In the area of evaluating competing observation technologies and managing various observing strategies and data gaps, Eumetsat, ESA and partner agencies have used Observational System Simulation Experiments (OSSE), and also data denial experiments from existing missions to evaluate the impact of data gaps. Both of these methods are useful for determining the relative role of different observation technologies and how they contribute to the overall weather forecast mission. Both of these techniques require computer and manpower resources to properly simulate and evaluate the technologies being considered. The benefit of both is that by evaluating these techniques and strategies early, decisions can be made before expensive development programs are started. In the long run, this saves a tremendous amount of money and lost effort.

However, even with these evaluation methodologies, funding pressures for next generation programs also exist and all members of Eumetsat and ESA with whom I have spoken are open to the capability and cost savings of commercial alternatives to complement whatever capability they implement in dedicated missions.

**7. Quality Assurance Protocols.**

Customer satisfaction will be a primary concern of GeoMetWatch and assurance that our products meet the requirements of our end users will be paramount. For these reasons, we have chosen a sensor spec and mission requirements that meet or exceed those of the most capable mission which will fly in the next decade (Eumetsat MTG IRS). In addition, we will insure our mission, both for launch failure, premature on-orbit failure and inability to meet mission requirements. GMW also plans a robust system architecture with an on-ground spare and eventual on-orbit spare capability at each orbit location. This means that all GMW customers will have uninterrupted service when the system is fully deployed. It is imperative that an observation system utilized for daily weather forecast capability is available 24/7. It is also a business imperative to keep our customers happy. GMW is willing to enter into conditional purchase agreements, where the quality of the data is verified by the end customer prior to final contract.

**8. Recommendations on how to best evaluate most cost-effective and diverse combination of weather capability.**

There are various ways to evaluate the roles of diverse capability. For similar measurements, simple inspection of observing frequency, resolution and coverage offer good first order comparison. For severe weather observation over the US, where short-term and continuous observations are the goal, this is our primary basis of comparison between an advanced commercial sounder in GEO and an advanced sounder on NPP/JPSS. An advanced GEO sounder is superior because it requires no sophisticated analysis, it simply makes 10's to 1000's of times more observations over the United States than a comparable observation on NPP/JPSS.

In the area of medium range and long- range Numerical Weather Prediction (NWP), the analysis requires more sophistication, in that the longer the forecast, the more global coverage is needed. For this reason, a system of Polar orbiting Weather satellites (not just one) is superior to a SINGLE GEO Imager/Sounder. However, the answer is not as clear cut when a global GEO hyperspectral system is compared with a Polar orbiting LEO system. This is the significant question to be addressed by new OSSE's that not only have the needed resolution to adequately compare these advanced technologies, but also the global coverage to assess the relative roles of a global Geo and Polar orbiting system. Additionally, OSSE's are desired by commercial providers to optimize the observing strategies needed to provide maximum weather observation benefit to our global customers. Finally, as Advanced GEO systems come online, true gap analysis may be used to assess the relative role of both Polar and GEO systems using real data.

GeoMetWatch
ADVANCED. AFFORDABLE WEATHER.

***Improving Weather Predictions***

***for***

# Tornadoes, Hurricanes, Floods, and Severe Storms

**March 28, 2012**

# HURRICANE AND SEVERE WEATHER PREDICTION STARTS TO DEGRADE IN 2014

- Early warning technology in the U.S. is 30 years old, dating back to the 1980s.
- Without a replacement, current hurricane and severe storm prediction capability will begin to degrade in 2014.
- In order to improve storm prediction capabilities, the National Weather Service needs better data, especially high vertical resolution profiles of temperature, water vapor and wind.
- An advanced hyper-spectral sounder is the only technology that can provide the data with the required geographic and temporal coverage.
- The advanced hyper-spectral sounder is the next generation technology chosen by NOAA for delivering this requirement .
- An advanced hyper-spectral sounder will improve NOAA/NWS severe weather warning efforts:
  - Warn on Forecast Project
  - Network of Networks
  - NEXTGEN Air Traffic Control
  - 2-D to 3-D RTMA Transition.

# CURRENT CAPABILITY VS ADVANCED HYPER-SPECTRAL SOUNDER

| | **Current Capability** | **Advanced Sounder Capability** |
|---|---|---|
| **Tornadic Storm Lead Time** (Alabama, 2011) | No current space based capability, ground based radar warnings 15 minutes or less, after development. Current capability for tornado warning is known as Warn on Detection and is limited to about 15 minutes. | Identification of atmospheric conditions for explosive convection and tornadic upper level features 30 minutes to hours prior to storm development. More accurate and smaller tornado watch and warning regions. |
| **Hurricane Landfall** (Hurricane Rita, 2005) | 300-500mile uncertainty in Landfall location | >50% improvement in track and landfall estimates |
| **Flood Predictions** (Tennessee, 2010) | Poor or sporadic knowledge of total precipitable water | Much improved knowledge of evolving total precipitable water due to more accurate and continuous water vapor profile monitoring |
| **Severe Storms** (Ongoing daily summer storms, especially: North Carolina, 2011; Washington, D.C., 2010) | Current GOES Sounder has poor Severe forecast capability because of its poor vertical resolution, slow scan rate, poor horizontal resolution. | High vertical resolution observations of temperature , water vapor and wind fields along with ability to continuous watch evolving severe weather every 15-60 seconds and high spatial resolution, enable much improved severe storm prediction and warnings. Key enable for Warn on Forecast capability. |

## STARTING IN 2020, NOAA PLANS TO OUTSOURCE SEVERE WEATHER PREDICTION TO FOREIGN GOVERNMENTS

- NOAA is currently planning to buy sounding data or the sounding instrument from Europe in the next decade or fly no sounder at all.
  - *This is the first time in U.S. history that the U.S. has relied on foreign governments for its weather data for the continental U.S.*

- Europe plans to use the advanced hyper-spectral sounder technology developed by the U.S.

- European data won't be available to the U.S. until 2024, leaving a gap in advanced hurricane and severe weather forecasts of nearly a decade!

- Gaps in hurricane and severe weather prediction are unacceptable, and relying on foreign data is risky.

- So, how do we meet the immediate need for this data?

# NOAA'S THREE OPTIONS:

**1) GOVERNMENT OPTION**

- Traditional, Cost-plus Acquisition Models are Risky and Expensive:
  - USG pays for design, development, sensor build, satellite design, development, rocket launch and operations at very high cost and risk.
  - USG shoulders all risk with no insurance.
  - NOAA has experienced repeated problems and costly overruns with this model.

**2) EUROPEAN OPTION**

- USG procures data and/or technology from Europe beginning in 2015.
- Europe delivers data to the U.S. government around 2024.
- High risk inherent in 26 member countries' collaborative decisions.
- High risk associated with European inexperience building and operating a sounder.

3) **COMMERCIAL OPTION**

- Private sector pays for design, development, launch, and operations.
- Will fly as co-hosted payload on a proven commercial communications satellite with established, fixed satellite operators.
- Private sector incurs 100% of the risk.
- US Government pays for data on a fee for service basis when sounder is operational.
- Model is proven and explicitly endorsed by the U.S. Space Policy of 2010 (e.g., GeoEye, Digital Globe).
- Commercial option will be operational by 2015 -- meaning no gap in U.S. coverage.

## WHAT HAPPENS IF WE DO NOTHING?

**LIVES WILL BE LOST.**

- Diminished forecasting capability for hurricanes and severe weather from 2014 to 2024.
- No advanced forecast and warning capability before 2024.
- Warnings for tornadoes, hurricanes, floods, and severe storms will degrade.

**AMERICAN COMPETITIVENESS WILL BE LOST.**

- NOAA will purchase data and/or instrument from Europe to meet advanced hyper-spectral sounding requirement.
- The European data will not be available until the middle of the next decade at the earliest.
- Americans will lose their science and technology leadership in the field of advanced Earth Observation.

## NOAA'S HAS ALREADY MADE INITIAL STEPS TOWARD COMMERCIAL DATA BUY OF SOUNDING DATA

- NOAA has initiated several solicitations for commercial delivery of space-based data in the last few years and has stated their intention to purchase commercially available Earth observation data to meet their operational needs. (e.g., National Lightning Detection Network )
- The US Department of Commerce granted the first license in 2010 to GeoMetWatch (through the Commercial Remote Sensing Act of 2003) to collect, process, and deliver advanced data for early warning of severe weather. Other US commercial systems are allowed and encouraged.

Chairman HALL. Thank you, sir. I now recognize our third witness, Mr. Bruce Lev, to present his testimony.

**STATEMENT OF MR. BRUCE LEV, VICE CHAIRMAN, AIRDAT LLC**

Mr. LEV. Thank you, Mr. Chairman, Ranking Member Miller and Mr. Barlett, thank you all for inviting AirDat to testify today. We are deeply grateful and honored to be part of this panel. We are going to bring the conversation from 22,000 miles up a little bit closer to the ground right now. We are pleased to have a chance to talk about the need to improve weather forecasting in this country.

As everyone knows, accurate and timely weather information can save lives, reduce injuries, save the taxpayers billions of dollars in costs that are sometimes associated with the misallocation of resources attributable to inaccurate or untimely weather forecasts.

In our view, the single most critical component of the forecasting process is the ability to collect a vast quantity of very accurate—and the phrase very accurate is significant—lower-atmospheric observations with high space-time resolution. Despite the numerous data collection systems deployed by NOAA, it may not surprise anyone in this room, that our country is still extremely under-sampled.

NOAA's forecast models are sophisticated, but the success of even the most advanced forecasting system depends entirely on the quality and quantity of the observations used as input. Without accurate data from critical regions, even the most cutting-edge computer models and the most talented forecasters can be significantly limited in their ability to provide a reliable forecast, particularly when the weather is volatile.

AirDat addresses this observational space-time deficiency by deploying an atmospheric observing system called TAMDAR. The TAMDAR system delivers unique real-time—emphasize real-time—high-resolution meteorological data for improved analysis and weather forecasting. The system is comprised of a multi-function sensor, which has been installed on several hundred currently flying commercial aircraft, real-time global satellite communications, which provides aircraft tracking, and computer processing, which rapidly extracts knowledge from extremely large data sets. Important to note, TAMDAR was developed in collaboration with NOAA, NASA and the FAA, and could today augment the National Weather Service's important balloon program.

The limited number of balloon sites in the United States—we only have 69 launch sites and they only launch twice a day—produces an average geographical data void of approximately 46,000 square miles and a temporal void of 12 hours, launching only twice a day. This space-time observational data gap can result in inaccurate and untimely forecasts.

In a four-year FAA funded NOAA data denial study, a term you have heard earlier today, TAMDAR has been fully vetted by NOAA and exceeds all of NOAA's rigorous quality assurance standards. TAMDAR data are as accurate as balloon data, and the study has demonstrated those data significantly improve weather forecasting.

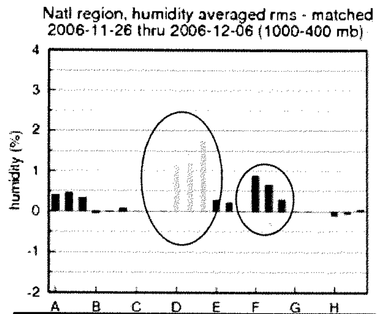
[Slide]

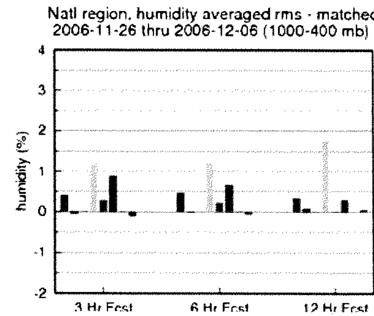
# Current Status of NCEP Conventional and Satellite Observations and the Impact of Observations on the RUC and GFS Models

Dr. DaNa L. Carlis
NOAA/NWS/NCEP/EMC

September 13, 2011

**Significant contributions from Brad Ballish (NCO), Ron Gelaro (GMAO), Stan Benjamin (ESRL), Jim Jung (JCSDA), Dennis Keyser (EMC), John Derber (EMC), and Geoff DiMego (EMC)**




WINTER

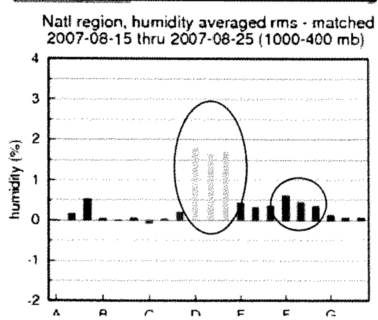
A - No-aircraft - control
B - No-profiler - control
C - No-VAD - control
D - No-RAOB - control
E - No-surface - control
F - No-GPS-PW – control
G - No-mesonet – control
H - No-AMV - control

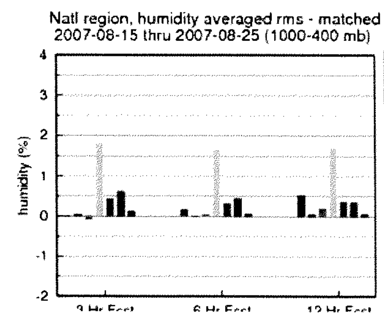
RH - national – 1000-400 hPa

#1 obs type = Raobs

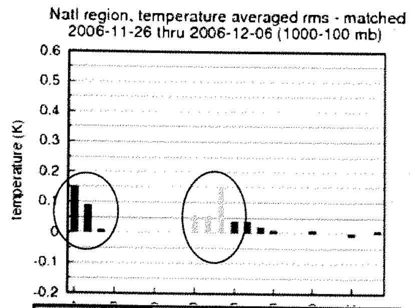
#2 = GPS-PW

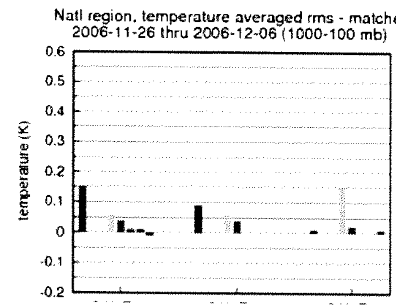





SUMMER



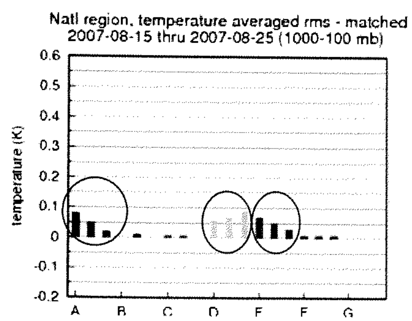



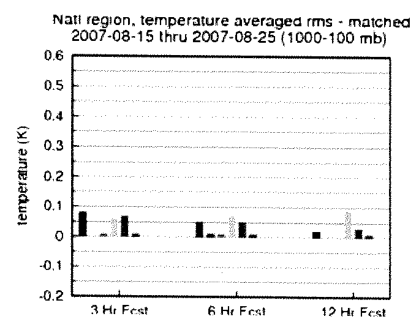

WINTER

A - No-aircraft - control
B - No-profiler - control
C - No-VAD - control
D - No-RAOB - control
E - No-surface - control
F - No-GPS-PW – control
G - No-mesonet – control
H - No-AMV - control

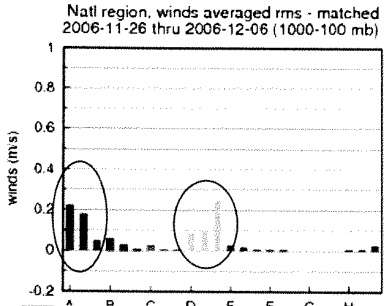
## Temp - national - 1000-100 hPa

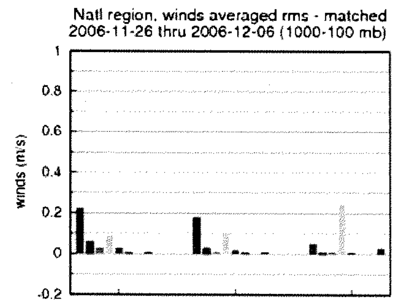
Tie for #1 = Aircraft, RAOBs
Aircraft more at 3h, RAOB-12h
Sfc ~ aircraft, RAOB in summer(!)




SUMMER



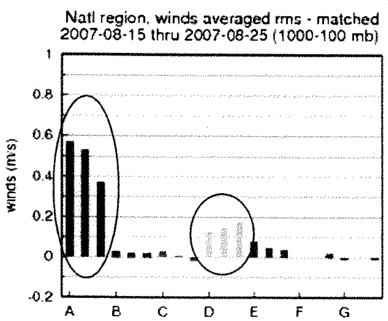



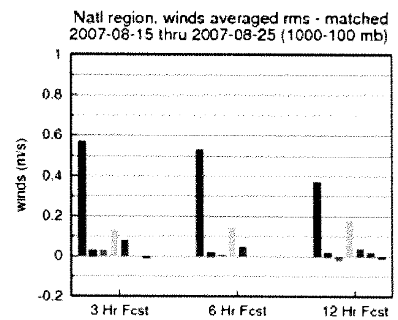

WINTER

A - No-aircraft - control
B - No-profiler - control
C - No-VAD - control
D - No-RAOB - control
E - No-surface - control
F - No-GPS-PW – control
G - No-mesonet – control
H - No-AMV - control

## Wind - national - 1000-100 hPa

#1 = Aircraft
#2 = RAOBs



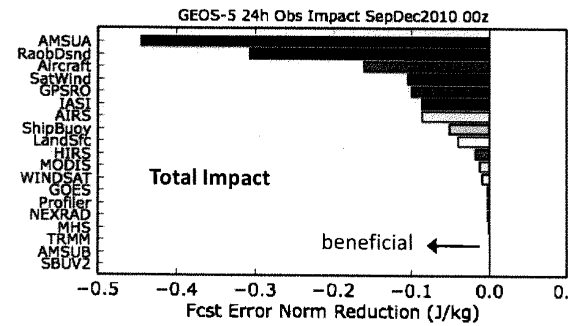

SUMMER

# Impact of Various Observing Systems in GEOS-5

01 Sep – 31 Dec 2010 00z

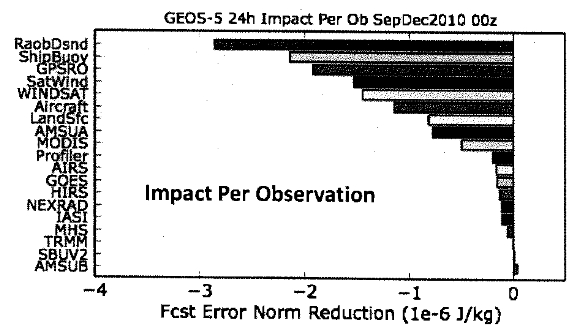
Total Impact

- AMSU-A radiances have the largest impact globally, but conventional data (raob, aircraft) still very important. GPSRO now a significant contributor.



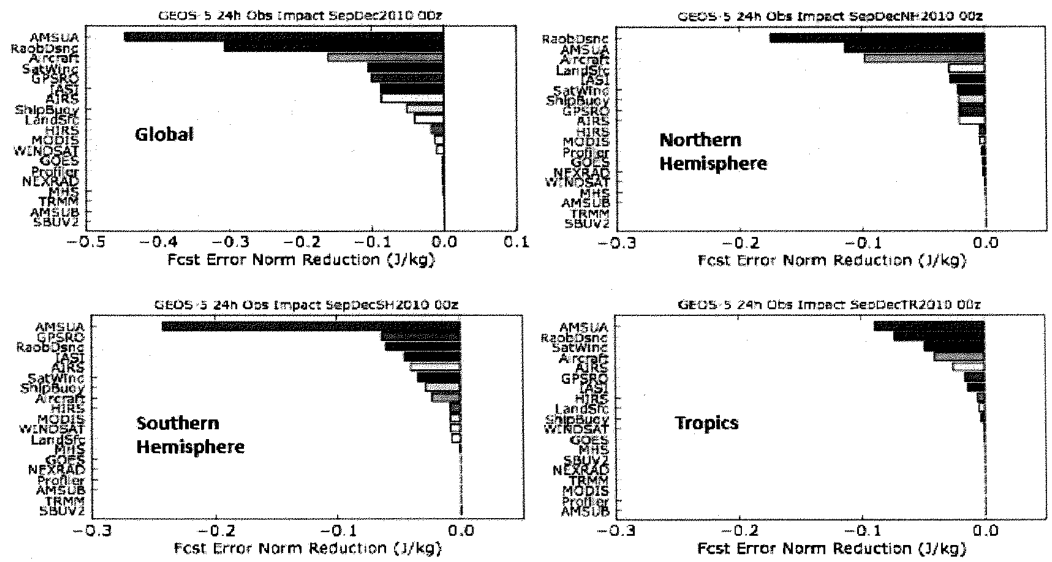

Impact Per Observation

- Raobs get large weight in the analysis and have large IPO. Ship obs are few, but are located where there are few other in-situ data.



## 24h Observation Impacts in GEOS-5

Average values at 00z for the period 01 Sep – 31 Dec 2010




Impact is measured in terms of the reduction of a global error metric (J/kg) that combines winds, temperature and surface pressure from sfc-150 hPa

Observation impact differs by region with the NH forecast error reduction being largest for RAOBs whereas the SH error reduction is largest for AMSUA.

# Mesoscale Modeling Branch: Where We Are and Where We' re Going

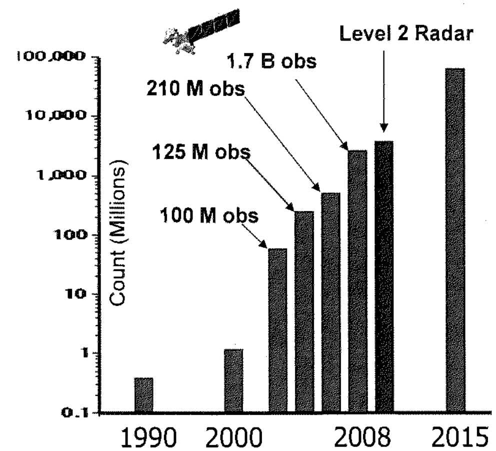
Geoff DiMego
geoff.dimego@noaa.gov
301-763-8000 ext7221
9 December 2008

Where the Nation' s climate and weather services begin

# Observational Data Ingest

## Mostly Satellite & Radar

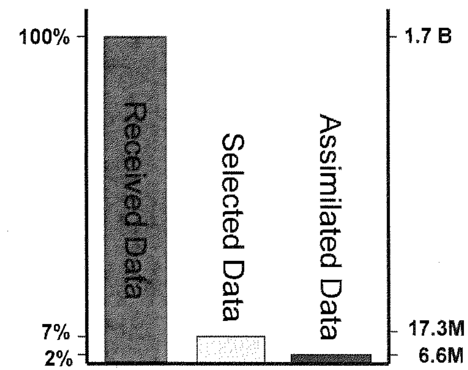
### Daily Satellite & Radar Observation Receipt Counts




**Five Order of Magnitude Increase in Satellite Data Over Fifteen Years (2000-2015)**

### Daily Percentage of Data Ingested into Models (Not Counting Radar)

2008 Data




Received = All observations received operationally from providers
Selected = Observations selected as suitable for use
Assimilated = Observations actually used by models

The displayed slide, which is before you and before the audience, indicates the significant improvements concluded in the four-year NOAA-conducted data denial study. Additionally, the volume of TAMDAR data is approximately 40 times greater than the balloon data at less than 1/10th of the cost per sounding.

Mr. Chairman, our TAMDAR system has been fully operational since 2005 and stands immediately ready to assist NOAA in improving its weather forecasting. Thank you very much for giving us an opportunity to chat with you today, and obviously we would be delighted to answer any questions.

[Statement of Mr. Lev follows:]

Testimony of Bruce Lev, Vice Chairman, AirDat, LLC
March 28, 2012

Chairman Harris, Ranking Member, Mr. Miller and distinguished members of the Subcommittee on Energy and Environment of the House Committee on Science, Space and Technology. My name is Bruce Lev and I am Vice-Chairman of AirDat. I am deeply honored and grateful for the opportunity to appear before this Subcommittee to discuss the need to improve our country's weather forecasting capability.

Accurate and timely weather information can save lives, reduce injuries, and save the federal, state and local governments billions of dollars in costs associated with the misallocation of resources resulting from inaccurate or untimely weather forecasts.

The single most critical component of the forecasting process is the ability to collect a vast quantity of very accurate lower-atmospheric observations with high space-time resolution. Despite the numerous data collection systems deployed by NOAA, our country is still extremely under-sampled.

NOAA's forecast models are very sophisticated, but the success of even the most advanced forecasting system depends entirely on the quality and quantity of the observations used as input. Without accurate data from critical regions, even the most cutting-edge computer models and the most talented forecasters can be significantly limited in their ability to provide a reliable forecast.

AirDat addresses this observational space-time deficiency by deploying an atmospheric observing system called TAMDAR (Tropospheric Airborne Meteorological Data Reporting).

The TAMDAR system delivers unique real-time high-resolution meteorological data for improved analysis and weather forecasting. The TAMDAR system is comprised of a multi-function sensor, which has been installed on several hundred commercial aircraft, real-time global SATCOM, which provides aircraft tracking, and computer processing, which rapidly extracts knowledge from extremely large data sets. TAMDAR was developed in collaboration with NOAA, NASA and the FAA, and augments the National Weather Service's balloon program.

The limited number of balloon sites in the US (69), which only launch twice daily, produces an average geographical data void of approximately 46,000 square miles, and a temporal void of 12 hours. This space-time observational data gap can result in inaccurate and untimely forecasts.

Despite advancements in satellite technology, remotely sensed satellite profiles have limited value in high-resolution numerical weather prediction compared to aircraft or balloon data.

In a four-year FAA funded study, TAMDAR has been fully vetted by NOAA, and exceeds all of NOAA's rigorous quality assurance standards. TAMDAR data are as accurate as balloon data, and the study has demonstrated those data significantly improve weather forecasting. The volume of TAMDAR data is 40 times greater than the weather balloons at less than 1/10th of the cost per sounding.

Mr. Chairman, Our TAMDAR system has been fully operational since 2005, and stands immediately ready to help NOAA improve its weather forecasting.

Respectfully, I would request the right to submit a more detailed statement for the record. Thank you.

Chairman HARRIS. [Presiding] Thank you very much. I now recognize our final witness, Dr. Moore, for five minutes to present your testimony.

**STATEMENT OF DR. BERRIEN MOORE, DEAN, UNIVERSITY OF OKLAHOMA COLLEGE OF ATMOSPHERIC AND GEOGRAPHIC SCIENCES, AND DIRECTOR, NATIONAL WEATHER CENTER**

Dr. MOORE. Thank you, Mr. Chairman, and Members of the Subcommittee for this opportunity to testify on the importance of continuing innovation to improve weather forecasting and warning.

I am Dr. Berrien Moore, Vice President of Weather and Climate Programs at the University of Oklahoma, as well as the Director of the National Weather Center and Dean of the University's College of Atmospheric and Geographic Sciences. These positions are new for me. I have been at Oklahoma only since June of 2010, and therefore, I am a later rather than a Sooner.

I appear, today, largely because of my responsibilities as the Director of the National Weather Center. However, this said, the views expressed in today's testimony are my own.

I am very appreciative of this opportunity to discuss the continuing need to use more sophisticated observational systems to help improve weather forecasting by integrating state and local surface data, known as mesoscale observations, or Mesonets, to help protect life and property before severe weather events, providing precious additional warning time that can often mean the difference between life and death.

Weather is something that Oklahoma knows well. As a consequence, it is not surprising that in 1990, the University of Oklahoma and Oklahoma State University joined forces with the governor of the State of Oklahoma, with an investment of approximately $3 million and deployed what today is a 120-station statewide network, which includes detailed weather observations in every one of Oklahoma's 77 counties. At each site, the environment is measured by a set of instruments located on a 10-meter tower, delivering observations every five minutes, 24 hours a day yearround. We provide a state-of-the-art observational weather system paid for and largely maintained with non-federal funds, with a surface weather observations that are reported more frequently and with more localized predictive value than those provided by the National Weather Service. Taken together, the data from the National Weather Service and the Oklahoma Mesonet complement and strengthen the predictive value of each network's information, making for a powerful partnership. It is an ideal model in these fiscally constrained times on how best to leverage investment from multiple entities to maximize the delivery of high quality information at a reasonable cost benefiting taxpayers and communities that depend upon more accurate weather forecasts.

But does this mean that we do not need weather satellites? Certainly not. As important as the Oklahoma Mesonet is, it tells us little about the Pacific Ocean. It tells us little about the weather over Europe. Weather is global. The interests of the United States, including its businesses and its citizens are global, and hence the U.S. weather observing system must be global. The weather observing system must be a network of networks—satellites, aircraft, balloons, and ground-based Mesonets.

The concept of a national Mesonet has been validated scientifically on a number of occasions, most notably in the path finding report issued in 2009 by the National Academy of Sciences, From the Ground Up: A Nationwide Network of Networks. I want to just single out two quotes. One, the report found, "An overarching national strategy is needed to integrate disparate systems from which far greater benefit could be derived and to define the additional observations required to achieve a true multi-purpose network at the national scope." And second, which is particularly relevant today, "Several steps are required to evolve from the current circumstance of disparate networks to an integrated, coordinated network of networks. First, it is necessary to firmly establish a consensus among providers and users that a network of networks will yield benefits in proportion to or greater than the effort required to establish it. This consensus-building step is essentially political."

Last fall, NOAA launched a campaign called a Weather-Ready Nation. Let me state clearly and for the record, America will only become a weather-ready Nation if we increase the number of observations used to make meteorological forecasting more accurate and more precise and then work with the public and local decision-makers to act upon those improved forecasts.

Thank you very much.

[The prepared statement of Dr. Moore follows:]

*To Observe and Protect: How NOAA Procures Data for Weather Forecasting*

STATEMENT OF

Dr. Berrien Moore III
Vice President, Weather and Climate Programs
Dean, College of Atmospheric and Geographical Sciences
Director, National Weather Center
University of Oklahoma

SUBCOMMITTEE ON ENERGY AND THE ENVIRONMENT
COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY
UNITED STATES HOUSE OF REPRESENTATIVES
MARCH 28, 2012

**Introduction**

Thank you, Mr. Chairman and Members of the Subcommittee for this opportunity to testify on the importance of continuing innovation to improve weather forecasting and warnings.

I am Dr. Berrien Moore, Vice President of Weather and Climate Programs at the University of Oklahoma, as well as Director of the National Weather Center and Dean of the University's College of Atmospheric and Geographical Sciences. These positions are a new role for me; I have been at Oklahoma only since June 2010; therefore, I am a "later" rather than a "sooner". I appear, today, largely because of my responsibilities as the Director of the National Weather Center; however, this said, the views expressed in today's testimony are my own

I am very appreciative of this opportunity to discuss the continuing need to use more sophisticated observation systems to help improve weather forecasting by integrating state and local surface data – known as mesoscale observations – or "Mesonets" – to help improve the reliability, accuracy and speed of local near-term weather forecasting. Mesonets are critical in helping to protect life and property before severe weather events, providing precious additional warning time that can often mean the difference between life and death. In addition, mesonet observations are increasingly important for the critical functioning of key parts of our national economy – including agriculture, commercial aviation, renewable energy generation and the management of the electric grid. Mesonets are also well suited for use by fire fighters, first responders, and emergency managers before, during, and after weather disasters.

**History and Evolution of the Mesonet Concept**

Weather has a greater impact on our society than ever before. This includes impacts to the lives and property of our citizens and to our economy. 2011 had the highest number of storms with damage in excess of a billion dollars in the history of recorded weather data. To provide the most accurate forecasts and warnings for weather, dense high quality observations are required. Without observations of the atmosphere, quality forecasts and warnings are not possible. Meteorological observations on the mesoscale (i.e., local/county scale) are of particular importance as evidenced by the fact that the vast majority of severe weather life and property losses are associated with mesoscale events such as tornados, thunderstorms, hurricanes, fronts and squall lines.

The mesonet concept was founded on the Southern Great Plains where severe weather, which can materialize with little warning and often times overwhelming intensity, is very common. Tornado Alley, which is loosely defined as the Plains states between the Rocky and Appalachian Mountain ranges, encounters more of these storms than anywhere else in the nation. In 1990, University of Oklahoma and Oklahoma State University joined forces with the Governor of the State of Oklahoma, with an investment of approximately $3 million, and deployed what today is a 120-station statewide network, which includes detailed weather observations in every one of Oklahoma's 77 counties. At each site, the environment is measured by a set of instruments located on or near a 10-meter-tall tower. The measurements are packaged into "observations" every 5 minutes, and then transmitted to a central facility every 5 minutes, 24 hours per day year-round. The Oklahoma Climatological Survey (OCS) at OU receives the observations, verifies the quality of the data and provides the data to Mesonet customers. It only takes 5 minutes from the time the measurements are acquired until they become available to the public.

The data quality and the assurance procedures exceed National Weather Service standards.

As a member of the National Mesonet Program Alliance, OU and the Oklahoma Mesonet demonstrate the strength of the National Mesonet Program. We provide a state of the art observational weather network, paid for and largely maintained with non-federal funds,[1] with surface (in situ) weather observations that are reported more frequently and with more localized predictive value than those provided by the National Weather Service due to the location and density of the network sensors. Taken together, the data from the National Weather Service and the Oklahoma Mesonet compliment and strengthen the predictive value of each network's information, making for a powerful partnership. It is an ideal model in these fiscally constrained times on how best to leverage investment from multiple entities to maximize the delivery of high quality information at a reasonable cost benefiting taxpayers and communities that depend upon more accurate weather forecasts.

Use of Mesonet data, including applications on virtually all smart phones embraced by millions of consumers, reflects recent advances in electronics technology. These advancements have also enabled the weather sensors to become smaller, faster, more accurate, more reliable and less expensive. Networking of the sensors via the Internet and wireless networks has enabled dense surface based observation networks to proliferate rapidly, building upon the original concept developed in Oklahoma. Environmental parameters, which were once not practical to observe at the surface, are now measured routinely. As a result, they are now used in critical decision making. In some cases, these breakthroughs

[1] For instance, in FY 2011 the state provided slightly more than $1,897,000; USDA, Army Corps of Engineers, and DoE provided $210,000; the Government of Quebec $44,900; the Noble Foundation of Oklahoma $5,000; media and other users $40,000, and NOAA provided via Earth Networks, $189,294—not quite 8% of the budget.

in surface based network technology potentially obviate the need to observe these parameters from space, where the costs and risks to do so are far higher. Generally, anything that can be observed from the surface should be observed at the surface due to the extremely high costs and risk factors inherent in any satellite based system.

But does this mean that we do not need our weather satellite system? Certainly not--as important as the Oklahoma Mesonet is, it tells us little about the oceans; about other parts of the planet, or for that matter, the upper part of the Oklahoma atmosphere. Weather is global; the interests of the United States—including its businesses and its citizens are global, and hence the US weather observing system must be global. The weather observing system must be a network of networks—satellites, aircraft, balloons, and ground-based mesonets.

Today, there are literally dozens of mesonet networks that range in size from a few dozen locations in a particular state or region to those in the commercial realm that can range from hundreds in number to more than 8,000 stations for the top commercial weather network. Most of these stations meet World Meteorological Organization (WMO) standards and are integrated with weather data from global sources, to deliver precise, accurate weather information directly to users around the world.

The concept of a national mesonet has been validated scientifically on a number of occasions, most notably in the path finding report issued in 2009 by the National Academy of Sciences, *From the Ground Up: A Nationwide Network of Networks*.[2] The report's key finding is very powerful—it also shows that proactive work needs to be done:

> "....the status of U.S. surface meteorological observation capabilities is energetic and chaotic, driven mainly by local needs without adequate coordination. While other providers act locally to satisfy particular regional monitoring needs, the federal government is unique in its capacity to act strategically and globally in the national interest. An overarching national strategy is needed to integrate disparate systems from which far greater benefit could be derived and to define the additional observations required to achieve a true multi-purpose network that is national in scope, thereby fully enabling mesoscale numerical weather prediction and other applications."

I would like to note one other conclusion in the Report that is directly relevant to today's hearing (emphasis added):

> Several steps are required to evolve from the current circumstance of disparate networks to an integrated, coordinated NoN [Network of Networks]. First, it is necessary to firmly establish a consensus among providers and users that a NoN will yield benefits in proportion to or greater than the effort required to establish it. *This consensus-building step is essentially political*, requiring agreement in principle at various levels of

[2] *Observing Weather and Climate from the Ground Up: A National Network of Networks* National Research Council, 2009; http://www.nap.edu/openbook.php?record_id=12540

public and private participation, which leads to the collaborative development of an implementation plan. The key elements of a NoN are twofold: (1) the provision of services and facilities that enable individually owned and operated networks to function, more or less, as one cohesive network, and (2) the provision of new observing systems or facilities to enable national objectives. The first is largely separable from the second, since considerable benefit may be achieved from improved functionality with existing observational assets.

**The National Mesonet and A Weather-Ready Nation**

Last fall, NOAA launched a new campaign to engage communities, scientists and emergency response leaders to embrace a new vision for weather forecasting and response known as the Weather-Ready Nation. OU and the National Weather Center hosted the first NOAA workshop on the topic last December.

NOAA's Weather-Ready Nation is about building community resilience in the face of increasing vulnerability to extreme weather and water events. Record-breaking snowfall, cold temperatures, extended drought, high heat, severe flooding, violent tornadoes, and massive hurricanes have all combined to reach, as mentioned earlier, the greatest number of multi-billion dollar weather disasters in the nation's history.

The devastating impacts of extreme events can be reduced through improved readiness, which is why the Weather-Ready Nation initiative is so important. Through operational initiatives, NOAA's National Weather Service is proposing to transform its operations to help America respond. In the end, emergency managers, first responders, government officials, businesses and the public will be empowered to make fast, smart decisions to save lives and livelihoods.

America will only become a "Weather-Ready Nation" if we increase the number of observations used to make meteorological forecasting more accurate and precise, and then work with the public and local decision makers to act on those improved forecasts.

The objective of weather and climate observing systems is to provide critical information on the current state of the atmosphere, oceans, and the terrestrial systems in a timely manner such that informed decisions can be made. This information will result in a better understanding of global weather patterns, which will lead to better decisions in hazardous weather such as floods, drought and winter weather or tropical storms. Each of these can affect large areas and many sectors of the economy over prolonged periods of time. Observing systems are also essential for short-fuse decisions (i.e., thunderstorms) for weather events that occur quickly and dramatically impact people, property and critical assets on the timescale of minutes.

Supporting these varying decisions and timescales requires various types of observation platforms, including mesonets as well as space based satellite systems. When seamlessly integrated, these complementary resources provide the foundation upon which an entire nationwide decision support system is built. These data are critical inputs to and required for the establishment of situational awareness, the generation of forecasts, as well as the subsequent dissemination of warnings and alerts for the protection of life, infrastructure and optimization of weather sensitive market sectors.

Because surface measurement technologies have only matured over the last decade, NOAA has built its observational forecasting largely on the basis of information from satellites and radar. As the Administrator recently testified, NOAA gets more than 90 percent of its weather data from satellites. The $5 billion investment to upgrade NOAA's own automated surface observing system (ASOS) over the last two decades, when combined with radar and satellite information, has significantly improved weather accuracy. But even the 1,200 stations that make up the NWS/FAA ASOS network, situated largely at commercial airports, are often times not enough. As we saw with the 2004 Baltimore Water Taxi incident or with the more recent severe weather events in Joplin, Tuscaloosa and the Indiana State Fair, there are gaps in the system because of the location and frequency of the NWS' own observational sensors that prevent even the most dedicated forecaster from detecting a storm's intensity or direction soon enough to give the public sufficient warning to avoid the loss of life.

Rather than have the Federal Government embark upon an expensive effort to upgrade its own ASOS network, mesonets have evolved as a means to dramatically improve the scale of observations at a fraction of the price of further federal efforts. In Oklahoma, our current federal support from the National Weather Service as part of the National Mesonet program represents less than 8% percent of the financial support necessary to maintain our network. The State of Oklahoma provides almost 80% of the budget. The total investment from state, federal, private sector and other sources enable us to make sure that our weather and climate stations have state of the art measurement sensors and are serviced continuously by technicians that make sure stations are working and in good order, and who conduct comprehensive calibration and preventive and reactive maintenance. This same approach is used currently by the other members of the National Mesonet Program Alliance, which includes private sector partners, universities and state governments, each of which maintain their own proprietary network.

While NOAA receives observations from thousands of non-federal weather stations today, the mesonet stations stand out because they generally provide data whose quality and precision exceeds that of observations provided by the NWS/FAA ASOS sensors. Prior to transmitting their data to customers, mesonet partners put the observations through quality assurance steps, including comparative analysis and range checks, to guarantee that the measurements reported by these networks are accurate. The mesonet partners' other lines of business enable them to support maintenance of their networks so that the effective cost to the Federal Government for access to these observations is pennies on the dollar, with no capital outlay by NOAA.

The current National Mesonet Program Alliance provides billions of observations annually to the National Weather Service from approximately 8,000 stations located in 26 states. I have included a map that outlines the number and configuration of stations by state.

New emerging sensor technology that measures total lightning and the boundary layer of the atmosphere are representative examples of what can and should be added to the current network, as well as more in situ surface, coastal and mobile stations. Total lightning – which measures important cloud-to-cloud lightning rather than just cloud to ground lightning, has proven effective in increasing warning lead times for thunderstorms by as much as 100 percent over existing technology. Likewise, emerging profiler technology, which measures conditions in the surface boundary layer, must also be an important part of any emerging mesonet strategy. The boundary layer is that part of the atmosphere that directly feels the effect of the earth's surface. Its' depth can range from just a few meters to several kilometers depending on the local meteorology. Turbulence is generated in the boundary layer as the wind blows over the earth's surface and by thermals, such as those rising from land as it is heated by the sun. Turbulence redistributes heat, moisture, pollutants and other constituents of the atmosphere. As such, turbulence plays a crucial role in modulating the weather (temperature, humidity, wind strength, air quality, etc) as we experience it, living on the surface. Expanding the profiler coverage with increased federal support would be especially valuable—this is a win-win decision.

**Current and Potential Users of the Mesonet**

While predicting severe weather is the most frequent use of mesonet data, there are a number of other critical applications that were noted by the National Academy in *From the Ground Up:* energy security, transportation, water resources, and food production. The report's authors concluded that the development of a surface based National Mesonet, with comprehensive data collection, quality control and dissemination capabilities, will provide the critical information needed to improve short and medium term weather forecasting (down to local scales), plume dispersion modeling, and air quality analyses. It increases the capabilities of the atmospheric community, but substantially improves the decision making for many key sectors of the economy and end user constituencies including energy, agriculture, homeland security, disaster management and emergency response (including wildfire management), insurance and economic forecasting, transportation, education, recreation and scientific research.

*Energy Benefits*

NOAA has stated that weather & climate data creates value for energy companies, as they make decisions to generate, buy or sell energy across regional power grids. A study by (Centrec, 2003) found that for every $1 that energy companies spend in acquiring NOAA climate station data they receive a potential benefit savings of $495 in related costs (i.e. not having to implement their own observing system to collect the data).[3] This yields a $65 million benefit when extrapolated across the entire US energy market, and the cost-benefit (value) ratio is likely to increase in time, as a national mesonet is implemented. This is particularly true for portions of the renewable energy sector like wind generation.

[3] Centrec Consulting Group, LLC, 2003: *Investigating the Economic Value of Selected NESDIS Products, 2003: Benefits of meteorological services. A report to National Environmental Satellite, Data, and Information Service (NESDIS). Centrec* Consulting Group, Savoy, IL, page 2.

*Transportation Benefits*

The transportation industry is very sensitive to changes in weather and climate conditions. The impacts of adverse weather, annually, on the Nation's highway system and roads are significant: 7,400 weather-related deaths; 1.5 million weather-related crashes; more than 700,000 weather-related injuries; and $42 billion in economic losses.[4] Delays caused by adverse roadway weather conditions have reached nearly 1 billion hours per year. Department of Transportation statistics also show that adverse weather was a factor in nearly 25% of total highway crashes. A national mesonet can help address the lack of roadway weather data and analysis by integrating weather observations nationally, and into multi-use formats that do not presently exist. The result being near-real time data sets that can be used for numerous surface transportation and environmental applications (e.g. input to weather and climate models; data for improved traffic management and road maintenance decisions; traveler information services; and data to improve weather and hydrologic warnings and forecasts). This greater capacity to understand weather and climate data near major U.S. roadways will result in saved lives and more efficient commerce. Commercial aviation is particularly weather dependent and the estimated benefits in routing efficiency, lower fuel costs, on-time performance and passenger safety and convenience envisioned by the FAA's proposed NexGen system will be dramatically enhanced by the availability of mesonet data integrated into the forecasting and predictive systems used by the aviation industry.

*Water Resources Benefits*

Water resource management is concerned with controlling river and lake water levels as contained in reservoirs often as part of a network of dams. This was one of the central reasons why the Oklahoma Mesonet was created. Water managers monitor how seasonal or annual changes in climate (e.g. drought, El Niño-Southern Oscillation) may affect the water levels to conserve for domestic, hydroelectric, industrial, and agricultural use throughout the year. Flooding and drought add to the challenges that water managers, city officials and emergency managers must take into consideration when making decisions. The National Hydrologic Warning Council projects that NOAA information and data provide for economic benefits of $240 million/year in mitigating flood losses, and an additional $520 million/year in benefits for water resource users including: hydropower, irrigation, navigation, and water supply.[5] A robust mesonet would increase these benefits for water resource users.

*Food Production Benefits*

The agriculture industry has long relied on NOAA weather and climate information to improve planning and decision-making in yielding crops. Environmental factors such as seasonal precipitation, drought vulnerability, mean & extreme temperatures, and the length of the growing season (i.e. the last spring and first fall freezes) - help to determine which type of crop will be most profitable in a specific region.

[4] Department of Transportation, Bureau of Transportation Statistics, *2007: National Transportation Statistics*, Washington, DC, [502 pp.]

[5] National Hydrologic Warning Council, *2002: Use and Benefits of the National Weather Service River and Flood Forecasts*. NOAA NWS National Hydrologic Warning Council, Silver Spring, MD, page 4.

However, over the course of a season, a farmer must make crop planning and management decisions at different time scales. For example, a widespread agricultural freeze for nearly two weeks in a previous January, in which overnight temperatures over a good portion of California dipped into the 20's, destroyed numerous agricultural crops and caused $1.4 billion in estimated damage/costs.[6] A national mesonet can assist a particular region by providing information, which may aid in operational decisions such as irrigation, the optimal time to apply pesticides, when to plant and harvest crops, etc. From what I have seen, there is not a farmer in Oklahoma that does not use the Oklahoma Mesonet—I have noticed that Congressman Frank Lucas has the Oklahoma Mesonet on his computer and looks at it many times a day—and he is also a farmer.

Another important climate information resource is the U.S. Drought Watch, which provides updated information on the presence and severity of U.S. drought. Information from the Drought Watch assists the agricultural community in adapting to drought conditions, which may result in improved planning and substantial economic, environmental, and social benefits. Drought conditions cost an estimated $6-8 billion annually across all sectors of the economy, making it, on average, one of the most costly of all natural disasters affecting our Nation.[7] To mitigate the impacts of drought, a national mesonet can provide an integrated, interagency drought monitoring and forecasting system for the Nation.

**Major Benefits For Severe Weather Prediction**

With the more intensive patterns of severe weather which Americans have faced in recent years, there are three primary reasons why a national mesonet is essential for the nation's weather enterprise moving forward.

First, use of mesonet data will substantially increase warning times. Data captured using total lightning and other mesonet data during last April's Super Outbreak of storms showed that these observations increased warning times on average by 13 minutes, nearly double the current National Weather Service standard. This leap in advance warning is potentially transformational in how weather observations are reported and can be acquired for modest sums in contrast to the upgrading of the ASOS network to achieve the same objective which would cost billions. Expanded warning times are a matter of life and death.

Second, mesonet data will enable forecasting and warnings to be far more targeted than the warnings of today. Mesonets provide far more detail of local weather patterns. As such, mesonet data enables forecasters and their computer models to evaluate a storm's surrounding environment with far greater certainty over far smaller tracts. This "micro-targeting" of storms means that communities can have a much more precise idea of a storm's longevity and severity. This means alerts can likely go to a smaller

[6] Lott, N., Ross, T., Houston, T., and A. Smith, *2008: Billion dollar U.S. weather disasters, 1980-2008.* Factsheet. [NOAA National Climatic Data Center, Asheville, NC, 2 pp.]

[7] Federal Emergency Management Agency (FEMA), *1995: National Mitigation Strategy: Partnerships for Building Safer Communities*, Federal Emergency Management Agency, Washington, D.C., 40 pp.

subset of a region or community so that they can better internalize the imminence of the threat that faces them.

Third, a national mesonet will lead to a significant reduction in the vexing problem of false alarms where today a large area is notified of a potential severe weather event, but because the weather pattern only touches a small portion of the region, the alert is ignored, giving a false sense of security to those in the destructive path of a storm. This "social behavior" challenge is one of the most difficult challenges identified by NOAA in its effort to achieve a Weather-Ready Nation. Some of the most recent tragedies we have witnessed from severe weather were in part caused because portions of the affected population ignored the warnings provided.

To achieve these benefits, however, we must have leaders with vision, and the desire to work for coordinated and continued investment. The National Mesonet Program was begun by Congress – in the wake of the Baltimore Water Taxi incident – because it saw the need for a public private partnership where NOAA could acquire the additional data and services it needs at a fraction of the cost of owning the network assets. The return required for the network deployment costs are amortized over a variety of market segments; the costs and risks are shared.

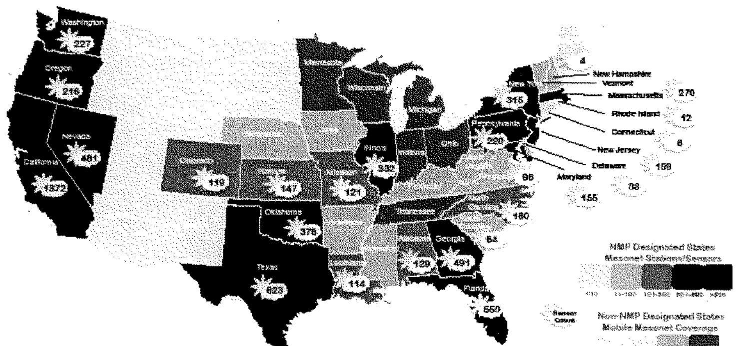
The National Mesonet Program has suffered from inconsistent investment patterns. The fiscal year 2012 NOAA appropriation for the national mesonet was just $12 million, a 40 percent reduction from the enacted appropriation for the program in fiscal year 2010. At a minimum, Congress should return to the fiscal year 2010 level of $20 million, but should respectfully consider continued expansion of the program so our nation can have truly have comprehensive coverage. A comprehensive national mesonet allows for the introduction of the new technologies that are essential for a Weather-Ready Nation.

This Committee, working with your colleagues on the Appropriations Committee, can sustain this public-private partnership. I strongly recommend that you take the steps necessary to make sure that the National Mesonet Program is restored to its 2010 levels in this year's budget, and that NOAA and the Administration be strongly encouraged to include it in future budgets so we can save more lives and more communities and become the Weather Ready Nation to which our country aspires.

In the National Weather Center in Norman, Oklahoma, the University of Oklahoma and the Oklahoma Mesonet are particularly close partners with our colleagues and neighbors at NOAA's Storm Prediction Center, the NOAA Norman National Weather Service Forecast Office, the NOAA National Severe Storms Laboratory, and the NOAA Warning Decision Training Branch. Our collective efforts – requiring a daily, joint commitment of time, people and funding – help save lives and improve the quality of those lives. The pioneering efforts on the Oklahoma Mesonet have set the gold standard for how mesonets can lead to great decisions saving lives, property, and money. By investing in the National Mesonet Program we can significantly improve our understanding of the world around us, allowing for more accurate and specific weather forecasts and warnings, and can truly reach our goal of being a Ready-Weather Nation.

**Appendix A**

## National Mesonet Program Alliance Non-Federal Stations & Sensors




| NMPA STATION/SENSOR COUNT | |
|---|---|
| In-situ 10m & below | 2,941 |
| Soil temp & moisture | 706 |
| Solar radiation | 2,304 |
| Winds above 10m | 1,132 |
| Road surface temp | 1,530 |
| **Total Assets** | **8,013** |

*Note:*
*Observations acquired in states shaded blue are required as part of the National Mesonet Program.*
*Observations acquired in states shaded green are not required, but provided as additional observations via mobile mesonet*

Chairman HARRIS. Thank you very much. Thank you all for your testimony, reminding Members that committee rules limit questioning to five minutes. The Chair will at this point open the round of questions. I recognize myself for the first five minutes.

Mr. Webster, your testimony stated that NOAA should consider fixed price procurements for satellite instruments. Why would fixed price be better than the current systems and would ITT be willing to bid for fixed price instrument contracts?

Mr. WEBSTER. Thank you, Mr. Chairman. Fixed price contracts allow the contractors to set the requirements so we can build an instrument in the most cost-effective way. It is usually actually cheaper for the government because the risk and the cost is borne by the company, not by the government. So you don't have the dramatic increases in costs, or if you do, it is the company's standpoint, not from the government's standpoint.

These are most effective when you have actually built, developed an instrument already. Most companies wouldn't want to do a development contract necessarily on a fixed price. But once you have built one of an instrument, you should be more able to reproduce them and manufacture them.

So from ITT's perspective, we have bid several contracts for fixed price. We are taking copies of the U.S. instruments and then making them for the international community. For Japan, we are under contract currently right now with Japan. That was a fixed price job. Hopefully Korea, potentially Canada. So yes, we would certainly bid fixed price contracts.

Chairman HARRIS. Thank you. Dr. Moore, in your written testimony, you state that, "Because surface measurement technologies have only matured over the last decade, NOAA has built its observational forecasting largely on the basis of information from satellites and radars, and I think you summarized some of the most significant maturations and improvements in surface measurement technologies. But what findings might be uncovered with regard to the relative value of those recently improved technologies if NOAA were to increase its number of what are called the Observing Systems Simulation Experiments, or OSSEs? I mean, do you think that we would uncover the true relative value of those techniques?

Dr. MOORE. Yes, I think we would, and as I pointed out in my testimony, NOAA saw the wisdom of establishing ground base. That is why there are 1,200 ground-based stations through a program that cost about $5 billion. From the private sector, you could increase that coverage to 8,000 stations at a fraction of the cost.

Chairman HARRIS. So you believe that they should do more of these simulation experiments——

Dr. MOORE. Yes. Excuse me. I think they should, and they should directly take into consideration what could be obtained from this very dense network in 26 states with 8,000 locations. Most of the ground-based systems that NOAA established were at commercial airports because of the joint program with the FAA. That doesn't necessarily get you the kind of coverage in the State of Oklahoma that you need.

Chairman HARRIS. Sure. Thank you. Mr. Webster, again, you mentioned NOAA should increase the use of simulation tools such as OSSEs and the requirements for polar imagers should be a candidate for reevaluation. Why do you think, if you do, that NOAA should reexamine polar imagers when the VIIRS is now flying and working on the NPP satellite?

Mr. WEBSTER. Thank you, Mr. Chairman. I think in terms of the costs and the continued technical risk of the instrument that is flying today called VIIRS, unofficial estimates are that it costs upwards of $1 billion to build the first one, and estimates of the second one are several hundred million dollars.

As I mentioned, ITT has built the legacy imager called AVHRR which is about the size of a roll-on suitcase. We have offered to modify the instrument to make it more capable, probably for costs under $50 million.

So I think a study of what an enhanced AVHRR would provide versus what the VIIRS provides for weather forecasting. There are some capabilities on a climate perspective that VIIRS does that we know our instrument probably couldn't do. But from a weather forecasting mission, if we could do 85 or 90 percent of that capability for less than 1/10 of the cost, I believe it is at least worth a study.

Chairman HARRIS. A study. Okay. Thank you. Dr. Crain, could you describe the potential of hyperspectral sounders to improve our ability to protect against severe weather outbreaks such as tornados and how does that potential compare to the severe weather forecasting contributions of the polar orbiting satellites?

Dr. CRAIN. Thank you, Mr. Chairman. The key advantage of the geosystem is that it is stationary over the United States. So a geostationary hyperspectral system over the United States can continually monitor evolving severe weather, where a polar orbiting will get a snapshot, six hours, 12 hours later we get another snapshot, with no knowledge of the intervening time period.

So in the case of advanced sounding, the JPSS has an advanced sounder. It has a hyperspectral sounder. But it makes one sample every 6 hours. In that same time period, a geostationary hyperspectral could take tens to thousands of soundings in the same region. So if we have emerging severe weather, we can see its evolution with much more finer resolution than we would see from the single or even multiple polar satellites.

Chairman HARRIS. Well, thank you very much. I recognize the Ranking Member, Mr. Miller.

Mr. MILLER. Mr. Crain, your testimony is that GeoMetWatch, your company, is confident that you can avoid the problem of a possible weather data gap and that you can launch late 2015 or early 2016, which seems to be just in time to avoid the gap. Given the problems that we have had, why is it that you feel sure that your company can do so much better, launch earlier, and what assurance do we have that you will be able to meet a timeframe when other contractors have slipped their schedule?

Dr. CRAIN. Thanks for the question.

Mr. MILLER. You have a launch vehicle line?

Dr. CRAIN. The situation that we are in right now, we actually have a contractual agreement or an agreement to launch our first satellite over Asia at 110 East which is approximately over Japan in the 2015, 2016 time period. We potentially have some slack in the schedule that we could also accommodate a U.S. mission in roughly that same time period.

The reason we feel we can do this at a low cost and risk is we are leveraging about $300 million of previous NASA and NOAA investment in a hyperspectral sounder for GEO that was developed through Langley and was built at Utah State University. That instrument is the basis of our commercial sounder, and we will be procuring that sounder under a fixed price contract as described by Eric. So that is why we have confidence that we can deliver it on time at a cost that is known to us.

The other advantage of this approach is we are really only responsible for building that sensor. We are teaming with a large, commercial communications satellite provider and operator in Asia. We are teaming with one of the largest satellite bus manufacturers in the world, Tosolini North America.

So we have a really good team that is going to bring their best commercial practices to fore to help us do this on a commercial basis.

Mr. MILLER. Mr. Webster, ITT is obviously the prime contractor for the satellite programs. Do you agree that a stationary orbit satellite can provide the data that we are looking for from the—orbiting satellites?

Mr. WEBSTER. Thank you, Mr. Miller. I think to clarify, the gap that you talk about is in the polar orbiting.

Mr. MILLER. Right.

Mr. WEBSTER. So I think what Dr. Crain has been talking about in terms of a geosounder would not get you that global coverage that the polar sounder would give, but the increase in capability would be most useful for U.S. severe storm forecasting on a nowcasting basis, as Dr. Crain said.

So I think the need of the potential gap in the polar orbit is still going to be there.

Mr. MILLER. It is undiminished. And have we had the same problems with the stationary orbiting satellites that we have had with the polar?

Mr. WEBSTER. Historically, yes, if you go back 15 or 20 years. There was a huge shift in technology from an actually spinning satellite to one that was three-axis stabilized so it could actually stare at the United States. That was in the late '80s when ITT actually first started building the instruments.

So we haven't been the prime contractor, we have been the prime instrument provider for the companies. The current GOES program is up and working well, and we are working on the next generation of instruments right now. And so far, we are still on schedule.

Costs have been growing in the program, but it is also because of technical changes that the government has wanted along with some issues we have had on our end. But we are still within the overall scope that NOAA has budgeted for the program.

Mr. MILLER. Okay. And I am sure the testimony of the first panel about the way in which the data from various sources complements each other. Do you believe that the polar orbiting satellite's data can be replaced, can be done without, with additional stationary orbit satellites or further ground sensors?

Mr. WEBSTER. I think, you know, in terms of what Dr. Crain has been trying to propose with GeoMetWatch, if they had six geostationary sounders that circled the globe, you could get that type of coverage. One or two would not get you the global data that is critical to the global forecast models, and as Mary Kicza had mentioned, 90 percent of the data in the forecast models is satellite-based data, and most of that comes from polar sounders because it actually gets the global coverage.

In terms of Mesonets or in-situ measurements, they are very critical for the finer resolution models and near-term forecasting. So again, the polar sounders, important for two to five day forecasts to tell you where severe weather might be in the southeast or in North Carolina, you might get a tornado in a couple of days. But as you get closer to that actual warning and forecast, that is when your radars and your Mesonets and your in-situ measurements come into a much higher fidelity.

As Mr. Murphy mentioned, from the National Weather Service, the forecaster uses the model to set the parameters and then as he is forecasting uses all the in-situ data to actually provide the warnings. So the difference is between the general forecast versus the actual warning.

Mr. MILLER. My time is expired.

Chairman HARRIS. Thank you very much. I now recognize the other gentleman from Maryland, Dr. Bartlett.

Mr. BARTLETT. Thank you, sir. Could we not place geospatial satellites in orbit such that they could stare at all the earth? We, I gather, have the orbiting satellites because they provide a more detailed look at weather, and so it provides us data in more detail. I gather we are looking at things from four different perspectives, one from way out there, 22,000 miles, and from 500 miles, and then we have a lot of ground-based stations. I remember several years ago I was working with our schools, many of which have weather stations, many of them collecting data as good as the weather collected at the airport. And since, as you mentioned, in Oklahoma you don't have airports in enough places to really provide wide coverage. I don't know, can't remember now, how we failed to get NOAA to look at these schools because there are many thousands of these across the country, and with a little coaching they could provide I would think much more detailed and broadly disbursed data input from the ground.

But then we have that mid-level that Mr. Lev talked about in his testimony, and that is between the ground and those 500-mile satellites, and we collect a little bit of data there with a few balloons that we send up from what, only 63 places and then only twice a day? So there are huge gaps in coverage, both in time and spatial coverage with that.

Mr. Lev, I understand the use of your technology, TAMDAR, does not just produce relatively better weather forecasting but dramatically better weather forecasting. Is that correct?

Mr. LEV. The slide we had up when I was giving my formal testimony, Mr. Bartlett, and thank you for the question, reflects the conclusions that NOAA itself derived from its own data denial study conducted over four years which was actually funded by the FAA, having considerable interest in high-resolution, highly accurate weather forecasts. Those results from a classic data denial study, when we had many fewer aircraft flying than we have today, indicated that in the significant meteorological parameters, particularly moisture which is a key driver of short-term weather forecasts, that we improve the reliability and accuracy of forecasts by up to 50 percent, 5–0 percent. Those are certainly, from our perspective and I think at the time NOAA's GSD division, considerably surprising and much greater than anyone thought might be the case. It turns out that as we add more aircraft and improve the type of modeling we are doing in terms of ingesting data, the reliability and accuracy has actually improved beyond 50 percent in many respects.

Mr. BARTLETT. I gather that your technology simply hitchhikes on the planes that are there anyhow for other purposes?

Mr. LEV. That is correct. One of the key issues in getting more data in the lower atmosphere if you will is you can't fly more balloons. They do get in the way of airplanes, and we have a lot more airplanes today than we had when the balloon program started almost 75 years ago. The only way to get good data, and that is what is critical is good, accurate data, is to hitchhike on aircraft, and that is what we do. We are in fact flying balloons, but we don't get in the way of anyone else, and we send that data in real time. It doesn't take 90 minutes to collect the data that is collected by the balloons, the radio sounds, as they rise into the atmosphere.

Mr. BARTLETT. How big are these devices and how much do they compromise the vehicle in which they are attached?

Mr. LEV. In the commercial configuration, the entire system weighs well under 10 pounds, thus it doesn't compromise the aircraft in any shape, form or manner, which is why 10 or more airlines have been delighted to have us install on their commercial aircraft. In an unmanned aerial vehicle configuration, and we have been flying on drones to comment on something that was offered up earlier in other testimony, we are down to I think about a pound or less with special materials, carbon fiber and the like. It is actually nominal, a non-event with respect to size, shape or weight.

Mr. BARTLETT. What vehicle do you use for transmitting this data to where it is processed?

Mr. LEV. The data comes off the sensor installed on the aircraft and is immediately sent in real time to the Iridium Satellite Network, a relatively well-known satellite network used both commercially and by the Department of Defense, by the way, sent in real time to our processing center, but could be sent anywhere on the planet, including to NOAA's processing centers if they so choose.

Mr. BARTLETT. Thank you, and I yield back, Mr. Chairman.

Chairman HARRIS. Thank you very much, and I want to thank the witnesses for your valuable testimony and again for your patience as we started late, and the Members for their questions. The Members of the Committee may have additional questions for you, and we will ask you to respond to those in writing. The record will remain open for two weeks for additional comments from Members. The witnesses are excused. Thank you all for being here today. The hearing is now adjourned.

[Whereupon, at 4:30 p.m., the Subcommittee was adjourned.]

# Appendix I

## ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

*Responses by Ms. Mary Kicza, Assistant Administrator, National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration (NOAA)*

**U.S. HOUSE OF REPRESENTATIVES**
**COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY**
**Subcommittee on Energy and Environment**

**Hearing Questions for the Record**
**The Honorable Andy Harris**

***To Observe and Protect: How NOAA Procures Data for Weather Forecasting***

**Ms. Mary Kicza**
**National Environmental Satellite, Data, and Information Service**

**Question 1: Was the decision to remove the Hyperspectral Environmental Suite or HES from the GOES-R manifest based on an objective, quantitative analysis that compared the benefits of these sounders against the benefits of other instruments or capabilities? If so, please provide the documentation supporting this analysis.**

**Response:**
In 2006, the decision to remove the Hyperspectral Environmental Suite (HES) was based on a review by the National Oceanic and Atmospheric Administration (NOAA) satellite acquisition professionals who analyzed several vendor design studies for developing the HES. These professionals determined that while development of the advanced sounder capability of HES was technically feasible, there were significant risks with developing both the hyperspectral sounding and ocean color imaging capabilities on the same instrument. These risks (i.e. technology readiness, instrument accommodation, and cost uncertainty) had to be reduced before NOAA could acquire the instrument for use in an operational environment. Opportunities for risk reduction using the NASA Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) did not materialize once NASA cancelled the project. The documents used to make that decision contain procurement sensitive information from various vendors. NOAA is happy to brief the Committee on the process used to make that decision.

The following factors influenced NOAA's decision not to pursue HES in the 2006 timeframe:

- The technological challenges that faced HES had not been resolved and, given the fiscal environment, it was not cost effective for NOAA, to pursue solutions.
- There was no on-going research within the United States to address the technological impediments we encountered on HES that would provide the needed foundation to allow NOAA to build and deploy the sensor on an operational GOES platform.
- Conducting research to address the technological impediments of HES was outside the scope of NOAA's operational mission.
- The continuity of data for National Weather Service operations was more important than pursuing technological solutions to the HES.

- With algorithm development, the National Weather Service would be able to use data from the Advanced Baseline Imager to develop sounding data products similar to legacy sounders on the GOES N-Series.
- The GOES-R series spacecraft bus did not have sufficient space or power on the spacecraft to accommodate a hyperspectral sounder.

**a. With the removal of HES, does NESDIS have plans to incorporate other instruments that would make up for the loss of this data stream?**

**Response:**
NOAA does not have plans to fly a hyperspectral sounder in the geostationary orbit. NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) plans to create GOES-legacy quality sounder products from a combination of the Advanced Baseline Imager (ABI) on GOES-R and weather model output in order to provide sounder products in the geostationary orbit. NOAA has determined that polar-orbiting hyperspectral sounding data are a higher priority than geostationary sounder data as input to numerical weather prediction (NWP) models, run by the National Weather Service (NWS) and other agencies across the world. NOAA currently uses hyperspectral sounder data from NASA's polar-orbiting Advanced Infrared Sounder (AIRS) and Metop's Infrared Atmospheric Sounding Interferometer (IASI). NOAA will use hyperspectral sounding data from Suomi National Polar-orbiting Partnership Program's (NPP) Cross-track Infrared Sounder (CrIS) combined with the Advanced Technology Microwave Sounder (ATMS) to measure global atmospheric temperature, moisture, and pressure profiles from space to continue and improve its weather forecasting capabilities.

**Question 2: Why did NOAA decide not to move forward with an advanced sounder on GOES-R? Have conditions and circumstances changed? Dr. Crain testified to the ability of his company to provide NOAA and others data from a commercially available geostationary satellite. It seems easier and cheaper for NOAA to just buy the data than build another satellite system.**

**Response:**
NOAA decided not to move forward with an advanced sounder on GOES-R because it required additional research and development beyond NOAA's mission and the funding required to overcome the technical challenges could not be accommodated within NOAA's GOES-R budget.

The cost of geostationary sounder data from a commercial source is unknown. No commercial entity has yet demonstrated that it is capable of building, launching, and operating a satellite that would provide hyperspectral data from geosynchronous (GEO) orbit. As such, there are no commercially available data for NOAA to use to make a comparison of whether it would be easier or cheaper to buy these data.

In 2011, the issue of whether to consider re-manifesting a hyperspectral sounder on the GOES-T or –U satellites was revisited and the conditions, circumstances, and challenges had not changed. Also, the NWS indicated that while it still has an interest in hyperspectral sounding in the geostationary orbit, it had placed a higher priority on other requirements, such as the continuity of geostationary meteorological weather and space weather data.

**a. Has NOAA evaluated this option in any detail? If not, why not? If so, please provide a summary and results analysis.**

**Response:**
On June 8, 2009, NOAA awarded two $25,000 contracts each to ITT (now known as Exelis) to provide NOAA with information on the technical feasibility and validated pricing for commercially available advanced sounding and ocean color data. ITT's studies confirmed NOAA's earlier analysis concluding that a geostationary sounder was technically feasible, but the study did not provide enough information for NOAA to determine whether a commercial solution was affordable. The details of ITT's study are marked company proprietary.

NOAA concluded in its analysis of the studies that vendors required a government up-front commitment to the commercial venture, including advance funding and assistance with technology risk reduction. Although potential vendors have proposed that NOAA can use its statutory authority to enter into a joint anchor-tenant agreement (51 U.S.C. § 50503), no proposal has demonstrated that all the key points of the statute could be met. For example, industry has not demonstrated it can provide data continuity without long-term reliance on the government as the primary purchaser of the commercial data.

NOAA has assessed the witness' mission concept of a geostationary hyperspectral sounder. In the 2010 timeframe, the witness met with NOAA officials to describe his proposal. In addition, the witness was an invited speaker at the 2011 NOAA / NASA / EUMETSAT Satellite Hyperspectral Sensor Workshop. His presentation[1] was similar to the one he gave during his March 28, 2012 Congressional testimony before the House Committee on Science, Space, and Technology, both of which do not provide sufficient technical information for NOAA to evaluate the feasibility of GeoMetWatch's proposed instrument development.

NOAA is not aware of any ongoing commercial development of an advanced geostationary sounder. The only advanced geostationary sounder development of which NOAA is aware is being conducted by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) for its next generation series of geostationary satellites, which is scheduled for launch in 2018.

**b. Please also detail instances in which NOAA has purchased information obtained from commercial satellites in the past.**

**Response:**
NOAA currently purchases synthetic aperture radar data from foreign providers to fulfill its sea ice monitoring needs for National Ice Center operations[2] and NWS operations in high

[1] http://www.star.nesdis.noaa.gov/star/meeting_Hyper2011Agenda.php
[2] http://www.natice.noaa.gov/mission.html?bandwidth=high

latitudes, such as Alaska, Great Lakes and the Northeast seaboard. NOAA also purchases high resolution imagery to support its data needs for the coral reef mapping program, and its Coastal Change Analysis Program. NOAA has purchased ocean color commercially in the past, before the Sea-viewing Wide Field-of-view Sensor on the Orbview-2 satellite failed. NOAA continues to pursue potential agreements with the commercial sector when it can provide data that addresses NOAA's requirements at a reasonable cost to the taxpayer.

**Question 3: The Committee has seen a study of the impact of observation systems on global forecast models. The MODIS instrument – the precursor to VIIRS – ranked 20 out of 25 for its value and importance.**

**Response:**
NOAA is not familiar with this study and cannot comment on the report or its results, but would be happy to comment on the study if it is made available.

It is important to understand that VIIRS serves other users beyond providing input into NOAA's forecast models. VIIRS, like MODIS, is used to observe fires, land surface temperatures, sea ice characterization, snow cover/depth, vegetation index, sea surface temperature, and aerosols, among other environmental parameters.

**a. Please provide the total cost of the first VIIRS instrument on board the NPP satellite. What is the total projected cost for the VIIRS instrument scheduled to fly on JPSS-1 and JPSS-2?**

**Response:**
The VIIRS Flight Model-1 (FM-1) on the Suomi NPP satellite cost $391 million to develop (excluding reserves and NASA and NOAA overhead expenses). This includes both NOAA and Department of Defense (DoD) funds. This cost was determined by tallying the contractor reported costs from FY 2003-FY 2010 of $382 million, and estimated costs from FY 2011-FY 2016 of $9 million (includes support for on-orbit anomaly work). Non-recurring expenses for the design of the original VIIRS instrument ($213 million) and pre-NPOESS prime contract studies ($74 million) conducted between FY 2000 to FY 2002 are not contained in these costs. The above costs exclude payload engineering and management, systems engineering and management, integration and test onto the spacecraft, and Northrop Grumman's award fee. Development of the Suomi NPP VIIRS sensor was managed by the now-closed NPOESS Integrated Program Office (IPO).

The VIIRS FM-2 which will fly on JPSS-1 is estimated to cost $337 million (excludes reserves and NASA and NOAA overhead expenses). This cost was determined by tallying the contractor reported costs from FY 2003-FY 2010 of $144 million, and estimated costs from FY 2011-FY 2023 of $193 million (includes support for on-orbit anomaly work). Non-recurring expenses of $213 million for costs associated with the design effort of the original VIIRS instrument are not included in this estimate of total costs for VIIRS on JPSS-1. The above costs exclude payload engineering and management, systems engineering and management, integration and test onto the spacecraft, and Northrop Grumman's award fee.

The cost of VIIRS FM-3 which will fly on JPSS-2 will be finalized when the instrument is placed under contract.

**b. Please list the criteria used to rank instruments as well as a comprehensive list of instruments (including free flyers) used onboard the GOES Satellite and the JPSS Satellite systems.**

**Response:**
For the Joint Polar Satellite System (JPSS), the Suomi NPP, JPSS satellites, and the Free Flyers will provide continuity of data and services from NOAA POES while providing technological infusion from NASA EOS. The primary criteria used to select, manifest, and fly these instruments is based on those instruments' contribution to providing continued and enhanced weather data and continuation of long term records of key climate measurements.

Using these criteria, three instruments provide critical weather data, and two instruments provide data communications support. The Advanced Technology Microwave Sounder (ATMS) and CrIS instruments provide high resolution global data needed for NWP models that support the 3 to 7 day long range weather forecast. The Visible/Infrared Imager/Radiometer Suite (VIIRS) instrument provides measurements (such as sea surface temperature for monitoring hurricane intensification) and imagery for detecting and tracking hurricanes and severe weather. The Advanced Data Collection System (A-DCS) provides relay of weather and oceanographic data from remote weather stations and open ocean buoys to NWP computing centers. The SARSAT systems are an important safety-net for mariners and aviators that may be stranded or in distress due to equipment failure or foul weather.

While the instruments above will provide climate-quality data, there are three instruments that provide measurements that will continue long time series of data collected by heritage instruments that currently fly on NOAA and NASA satellites. They are the Cloud and Earth Radiant Energy System (CERES), Total Solar and Spectral Irradiance Sensor (TSIS), and the Ozone Mapping and Profiler (OMPS). There are many uses and users of these data and services, and each of these instruments has been chosen for flight through a rigorous process.

| Instruments in JPSS Program |
|---|
| Cross-track Infrared Sounder (CrIS) |
| Advanced Technology Microwave Sounder (ATMS) |
| Visible/Infrared Imager/Radiometer Suite (VIIRS) |
| Advanced Data Collection System (A-DCS) |
| Total Solar and Spectral Irradiance Sensor (TSIS) |
| Cloud and Earth Radiant Energy System (CERES) |
| Ozone Mapping and Profiler (OMPS)-Nadir |
| OMPS-Limb |
| Satellite-assisted Search and Rescue (SARSAT) |

For the GOES-R Program, the instruments are improvements over those currently flying on the GOES N-Series and support NOAA's meteorological weather and space weather programs. All four satellites in the GOES-R Series will carry the instruments detailed below.

The GOES-R Advanced Baseline Imager (ABI) is the main imager for detecting and monitoring severe weather and hurricanes. ABI will provide higher resolution images to track the development of storms in their early stages. Additionally, ABI provides high spatial, temporal images; including cloud cover, vegetation health, fire detection, and sea surface temperature. NOAA plans to develop algorithms that will use the temperature and pressure data from ABI to develop sounding products analogous to legacy sounding on the current GOES-N Series.

The Geostationary Lightning Mapper (GLM) is a new instrument which will detect and map destructive thunderstorms continuously day and night over land as well as ocean areas. Along with the ABI enhancements, the GLM instrument will provide significant contributions to NWS forecasts and warnings.

The Data Collection System (DCS) will provide relay of weather and oceanographic data from remote weather stations, river and coastal gages to a central computing station.

The SARSAT systems are an important safety-net for mariners and aviators that may be stranded or in distress due to equipment failure of foul weather. SARSAT on GOES satellites are complementary to polar-orbiting satellites, in that GOES satellites will pick up a signal, while the polar-orbiting satellites will give a precise location.

There are a series of space weather instruments that will provide data in support of NOAA's Space Weather Prediction Center and will be used by the Air Force Weather Agency to support its operational missions. These instruments are: Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS), Space Environment In-Situ Suite (SEISS), Magnetometer (MAG), and Solar Ultraviolet Imager (SUVI).

| **Instruments in the GOES-R Program** |
|---|
| Advanced Baseline Imager (ABI) |
| Geostationary Lightning Mapper (GLM) |
| Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS) |
| Space Environment In-Situ Suite (SEISS) |
| Magnetometer (MAG) |
| Solar Ultraviolet Imager (SUVI) |
| Data Collection System (DCS) |
| Satellite-assisted Search and Rescue (SARSAT) |

**Question 4: The VIIRS instrument on the NPP satellite has turned itself off a number of times. Please detail all the problems VIIRS has experienced since launch in October 2011 and a description of the causes of these problems. Given that the contract for the next VIIRS instrument is already in place, please describe what is being done to ensure the same problems are not repeated on the next instrument. What process exists to ensure that lessons learned are incorporated in subsequent satellites?**

**Response:**

The Suomi NPP satellite was launched on October 28, 2011. It is currently undergoing calibration and validation. The satellite and instruments are performing well, especially given the fact that these are new instruments that are being flown in space for the first time. VIIRS experienced anomalies on November 25, 2011; February 18, 2012; March 10, 2012; and March 28, 2012. On these four separate occasions, VIIRS stopped communicating with the spacecraft. Recovery from this anomaly has been developed, requiring a command from the Ground Operations to recycle power to the VIIRS instrument.

The issue has been traced to the Single Board Computer (SBC) on VIIRS; however, the root cause has not been determined. The investigation continues into the root cause and corrective action. The VIIRS contractor, Raytheon, has established an Anomaly Investigation Team, which is also being supported by the JPSS Program. Raytheon has also established a contract with Honeywell (manufacturer of the Single Board Computer) to help work on the issue. The SBC parts lists are being re-reviewed by Raytheon and NASA radiation experts. The VIIRS Flight Software has been delivered and is also being reviewed by NASA for potential issues. Once the root cause is found, changes or modifications will be made to the VIIRS sensor for JPSS-1 and JPSS-2.

A separate but unrelated event on VIIRS was detected on December 5, 2011. In analyzing the solar diffuser calibration, the VIIRS team members found a larger than expected and persistent drop in instrument responsiveness in the near-infrared bands. Four channels were directly affected by this degradation. The team subsequently determined that the degradation was caused by tungsten contamination introduced during a non-standard (off-nominal) process step during silver coating of telescope mirrors at a subcontractor's facility. This was determined as the root cause and was confirmed by review of the subcontractor's coating records, and by test of telescope witness mirrors which showed tungsten contamination and which mimicked on-orbit degradation in UV exposure test. JPSS-1 witness mirrors, or spare mirrors used for testing, have been UV tested to confirm no tungsten exists. As of May 2012, the VIIRS instrument degradation has slowed. NASA and VIIRS contractors are monitoring the situation closely.

**a. Please explain the current functionality of all the instruments on NPP and the status of the satellite check-out. Are there mechanisms in place to override a system failure such as this?**

**Response:**
There have been no system failures during the Suomi NPP check out. All of the sensors are operating as expected, with science data production underway, which includes calibration and validation work, and initial data products used to integrate algorithms for Numerical Weather Prediction. Satellite check out was completed on March 7, 2012. In order to develop usable products, the program must now calibrate sensors data, which is the main focus of the program at this time. No other sensors have experienced the same communication issue as VIIRS. Recovery procedures are in place to address potential anomalies on the other sensors and the spacecraft.

**Question 5: Given the significant costs of NOAA's satellite program, difficult decisions are required regarding current and future capabilities. Please provide an example of a previous such satellite procurement decision, and what process was used to evaluate the information to make the right choice. Please describe the role of all offices in contributing to such decisions.**

**Response:**
Below are two examples when difficult decisions have been made regarding satellite procurements:

**First Study: GOES-R Hyperspectral Environmental Suite**

NOAA's environmental observation requirements required to address its full range of missions are documented in NOAA's Consolidated Observational Requirements List (CORL). The CORL contains the platform-independent environmental parameters (i.e., temperature, wind, precipitation) and their associated attributes of geographic coverage, spatial and temporal resolutions, and measurement accuracy, specified by NOAA Programs. The Hyperspectral Environmental Suite (HES) was an instrument concept designed to address CORL requirements for measurements of both the vertical profiles of the Atmospheric Temperature and Moisture parameters needed to aid in forecasting severe weather outbreaks throughout the conterminous U.S. and the Ocean Color parameters needed to detect harmful algal blooms and manage coastal ecosystems in U.S. coastal waters. In the fall of 2006, a review by the GOES-R Program indicated that the HES concept was too technically challenging for implementation in an operational satellite program. An Analysis of Alternatives (AoA) was commissioned to explore alternatives for advanced hyperspectral sounding and coastal waters imaging in the absence of HES[3].

To initiate the AoA, matrices of 32 alternatives were produced for advanced sounding and coastal waters imaging options. Trade space included satellite and non-satellite alternatives. Each alternative was rated on a scale of 1 to 9 against its ability to meet requirements (i.e., coverage, revisit, resolution), then weighted, summed, and normalized to produce a measure of value. Of the original 32 sensor/platform configurations identified by the AoA Study Team, 13 different satellite concepts were studied in detail by the Aerospace Corporation's Concept Design Center (CDC). For those concepts not meeting the one-to-one comparison criteria, a narrative (i.e., non-CDC analysis) was provided. For CDC alternatives, rough cost estimates were developed. The capability measure of value was used along with cost to create rating that could be used to compare similar alternatives (e.g., demonstration with demonstration or operational with operational). A schedule was then developed to lay out the timing for the most reasonable architecture path forward.

**Second Study: Scatterometer Instrument Accommodation on Foreign Partner Satellite Mission**

---

[3] As briefed to the National Academy of Sciences Space Studies Board on April 23, 2007

NOAA faced a difficult decision to forgo funding a scatterometer to provide ocean surface vector wind measurements after the end of life of NASA's QuikSCAT satellite. NOAA had contracted with the NASA Jet Propulsion Laboratory to study options for a QuikSCAT follow-on mission, which included the Extended Ocean Vector Wind Mission (XOVWM) called out in the National Research Council's (NRC) Earth Science Decadal Survey. NOAA also conducted a parallel QuikSCAT Follow-on user impact study. While scatterometer data is useful for a range of open-ocean and tropical weather detection and forecasting, a solely NOAA-funded QuikSCAT follow-on mission was determined to be lower priority than other missions such as other NOAA satellites, ships, aircraft, and land and ocean observing systems. To mitigate the loss of scatterometer data, NOAA decided to rely on the coarser-resolution scatterometer flown by our EUMETSAT partner, and to develop a new partnership with India to take advantage of its new research scatterometer on its Oceansat-2 satellite.

**Question 6: A large commercial satellite manufacturer has approached the Interagency JPSS office with an offer to integrate and launch TSIS as a hosted payload on one of their commercial satellites launching in 2014, and that the price would be significantly less than NOAA trying to procure a bus and launch to get TSIS into space. Furthermore, this would be a highly reliable platform allowing for the full 7+ year TSIS mission. Is NOAA considering this option? If not, why not? If so, what is the timeline for such a decision and what factors will be considered?**

**Response:**
JPSS had considered options for accommodating TSIS, such as hosting it with other instruments on a free flyer. However, an opportunity presented itself. The Total Solar Irradiance Calibration Transfer Experiment (TCTE) would provide for a 2013 launch of a Total Irradiance Monitor (TIM) instrument to be placed on board a US Air Force mission. TCTE would provide some mitigation of a potential and likely gap in a 34-year solar data record due to the 2011 loss of the NASA Glory mission in 2011. NOAA's longer term strategy is to launch TSIS and the Advanced Data Collection System and SARSAT on a Free Flyers using ride shares. NOAA will assess whether the commercial sector could provide ride share opportunities.

**Question 7: During the March 6, 2012 budget hearing, Administrator Lubchenco stated that there were "no options" for filling the coming data gap for polar satellites. During the hearing, there were a number of possibilities discussed to procure supplementary data to reduce the forecasting degradation that has been predicted will occur during the gap.**

**Has NESDIS conducted any objective, quantitative analysis to evaluate the potential for any of these other solutions? If not, why not? If so, please provide the supporting documentation. What objective analysis was conducted to lead the Administrator to conclude there were no options for a gap filler? Was the analysis quantitative or qualitative? What NOAA line offices participated in this analysis? Please submit such analysis to the Committee.**

**Response:**

There is no viable alternative to close the gap in the afternoon orbit that could occur if NPP fails before JPSS-1 becomes operational, due to the well-known time and cost necessary to design, develop and procure satellite assets to meet NOAA's requirements for these observations. Based on over 40 years of acquiring satellites, NOAA is not optimistic that any commercial provider would be able to build, test, and launch a gap filler mission in time for late-CY 2016, when Suomi NPP is expected to reach the end of its design life. To date, other than the contractors that are developing JPSS-1 instruments, NOAA knows of no other commercial provider that is building or is initiating the development of an instrument that would meet NOAA's requirements.

NESDIS has conducted a number of qualitative assessments of current and planned missions that would fly in the mid-CY 2016 through mid-CY 2018 time period, i.e., the time period of the likely gap between the end of the Suomi NPP mission and the time when JPSS-1 will complete its calibration and validation. These assessments compared NOAA's validated requirements documented in NOAA's Consolidated Observational Requirements List (CORL) against U.S. and international missions that are either currently flying or will be launched in that time frame. A list of these missions is maintained by the World Meteorological Organization[4], with input from all contributing space agencies, including NOAA, in the framework of the Coordination Group on Meteorological Satellites. During these assessments, NESDIS consulted with NWS, the Office of Oceanic and Atmospheric Research (OAR), the National Ocean Service (NOS), and the National Marine Fisheries Service (NMFS) technical personnel through the NOSC.

The analyses indicated that there were no commercial providers that had satellites planned for launch that could provide data to meet NOAA's requirements in that time frame. The analyses indicated that there is one satellite that could possibly provide data: the China Meteorological Administration Feng Yun 3B (FY-3B) satellite that was launched in the afternoon orbit on November 2010 with instruments that are similar to NASA Earth Observing System (EOS) satellites[5]. In this case, there are information technology security and algorithm challenges that would need to be addressed first.

At the March 28, 2012 hearing, several witnesses on Panel II spoke of planned and proposed observing systems that could become a part of the overall integrated observing system to help scientists better understand and predict the environment. However, none of those observing systems will meet the NOAA requirement for accurate vertical profile measurements of temperature and moisture on a global scale that only the instruments aboard the Suomi NPP/JPSS satellites provide.

The witness who represented Exelis proposed a less capable imager than both the one currently flying on Suomi NPP and planned for JPSS. The witness proposed upgrading the Advanced Very High Resolution Radiometer (AVHRR), the imager currently flying on the POES (afternoon orbit) and EUMETSAT Metop (mid-morning) satellites. He proposed an upgrade to this legacy sensor that would increase the number of channels. However, the

---

[4] http://www.wmo.int/pages/prog/sat/gos-dossier_en.php

[5] http://journals.ametsoc.org/doi/pdf/10.1175/2009BAMS2798.1

AVHRR does not meet NOAA's requirement for global sounding data. It is also unlikely that the instrument can be built in time to mitigate or lessen the potential data gap.

The witness who represented GeoMetWatch proposed a constellation of up to six geostationary satellites that would span the globe flying an advanced sounder capable of making measurements of a similar accuracy to the infrared sounder flown on Suomi NPP and that will fly on JPSS. The technical feasibility of an advanced geostationary sounder is based in large part on a partial ground-based demonstration in a simulated space environment of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS), conducted by NASA in the early 2000's. To date, this capability has not been demonstrated in an operational environment. In addition, the witness' proposed six geostationary satellite constellations cannot provide data over the Earth's polar regions, given geostationary satellites' inability to view the poles due to the Earth's curvature—a limitation not faced by polar-orbiting satellites.

The TAMDAR and Mesonet capabilities were discussed by two separate witnesses. Both of these witnesses described technologies that would provide data in a much smaller footprint than the wider footprint that satellite data can provide. In-situ data cannot replace satellite data – nor can satellite data replace in-situ data. Both have complementary strengths and provide observations critical to NOAA's mission.

NOAA has reviewed these options and concludes that they are not sufficient to meet our operational requirements. However, NOAA will continue to pursue potential agreements with the commercial sector when it can provide data that addresses NOAA's requirements at a reasonable cost to the taxpayer.

**The Honorable Randy Neugebauer**

**Question 1: Could you please briefly detail the programs at NOAA designed to reduce the impact of tornadoes, hurricanes, and windstorms? How would reauthorization and codification of windstorm impact reduction programs help NOAA's efforts to accomplish those objectives?**

**Response:**
Public Law 108-360, Title II, known as the National Windstorm Impact Reduction Act (NWIRA) of 2004, was signed into law on October 25, 2004. This law established the National Windstorm Impact Reduction Program (NWIRP), the objective of which is to measurably reduce the national loss of life and property caused by windstorms. Regarding NOAA, the law states, "NOAA shall support atmospheric sciences research to improve the understanding of the behavior of windstorms and their impact on buildings, structures, and lifelines."

Hazardous windstorm research, observations, and forecasting are an important component of the NOAA portfolio. At the same time, NOAA does not have a program office dedicated to carrying out the NWIRP, nor is there a line within its budget that exclusively provides funding in support of the NWIRA. Therefore, the authorization language has not changed NOAA's windstorm-related activities or organization.

NOAA is engaged in a variety of research and operational activities related to the goals and objectives of the NWIRP. These activities ranged from research to improve observations of physical phenomena, to development of novel data assimilation and forecasting techniques, to applications of observations, models, and forecasts to assess wind impacts. The following list is NOAA's windstorm-related activities from FY 2009-2010 (the latest reporting period for the NWIRP):

- VORTEX-II (Project Lead: NOAA National Severe Storms Laboratory)
- Hazardous Weather Testbed (Project Leads: NOAA/NWS StormPrediction Center and NOAA National Severe Storms Laboratory)
- Warn-On-Forecast (Project Lead: NOAA National Severe Storms Laboratory)
- Derecho Studies (Project Lead: NOAA National Severe Storms Laboratory
- Severe Hazard Algorithm Verification Experiment (Project Lead: NOAA National Severe Storms Laboratory)
- Microburst Studies (Project Lead: NOAA National Severe Storms Laboratory
- *In situ* Measurements of Turbulence in Hurricanes – Extreme Turbulence Probe (Project Lead: NOAA Air Resources Laboratory
- High-Resolution Rapid Refresh (Project Lead: NOAA Earth System Research Laboratory)
- Large-Scale Influences on Seasonal Severe Weather Behavior (Project Lead: NOAA/NWS Storm Prediction Center)
- Hazardous Weather System for U.S. Space Centers (Project Lead NOAA Earth System Research Laboratory)
- Reducing Wind-Induced Damages (Project Lead: Iowa State University)
- H*WIND – Hurricane Wind Analysis System (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)
- Alternative Metrics of Tropical Cyclone Impact: Integrated Kinetic Energy and Surge/Wave Destructive Potential (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)
- State of Florida Public Hurricane Loss Model (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)

Reducing impact of events is a holistic collaboration of planning, anticipation, response and recovery. As the implementation plan for the NWIRP outlines (2006 subcommittee on disaster reduction, www.sdr.gov), various agencies have lead roles for each of these phases and support of each other when dealing with high impact weather.

**Question 2: Based on progress in science and modeling capabilities, what are your projections and assessments for the future of windstorm forecasting and impact mitigation over the next decade? How can we continue to improve our capabilities in this area?**

**Response:**

NOAA is working to lengthen the lead-time and improve the accuracy of the prediction of high-wind events - tornadoes, hurricanes, and severe storms. The framework to improve high-impact weather prediction involves increased observations; advancing forecast models through research, development and engineering; and increasing computing resources and efficiencies. These advances will lead to improved forecasts, which will in turn provide better information for preparation and response. In addition, NOAA is working toward impact mitigation through social science research and outreach to first responders and the public.

NOAA is working on innovative observation technology solutions to advance the forecasting of high-impact weather events. For example, the President's FY 2013 budget requests an increase of $855,000 for wind boundary layer research to improve weather predictions. A better understanding of mid-level altitude winds will allow us to produce a more accurate forecast of wind speeds and direction. In addition, NOAA is researching and evaluating emerging technologies through remote sensing on various platforms (e.g, unmanned aircraft systems, Phased-Array Radar).

There is great potential for improved weather prediction through improved models because the sophistication of the assimilation, dynamic models and physical packages needed for Numerical Weather Prediction are advancing. A major opportunity that NOAA is pursuing is called "Warn On Forecast." This program is based on a new generation of models that can predict where tornado producing thunderstorms will appear an hour or two in advance – allowing people to move to shelters. NOAA's current warnings typically have 10 to 30 minutes of lead time, and are designed to help the public to seek shelter within their immediate dwelling or location.

Another important reason that the models are improving is that the speed of the fastest supercomputers continues to grow rapidly. In the last few years, a new supercomputer revolution is underway based on Massively Parallel Fine Grain computers. One example of this type of computer is the Graphics Processor Units, which were originally designed for computer games. A NOAA team has used a current version of the NVIDIA Graphics Processing Unit (GPU), which has 512 64 bit supercomputers on a single board, to show that its weather models could run 10 to 20 times faster (or alternately, could cost less than 10% as much for the same computing) than the current generation of supercomputers. NVIDIA is an American global technology company.

And finally, as part of the agency's goal to make the United States a Weather-Ready Nation (www.noaa.gov/wrn), NOAA is working to leverage and integrate ongoing interdisciplinary research programs, including social science research cosponsored by NSF and NOAA, towards improving understanding of individual and community decisions that tend to increase or decrease their vulnerability to windstorm hazards. NWS is also conducting outreach to first responders and the public on how to better understand and respond to forecasts of these types of severe weather events and have enlisted the support of social scientists to better work with the public and partner agencies.

*Responses by Dr. Alexander MacDonald, Deputy Assistant Administrator for Research Laboratories and Cooperative Institutes, Office of Oceanic and Atmospheric Research, NOAA*

**U.S. HOUSE OF REPRESENTATIVES**
**COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY**
**Subcommittee on Energy and Environment**

**Hearing Questions for the Record**
**The Honorable Andy Harris**

***To Observe and Protect: How NOAA Procures Data for Weather Forecasting***

**Dr. Alexander MacDonald**
**Office of Oceanic and Atmospheric Research**

**Question 1: Are you aware if the decision to remove the Hyperspectral Environmental Suite, or HES, instrument from the GOES-R manifest was based on an objective, quantitative analysis that compared the benefits of these sounders against the benefits of other instruments or capabilities? Do you believe such an analysis would be helpful? Did OAR participate in such an analysis? If not, how could OAR have assisted NESDIS and NWS in making the decisions?**

**Response:**
Beginning in 2002, when NOAA first started planning for the follow-on to the Geostationary Operational Environmental Satellite N-Series (GOES-N Series), NOAA explored the concept for developing an advanced sounder and coastal water imaging capability, or HES, for deployment on the Geostationary Operational Environmental Satellite-R (GOES–R) series. Through the NOAA Observing Systems Council (NOSC), NESDIS led this decision-making process in coordination with the NWS, OAR, and all other NOAA Line and Program Offices. Further input was gathered from a cross section of the community at NOAA's Center for Satellite Applications and Research's September 2006 meeting, which included more than 40 sounding experts and users from NOAA, NASA, and academia. In addition, NOAA's plans for meeting geostationary sounding needs were also briefed and discussed during the Satellite Symposium at the January 15-18, 2007 American Meteorological Society (AMS) Annual Meeting. NOAA finally determined that the HES concept was too technologically complex and expensive for NOAA to develop and implement for GOES–R.

The following factors influenced NOAA's decision not to pursue HES on GOES-R in the 2006 timeframe:

- The technological challenges that faced HES had not been resolved and, given the fiscal environment, it was not cost effective to pursue solutions.
- There was no on-going research within the United States to address the technological impediments we encountered on HES that would provide the needed foundation to allow NOAA to build and deploy the sensor on an operational GOES platform.
- Conducting research to address the technological impediments of HES was outside the scope of NOAA's operational mission.
- The continuity of data for National Weather Service operations was more important than pursuing technological solutions to the HES.

- With algorithm development, the National Weather Service would be able to use data from the Advanced Baseline Imager to develop sounding data products similar to legacy sounders on the GOES N-Series.
- The GOES-R series spacecraft bus did not have sufficient space or power on the spacecraft to accommodate a hyperspectral sounder.

OAR did not conduct an objective quantitative analysis that compared the benefits of these sounders against other capabilities. OAR could have further tested the prospective role of advanced hyper-spectral geostationary sounders in the global observing system through Observing System Simulation Experiments (OSSE, but OAR's capability to conduct these OSSEs was not as mature as it is today. Currently, OAR, NESDIS, and NWS are partnering to conduct an OSSE to evaluate the possibility of a HES in the future.

**Question 2: Dr. Crain testified to the ability of his company to provide NOAA and others data from a commercially available geostationary satellite. It seems easier and cheaper for NOAA to just buy the data than build another satellite system.**

**a. How could NOAA OAR contribute to evaluation of such an option?**

**Response:**
OAR has the technical capability and expertise to evaluate and test the prospective role of advanced hyperspectral geostationary sounders in the global observing system through Observing System Simulation Experiments (OSSEs), but the benefits would still need to be weighed against NOAA's existing observational priorities and resources before the agency could make the decision to pursue HES.

Since the hearing was held, NOAA determined that an OSSE would be beneficial to inform the agency's decision-making about a HES. To that end, OAR, NESDIS, and NWS are now partnering to conduct an OSSE to evaluate the HES as an option.

**b. Is OAR currently undertaking any analyses to inform tradeoffs associated with various satellite data capabilities?**

**Response:**
Yes, NOAA is currently undertaking analyses to inform tradeoffs associated with various satellite data capabilities; however, these experiments are confined to particular regions. For example, NOAA is performing regional OSSEs to evaluate the use of a variety of in situ and remote sensing systems to improve hurricane prediction and to prepare for future oil spills. These OSSEs are exploring the value of GOES-R Advanced Baseline Imager (ABI) brightness temperature data assimilation, as compared to Doppler radar data assimilation and simultaneous assimilation of both data sets. The OSSEs needed to evaluate entire satellite systems would be larger in scale because they would need to compare methods used to take measurements across the globe. NOAA has the technical capability to conduct global OSSEs.

**Question 3: In the March 6 NOAA FY13 Budget hearing, Dr. Lubchenco said she was not familiar with a quantitative approach to evaluating observing systems known as an**

**Observing System Simulation Experiment, or OSSE. But in an article she co-authored in March of this year in *Physics Today*, she stated that OSSEs were a "powerful tool" to "inform our strategies for investing in observation networks."**

**a. How often has NOAA conducted OSSEs?**

**Response:**
Dr. Lubchenco did not understand the Chairman's question in the hearing; she is very familiar with OSSEs. OSSEs could help determine which satellite systems and instruments to invest in and which investment will provide the best value. As such, there are multiple uses for OSSEs, and they can vary from testing a particular set of observing instruments for a regional weather forecast, to testing a mix of instruments that will take measurements across the globe.

NOAA is increasingly conducting OSSEs that compare the use of platforms, such as unmanned aircraft systems, weather balloons, and radar for severe weather forecasts, including hurricane track and intensity forecasts. We call these "regional" OSSEs because they are confined to a certain time and space scale. NOAA is conducting several regional OSSEs to determine the best mix of new instruments for weather, ocean, and climate prediction systems. These regional OSSEs also compare the use of these platforms and instruments with the subset of satellite data for that area.

Because satellites take pictures across the globe, OSSEs that evaluate the satellite systems are larger in scale and are more expensive. We refer to these types of OSSEs as "global" OSSEs.

**b. What would an "OSSE" tell us and get us? Could it potentially identify alternative satellite data options worthy of pursuing?**

**Response:**
An OSSE is a type of observing system experiment aimed at assessing the impact of a hypothetical data type on a forecast system. Thus, OSSEs have the capability to assess the potential impact of proposed/future observing systems on numerical weather, ocean, and climate prediction systems and to inform decision-makers prior to acquisition or construction of the proposed observing system. An OSSE may help evaluate the types of observing systems that could potentially yield optimization of both systems and savings in the future and could potentially identify alternative satellite data options worthy of pursuing.

An OSSE could help determine which satellite systems and instruments to invest in and which investment will provide the best value, however it should be noted that OSSEs cannot select which instruments would be the best to pursue out of several different options without testing each option individually. In addition, conducting OSSEs on the global scale, such as would be required for a satellite system, would necessitate significant resources and can take as much as 1-3 years to complete.

**c. Did NOAA conduct a comprehensive assessment prior to devoting more than 30 percent of its budget to the current planned satellite configuration, instead of alternative**

**configurations, such as the national Profiler Network, the national Mesonet program, tropospheric data collection like TAMDAR, and making strategic non-investments in modeling, data assimilation, or radar developments?**

**Response:**
NOAA currently utilizes the NOSC to develop, validate, and seek the most effective means to meet its observation requirements. The NOSC is a cross-agency council which is tasked with developing recommendations on all aspects of NOAA's observing and data management capabilities. The NOSC has implemented a process for documenting, verifying, and validating "system independent" observing requirements. These requirements are the foundation for evaluating the optimal portfolio of observing systems to best meet NOAA's mission needs. The processes and systems utilized by the NOSC help to inform NOAA leadership when making investment decisions which, of course, need to also take into account other factors – such as available resources, international and inter-agency agreements, and risks.

Regarding assessments that NOAA has run on observing systems, NOAA ran several Observation System Experiment (OSEs) (also called data denial experiments) on the current observing system configuration. An OSE is typically used to assess *existing* observing systems to provide decision makers with an understanding of the impact of additions or losses of data from those systems on a numerical forecast, whereas OSSEs use simulated observations to estimate the benefits of a hypothetical (either new or modified) *future* observing system. OSEs require running model predictions many times to see the effect of the different observing systems. In 2010, OAR conducted an OSE to help examine the relative impacts of a wide variety of weather observational systems impacting short-range forecasts including aircraft (including commercially available TAMDAR data), NOAA's profiler network (NPN), radiosonde, velocity-azimuth display vertical wind profiles, GPS-derived precipitable water, national Mesonet, and non-NOAA mesonet observations. In 2004, OAR also developed a cost and effectiveness evaluation analysis on the NPN to assess the relative importance of the profiler data for short-range wind forecasts.

**Queston 4: Does NOAA have the technical capability to conduct OSSEs? If so, can you explain why NOAA has not conducted an OSSE to assess the potential alternatives to its current plans or ways to reduce the negative impact of the current expected data gap?**

**Response:**
NOAA has the expertise to conduct OSSEs at both the regional and global scale. Since the hearing was held, NOAA has revisited the issue and determined that an OSSE would be beneficial to inform the agency's decision-making about a HES. To that end, OAR, NESDIS, and NWS are now partnering to conduct an OSSE to evaluate the HES. Once assessments are completed, NOAA will evaluate whether space-based deployment of an advanced hyperspectral sounder in geostationary orbit would be a timely, efficient and cost-effective means to improve the forecasting of severe weather.

In addition,, as described in answer 15(c), NOAA ran several Observation System Experiment (OSEs) (also called data denial experiments) on the current observing system configuration to help examine the relative impacts of a wide variety of weather observational systems impacting short-range forecasts.

**Question 5: Dr. MacDonald, Please discuss the status and outlook of using computer modeling to assist in weather prediction. What is the potential and what is needed to make modeling more useful to forecasters? How much does modeling cost relative to that of other observing systems?**

**Response:**
Studies indicate that most of the improvements to weather prediction in recent decades are due to the improvement of weather models, with the remainder of improvements attributable to better observations such as those from advances in satellites. The evidence includes studies of skill scores from forecasters, whose improved predictions closely follow the model improvements. Other studies include running today's prediction models on the observational data that was available in previous decades; the results show that model improvements are a larger factor than observational improvements.

The outlook for improved weather prediction is excellent, primarily because of two factors. First, the speed of the fastest supercomputers continues to grow rapidly. Second, the sophistication of the assimilation, dynamic models and physical packages needed for Numerical Weather Prediction (NWP) are also advancing rapidly. In the last few years a new supercomputer revolution is underway based on Massively Parallel Fine Grain computers. One example of this type of computer is the Graphics Processor Units (GPUs) which were originally designed for computer games. OAR has used a current version of the NVIDIA GPU which has 512 64 bit supercomputers on a single board to show that its weather models could run 10 to 20 times faster (or alternately, could cost less than 10% as much for the same computing) than the current generation of supercomputers. NVIDIA is an American global technology company.

NOAA is endeavoring to use these exciting advances in weather prediction models to bring the nation the many advantages that better knowledge of future weather can bring. A major opportunity that NOAA is pursuing is called "Warn On Forecast." This program is based on a new generation of models, which in a research environment, has demonstrated that they can predict where tornado producing thunderstorms will appear an hour or two in advance – allowing people to move to shelters. Our current warnings typically have 10 to 30 minutes of lead time, and are designed to help the public to seek shelter within their immediate dwelling or location.

**a. Where would you rank U.S. forecasting capabilities compared to other countries?**

**Response:**
U.S. forecasting is the world leader in very short range prediction and warning services. These are forecasts of less than 24 hours that are crucial for public safety, and that are based on radar, satellite, information systems and very high resolution models. For forecasts of a day or longer, the United States lags behind other countries, most notably the European Center for Medium Range Weather Prediction). Limited operational computing resources

and the diversity of NOAA's operational forecast mission compared to ECMWF and UKMO are the primary reasons for lagging behind. The focus in the United States has been on the shorter range forecasts, i.e., severe weather, since our nation experiences those unique weather phenomena with much more frequency than any other nation on earth. NOAA expects increases in computing capacity once it transitions to a new, operational high performance computing system in FY 2014.

**b. Is there cooperation between countries on forecast modeling? Please describe any such international cooperation related to this effort.**

**Response:**
There is excellent cooperation between countries on forecast modeling. In addition to publications that detail improvements that each country is making in their weather forecast models, there are numerous conferences and workshops to help spread improved capabilities. The most recent such meeting is the "Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction," organized by the World Meteorological Organization (WMO) from 22 to 25 May 2012 in the US. Participants came from all the major NWP centers active in the area of impact studies.

There are also many exchanges between nations, which allow scientists from one country to work for a period of months to a year or two to learn the improvements that other centers are using. In July 2010, a Memorandum of Understanding was signed to include NOAA's National Centers for Environmental Prediction as a partner with the European Center for Medium Range Weather Forecasts (ECMWF), Meteo-France and the UK Met Office in seasonal weather prediction. The EUROpean multi-model Seasonal to Internannual Prediction System (EUROSIP) will: (1) provide more accurate seasonal predictions (especially temperature and precipitation) through world-class prediction models run at the four national centers and (2) strengthen collaboration on enhancing multi-model techniques for seasonal forecasting.

**The Honorable Randy Neugebauer**

**Question 1: Could you please briefly detail the programs at NOAA designed to reduce the impact of tornadoes, hurricanes, and windstorms? How would reauthorization and codification of windstorm impact reduction programs help NOAA's efforts to accomplish those objectives?**

**Response:**
Public Law 108-360, Title II, known as the National Windstorm Impact Reduction Act (NWIRA) of 2004, was signed into law on October 25, 2004. This law established the National Windstorm Impact Reduction Program (NWIRP), the objective of which is to measurably reduce the national loss of life and property caused by windstorms. Regarding NOAA, the law states, "NOAA shall support atmospheric sciences research to improve the understanding of the behavior of windstorms and their impact on buildings, structures, and lifelines."

Hazardous windstorm research, observations, and forecasting are an important component of the NOAA portfolio. At the same time, NOAA does not have a program office dedicated to carrying out the NWIRP, nor is there a line within its budget that exclusively provides funding in support of the NWIRA. Therefore, the authorization language has not changed NOAA's windstorm-related activities or organization.

NOAA is engaged in a variety of research and operational activities related to the goals and objectives of the NWIRP. These activities ranged from research to improve observations of physical phenomena, to development of novel data assimilation and forecasting techniques, to applications of observations, models, and forecasts to assess wind impacts. The following list is NOAA's windstorm-related activities from FY 2009-2010 (the latest reporting period for the NWIRP):

- VORTEX-II (Project Lead: NOAA National Severe Storms Laboratory)
- Hazardous Weather Testbed (Project Leads: NOAA/NWS StormPrediction Center and NOAA National Severe Storms Laboratory)
- Warn-On-Forecast (Project Lead: NOAA National Severe Storms Laboratory)
- Derecho Studies (Project Lead: NOAA National Severe Storms Laboratory
- Severe Hazard Algorithm Verification Experiment (Project Lead: NOAA National Severe Storms Laboratory)
- Microburst Studies (Project Lead: NOAA National Severe Storms Laboratory
- *In situ* Measurements of Turbulence in Hurricanes – Extreme Turbulence Probe (Project Lead: NOAA Air Resources Laboratory
- High-Resolution Rapid Refresh (Project Lead: NOAA Earth System Research Laboratory)
- Large-Scale Influences on Seasonal Severe Weather Behavior (Project Lead: NOAA/NWS Storm Prediction Center)
- Hazardous Weather System for U.S. Space Centers (Project Lead NOAA Earth System Research Laboratory)
- Reducing Wind-Induced Damages (Project Lead: Iowa State University)
- H*WIND – Hurricane Wind Analysis System (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)
- Alternative Metrics of Tropical Cyclone Impact: Integrated Kinetic Energy and Surge/Wave Destructive Potential (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)
- State of Florida Public Hurricane Loss Model (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)

Reducing impact of events is a holistic collaboration of planning, anticipation, response and recovery. As the implementation plan for the NWIRP outlines (2006 subcommittee on disaster reduction, www.sdr.gov), various agencies have lead roles for each of these phases and support of each other when dealing with high impact weather.

**Question 2: Based on progress in science and modeling capabilities, what are your projections and assessments for the future of windstorm forecasting and impact mitigation over the next decade? How can we continue to improve our capabilities in this area?**

**Response:**
NOAA is working to lengthen the lead-time and improve the accuracy of the prediction of high-wind events - tornadoes, hurricanes, and severe storms. The framework to improve high-impact weather prediction involves increased observations; advancing forecast models through research, development and engineering; and increasing computing resources and efficiencies. These advances will lead to improved forecasts, which will in turn provide better information for preparation and response. In addition, NOAA is working toward impact mitigation through social science research and outreach to first responders and the public.

NOAA is working on innovative observation technology solutions to advance the forecasting of high-impact weather events. For example, the President's FY 2013 budget requests an increase of $855,000 for wind boundary layer research to improve weather predictions. A better understanding of mid-level altitude winds will allow us to produce a more accurate forecast of wind speeds and direction. In addition, NOAA is researching and evaluating emerging technologies through remote sensing on various platforms (e.g, unmanned aircraft systems, Phased-Array Radar).

There is great potential for improved weather prediction through improved models because the sophistication of the assimilation, dynamic models and physical packages needed for Numerical Weather Prediction are advancing. A major opportunity that NOAA is pursuing is called "Warn On Forecast." This program is based on a new generation of models that can predict where tornado producing thunderstorms will appear an hour or two in advance – allowing people to move to shelters. NOAA's current warnings typically have 10 to 30 minutes of lead time, and are designed to help the public to seek shelter within their immediate dwelling or location.

Another important reason that the models are improving is that the speed of the fastest supercomputers continues to grow rapidly. In the last few years, a new supercomputer revolution is underway based on Massively Parallel Fine Grain computers. One example of this type of computer is the Graphics Processor Units, which were originally designed for computer games. A NOAA team has used a current version of the NVIDIA Graphics Processing Unit (GPU), which has 512 64 bit supercomputers on a single board, to show that its weather models could run 10 to 20 times faster (or alternately, could cost less than 10% as much for the same computing) than the current generation of supercomputers. NVIDIA is an American global technology company.

And finally, as part of the agency's goal to make the United States a Weather-Ready Nation (www.noaa.gov/wrn), NOAA is working to leverage and integrate ongoing interdisciplinary research programs, including social science research cosponsored by NSF and NOAA, towards improving understanding of individual and community decisions that tend to increase or decrease their vulnerability to windstorm hazards. NWS is also conducting outreach to first responders and the public on how to better understand and respond to forecasts of these types of severe weather events and have enlisted the support of social scientists to better work with the public and partner agencies.

*Responses by Mr. John Murphy, Chief, Programs and Plans Division, National Weather Service, NOAA*

**U.S. HOUSE OF REPRESENTATIVES**
**COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY**
**Subcommittee on Energy and Environment**

**Hearing Questions for the Record**
**The Honorable Andy Harris**

***To Observe and Protect: How NOAA Procures Data for Weather Forecasting***

**Mr. John Murphy**
**National Weather Service**

**Question 1: Please describe how the National Weather Service develops and updates its requirements for observing systems in order to deliver the best forecasting capability for preventing loss of lives and property?**

**Response:**
NOAA maintains the Consolidated Observational Requirements List (CORL) and requirements are developed and ranked NOAA-wide. The CORL is based on platform-independent environmental parameters; these data needs are not instrument- or technology-specific. Technical capabilities are analyzed for their ability to meet the requirements.

**a. Prior to its removal from the GOES-R geostationary satellite manifest, where did the Hyperspectral Environmental Suite or HES instrument rank on the NWS requirements list?**

**Response:**
In September 2010, the NWS was asked to prioritize four potential acquisitions (DSCOVR, GCOM Dual Frequency Scatterometer (DFS), COSMIC-2, and HES accommodation to GOES T&U). The HES ranked 4th as documented in a September 15, 2010, memorandum from the NWS Director to the NESDIS Director. For GOES instruments only, the HES was ranked below the GOES-R ABI and GLM.

**b. Does a hyperspectral sounder in geostationary orbit still exist on the NWS requirements list? If not, when did NWS remove the requirement, before or after it was removed from the GOES-R manifest? Please provide supporting documentation detailing this timeline and the analysis used to inform the decision.**

**Response:**
NOAA maintains the CORL and observing requirements are developed and ranked NOAA-wide. The CORL is based on platform-independent environmental parameters; these data needs are not instrument- or technology- specific. Rather, technical capabilities are analyzed for their ability to meet the requirements in the CORL. A geostationary sounder appears to provide some capability, but does not meet all CORL requirements for soundings and boundary layer measurements of temperature and moisture and tropospheric winds. After reviewing currently available technologies, the NWS Office of Science and Technology

believes that a combination of complementary observing systems appears to provide greater capability compared to a single observing system.

The FY 2012 Appropriations language required NOAA to "develop a plan for a mid-decade deployment of an advanced hyper-spectral sounder…" and submit it to Congress. The agency is working on a plan for new observing systems to support an augmented severe weather warning and forecast capability that includes an analysis of a geostationary hyperspectral infrared sounder as a contributor to address CORL requirements.

**c. If the requirement for a hyperspectral sounder in the geostationary orbit still exists, how will NWS procure this data? What will NESDIS's role be in assisting NWS procure this data? Has NWS considered commercial providers as an option for procuring this data?**

**Response:**
Since the hearing was held, NOAA determined that an OSSE would be beneficial to inform the agency's decision-making about a HES. To that end, OAR, NESDIS, and NWS are partnering to conduct an OSSE to evaluate HES. Once geostationary hyperspectral data are proven effective and affordable, NOAA will explore all options to obtain those. However, to date, the data are not proven to be scientifically sound and cost effective and there are no commercial providers that have demonstrated that they have built, launched, and are operating a satellite in geostationary orbit that can provide hyperspectral sounding measurements for NWS use.

The impact of a Geostationary Hyperspectral Infra Red Satellite (GHIRS) on operational weather forecast skill has not been assessed. The 2019 launch of the EUMETSAT Meteosat Third Generation Infrared Sounder (MTG IRS) on a geostationary satellite will allow the assessment of a hyperspectral sounder in geostationary orbit and whether such data will improve computer-generated weather forecasts. While NOAA GOES satellites continuously observe the eastern hemisphere of the Earth, they do not provide global coverage needed by numerical weather prediction models. The weather and satellite communities need to perform the background research and development (R&D) relevant to the operational use of GHIRS in order to assess its importance relative to other alternatives. These data will be available to international users and can be used, after sufficient analysis, validation and research and development, to evaluate the impact of a GHIRS on forecasts. GeoMetWatch, a private company, is proposing a constellation of GHIRS. The proposal has a system over Asia in the 2015 time frame. Similarly to the MTG IRS, data from this system could be used to evaluate the value of GHIRS data for operational use. Each potential observing system alternative must be evaluated for its cost-benefit, suitability for integration into the observing enterprise and merits compared to all alternatives. Based upon the best science currently available, NOAA is committed to the advanced hyperspectral sounder in the polar orbit. In its efforts toward improved forecasts, NOAA will continue its evaluation of the GHIRS as a potential observation system.

**Question 2: The National Weather Service is requesting a $12.4 million increase for "ground system readiness, ensuring that NWS will be prepared to ingest data coming from**

**NOAA's investment in new weather satellites." How will this additional funding help if there is a polar data gap?**

**a. In the event that the requested budget is not met, what initiatives can be undertaken to mitigate a stopgap in data collection? What effect will this have on preparedness in severe weather events?**

**Response:**
This funding is not related to the impending polar-orbiting satellite data gap, but is related to the overall NOAA effort to provide improved data products to the Nation.

The NWS Ground Readiness Project (GRP) will enable NWS to use the data provided by the new (Suomi NPP, JPSS and GOES-R) satellites as well as the increased number and size of higher resolution products these data will ultimately generate. There are no mitigating capabilities if the GRP is not funded for the needed NWS IT Infrastructure upgrades. In essence, NWS will not be able to use the new data coming from the satellites (including Suomi NPP) or provide increased resolution model guidance. The data from these new satellites are at a higher resolution and include more detail than the current satellite data stream. The improved data from the Suomi NPP, JPSS, and GOES-R satellites will support increased detail and accuracy in forecast model guidance and will enable advances in predicting and preparation for severe weather events. These advanced computer models will also support predictions for emerging societal needs, such as for renewable energy. The GRP funding ensures that taxpayers fully benefit from the next generation of polar and geostationary satellites

**Question 3: In the FY13 budget request, NOAA proposes to keep 3 wind profilers in Alaska, thereby requiring an investment in infrastructure, networking, software updates and technician training. However, the budget request does not include funding for replacing the more than 30 profilers currently in operation in Tornado Alley that provide valuable wind data for tornado warnings.**

**a. Why didn't NOAA request funding for replacing these profilers? What cost savings exist if NOAA is already intending to make the investment in the networking, software updates and technician training?**

**Response:**
Forecasters primarily rely on Next-Generation Radar (NEXRAD) for issuing tornado warnings, while incorporating profiler data for longer timeframe severe thunderstorm outlooks and watches. The deployment of dual-polarization capability into the NEXRAD network has demonstrated the capability to improve tornado detection, which may also improve tornado warning capability. Given the improvements in computer model systems, NOAA does not anticipate a significant impact to its forecast and warning services with the retirement of the wind profiler network in the continental U.S.

In order to preserve the NWS core warnings and forecast mission, NOAA did not request funding to upgrade and convert the NOAA Profiler Network (NPN). NOAA assessed these

NPN as being a lower priority to other advancements, such as dual-polarization technology and decided not to support the upgrade and convert of the additional 30 profilers located in the middle portion of the country. The cost for complete technology refreshment and required frequency conversion contributed to the decision to discontinue these wind profilers.

The decision to maintain the Alaskan profilers relates to their contribution toward unique volcanic ash and aviation weather forecasting support requirements. In addition, the Alaskan profilers currently operate at an acceptable frequency in the portion of the electromagnetic spectrum available for U.S. Government use. While reducing the number of wind profilers, NOAA is making reductions to system support requirements, including support systems and training requirements.

**b. What is NOAA's plan to replace the data lost by shutting down the Wind Profiler Network? If there is no plan to replace the data, what will be the effective impact to the length of tornado warnings?**

**Response:**
Forecasters primarily rely on Next-Generation Radar (NEXRAD) for issuing tornado warnings, while incorporating profiler data for longer timeframe severe thunderstorm outlooks and watches. The deployment of dual-polarization capability into the NEXRAD network has demonstrated the capability to improve tornado detection, which may also improve tornado warning capability. Given the improvements in computer model systems, NOAA does not anticipate a significant impact to its forecast and warning services with the retirement of the wind profiler network in the continental U.S. Improved computer modeling systems combined with expansion of other systems sampling the atmosphere, such as aircraft observations and geostationary satellite data, will help mitigate the loss of data from the wind profilers for forecasts of tornados and severe weather.

**c. There have been a number of reports praising the data provided by wind profilers in increasing time for tornado warnings and the overall benefit of the data stream. Has NWS conducted any studies examining the practical effect of eliminating this data stream? What objective analysis was done to determine that the value of the data from wind profilers was not worth the cost of replacing them? Please provide the supporting documentation with this analysis.**

**Response:**
In 2004, OAR conducted a Cost and Operational Effectiveness Analysis for the NPN in response to a request from the Senate Appropriations Committee. The results from an Observation System Experiment (OSE), or "data-denial" experiment, related to the Cost and Operational Effectiveness Analysis were published as an American Meteorological Society article titled, "The Value of Wind Profiler Data in U.S. Weather Forecasting." In addition, in 2006 and 2007, OAR conducted an OSE in which various data sources were denied in order to assess the relative importance of the different data types for weather forecast models. These experiments showed that aircraft observations had the largest overall impact, followed by radiosonde observations; and that NPN data, GPS-precipitable water estimates, and surface observations also led to improvements in short-range model forecast skill, although

not specifically on tornado warning lead times. The study was published in 2010 with the title, "Relative Short-Range Forecast Impact from Aircraft, Profiler, Radiosonde, VAD, GPS-PW, METAR, and Mesonet Observations via the RUC Hourly Assimilation Cycle." The result of these and other profiler studies indicate that profiler networks have a beneficial effect on the skill of weather prediction models.

The National Weather Service conducted an analysis and review of the NPN program to inform the management decision to reduce the NPN capability. From the review, NPN data were considered supplemental to the NEXRAD Doppler radar network, which provides the primary source of information for NWS tornado warnings. Preservation of NWS core warnings and forecast mission has been the cornerstone of all NWS fiscal decisions. As such, NOAA's investments have focused on the deployment of dual-polarization capability into the NEXRAD network, which has demonstrated the capability to improve tornado detection and may also improve tornado warning capability. NOAA would have required a significant funding increase to refresh and convert the frequency of 30 profilers currently operating in the middle portion of the country. The cost and the recognition of NPN data as supplemental to the severe weather warnings led to the decision in FY 2013 to discontinue the wind profilers.

**Question 4: By all accounts, the National Mesonet Program has been a success. Why did NOAA's FY 13 budget request zero out the program? How will NWS make up for the loss of data provided by the Mesonet Program?**

**Response:**
While mesonet data are useful, they are not crucial to NWS core mission responsibilities. Mesonet data are used as a supplemental tool by NWS forecasters in local offices to detect local-scale phenomena and apply this detection in forecast and warning operations and warning verification. In lieu of funding the Mesonet program, NOAA plans to leverage existing networks operated by state and local governments, the private sector, and other federal agencies that provide data when and where available, and free of charge.

**Question 5: Last November, NWS did not renew its contract with AirDat LLC for TAMDAR data.**

**a. What was the reason for the termination of this contract?**

**Response:**
The decision to terminate procurement of TAMDAR data was based on financial considerations during contract extension negotiations with AirDat LLC. NOAA believes TAMDAR data, while useful, are no longer a cost-effective solution as TAMDAR data cost per sounding is 6 times greater than alternative solutions. NOAA has a long-standing partnership with the FAA for providing atmospheric observations from commercial aircraft through a system called the Meteorological Data Collection and Reporting System (MDCRS). The MDCRS provides NOAA more cost-effective temperature and wind observations while adding a water vapor measure capability (Water Vapor Sensing System, WVSS) to MDCRS aircraft gives the same measurement capability as TAMDAR and

operational radiosondes. NOAA is working with the FAA to expand the number of WVSS-equipped aircraft.

**b. What was the value of the TAMDAR data to weather forecasts?**

**Response:**
Under the terminated contract, NWS received only 50 soundings per day from TAMDAR, versus approximately 500 per day through MDCRS. Overall, TAMDAR data were supplementary data that added limited value when combined with observations from radiosondes, MDCRS, and WVSS aircraft and satellites. MDCRS data are more voluminous than previously-available TAMDAR data and, therefore, have a larger impact on model forecast accuracy. NOAA is working with the FAA to expand the number of WVSS-equipped aircraft as NOAA believes WVSS provides a more cost-effective data source for the short-term (next few years) compared to TAMDAR at current pricing.

**c. Did NWS conduct a cost-benefit analysis on the TAMDAR data prior to terminating the contract? If so, please provide the documentation of such analysis. If not, how does NWS determine the benefits of different data streams it purchases from commercial providers and whether or not such benefits are worth the costs of buying them?**

**Response:**
Yes. A cost-benefit analysis was performed to compare the value of TAMDAR observations relative to WVSS observations. Both TAMDAR and WVSS provide soundings of temperature, moisture, and wind. WVSS provides these data from 40,000 ft to the surface while TAMDAR coverage is from 20,000 ft to the surface. The cost per sounding is $7 for WVSS and $50 for TAMDAR. Therefore, NWS could not justify the substantial difference in cost for this limited TAMDAR data.

**The Honorable Randy Neugebauer**

**Question 1: Could you please briefly detail the programs at NOAA designed to reduce the impact of tornadoes, hurricanes, and windstorms? How would reauthorization and codification of windstorm impact reduction programs help NOAA's efforts to accomplish those objectives?**

**Response:**
Public Law 108-360, Title II, known as the National Windstorm Impact Reduction Act (NWIRA) of 2004, was signed into law on October 25, 2004. This law established the National Windstorm Impact Reduction Program (NWIRP), the objective of which is to measurably reduce the national loss of life and property caused by windstorms. Regarding NOAA, the law states, "NOAA shall support atmospheric sciences research to improve the understanding of the behavior of windstorms and their impact on buildings, structures, and lifelines."

Hazardous windstorm research, observations, and forecasting are an important component of the NOAA portfolio. At the same time, NOAA does not have a program office dedicated to carrying out the NWIRP, nor is there a line within its budget that exclusively provides funding in support of the NWIRA. Therefore, the authorization language has not changed NOAA's windstorm-related activities or organization.

NOAA is engaged in a variety of research and operational activities related to the goals and objectives of the NWIRP. These activities ranged from research to improve observations of physical phenomena, to development of novel data assimilation and forecasting techniques, to applications of observations, models, and forecasts to assess wind impacts. The following list is NOAA's windstorm-related activities from FY 2009-2010 (the latest reporting period for the NWIRP):

- VORTEX-II (Project Lead: NOAA National Severe Storms Laboratory)
- Hazardous Weather Testbed (Project Leads: NOAA/NWS StormPrediction Center and NOAA National Severe Storms Laboratory)
- Warn-On-Forecast (Project Lead: NOAA National Severe Storms Laboratory)
- Derecho Studies (Project Lead: NOAA National Severe Storms Laboratory
- Severe Hazard Algorithm Verification Experiment (Project Lead: NOAA National Severe Storms Laboratory)
- Microburst Studies (Project Lead: NOAA National Severe Storms Laboratory
- *In situ* Measurements of Turbulence in Hurricanes – Extreme Turbulence Probe (Project Lead: NOAA Air Resources Laboratory
- High-Resolution Rapid Refresh (Project Lead: NOAA Earth System Research Laboratory)
- Large-Scale Influences on Seasonal Severe Weather Behavior (Project Lead: NOAA/NWS Storm Prediction Center)
- Hazardous Weather System for U.S. Space Centers (Project Lead NOAA Earth System Research Laboratory)
- Reducing Wind-Induced Damages (Project Lead: Iowa State University)
- H*WIND – Hurricane Wind Analysis System (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)
- Alternative Metrics of Tropical Cyclone Impact: Integrated Kinetic Energy and Surge/Wave Destructive Potential (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)
- State of Florida Public Hurricane Loss Model (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)

Reducing impact of events is a holistic collaboration of planning, anticipation, response and recovery. As the implementation plan for the NWIRP outlines (2006 subcommittee on disaster reduction, www.sdr.gov), various agencies have lead roles for each of these phases and support of each other when dealing with high impact weather.

**Question 2: Based on progress in science and modeling capabilities, what are your projections and assessments for the future of windstorm forecasting and impact mitigation over the next decade? How can we continue to improve our capabilities in this area?**

**Response:**
NOAA is working to lengthen the lead-time and improve the accuracy of the prediction of high-wind events - tornadoes, hurricanes, and severe storms. The framework to improve high-impact weather prediction involves increased observations; advancing forecast models through research, development and engineering; and increasing computing resources and efficiencies. These advances will lead to improved forecasts, which will in turn provide better information for preparation and response. In addition, NOAA is working toward impact mitigation through social science research and outreach to first responders and the public.

NOAA is working on innovative observation technology solutions to advance the forecasting of high-impact weather events. For example, the President's FY 2013 budget requests an increase of $855,000 for wind boundary layer research to improve weather predictions. A better understanding of mid-level altitude winds will allow us to produce a more accurate forecast of wind speeds and direction. In addition, NOAA is researching and evaluating emerging technologies through remote sensing on various platforms (e.g, unmanned aircraft systems, Phased-Array Radar).

There is great potential for improved weather prediction through improved models because the sophistication of the assimilation, dynamic models and physical packages needed for Numerical Weather Prediction are advancing. A major opportunity that NOAA is pursuing is called "Warn On Forecast." This program is based on a new generation of models that can predict where tornado producing thunderstorms will appear an hour or two in advance – allowing people to move to shelters. NOAA's current warnings typically have 10 to 30 minutes of lead time, and are designed to help the public to seek shelter within their immediate dwelling or location.

Another important reason that the models are improving is that the speed of the fastest supercomputers continues to grow rapidly. In the last few years, a new supercomputer revolution is underway based on Massively Parallel Fine Grain computers. One example of this type of computer is the Graphics Processor Units, which were originally designed for computer games. A NOAA team has used a current version of the NVIDIA Graphics Processing Unit (GPU), which has 512 64 bit supercomputers on a single board, to show that its weather models could run 10 to 20 times faster (or alternately, could cost less than 10% as much for the same computing) than the current generation of supercomputers. NVIDIA is an American global technology company.

And finally, as part of the agency's goal to make the United States a Weather-Ready Nation (www.noaa.gov/wrn), NOAA is working to leverage and integrate ongoing interdisciplinary research programs, including social science research cosponsored by NSF and NOAA, towards improving understanding of individual and community decisions that tend to increase or decrease their vulnerability to windstorm hazards. NWS is also conducting outreach to first responders and the public on how to better understand and respond to forecasts of these types of severe weather events and have enlisted the support of social scientists to better work with the public and partner agencies.

*Responses by Mr. Eric Webster, Vice President and Director, Weather Systems, ITT Exelis*

ITT Exelis
1919 West Cook Road
Fort Wayne, IN 46818

260 451 6000
260 451 3309 Fax
www.exelisinc.com

ITT EXELIS

The Honorable Adam Harris
Chairman
The Honorable Brad Miller
Ranking Member
Subcommittee on Energy and Environment
Committee on Science, Space and Technology
U.S. House of Representatives
Room 2321
Rayburn House Office Building
Washington, D.C. 20515

Dear Chairman Harris and Ranking Member Miller:

It was an honor and privilege to testify before your Subcommittee on March 28, 2012 for the hearing, "To Observe and Protect: How NOAA Procures Data for Weather Forecasting." This letter is in response to your request for a review of the transcript and your request for answers to follow up questions. I am attaching a PDF copy of the minor corrections to the transcript and answers to the questions are below.

Question 1: Could you please explain for the Committee the value – or relative lack of utility – that polar satellites can offer in the form of data and observations used to provide effective forecasting and warnings for individual, localized outbreaks of severe weather, such as the recent string of tornado outbreaks over the past year?

Answer: Since the early 1970s polar weather satellites have been providing NOAA and the National Weather Service with critical data and information used in weather forecasting. Specifically, the polar satellites fly about 500 miles above the earth, traveling from pole to pole as the earth spins underneath, allowing for global data gathering. According to NOAA, these satellites provide more than 90 percent of the information used to develop global weather forecast models. In particular, it is the polar sounding instruments providing measurements throughout the atmospheric column, which are most crucial. These global forecast models provide the nation with the 2-7 day forecast. Through continued increase in capability and accuracy, these models can now predict certain large-scale severe weather outbreaks, such as tornadoes or major snow storms days in advance. Starting on April 7, 2012, the National Weather Service was able to issue forecasts and predictions of likelihood of tornadoes seven days in advance of the outbreak on April 14, 2012. Each day the forecast became more refined and specific with additional information, but federal, state and local officials had several days to prepare. The polar satellites and in particular the sounders played the major role in providing the data for that seven day warning of severe weather. But as the day and hours grew closer, the localized forecasts and hourly updates during the events relied on data and images from the geostationary (GOES) satellites as well as data and information from radar, other in-situ instruments to refine the forecast and warning areas even more. These refinements are critical for understanding where the storms are forming, where they are heading and likely duration for the warning areas. This information is not possible from the polar satellites.

Question 1 a: In your opinion, are there other cost-effective options that can provide a larger scale of observational data with a higher level of quality control and operational utility?

Answer: For the purposes of providing global weather data and information, polar satellites currently provide the largest scale of observational data and high level of quality control and operational utility. As we discussed in the hearing, some scientists believe a ring of six geostationary satellites with hyperspectral sounders on each satellite could provide significant improvements as they could monitor constantly the weather and its movements around the world, whereas current polar sounders provide a snapshot of each location as they move across the globe with revisit times of 12 hours or more. It is not clear if hyperspectral sounders at the geostationary orbit would be a cost-effective option to replace the entire polar satellite mission. One aspect we did not discuss in the hearing was the data and information provided by polar imagers. These sensors also provide useful data for global forecasts and play a specific role in helping to forecast severe weather in Alaska as the geostationary imagers, which monitor the U.S. constantly for severe weather, cannot provide clear images in the higher latitudes because of the curvature of the earth. Thus, the polar imagers are important to provide the cloud and other images and data needed to help forecasting in those northern latitudes where even other in-situ data is sparse because of the conditions. A ring of just geostationary sounders could potentially provide similar information to polar sounders, but they could not do the polar imager mission for northern latitudes. More studies would also have to been conducted on the cost and implications to NOAA's ground systems and ability to assimilate data into its models to determine if a ring of geostationary sounders would be cost effective to replace pieces or potentially the whole JPSS mission.

Question 1b: What processes could be used to quantify the value of these cost-effective options? What is NOAA currently doing in this regard – or, more importantly, what could and should they be doing?

Answer: NOAA would need to run OSSEs and other modeling studies to examine the benefits and impacts to the forecast and ground stations of hyperspectral data from geostationary orbit. A cost-benefit trade would then need to be conducted on the improvements versus the cost and then compared to the cost-benefit of other observations or improvements to overall forecast (i.e. more computing power, or other instu measurements). I am unaware if NOAA is conducting these specific analyses at this time. NOAA should consider conducting these studies if resources are available.

Question 2: ITT has been in discussions with the Air Force regarding polar imagers for its weather satellite program. Why isn't the Air Force continuing to procure a VIIRS instrument like NOAA? What is the cost and capability of ITT's solution?

Answer: The Air Force has been under significant pressure from Congress and from within the Department of Defense to justify the need and cost of a polar satellite program since the Administration's decision to split the NPOESS program into a military program (DWSS) and a civilian program (JPSS). In our meetings, the Air Force believes its requirements justify a weather satellite program, but it is re-examining the cost and benefit of a VIIRS instrument and looking at alternative approaches for its infrared imaging needs. ITT Exelis has built 19 of the NOAA polar weather legacy infrared imagers called AVHRR. These instruments, the size of a roll-on suitcase, are very stable and have been providing the primary polar imagery information to the National Weather Service, NASA, Europe and the world for several decades. ITT Exelis has provided the Air Force several options and capability levels using the AVHRR design as the foundation to significantly lower cost and overall risk, while providing substantial improvements from current DMSP (Air Force legacy polar satellite program) capabilities. The enhancements would provide finer resolution and additional channels for more cloud forecasting products, a top priority for the DOD mission. Specific cost estimates for an AVHRR are proprietary but we would be happy to provide those to the Committee separately from this public response. But the costs are much less than 1/10$^{th}$ of the estimated cost of second VIIRS flight unit. Also, because of the small size of the AVHRR, it can fit on a very small spacecraft, with a small launch vehicle, which taken together provide even more savings and flexibility to the Department of Defense.

Question 3: Your testimony stated NOAA should conduct studies to re-examine the requirement for an advanced geostationary sounder. Why and how should NOAA re-examine its decision? Given your concerns about the procurement process, do you believe NOAA should just buy data from a commercial vendor?

Answer: In 2006, NOAA decided against proceeding with the Hyperspectral Environment Suite (HES) instrument for its GOES-R program because of technical risks, cost and potential schedule implications. The HES instrument was a combination hyperspectral sounder and coastal imager wrapped into one instrument. There was difficulty in finalizing the requirements for this complicated instrument and in determining the capability and needs for a ground system to collect all the data. Since the decision, the desire for this capability has continued to grow along with some research into its potential benefits. In addition, the technology used to develop the ITT Exelis Advanced Baseline Imager (ABI) for the GOES-R program is very similar to the technology needed to develop and build a hyperspectral geostationary instrument. Thus, as we are in production of the first ABI flight unit, we believe the overall technical risk is now much lower, and because we are on contract to build several ABI instruments the cost of an additional copy with modifications for a hyperspectral sounding mission is significantly lower than projections in 2006. There have also been advances in data processing capabilities to ensure the data can be down-linked and assimilated by the National Weather Service. NOAA should conduct OSSEs and other simulations to determine the specific impacts to the forecast of adding a geostationary hyperspectral sounder to determine benefits versus the costs.

At this juncture in the GOES-R program the addition of a hyperspectral sounder would not fit on the existing spacecraft. Therefore, it would be much more cost-effective and quicker for NOAA to purchase the data from a commercial entity than for the government to pay for the development of an instrument, pay to build a satellite bus, and pay for it to be launched into space. The commercial industry could build its own instrument and share a spacecraft and a launch vehicle with a telecommunications company for the lowest cost options and then provide the data to NOAA for a fee, at a fraction of government's total procurement cost.

Thank you for the opportunity to testify and provide additional information to the Subcommittee. We appreciate your leadership and efforts to help NOAA and our nation have the most robust and cost-effective weather forecast and warning system in the world. Please let me know if you have any additional questions.

Sincerely,

Eric Webster
VP and Director
Weather Systems
Geospatial Systems Division
ITT Exelis

*Responses by Dr. David Crain, Chief Executive Officer, GeoMetWatch*

Thank you very much for the opportunity to further clarify our testimony and address specific questions passed along by the committee.

The overarching and continuing concern which many members of the science community and I have is that is very little transparency as to how NOAA makes important decisions on its weather and earth observation satellite acquisition strategy.

NOAA expends significant funds and technical resources conducting multiple Cost Benefit Analyses for its weather observations enterprise. What is disturbing is that the results of these CBAs are either routinely ignored or completely misrepresented in past testimony to this and other committees of Congress.

The most recent example of this misrepresentation was in Administrator Lubchenco's testimony on March 8, 2012. In her written statement she referred to the extensive CBA conducted on the GOES-R program Dr. Luchenco claimed that the benefits of the GOES-R Advanced Baseline Imager (ABI) program exceeded $50M/year by reducing avoidable weather-related (aviation) delays. However, the GOES-R CBA makes it explicitly clear that these benefits are derived from the Hyperspectral Environmental Suite (HES) or GEO hyperspectral sounder.

The summary of these benefits is shown below from the CENTREC Consulting Group study.

**Table 60. Allocation of Benefits by Instrument**

| Case Study | Benefit Portion HES | Benefit Portion ABI | Present Value of Benefits ($M) HES | Present Value of Benefits ($M) ABI | Present Value of Benefits ($M) Total |
|---|---|---|---|---|---|
| Aviation | | | | | |
| Avoidable weather-related delays | 100% | | $504 | | $504 |
| Volcanic ash plumes | | 100% | | $265 | 265 |
| Energy | | | | | |
| Electricity | 50% | 50% | 1,256 | 1,256 | 2,512 |
| Natural gas transmission | 50% | 50% | 10 | 10 | 19 |
| Natural gas utilities | 50% | 50% | 16 | 16 | 32 |
| Irrigated agriculture | 50% | 50% | 545 | 545 | 1,090 |
| Recreational boating | | 100% | | 141 | 141 |
| Total | | | $2,331 | $2,232 | $4,563 |
| Portion of benefits | | | 51% | 49% | |

*from: "An Investigation of the Economic and Social Value of Selected NOAA Data and Products for Geostationary Operational Environmental Satellites (GOES), submitted by CENTREC Consulting LLC, Feb. 2007"*

In fact, the entire theme of the CENTREC study indicates that the majority of the economic benefit of the GOES-R mission is derived from the HES geostationary hyperspectral sounder, which NOAA canceled.

The following table from this same study also shows that the estimated benefits for the High Resolution Spectral Sounder (HRSS) geostationary hyperspectral sounder are *significantly greater* (15% vs. 5%) in the area of Tropical Cyclone (hurricane) track and intensification prediction.

**Table 1. Summarized Technological Impacts of Improved Geostationary Data on Tropical Cyclone Forecasts**

| | Base Case (ABI) | Enhanced Technology (ABI plus HRSS) |
|---|---|---|
| Instrument focus | ABI | ABI plus more accurate technology performance such as a high resolution spectral sounder (HRSS) |
| Improved GEO data's impact on TC forecasts | Analysts' most conservative estimates | More aggressive estimates[2] |
| Impact on watch/warning and evacuation areas | 5% | 15% |

*From* **"Potential Socio-Economic Benefits of GOES-R" By Sharon K. Bard, Todd A. Doehring and Steven T. Sonka Presented at the Fifth GOES Users' Conference January 24th, 2008**

And yet, in the April 23th, 2012 edition of 'Space News' NOAA spokesman John Leslie said, " NOAA has determined that geostationary (hyperspectral) sounding data are not as high of a priority as other currently unfunded operational data needs."

Statement such as that, erode NOAA's credibility and conflict with NOAA's own multiple CBAs, which confirm that *geostationary hyperspectral sounding data are likely more important than the sum of all of their current unfunded operational data needs*, and are of comparable or greater value to the ABI on GOES-R. It is anticipated that if a comprehensive, high-resolution observing system simulation experiment (OSSE) were done the same results will emerge.

Furthermore, the NOAA CBA and the GOES-R AOA (Analysis of Alternatives) for the Geo Hyperspectral Sounder (in the wake of the canceled HES) assumed an implementation cost of ranging from $600M to over $1B. *A commercial alternative of these data is drastically cheaper, available sooner and delivers the full benefit at lower cost and risk.*

**According to** the National Academy of Sciences report, released on May 2, 2012, "*Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey,* the Academy has made repeated and explicit recommendations to restore Advanced Geo Sounding Capability which have been essentially ignored (p.82-84).

The report further comments that NOAA's claim that a sounder is not a priority is "ironic" since they have flown sounders on every previous GOES mission (p.79). These are EXACTLY the kind of recommendations, which can be explicitly addressed with a comprehensive Cost Benefit Analysis and Observing System Simulation Experiment (OSSE) study.

As compared to the current GOES Sounder, the GMW STORM sensor offers a quantitative improvement in information content, approaching 4000x as summarized in the figure below. It is hard to see how such a capability has less "value" than the current GOES Sounder, especially when its cost is less!

***Geostationary Weather/Environment Sounding Instrument Performance Comparison***

| Specification | | GOES/NOAA | STORM/GMW | Improvement Factor |
|---|---|---|---|---|
| # Spectral Band | IR | 18 | ~1600 | **~89** |
| | VIS. | 1 | 4 | **4** |
| IR Spectral Resolution (1/cm) | | ~30-50 | ~0.625 | **~64** |
| Absolute Accuracy (K) | | 1 | 0.1 | **10** |
| Temporal Sampling Rate (minutes) | | 42 (3000 by 3000 km) | 6 (3072 by 3072 km) | **7** |
| Spatial Sampling (km) | | 10 by 10 | 4 by 4 | **~6** |
| Vertical Resolving Power (km) | Temperature | 3-5 | ~1 | **~3** |
| | Water Vapor | 6-8 | ~2 | |
| Domain Coverage | | Regional (Western Hemisphere) | Global | **~3** |
| # of gases/particles measured | | 1 ($O_3$) | 6 ($CO_2$, $O_3$, CO, aerosol, ash, dust) | **6** |
| **Overall Performance** | by 1) Accuracy 2) Temporal 3) Spatial 4) Vertical & 5) Coverage | 1) 1K 2) 42 minutes 3) 8 x 8 km 4) 3-5/6-8 5) Regional | 1) 0.1K 2) 6 minutes 3) 4 by 4 km 4) 1/2 5) Global | **3,780** (10x7x6x3x3) |

***SUMMARY: GeoMetWatch STORM is designed to specification that far exceed existing technology with more than 3 orders of magnitude (3,780 times) better measurement performance than its current operational counterpart, NOAA GOES-Sounder***

And to further highlight the critical need and significance of this mission, the National Academy of Sciences, released on May 2, 2012 its latest report concluding that **"....The United States is facing a "precipitous decline" in its ability to explore and monitor the Earth from space... and that that critical Earth science and weather observations face a decline of 75% (or more) in the coming decade".**

Finally, it is disingenuous for NOAA to claim they have no plans for an advanced Geo Hyperspectral Sounder, when their official plan is to purchase an advanced sounder from EUMETSAT by 2024. This plan was signed by the NOAA NESDIS director in September of 2010 and delivered to the NWS director. Given current estimates of the European third-generation meteorological satellite (MTG) program costs and the level of support which NOAA would likely need to provide, this is at least a $1B program, which will not deliver data until the next decade at the earliest.

Our recommendations to this committee are as follows:

1. Make every effort to restore the Advanced Geostationary Sounding Capability at the earliest opportunity by the most cost-effective means. We feel a commercial option offers the lowest technical risk, lowest cost and earliest available capability over all other options. To put it bluntly, geostationary hyperspectral sounding data are too important to put off until the next decade. Lives and property will be continue to be unnecessarily lost due to severe weather for lack of these data.

2. Enable NOAA and/or the NWS with explicit authorization and direction to make data purchases to meet their standing requirements expeditiously. The standing requirement for gridded, high-resolution vertical atmospheric profiles is critical for improving US Severe weather forecasting and hurricane prediction. This is also a NOAA deliverable to the Federal Aviation Administration (FAA) for their high-priority NextGen air traffic management implementation.

3. Enable NOAA and NWS to upgrade its infrastructure to ingest commercial weather data to maximize the improvement of severe storm forecasting.

4. Provide direction and resources to enable comprehensive OSSE studies and demand transparency and disclosure of those results. When missions are canceled, there needs to be an evaluation of what capabilities will be lost and the reasons for cancelation need to be clear to all stakeholders. When new missions are proposed, there must be a clear understanding of the mission requirements. When the capability to deliver these requirements is canceled, the viability of the baseline mission must be reexamined.

5. Restore an active, full-time Director to lead the Office of Space Commercialization. The director is a *critical* advocate for commercial, cost-effective alternatives to standing observational requirements within the government, and should not hold dual positions as both a procurement official *and* a commercial advocate – clearly conflicting responsibilities.

Specific Answers to Committee Questions:

1. Do you agree that NOAA needs to do better quantitative analysis when evaluating and funding observing systems? Do you have any other recommendations for analyses which you believe NOAA should use in their evaluations?

   a. Do you believe that more frequent use of Observing System Simulation Experiments (OSSE) would improve this process?

   b. Would you please explain the specific benefits that OSSEs could provide to the quantitative analysis used in NOAA's evaluation of observing systems?

2. Could you please explain for the Committee the value—or relative lack of utility—that polar satellites can offer in the form of data and observations used to provide effective forecasting and warnings for individual, localized outbreaks of severe weather, such as the recent string of tornado outbreaks over the past year?

   a. In your opinion, are there other cost-effective options that can provide a larger scale of observational data with a higher level of quality control and operational utility?

   b. What processes could be used to quantify the value of these cost-effective options? What is NOAA currently doing in this regard—or, more importantly, what could and should they be doing?

3. Given how hard it is to build space-based instruments, why are you so confident your company can do it and make money on selling the data?

4. What would an OSSE study of advanced geostationary sounders show?

5. Please elaborate on the potential cost savings associated with weather data acquisition under the model that GeoMetWatch is proposing vs. the current system? How do the capabilities compare?

6. Has the US Government engaged in the procurement of commercial satellite data in other areas? What are the risks and what would happen if a GeoMetWatch satellite failed?

1. In the past, NOAA has had comprehensive plans to evaluate current and future capability. However, as programmatic performance and cost overruns have plagued NESDIS over the past decade, NOAA has ignored the recommendations of their own evaluations and those of outside organizations (NRC, NAS, WMO, ITOVS, and NWA, among others) that have continuously called for reinstatement of the Advanced Geo Sounder Mission for reasons of mere expediency.

How else can decisions to cancel the sounder and ranking it lower the other "unfunded operational data sets" be justified? These other unfunded missions do have value, including COSMIC, DSCVR, and JASON, but----and this should be clear----the SUM of their value is a fraction of the Advanced Geo Sounder Value according to NOAA's own analysis!

However these missions do address different mission areas, so a one to one comparison is not entirely possible. Furthermore, a TRUE cost benefit analysis would further show, that if the cost of the Advanced Sounder Mission can be delivered even cheaper than NOAA estimates (as is possible with a commercial mission), then the benefit is even greater. None of the other unfunded missions have a fraction of the capability to improve severe weather forecasts, hurricane landfall and intensification and medium and long range numerical weather prediction. In fact, NOAA has no funds for these missions either and if they are so important, they should consider commercial options for them also. All of these missions can be flown cheaper and more effectively by private enterprise. GMW is prepared to do this for any and all of these missions, but in our assessment, the Geo Sounding mission is orders of magnitude more valuable

Observational System Simulation Experiment (OSSEs) can help demonstrate all of these comparative benefits.

In general the function of an OSSE is to trade the comparative value of two or more observational datasets to improve prediction capability for a specific event or for a numerical weather forecast. Because of the sophistication and variability of the wide range of observations that can be assimilated into weather prediction models, care must be taken that the background atmospheric model (known as a nature run) has sufficient dimensional (horizontal and vertical) and temporal resolution to adequately compare the observations being evaluated. It is also important that the physical processes in the model or in its step size or resolution do not bias the results.

OSSE's have been done in the past to compare low resolution systems, such has broadband sounders vs. Microwave sounders vs. Radio occultation sounders. Because each of these systems have limited resolutions, the nature runs required to compare these observations are relatively course. These nature runs are inadequate for a Geo Hyperpsectral Sounder comparison, mainly because their dimensional and temporal resolution is too course. What this means if that an OSSE is done using an inadequate nature run the results will underestimate the value of the higher resolution system, if the nature run does not have comparable or better resolutions. This is problem one which must be addressed in performing on OSSE for an advanced Geo Sounder. Better nature runs, must be calculated.

Problem Two is that these higher resolution nature runs take significantly more computer resources than lower resolution runs. In order for these OSSE's to be done in a timely manner, adequate computer resources must be made available.

Finally, it's important to fully evaluate all aspects of new observations, some of which may not be obvious from previous OSSE's of less capable systems. An example in the case of Advanced Geo Sounding is that while a normal OSSE may compare the impact of various vertical profiles determined by the different techniques being compared, it is also important to make use of unique capability of one system or the other. In the case of comparing a Hyperspectral Geo Sounder to a Hyperspectral LEO sounder, it would be easy to compare individual profiles on a one-to-one basis. This might even show that the LEO sounder produces a slightly better profile when individual observations are compared. This highlights an advantage of the LEO system, its closer to the atmosphere, so makes a slightly better radiance observation from a noise perspective. However, this neglects the most significant advantage of the Geo system, it makes continuous observations! These means that over time, the GEO observations become better and better while the LEO observations remain the same, until the next sample. Since the GEO system can sample the same column of atmosphere dozens, hundreds or thousands of times per day compared to 2 or 3 for a LEO system, the advantage of the GEO system begins to become obvious. Furthermore, the continuous sampling of the GEO system allows for unique observations or 3-D wind observations and better sounding in and around clouds. When all of these capabilities are comprehensively compared in an OSSE, we are confident that the clear merit of the GEO Hyperspectral Sounder will be obvious. NOAA HAS NOT DONE THIS ANALYSIS.

a. It's imperative that an objective means be used to evaluate the value and benefit of current and future systems and that a transparent process be used. Even today, 5 years after HES was cancelled on GOES-R, nobody knows why. The fact remains that even after the mission was canceled, NWS still has a requirement for GLOBAL and regional High Horizontal and Vertical Resolution Atmospheric Profiles that cannot be achieved by any other observational system on a regional and global basis.

2. Polar satellites, by themselves and as individual satellites, have very little capability to provide effective observations for localized severe weather. This is primarily due to the fact that a single Polar satellite can only observe a give region of the US a few times per day separated by many hours. A single polar satellite can provide a cost effective means to make global observations for numerical weather prediction and very good observations of high latitude regions. However at lower latitudes as in the continental United States, the sampling frequency is simply too low. At best a Polar Satellite can only take a single snapshot of any severe weather system. It alone cannot observe if the severe weather is weakening or strengthening and sometimes cloud cover can obscure effective observation.

a.) A Geostationary system addresses all the weaknesses of a polar satellite (and is the reason both systems have been flown together, because of the complementary nature of their observations) but at the expense of global coverage. A single geostationary satellite makes continuous observations over the same region of the Earth, continuously with no lapse in coverage. A single geostationary satellite operating between about 80-120W Longitude can cover the entire US. Two Geo satellites operating around 75W and 135W can cover the entire US and most of the Atlantic and Pacific regions which influence near term weather over the US (These are the current locations in which NOAA operates the GOES series of weather satellites). However, while the current GOES series of spacecraft have a low spectral resolution sounder, the future GOES-R series does not have a dedicated sounder at all. Additionally, since there is only a single imager on each satellite of the GOES-R series, there is no backup capability if the primary sensor fails. All GMW sensors will have both sounding and imaging capability and while the primary mission is high resolution sounding, the imaging capability of each GMW sensor will be equivalent or better than the current GOES Imaging mission.

b.) NOAA has in the past evaluated in a fairly comprehensive way the relative value of the GOES-R Imaging and Advanced Sounding missions. These Cost benefit Analysis were used both in the requirement definition phase and in the rationale NOAA used to justify the original GOES-R mission. These analyses revealed that the majority of the economic benefit of the entire GOES-R Mission was derived from the two primary sensors, the Advanced Baseline Imager (ABI) and the Sounding mission within the Hyperspectral Environmental Suite (HES). There have been several versions of these Cost Benefit Analysis (CBA's) with the most recent being published in 2003 and 2007. These CBA's examined a wide range of benefits due to observations from the sensors manifested for the GOES-R mission. The irony, is that these studies showed that the benefit of the Hyperspectral Sounder was equal or greater than the benefit of the Advanced Imager. To this day, there has still not been an adequate justification given as to why one primary sensor was kept and another was canceled. It is likely merely for the reason that at the time which the NPOESS program was undergoing its first Nunn-McCurdy event, the GOES-R Imager contract had been awarded, but the Sounder contract had not. It is interesting to speculate whether the Imager would have been canceled if the Sounder contract had been awarded first.

The important point here, is that NOAA did do a good job in its original determination of what was needed for an effective

GOES-R mission. However, when other programs began to have problems, it seems that the Advanced Sounder was one of the first to be canceled.

3. GMW could not do this mission without significant prior government investment in hyperspectral technology. GMW's situation is unique in that hundreds of millions of dollars were spent on the development of the hyperspectral sensor technology. GMW is able to leverage this previous investment and make use of best practices in the commercial space market to design a complete mission concept that is sustainable, affordable, and with much lower technical and programmatic risk to our customers. GMW's sensor contractor, Utah State University's Space Dynamics Lab (SDL), has a multi-decade history of delivering its sensors payloads on time and on budget. In this case, SDL has already built the prototype for the GMW sounder, called STORM.

GMW has licensed a global constellation of six hyperspectral sounders. Our constellation architecture with inherent redundancy assures reliable data service for our customers. This means that even if we have a launch or premature on-orbit failure we will have a backup either already in orbit or ready to launch within a short period of time. The GMW global constellation is also designed to have overlapping coverage so that no single sensor failure will significantly impact our global observation capability.

We have priced the GMW service to be a small fraction of what a dedicated satellite system would cost, but the revenue is also sufficient to insure a sustainable and ongoing capability. Just like in the commercial communication satellite market, GMW will be incentivized to offer service everywhere we have customers. We think there is sufficient need and our price point is low enough that we will be able to offer a true global service at less than one tenth of the cost of a conventional alternative.

In the early 1960s the United States invented the weather satellite, the Television and Infrared Observing Satellite (TIROS) and has been the leading innovator of new technology to improve earth observation and weather prediction. As stated in the National

Academies' report, the U.S. is currently at risk of losing not only our existing capability, but our technological lead as well. The geostationary hyperspectral mission is too important to abandon or put on hold for a decade or more. Other countries around the world are continuing to fund sounder programs of their own. Far better to continue to lead and sell our data to international governments than have them eclipse our technology and be forced to procure data from them.

Our goal is to guarantee the availability of these critical hyperspectral data on a serial, overlapping and sustainable basis. By selling to multiple countries and pricing our system at a fraction of what the G20 countries currently spend on their own operational weather systems, we can insure affordability while still pushing the state-of-the-art in hyperspectral capability.

Finally, as a truly commercial venture, GMW assumes all of the risk. We were issued a license because of the stated NOAA need and the lack of any planned NOAA hyperspectral missions until well into the next decade. We ask for no funds up front, only a commitment to buy data when it is available and only if it meets the customer's expectations. Our success will also be the government's success as we will have fulfilled the original Advanced Sounder mission which congress intended when GOES-R was authorized. Furthermore, our success will demonstrate that operational weather programs can be put on an affordable basis going forward without sacrificing life-saving new observation capability.
Because we have purposely based our business around a mission that NOAA has chosen not to fly, there is no risk to the current or future operational plan if we should fail.

4. At its simplest, an OSSE would compare continuous, uninterrupted, high-resolution coherent observations of the entire 3-D structure of the atmosphere including winds (for a GEO Hyperspectral Sounder) VERSUS intermittent, random, infrequent and disparate observations (for a LEO Polar satellite).
This simulation will show that not only will severe weather and hurricane track and intensification forecasts improve, but that

medium and long range numerical weather predictions will improve as well.

5. There are several ways to compare the cost savings:
   - No funds spent up front: GMW only expects payment for services received. No development costs, extremely low exposure to launch delays. To date GOES-R alone has already cost several billion dollars.
   - Another way to compare cost. Instead of comparing to an individual program, just compare to the 10 year average of what NOAA spends to develop, procure and operate its weather satellite systems. This is conservatively (from all sources NOAA, NASA, DOD) about $3B/year. 20 years (at no cost growth, which is unlikely) would cost the US about $60B. GeoMetWatch will offer service at fixed prices to the U.S. Government at about $250M for all data from our global system. This amounts to $5B over the same 20 year period, a savings of $55B and less than 10% of what a comparative conventional capability would cost. Plus the GMW architecture is global and offers three times the coverage of the current GOES operational system.
   - Finally, the capability of a global hyperspectral sounder system would be *superior in data quality to any system currently planned by any country*. The total number of soundings per day will exceed 600 million observations globally. This is about twenty times the total number of soundings observed from ALL sources today. In addition, the GMW system will have global imaging capability to either backup or supplement the geo imaging systems operating today and in the future. The GMW imaging capability will equal or exceed all current GEO Imagers flying today and offer true global coverage.
   - The specifics of the GeoMetWatch STORM sensor will provide a technologically and scientifically sound solution to our nation's future requirements in forecasting and monitoring, requirements. STORM is to be built to specifications that far exceed existing sensor technology

(see table below). The enhanced STORM sensing capability, estimated to be ~3,780 time better performance than its current counterpart GOES-Sounder operated by NOAA. STORM will, 1) be faster (~7x), 2) be more frequent (seconds to minutes), 3) capture finer scale of events (few km), 4) resolve vertical fine scale (~1-2 km), 5) be more flexible in areal coverage (from ~1,000 km by ~1,000 km to ~10,000 km by ~10,000 km to global coverage except poles), 6) be more sensitive to hazards and pollution (storms, hurricane, dust/aerosol, volcanic ashes/gases, carbons, trace gases) and most important, 7) provide around the clock, highly accurate information needed for hazard alerts and disasters warning and decision making for risk mitigation.

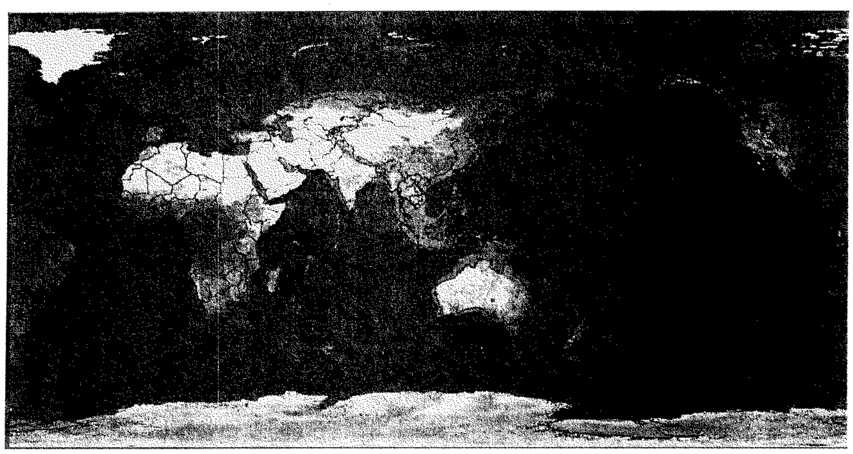
- The Quantitative Impacts of these technical improvements are precisely what an OSSE is most useful for. It also allows for GeoMetWatch and its users to optimize overall observing strategies for maximum benefit to each mission area: Severe Weather Forecast/Warning, Hurricane Track/Intensification, Numerical Weather Prediction, etc. Each mission area may benefit from changes in observing strategy and OSSE's can help best assess how the GMW system can be utilized by NOAA and NWS users. This has benefit above and beyond simple mission assessment and represents an additional benefit for such OSSEs.

| *Geostationary Weather/Environment Sounding Instrument Performance Comparison* | | | | |
|---|---|---|---|---|
| Specification | | GOES/NOAA | STORM/GMW | Improvement Factor |
| # Spectral Band | IR | 18 | ~1600 | **~89** |
| | VIS. | 1 | 4 | **4** |
| IR Spectral Resolution (1/cm) | | ~30-50 | ~0.625 | **~64** |
| Absolute Accuracy (K) | | 1 | 0.1 | **10** |
| Temporal Sampling Rate (minutes) | | 42 (3000 by 3000 km) | 6 (3072 by 3072 km) | **7** |
| Spatial Sampling (km) | | 10 by 10 | 4 by 4 | **~6** |
| Vertical Resolving Power (km) | Temperature | 3-5 | ~1 | **~3** |
| | Water Vapor | 6-8 | ~2 | |
| Domain Coverage | | Regional (Western Hemisphere) | Global | **~3** |
| # of gases/particles measured | | 1 ($O_3$) | 6 ($CO_2$, $O_3$, CO, aerosol, ash, dust) | **6** |
| **Overall Performance** | by<br>1) Accuracy<br>2) Temporal<br>3) Spatial<br>4) Vertical &<br>5) Coverage | 1) 1K<br>2) 42 minutes<br>3) 8 x 8 km<br>4) 3-5/6-8<br>5) Regional | 1) 0.1K<br>2) 6 minutes<br>3) 4 by 4 km<br>4) 1/2<br>5) Global | **3,780**<br>(10x7x6x3x3) |
| *SUMMARY: GeoMetWatch STORM is designed to specification that far exceed existing technology with more than 3 orders of magnitude (3,780 times) better measurement performance than its current operational counterpart, NOAA GOES-Sounder* | | | | |

6. The precedent of the US Government purchasing commercial space-based data is already well established through ongoing purchases of commercial high-resolution imagery from GeoEye and DIgitalGlobe, lower resolution imagery from RapidEye and Synthetic Aperture Radar data

from foreign sources. GMW would anticipate similar contractual arrangement for purchasing its hyperspectral data services.
The GeoMetWatch system will be fully insured and any launch or on-orbit failure will be replaced. Because GMW is building many sensors (6 +2 spares), there will minimal production delay for any replacement. Finally, the full GMW system will have some overlap, so that loss of any one sensor will not lead to a complete lack of data.

This overlap is shown for our prospective Asia Orbit locations note below:



*Responses by Mr. Bruce Lev, Vice Chairman, AirDat LLC*

U.S. House of Representatives
Committee on Science, Space, and Technology
Subcommittee on Energy & Environment

Hearing Questions for the Record
The Honorable Andy Harris

*To Observe and Protect: How NOAA Procures Data for Weather Forecasting*

Mr. Bruce Lev

1. Do you agree that NOAA needs to do better quantitative analysis when evaluating and funding observing systems? Do you have any other recommendations for analyses which you believe NOAA should use in their evaluations?

   Yes. The observing system impact studies performed by NOAA are lagging behind those of other global government meteorological agencies (e.g., ECMWF and UKMO). The real shortcoming exists in the cost-benefit analysis, and how that is linked to direct impacts over the tax-paying domain. For example, it is well documented that satellite radiance data show far more positive impact in the Southern Hemisphere (please see Attachment A), but how does this directly benefit the US if the weather patterns are equatorially bifurcated? I would suggest that NOAA spend more time conducting cost-benefit analysis and impact verification on *available* observing systems over the US (i.e., tax-paying) domains.

   a. Do you believe that more frequent use of Observing System Simulation Experiments (OSSEs) would improve this process?

      No. OSSEs are valuable tools for determining the potential impact of future observing systems, which are not currently in existence. If NOAA is unable to extract the maximum value from existing observing systems, I do not see the point of financing hypothetical what-ifs. NOAA is being outperformed in the world of numerical weather prediction (NWP) by the private sector, as well as many other governmental meteorological agencies (Attachment B). Since these other entities are using the same data as NOAA, it is clear that NOAA is not adequately utilizing their present resources.

      OSSEs are valuable, but they should be left to hardware manufacturers and the university research community, and vetted through scientific peer review. NOAA should be focusing its efforts on solving current forecasting problems plaguing the tax-paying public with the under-utilized observing systems presently at their disposal.

   b. Would you please explain the specific benefits that OSSEs could provide to the quantitative analysis used in NOAA's evaluation of observing systems?

      An OSSE provides no value for an existing observing system. The value of an OSSE is the predictive ability of the experiment to estimate the potential impact a *future* observing system would have, should it be deployed. The OSSE is just that: a *simulation* of an observing system. A more valuable test of an existing observing system would be a Forecast Sensitivity to Observation (FSO) experiment. The FSO test would not only allow a realistic quantitative impact assessment of an existing observing system, but the cost-benefit analysis should be straightforward since it already exists. A cost-benefit analysis of a simulated observing system would require a simulated (i.e., fictitious) cost estimate.

2. Could you please explain for the Committee the value—or relative lack of utility—that polar satellites can offer in the form of data and observations used to provide effective forecasting and warnings for individual, localized outbreaks of severe weather, such as the recent string of tornado outbreaks over the past year?

   Satellites provide value to the forecaster in terms of visualization. Various forms of imagery (e.g., visible, inferred, etc.) allow forecasters to alter predictions in the short term, and verify modeled forecasts. Satellites also provide raw data for use as initial conditions in NWP. The main value of these data is over regions where no other data exist. For example, radiance profiles, including those from hyperspectral sounders, as well as motion vector winds, add value over the open ocean, but they add little value over regions that contain in-situ observations (e.g., aircraft, balloons, etc.).

   i) The vertical resolution is not adequate for high-resolution modeling. A very high vertical resolution satellite profile may achieve 500 meters in optimal weather conditions, whereas RAOBs (i.e., balloon observations) and aircraft have a vertical resolution on the order of 1 meter.

   ii) The profiles from satellites must be processed through an additional "forward" model because satellites do not actually observe model variables directly. They observe proxy spectra or spectral signals. The process of converting the spectral profiles into state variables (i.e., moisture and temperature) adds an additional source of significant error.

   Because of these two issues, satellite data will add value for coarse-resolution global modeling, where open ocean sampling is needed. They also add value in regions lacking other observing systems (e.g., Southern Hemisphere). In fact, most prediction centers only use satellite observations over the ocean. For events like predicting intensity and track of tropical systems off the coast of Africa, satellites are quite valuable. However, for predicting high-resolution convective events like the tornado outbreak over the eastern US, they would add little, if any, value.

   a. In your opinion, are there other cost-effective options that can provide a larger scale of observational data with a higher level of quality control and operational utility?

      Almost any in-situ observing system would greatly outperform a satellite when it comes to cost-effectiveness on a per-observation impact assessment, and particularly for convective and tornadic events, as well as precipitation type events (e.g., ice, sleet, snow, etc.). A study performed by Benjamin et al. (2010) shows that RAOBs and aircraft were by far the largest contributors to forecast skill (Attachment A), **yet the combined budgets for these observing systems are approximately 0.5% of the NOAA satellite budget.**

   b. What processes could be used to quantify the value of these cost-effective options? What is NOAA currently doing in this regard—or, more importantly, what could and should they be doing?

      NOAA should place greater emphasis on FSO studies. The one problem with this situation is the results are a function of not only the value of the data, but also how well the forecast model can use the data. Since NOAA's modeling lags behind that of agencies like ECMWF and UKMO, identical data tested in both systems may yield different results, as a function of antiquated data assimilation techniques, and not necessarily related to data quality (Attachment B).

      The FAA funded a NOAA 4-year FSO impact study on TAMDAR data, and the results were stunning (Moninger et al. 2010). The goal was to see if TAMDAR would improve the forecast over the US, and this was *in addition* to every available observing system. A success would be considered an improvement of 1-5%. Just 20% of the available TAMDAR data set was shown to improve the forecast skill over the US by 35-50% (despite using NOAA's antiquated assimilation techniques), and the largest improvements were seen in more severe weather conditions.

3. In your written testimony you state that "The single most critical component of the forecasting process is the ability to collect a vast quantity of very accurate lower-atmospheric observations with high space-time resolution."

   a. Could you please elaborate on this statement, and also briefly explain how our country is "under-sampled" despite data collection systems deployed by NOAA?

   A forecast is a prediction by a set of equations that are well accepted in the scientific community. Their ability to properly predict the future atmospheric state relies entirely on the accuracy of the initial conditions that are fed into the equations (i.e., garbage in, garbage out). It is absolutely imperative that the model be initialized with the best representation possible of the current state of the atmosphere. To achieve this, one must do two things: i) observe the atmosphere with high precision and accuracy, as well as high space-time density and frequency, and ii) assimilate these observations into the model in their proper space-time location with proper weight.

   With respect to precision and accuracy, in-situ observations (RAOBs [weather balloons] and aircraft) are far superior to those that are remotely sensed (cf. response to #2 subpoint i). With respect to space-time density, RAOBs, which are the gold standard for upper-air observation accuracy, are limited to 91 locations in North America (e.g., roughly a 45,000 $mi^2$ void between each site). They are launched twice a day, so there is also a 12-hour temporal data void. With cutting-edge models able to reinitialize hourly, and process data on grids finer than 1 km, it is clear that 12 hour data voids over regions exceeding 45,000 $mi^2$ is vastly insufficient. Aircraft data such as TAMDAR, which include all the same metrics as RAOBs with accuracy equal to RAOBs, and transmission in real time (opposed to the RAOB latency of 2 h) mitigate this to a large degree. Other observing systems deployed by NOAA, particularly satellites, fall well short of replicating the accuracy of RAOBs and TAMDAR.

   b. You later note that "remotely sensed satellite profiles have limited value in high-resolution numerical weather prediction compared to aircraft or balloon data." Could you explain this concept and in doing so discuss the value of you company AirDat's TAMDAR system?

   The limitations of satellite profiles for high-resolution NWP are discussed in the responses above.

   The TAMDAR system observes temperature, wind, moisture, pressure, icing, and turbulence. The icing and turbulence are valuable for aviation safety. The other observations are identical to those observed by RAOBs. The TAMDAR data has been shown in peer-reviewed literature to be at least as accurate as RAOBs (Gao et al. 2012).

   The additional value of TAMDAR beyond RAOBs comes with the nature of the real-time data relay. RAOB data takes roughly 2 hours to collect, process and be ready for model use. TAMDAR data is relayed through a quality control system and transmitted in less than 60 seconds. Another benefit is planes equipped with TAMDAR fly to well over 300 locations in North America, which doesn't include the European coverage, and produce more than 20x the number of vertical profiles compared to RAOBs. Also, data is streamed continuously around the clock, and not just once every 12 hours.

   To summarize, RAOBs are the gold standard for observational data quality. Satellites cannot, and may never, come close to the accuracy of a RAOB. However, RAOB data is geographically sparse (>45,000 $mi^2$) with 12 h voids in sampling, and a 2h delay in receiving the data. TAMDAR replicates the accuracy of RAOBs, solves the temporal and geographical data void problem, and reduces the transmission delay from 2 h to 60 seconds at a lower cost per sounding than RAOBs.

4. What other systems or data sources that you are familiar with might offer a proportional increase in forecast utility and cost-effectiveness when compared to NOAA's satellite systems?

   Unfortunately, there is no other observing system that can do this. There has been some promising research involving GPS signals from ground-based sensors to obtain moisture values, and this has been shown to have notable impact in NWP. Profiler networks also add value, but they are both very expensive, and require land acquisition for the ground-based siting. The hope is that some day, satellites will achieve the resolution and accuracy of RAOBs or TAMDAR, but this is decades (and billions of dollars) away, so until then, nothing can come close to RAOB and aircraft data such as TAMDAR. In addition, the cost-benefit ratio for TAMDAR aircraft observations is significantly better than that for RAOBs.

*Responses by Dr. Berrien Moore, Dean, University of Oklahoma College of Atmospheric and Geographic Sciences, and Director, National Weather Center*

# Response
# 23 April 2012
# Letter from the Chair

Berrien Moore III

1. Do you agree that NOAA needs to do better quantitative analysis when evaluating and funding observing systems? Do you have any other recommendations for analyses, which you believe NOAA should use in their evaluation?

   This is an important issue. The fatal step in the NPOESS program was that the requirements setting process was open-ended and without tight financial constraints. Furthermore, I do think that NOAA needs to do a better job in conducting quantitative assessments on data use, cost, and value. In this regards, the perfect while better is always far more costly that estimated, and therefore, I would be mindful of having the perfect become the enemy of the good. However, we also need to recognize that there is no simple mechanical approach to this analysis. There will be competing demands and not everything can be easily quantified. For example, NOAA and the DoD flew the AVHRR instrument, which was primarily used for cloud analysis; however, AVHRR proved to be of extraordinary value for vegetation studies. In fact, it was Dr. Compton Tucker at NASA GSFC that created the Normalized Difference Vegetation Index that was based on the AVHRR instrument and which proved to be of extraordinary vale in the study of terrestrial ecosystems. This was hardly foreseen when AVHRR was selected.

   a. Do you believe that more frequent use of Observing System Simulation Experiments (OSSEs) would improve this process?

      Yes. But OSSE's are somewhat difficult to set up and the are subtle issues in the "set-up" that can influence the outcome. In other words, and as stated above, it is not a purely mechanical analysis, and judgment and qualitative elements will be important to fully conduct the needed analysis. But OSSEs are and will be important.

b. Would you please explain the specific benefits that the OSSEs could provide to the quantitative analysis used in NOAA's evaluation of observing systems?

Simply stated, it would present an apples to apples comparison on a quantitative basis. But please also note my cautionary comments above.

2. Could you please explain for the Committee the value---or relative lack of utility---that polar satellites can offer in the form of data and observations used to provide effective forecasting and warnings for individual, localized outbreaks of severe weather, such as the recent sting of tornado outbreaks over the past year?

For hurricanes, we are now able to detect the early formation off of west Africa, and this has proven to be of real value as we can begin early to prepare a region with what to expect and when. As the hurricane comes into view of our geostationary systems, then we can begin to interplay both the LEO and the GEO systems extracting the best from each.

Tornadoes present a more challenging problem – it is more like countering a sniper or terrorist attack. Tornadoes are highly localized in space and time, which makes warnings more complicated to make and more complicated to deliver. However, our ability to forecast with skill the areas that *potentially will have severe tornadic weather* has been extended to days in advance, but this requires observations outside of the field of regard by our GEO assets. This longer-term forecast about potentially dangerous evolving situations is highly valuable because we can preposition equipment and personnel. Of course, as we get closer to the event, then the field of regard narrows and the GEO and particular ground-based systems become of fundamental importance.

Finally, the high latitudes experience severe weather of other types. and these regions are not well observed by GEO satellites.

a. In your opinion, are there other cost-effective options that can provide a larger scale of observational data with a higher level of quality control and operation utility?
No—satellites are necessary and the current GOES-R and JPSS-1 systems are needed. This said, I do believe that we could make real improvements in forecasting at higher time and space scales for severe convective weather like tornadoes and dangerous thunder storms by enhancing our ground

observing network and by exploring the added use of UAVs (with down-looking radars) in a *launch on forecast* mode.

b. What processes could be used to quantify the value of these cost-effective options? What is NOAA currently doing in this regard---or, more importantly, what could and should they be doing?

I think that we should consider the value proposition—enhancements to the ground system could be done at a fraction of the costs; therefore, a cost to benefit analysis is quite positive. But again, one is still going to need systems about like GOES-R and JPSS-1. However, the costs for the ground enhancement is essentially so low and the benefits are positive that it makes good sense, even in tight budget periods, to make the useful expansion and upgrades to the ground system

3. In your written testimony you state that "Because surface measurement technologies have only matured over the last decade, NOAA has built its observational forecasting largely on the basis of information from satellites and radar."

a. Could you please provide a brief summary of some of the most significant maturations and improvements in these surface measurement technologies? In your opinion, where does NOAA stand with regards to technological advancements in this category? Are other countries catching up?

I think that one of the dramatic enhancements is in the area of radar. First, we have fortunately been able to add more radars; there has been a steady (though too slow) increase in the areas covered. There has also been an increase in the density of the networks in key areas--in part to address the problem of blind areas because of the Earth's curvature. More recently, there has been the insertion of Dual Polarized radars, which have proven particularly effective in severe convective events (thunderstorms and tornadoes).

Amongst the specific improvements from Dual Polarization:

- Improved data quality through enhanced mitigation of contaminating signals.
- The ability to classify weather echoes into different types (e.g., rain, hail, snow, freezing rain, etc.), thereby greatly improving the accuracy of severe weather warnings.

- Significant improvements (100-200%) in the accuracy of rainfall estimation, which in turns improves flash flood warnings, drought monitoring, etc.
- Better understanding of clouds and precipitation, greatly improving numerical prediction models.
- Improved data quality for model initialization, providing more accurate weather forecasts.
- The ability to detect dangerous conditions for aircraft icing and microbursts.

The area where others are catching-up is in the "assimilation" techniques and operations whereby satellite data is incorporated more effectively into weather models. The "Others" in this case is Europe, and they are not catching-up, but rather in surpassing the US. We can learn from European Centre for Medium-Range Weather Forecasts (http://www.ecmwf.int/).

4. In your written testimony you highlighted the fact that "While NOAA receives observations from thousands of non-federal weather stations today, the mesonet stations stand out because they generally provide data with quality and precision exceeding that of observations provided by the NWS/FAA ASOS sensors?
   a. Could you please briefly explain this statement and the data quality comparison you offer in contrast to observations provided by the NWS/FAA ASOS?

      The main issues are two: siting and instrument maintenance. Many of the NWS/FAA ASOS are at airports, and while this siting strategy made sense in the expansion of and focus upon air travel, it is not adequate or even logical for weather casting at local to regional scales. Secondarily, our experience with the Oklahoma Mesonet has taught us the very real need for an aggressive instrument calibration and validation program—there are no short cuts here.

   b. Are you able to generally quantify for the Committee the relative cost-effectiveness derived from this increased accuracy and data quality of observations from mesonet stations when compared to other sources?

      Not really, but let me note that for the Oklahoma Mesonet data that NOAA only pays 0.07 on the dollar for data; the majority of the costs are carried on the state side.

c. Would NOAA be able to conduct a similar assessment, but with a more comprehensive level of analysis, that might better inform its overall evaluation and funding of its observational systems?

The NRC has done it for NOAA: *OBSERVING WEATHER AND CLIMATE FROM THE GROUND UP; A NATIONWIDE NETWORK OF NETWORKS*
http://www.nap.edu/openbook.php?record_id=12540&page=R1

# Appendix II:

---

ADDITIONAL MATERIAL FOR THE RECORD

SUBMITTED MATERIALS BY MR. BRUCE LEV, VICE CHAIRMAN, AIRDAT LLC



# Evaluation of Regional Aircraft Observations Using TAMDAR

WILLIAM R. MONINGER, STANLEY G. BENJAMIN, BRIAN D. JAMISON,* THOMAS W. SCHLATTER,+
TRACY LORRAINE SMITH,* AND EDWARD J. SZOKE*

*NOAA/Earth System Research Laboratory, Boulder, Colorado*

(Manuscript received 18 June 2009, in final form 18 November 2009)

ABSTRACT

A multiyear evaluation of a regional aircraft observation system [Tropospheric Aircraft Meteorological Data Reports (TAMDAR)] is presented. TAMDAR observation errors are compared with errors in traditional reports from commercial aircraft [aircraft meteorological data reports (AMDAR)], and the impacts of TAMDAR observations on forecasts from the Rapid Update Cycle (RUC) over a 3-yr period are evaluated. Because of the high vertical resolution of TAMDAR observations near the surface, a novel verification system has been developed and employed that compares RUC forecasts against raobs every 10 hPa; this revealed TAMDAR-related positive impacts on RUC forecasts—particularly for relative humidity forecasts—that were not evident when only raob mandatory levels were considered. In addition, multiple retrospective experiments were performed over two 10-day periods, one in winter and one in summer; these allowed for the assessment of the impacts of various data assimilation strategies and varying data resolutions. TAMDAR's impacts on 3-h RUC forecasts of temperature, relative humidity, and wind are found to be positive and, for temperature and relative humidity, substantial in the region, altitude, and time range over which TAMDAR-equipped aircraft operated during the studied period of analysis.

## 1. Introduction

As of late 2009, commercial aircraft provide more thau 239 000 observations per day of wind and temperature aloft worldwide (Fig. 1). The general term for these data is aircraft meteorological data reports (AMDAR). These data have been shown to improve both short- and long-term weather forecasts and have become increasingly important for regional and global numerical weather prediction (Moninger et al. 2003). Figure 2 shows the AMDAR coverage over the contiguous United States.

Two shortfalls of the current AMDAR dataset have been the near absence of data below 20 000 ft between major airline hubs (Fig. 3) and the almost complete absence of water vapor data at any altitude. To address these deficiencies, a sensor called the Tropospheric AMDAR (TAMDAR), developed by AirDat, LLC, under the sponsorship of the National Aeronautics and Space Administration's (NASA) Aviation Safety and Security Program, was deployed on approximately 50 regional turboprop commercial aircraft flying over the north-central United States and lower Mississippi Valley (Daniels et al. 2006). These turboprops are operated by Mesaba Airlines (doing business as "Northwest Airlink"). The aircraft cruise at lower altitudes (generally below 500 hPa) than traditional AMDAR jets, and fly into regional airports not serviced by AMDAR-equipped jets. Figure 4 shows TAMDAR data along with traditional AMDAR data, and shows how TAMDAR fills in the region between major hubs in the U.S. midwest. For example, in the Great Lakes region, traditional AMDAR-equipped aircraft serve 23 airports—providing ascent and descent atmospheric soundings at each, while TAMDAR-equipped aircraft serve 62 airports.

Like the rest of the AMDAR fleet, TAMDAR measures wind and temperature. But unlike most of the rest of the fleet, TAMDAR also measures humidity, turbulence, and icing. [The Water Vapor Sensing System-II (WVSS-II) sensor (Helms et al. 2005) also provides water vapor measurements from several commercial aircraft and is scheduled to expand substantially in the near fnture. But the then-current version of the WVSS-II provided

* In collaboration with the Cooperative Institute for Research in the Atmosphere, Fort Collins, Colorado.
+ Retired.

*Corresponding author address:* William R. Moninger, ERSL, 325 Broadway, Boulder, CO 80304.
E-mail: bill.moninger@noaa.gov

DOI: 10.1175/2009WAF2222321.1

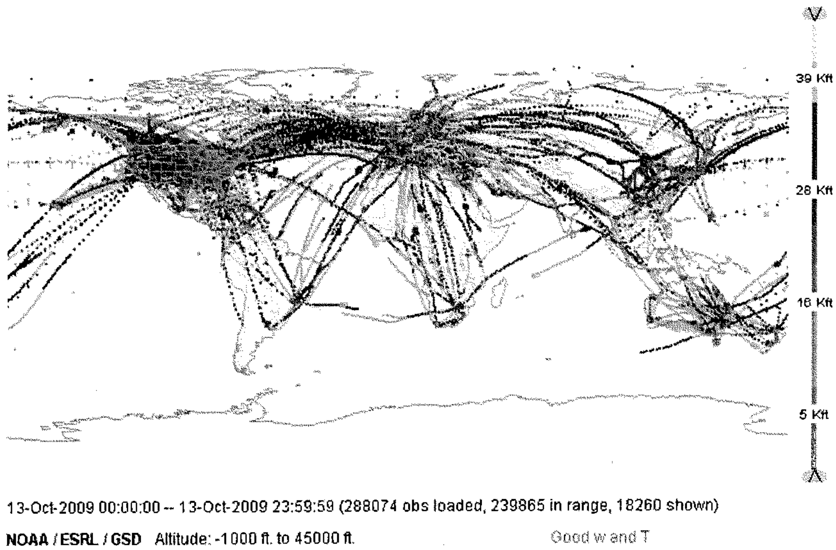



FIG. 1. Worldwide AMDAR reports, Tuesday, 16 Oct 2009. There were 239 865 observations of wind and temperature.

relatively few reliable water vapor measurements during the time period studied here.]

The National Oceanic and Atmospheric Administration/Earth System Research Laboratory/Global Systems Division (NOAA/ESRL/GSD) has built an extensive system for evaluating the quality of TAMDAR and AMDAR data, and has applied this system for the 4 yr that TAMDAR has been in operation. This evaluation system relies on the Rapid Update Cycle (RUC) numerical model and data assimilation system (Benjamin et al. 2004a,b, 2006a).

Under FAA sponsorship, NOAA/ESRL/GSD performed careful TAMDAR impact experiments. The RUC is well suited for regional observation impact experiments due to its complete use of hourly observations and diverse observation types.

## 2. RUC experiments to study TAMDAR data quality and forecast impacts

Between February 2005 and December 2008, we ran two real-time, parallel versions of the RUC with the following properties:

- Dev (or "development version 1") assimilated all hourly non-TAMDAR observations.
- Dev2 is the same as dev but also assimilated TAMDAR wind, temperature, and relative humidity observations.
- The same lateral boundary conditions, from the National Centers for Environmental Prediction's (NCEP's) North American Model (NAM; Rogers et al. 2009), were used for both dev and dev2 runs.
- These RUC experiments are run at 20-km resolution, but using more up-to-date 13-km-version code.

In February 2006 and subsequently in April 2007, the analysis and model code in the dev–dev2 versions of the RUC used for the TAMDAR impact experiments were upgraded to improve the observation quality control and precipitation physics. These modifications were generally the same as those implemented into the operational NCEP 13-km RUC, with the exception that dev and dev2 do not ingest radar data (implemented in the NCEP RUC in November 2008).

The studies herein focus on these real-time model runs and, also, on retrospective runs (also at 20-km resolution) over two 10-day periods: one in winter and one in summer. These same test periods were used in a broader set of observation sensitivity experiments (OSEs) for eight different observation types described by Benjamin et al. (2010).

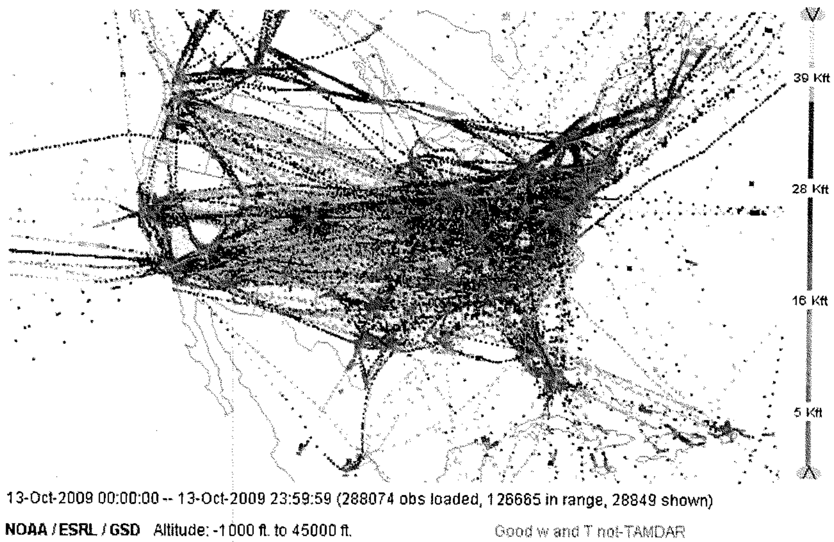



FIG. 2. Traditional AMDAR (i.e., non-TAMDAR) reports over the contiguous United States, on Tuesday, 13 Oct 2009, for a total of 126 665 observations.

The 20-km RUC version used for the TAMDAR experiments includes complete assimilation of nearly all observation types (as used in the operational RUC), including cloud analysis [Geostationary Operational Environmental Satellite (GOES) and aviation routine weather reports (METARs)], full METAR assimilation (temperature, dewpoint, winds, pressure, cloud, visibility), GPS precipitable water, GOES precipitable water, all other aircraft, profilers, mesonets, and raobs. A summary of the characteristics of the June 2006 operational RUC is available online (http://ruc.noaa.gov/ruc13_docs/RUC-testing-Jun06.htm). More details on the RUC assimilation cycle and the RUC model are available in Benjamin et al. (2004a,b). Other details on the RUC TAMDAR experimental design are described in Benjamin et al. (2006a,b, 2010).

## 3. TAMDAR data quality

To evaluate the *quality* (as opposed to the *model forecast impacts*) of TAMDAR, ESRL/GSD maintains a database of AMDAR (including TAMDAR) observations, and 1-h forecasts interpolated to the AMDAR observation point from the RUC dev and dev2 cycles. This allows us to calculate the mean and RMS differences between RUC 1-h forecasts and aircraft-observed temperature, wind, and relative humidity.

Model data are interpolated vertically (linear in log$p$) and horizontally to the locations of the observations. No temporal interpolation is performed; observations are compared with the 1-h forecast valid at the nearest hour.

For each observation time and location, we store the observed and forecasted temperature, relative humidity, wind direction and speed, and phase of flight (ascent, descent, or en route). In addition, the RUC quality control disposition of each observation (independent QC for each variable) was stored between December 2005 and December 2008, as well as which variable(s) were actually used in the RUC analysis.

### *a. Web-based access to the AMDAR-RUC database*

Access to the AMDAR-RUC database is available online (http://amdar.noaa.gov/RUC_amdar/). Because access to real-time (i.e., less than 48 h old) AMDAR data is restricted to NOAA and selected other users, access to the real-time portions of this site is restricted (information online at http://amdar.noaa.gov/FAQ.html).

Database access is provided in the following forms:

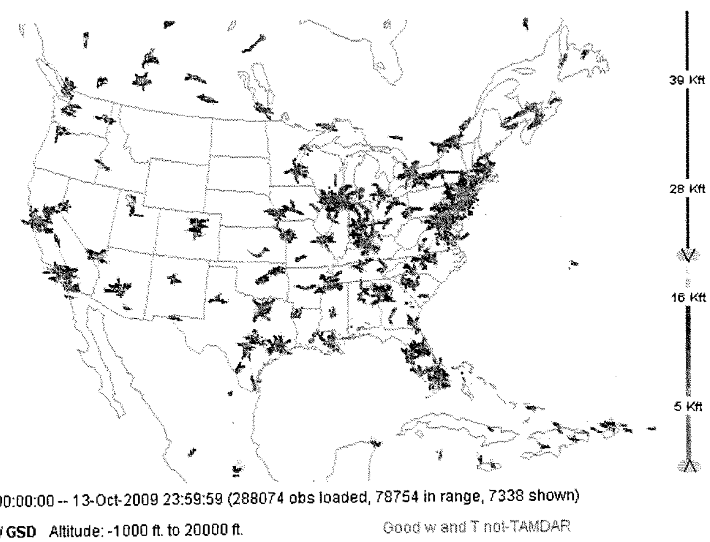



FIG. 3. As in Fig. 2 but below 20 000 ft. There were 78 754 observations.

- 7-day statistical summaries for each aircraft for four altitude ranges (all altitudes, surface to 700 hPa, 700–300 hPa, and above 300 hPa), sortable by a variety of values, and
- time series data for any aircraft (restricted).

*b. Error characteristics of the TAMDAR/AMDAR fleet*

In this section we look at aircraft differences with respect to the RUC dev2 cycle. We do not consider the RUC dev2 1-h forecasts to be "truth"; rather, we use them to be a common benchmark (assimilating all aircraft types) with which to compare the error characteristics of various aircraft fleets. The 1-h forecast through the RUC forecast model and initialization (Benjamin et al. 2004a,b) forces some (but not total) independence from any particular observation type. We focus on 1–30 October 2006, a reasonably representative month in terms of RUC forecast error and TAMDAR impacts, as will be discussed further in section 4b.

We look at aircraft–RUC differences over the TAMDAR Great Lakes region (the small rectangle shown in Fig. 5), which includes the upper midwestern region of the United States, for "daylight" hours (1200–0300 UTC) when TAMDAR-equipped aircraft generally fly.

In our analyses of aircraft–RUC differences, we found it useful to stratify the data by phase of flight (descent and en route/ascent) as well as altitude. There are enough TAMDAR data that each point we show in this section is the average of at least 100 observations; in most cases, especially lower in the atmosphere, each data point represents the average of more than 1000 observations.

Temperature bias relative to the RUC 1-h forecast for traditional AMDAR jets and TAMDAR turboprops is shown in Fig. 6. The jets show a small warm bias at most altitudes peaking at 0.3–0.4 K between 800 and 500 hPa, and descents (blue) show less warm bias than enroute–ascent (red) data above 600 hPa. Below 800 hPa, descents show a slightly warmer bias than ascents for this time period. TAMDAR shows a smaller temperature bias (nearer zero) than AMDAR from 800 to 500 hPa. In general, both AMDAR and TAMDAR temperature biases with respect to the RUC are small—less than 0.4 K in absolute magnitude.

The temperature RMS difference from RUC 1-h forecasts for TAMDAR and AMDAR (Fig. 7) is about 1 K at most levels, with TAMDAR RMS being generally equivalent to that of AMDAR jets. Some of this difference is attributable, of course, to RUC forecast error, which would affect TAMDAR and AMDAR equally.

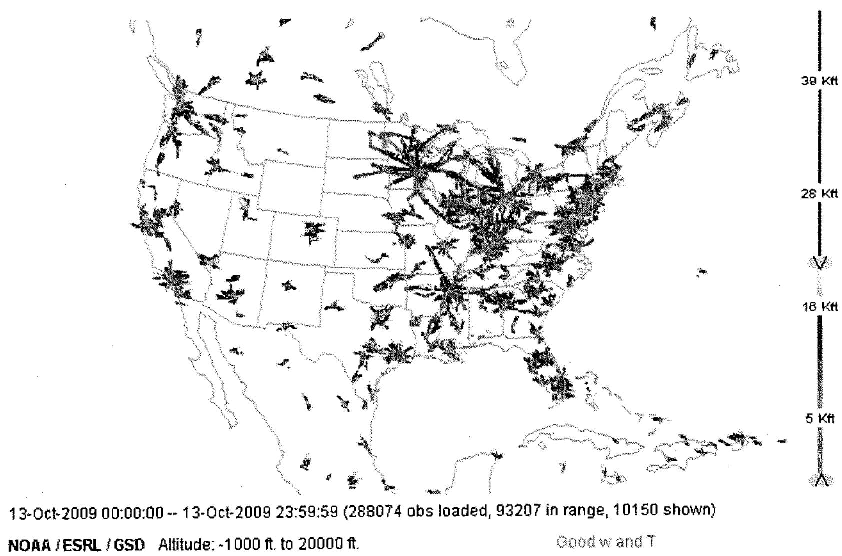



FIG. 4. As in Fig. 3 but with TAMDAR observations included. There were 93 207 observations.

The RMS vector wind differences between aircraft-measured winds and RUC 1-h forecast winds (Fig. 8), in contrast to temperature, are considerably larger for TAMDAR (turboprops) than for AMDAR jets, and TAMDAR's differences on descent are larger than those on ascent and en route. The lower quality of the wind data from TAMDAR is likely due to the less accurate heading information provided to TAMDAR by the Saab-340b avionics system. Accurate heading information is required for the wind calculation, and the Saab heading sensor is magnetic and known to be less accurate than the heading sensors commonly used on large jets.

The greater error on descent is due, we believe, to aircraft maneuvers, which occur more often on descent than on ascent. In response to this, we eliminated TAMDAR wind measurements taken on descent in the RUC experiments described here. Also, in our current versions of the RUC, we have also implemented a larger observational error estimate for TAMDAR turboprop winds in the RUC analysis, where code allows for different error estimates for each aircraft fleet.

We also examine the relative humidity bias (observation − forecast; Fig. 9) for TAMDAR but not for other aircraft, because most traditional AMDAR jets do not measure moisture. [A few WVSS-II moisture sensors (Helms et al. 2005) were flying at this time; we do not consider them in our analysis.] The humidity bias is generally below 5% RH.

The relative humidity RMS differences for TAMDAR from RUC 1-h forecasts (Fig. 10) are generally similar for the ascent/en route versus descent reports, and increase from ~9% RH near the surface to ~20% RH at 500 hPa. To put this statistic in perspective, the assumed raob RMS observational error used by the North American Mesoscale (NAM) model, run operationally at NCEP in its assimilation cycle (D. Keyser 2006, personal communication), is shown in black. This error varies from ~8% RH near the surface to ~16% above 600 hPa. Note that assumed RH errors for raobs (often taken as a rougb data standard, reflecting the observation error only from the measurement and spatial representativeness) do not differ greatly from the RH errors shown by TAMDAR (reflecting the combination of TAMDAR observation error, representativeness error, and RUC 1-h forecast error).

We summarize this section as follows:

- Temperature measurements from TAMDAR turboprops and AMDAR jets are approximately equally accurate.

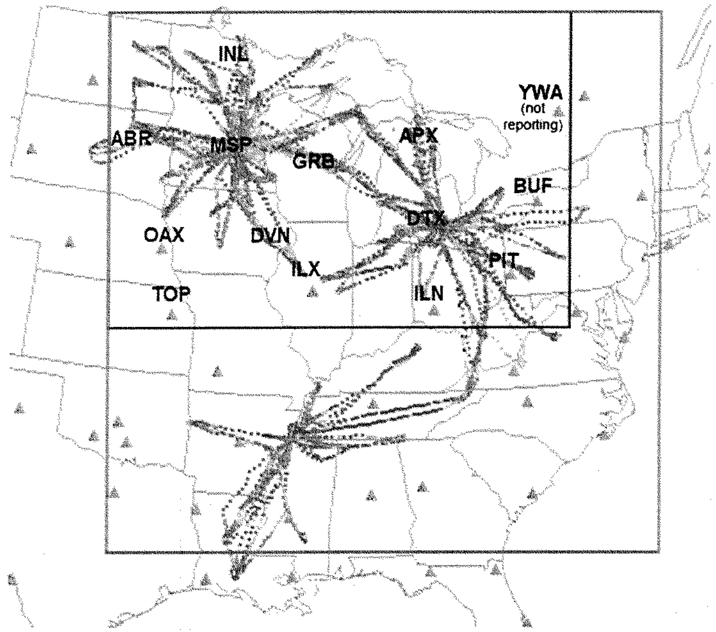



FIG. 5. TAMDAR observations typical for a 24-h period in 2007. Verification areas are shown by the blue rectangle (Great Lakes region, 13 raobs) and magenta rectangle (eastern U.S. area, 38 raobs).

- Wind measurements from TAMDAR turboprops are worse than for AMDAR jets, due to less-accurate heading information from the turboprops. (The Saab-340B turboprops flown by Mesaba, like many turboprop aircraft, use flux-gate heading sensors, which are less accurate than the laser-gyroscopic sensors used on most jets.)
- On descent, wind measurements from TAMDAR turboprops are significantly degraded over those taken on ascent, likely due to enhanced heading errors during maneuvers.
- Relative humidity measurement errors from TAMDAR are commensurate with assumed errors for raobs.

## 4. TAMDAR's impact on RUC forecasts

The forecast skill of the RUC is evaluated against raobs. Figure 5 shows the specific regions for which we generate results (the eastern United States and the Great Lakes).

In studying TAMDAR's impacts, we take a two-pronged approach. First, we consider the two real-time RUC cycles discussed above (dev and dev2), to see the long-term stability and trends. Second, we consider two 10-day intensive study periods: one in winter and one in summer. For each of these periods, we performed several retrospective experiments, with and without TAMDAR, and with varying data assimilation strategies. These experiments complement a broader set of observation impact experiments for the same summer and winter retrospective periods described in Benjamin et al. (2010).

### a. *Forecast verification procedure*

In 2006 we developed a new raob verification procedure for these evaluations. Under the previous verification procedure, the following conditions applied:

- RUC–raob comparisons were made only at mandatory sounding levels (850, 700, and 500 hPa in the TAMDAR altitude range).

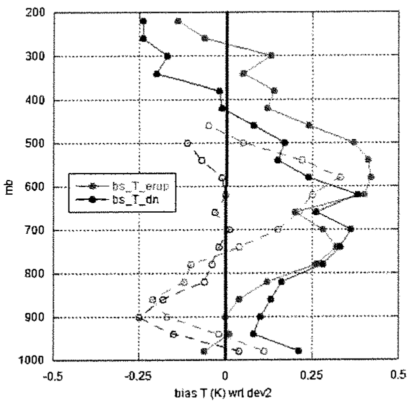



FIG. 6. TAMDAR (open circles) and AMDAR (solid circles) temperature "biases" (aircraft − RUC dev2 1-h forecasts) for October 2006. Observations taken during descent are shown in blue and labeled with the suffix "_dn"; observations taken during ascent and en route are shown in red and labeled with the suffix "_erup."

- Verification used RUC data interpolated horizontally and vertically to 40-km pressure-based grids from the RUC native coordinate (isentropic-sigma 20 km) data.
- Raob data that failed quality control checks in the operational RUC analyses were not used.

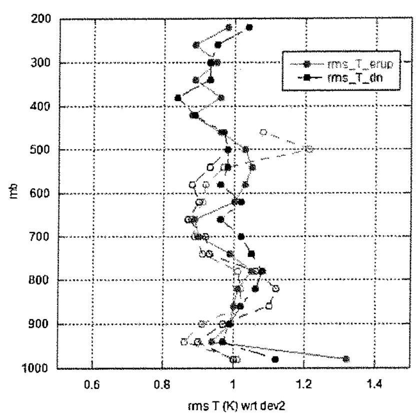



FIG. 7. As in Fig. 6 but for the temperature RMS difference from the RUC dev2 1-h forecasts for October 2006.

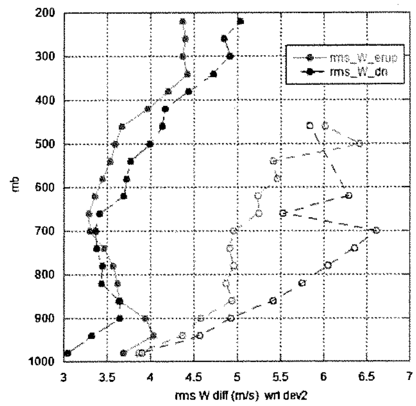



FIG. 8. As in Fig. 6 but for the RMS wind vector differences.

Under the new verification system, the following conditions apply:

- Full raob soundings, interpolated to every 10 hPa, are compared with model soundings.
- Model soundings, interpolated to every 10 hPa, are generated directly from RUC native files (20-km resolution, isentropic-sigma native levels).
- Comparisons are made every 10 hPa up from the surface.

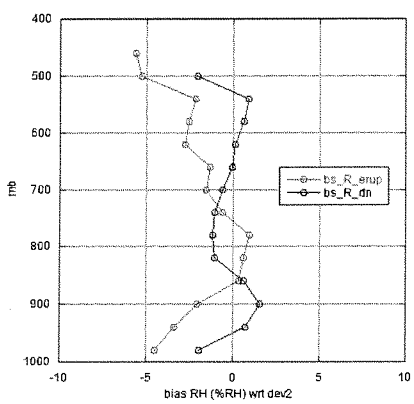



FIG. 9. As in Fig. 6 but for the RH, for TAMDAR only.

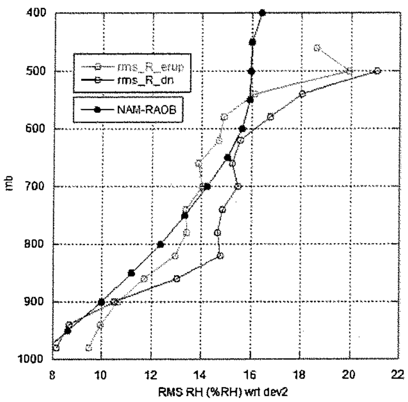



FIG. 10. TAMDAR (open circles) RH RMS with respect to RUC dev2 1-h forecasts for October 2006. Solid black circles show the raob RH error assumed by the operational NAM model run at NCEP.

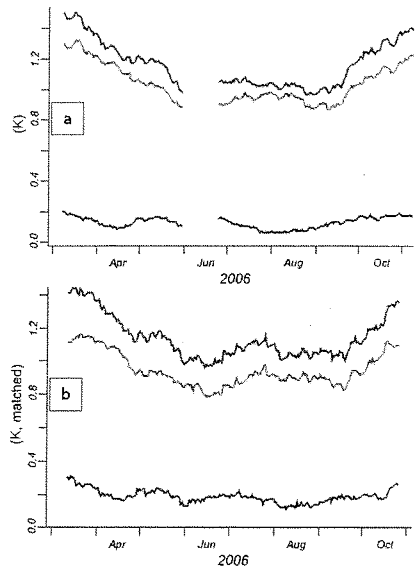



FIG. 11. The 850-hPa temperature 3-h forecast (valid at 0000 UTC, Great Lakes region) RMS difference between the model and raobs for 3-h RUC dev (blue) and RUC dev2 (red), for the (a) old and (b) new verifications. Thirty-day running averages were used.

- No raob data are automatically eliminated based on differences from the operational RUC analysis data. (Fifteen obviously erroneous raobs were eliminated by hand between 23 February 2006 and December 2008.)

To compare the old and new verification methods, we look at the temperature impacts from TAMDAR at 850 hPa [discussed further in section 4b(1) below]. For most of the verified variables at various levels, the old and new methods give nearly identical answers, as shown in Figs. 11a and 11b for 850-hPa temperature. For this variable and level, the differences in QC screenings between the old and new verification methods made almost no difference. Almost identical results were evident, with au average 0.2-K improvement from dev2 (assimilating TAMDAR) over dev (no TAMDAR) 3-h forecasts in the Great Lakes region for the April–October 2006 period. As will be discussed in section 6, this is generally consistent with the current results.

The new verification system has allowed us more vertical precision; we can now inspect TAMDAR's impacts in the lowest 1500 m above the surface, below 850 hPa. Moreover, inclusion of more raob data has revealed previously obscured positive TAMDAR impacts on the relative humidity forecasts. These impacts were also obscured because some correct raob data were rejected by the old verification system—primarily at 500 hPa—and inclusion of these data resulted in greater calculated skill for dev2 with respect to dev, and hence a greater TAMDAR impact, especially for RH in the middle troposphere. No longer excluding raob data based on their differences from the operational RUC values has made a substantial difference in the new verification of the 600–400-hPa RH forecasts, as shown in the next example.

A comparison using the old and new verifications for the 500-hPa RH RMS errors for dev and dev2 forecasts is presented in Figs. 12 and 13. The new verification (Fig. 13) yields higher RMS error because of the use of *all* raob RH values. However, the new verification also shows a much greater *difference* between dev and dev2, indicating that the previously missing raob data have affected the verification of the two cycles unequally. Apparently, assimilation of TAMDAR RH observations improves the RUC RH forecasts in cases with large errors in the middle troposphere where raob values were being flagged using the old verification method. Note that the spacing on the vertical axis is equal, even though the magnitude of the error is larger with the new verification.

To see why this is so, we look at a particular case. Table 1 shows 500-hPa RH values for raob observations

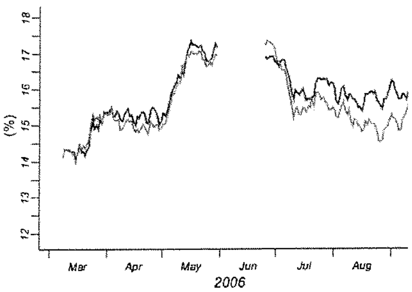



FIG. 12. RMS RH 500-hPa 3-h forecast error for RUC forecasts for dev (no TAMDAR, blue) and dev2 (TAMDAR, red) against raobs for the old verification system (centered at 15% RH). Thirty-day running averages were used.

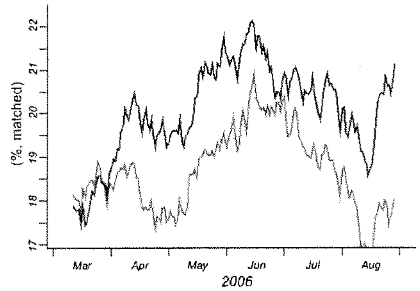



FIG. 13. As in Fig. 12 but for the new verification system (centered at 20% RH).

and the 3-h dev and dev2 RUC forecasts, all valid at 0000 UTC 1 July 2006. The old verification did not use the 500-hPa RH raobs at Pittsburgh, Pennsylvania (PIT) and Lincoln, Illinois (ILX). In both cases (see soundings in Figs. 14 and 15), strong subsidence layers were evident, with very dry air with bases just below 500 hPa, accompanied by sharp vertical moisture gradients in the 500–520-hPa layer. The QC screening algorithm used in the previous verification method flagged the 500-hPa RH observations at these two stations since the operational RUC analysis did not maintain this vertical gradient quite as sharply as in the full raob data. In both of these cases, the TAMDAR data led the dev2 RUC to better capture this vertical moisture gradient.

Figure 14 shows the observed raob and 3-h forecasts for RUC dev and dev2 soundings at ILX. The dev2 forecast sounding suggests that TAMDAR had detected a dry layer at 500 hPa. Nearby raobs (not shown) also suggest that the observed dry layer at and above 500 hPa was real.

Figure 15 shows the soundings for PIT. In this case, the accuracy of the dry raob observation at 500 hPa is less clear, but is not obviously wrong. Apparently, the much stronger TAMDAR impacts shown in Fig. 13 between the dev and dev2 500-hPa RH forecasts with the *new* verification screening are attributable to these cases with very sharp vertical moisture gradients near 500 hPa, also suggested by Szoke et al. (2007). Assimilation of the TAMDAR data allows the dev2 RUC forecasts to better capture these features.

In fact, the TAMDAR impacts on RH forecasts are potentially larger than this: in section 5a, we describe that a change in the RH error characteristic used in the dev2 assimilation of TAMDAR data—not implemented until 26 April 2007—increases the TAMDAR RH impacts.

This new verification system also provides much finer vertical resolution than the old and provides data below 850 hPa. Figure 16 shows vertical profiles of the RH biases for dev and dev2. Note that the RH biases of both models starts positive (more moist than the raobs) near the surface, become negative between approximately 900 and 700 hPa, then become increasingly positive with increasing altitude. The old verification system produced data on only three levels at and below 500 hPa (500, 700, and 850 hPa), thereby obscuring vertical variations such as these.

Since some of the finer resolution results from interpolating linearly in log$p$ between significant levels, we investigated the extent to which this interpolation might differ from the actual atmospheric values. One-second-resolution data now available from the Radiosonde Replacement System (Facundo 2004) allowed us to study this. To test the effects of interpolation over relatively large pressure ranges, we chose a sounding with relatively few significant levels (Grand Junction, Colorado, at 0000 UTC

TABLE 1. RH values at 500 hPa at 0000 UTC 1 Jul 2006.

| ID | Name | Raob | 3h-Dev | 3h-Dev2 |
|---|---|---|---|---|
| ABR | Aberdeen, SD | 85 | 90 | 87 |
| APX | Alpena, MI | 6 | 6 | 9 |
| BUF | Buffalo, NY | 8 | 37 | 7 |
| DTX | Detroit, MI | 14 | 15 | 11 |
| DVN | Davenport, IA | 16 | 39 | 41 |
| GRB | Green Bay, WI | 30 | 18 | 31 |
| ILN | Cincinnati, OH | 33 | 61 | 48 |
| ILX | Lincoln, IL | 19 | 84 | 40 |
| INL | International Falls, MN | 26 | 10 | 21 |
| MPX | Minneapolis, MN | 9 | 28 | 33 |
| OAX | Valley, NE | 15 | 53 | 41 |
| PIT | Pittsburgh, PA | 3 | 76 | 33 |
| TOP | Topeka, KS | 57 | 83 | 75 |

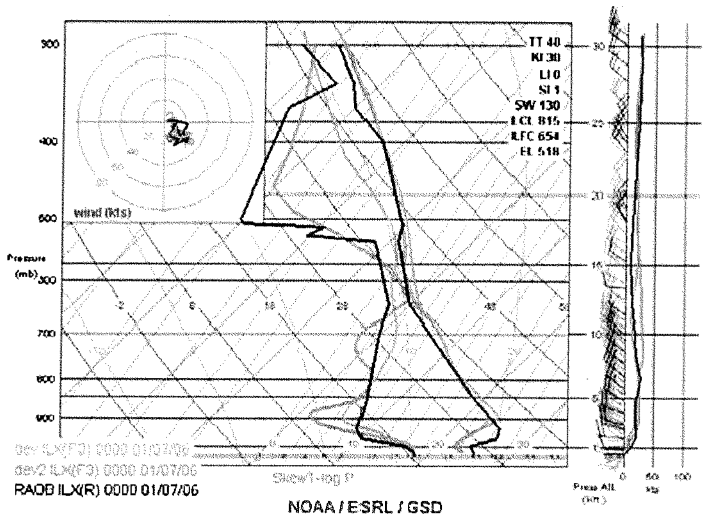



FIG. 14. Soundings at ILX at 0000 UTC 1 Jul 2006. Raob is shown in black, RUC dev 3-h forecasts in orange, and RUC dev2 3-h forecasts in magenta.

29 June 2009; Fig. 17). In this case, the interpolation extended over pressure ranges up to 120 hPa (between 820 and 700 hPa). For this sounding we calculated the average and RMS difference for temperature, relative humidity, and wind, between the 1-s data and the 10-mb interpolated sounding. Results are shown in Table 2 for various pressure bands; they are lower by a factor of 3–10 than the RMS values in the various data deprivation experiments we discuss below, particularly for temperature. Thus, we are confident that our interpolation scheme is not obscuring or skewing our forecast impact results and that the linear approximation between raob significant levels agrees well with the 1-s data, especially for temperature.

### b. *Effect of TAMDAR assimilation on RUC forecast skill*

#### 1) TEMPERATURE

TAMDAR impacts on 3-h RUC temperature forecasts averaged over the 1000–500-hPa layer for the 2006–08 period are shown in Fig. 18. The temperature RMS errors for both RUC dev (without TAMDAR) and dev2 (including TAMDAR) show the common seasonal variations with larger errors in winter and smaller errors in summer, when the lower troposphere is more commonly well mixed with a deeper boundary layer. We consider only 0000 UTC raobs because this is the time when we expect to see the maximum TAMDAR impact, given the schedule (1200–0300 UTC, primarily daylight hours) of the Mesaba TAMDAR fleet.

The TAMDAR impacts (black line in Fig. 18) are always positive and are largest in winter, when the temperature forecast errors are themselves largest. In winter, TAMDAR reduces the 3-h temperature forecast error by an average of 0.2 K over the entire 1000–500-hPa depth.

Figure 18 can help put the results discussed in section 3b into climatological perspective. Note that October 2006—the period over which TAMDAR's errors were evaluated in section 3b—is a transition period between the relatively lower RUC RMS errors and TAMDAR impacts of summer and the larger errors and impacts of winter, but is otherwise generally consistent with the RUC behavior and TAMDAR impacts over the entire 3-yr period, and is consistent with the behavior in the autumns of 2007 and 2008. Thus, we are confident that the results in section 3b are reasonably representative of any fall period.

A vertical profile of the temperature RMS error for the RUC dev and dev2 3-h forecasts for March 2008 is

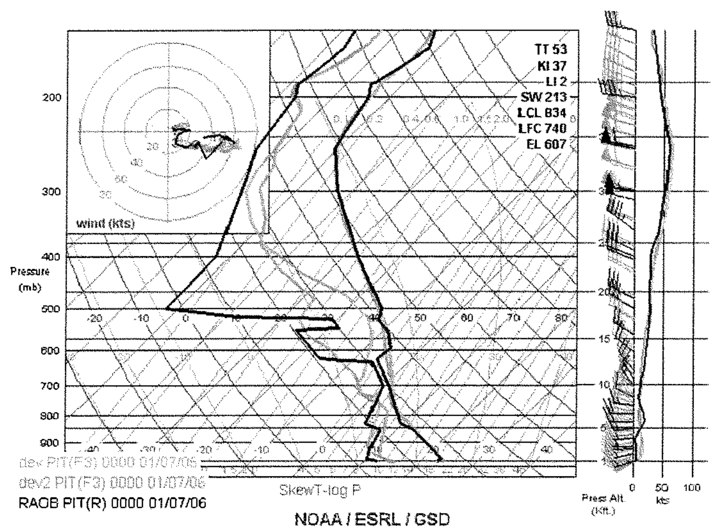



FIG. 15. As in Fig. 15 but for PIT.

shown in Fig. 19. Figure 18 suggests that this is a typical spring period in terms of RUC temperature error and TAMDAR impacts. Inaccuracy in forecast temperatures associated with errors in planetary boundary layer (PBL) depth results in a maximum from 950 to 800 hPa in the vertical profile for temperature errors in the RUC dev model forecasts (without TAMDAR). The dev2 has lower errors for all levels between the surface and 320 hPa but especially between 850 and 950 hPa. We interpret this as TAMDAR's ascent–descent profiles being particularly important in defining the PBL depth more accurately. The maximum RMS error difference between dev and dev2 occurs at 900 hPa and is about 0.4 K.

To put this TAMDAR impact into perspective, we present profiles of 3-h temperature forecast errors (Fig. 20) from the November–December 2006 retrospective period (see section 5) for 1) all AMDAR data (including TAMDAR), equivalent to the dev2; 2) no TAMDAR data, equivalent to the dev; and 3) no AMDAR data at all.

The TAMDAR impacts (the black curve) peaks at 0.4 K at 900 hPa, just as they do in Fig. 19. The AMDAR impacts also peak at 900 hPa and have a value of nearly 1.1 K. AMDAR impacts also have an additional peak at 500 hPa, above the region where Mesaba turboprop aircraft (carrying TAMDAR) fly most of the time.

2) WIND

TAMDAR impacts on 3-h wind forecasts, also averaged over the surface–500-hPa layer (Fig. 21) were consistently positive, although small. This indicates that even though TAMDAR wind errors are greater than those of the traditional AMDAR jet fleet, as discnssed in

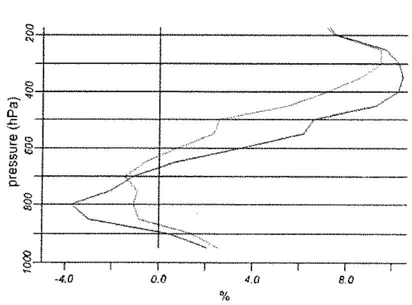



FIG. 16. Vertical profile for RH bias (model − raob) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red) 3-h forecasts with respect to raobs at 0000 UTC in the Great Lakes region for the April–August 2006 period.

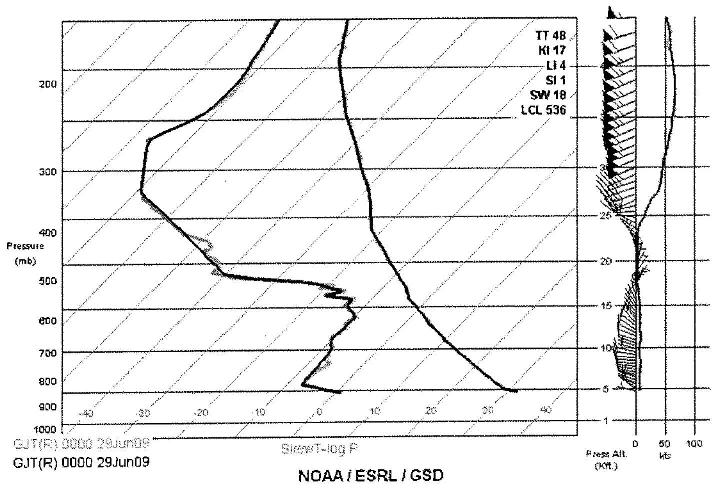



FIG. 17. Grand Junction, CO, raob at 0000 UTC 29 Jun 2009. Data interpolated to 10 hPa from mandatory and significant levels are shown in black; data from 1-s data are shown in magenta. (One-second wind barbs are not shown.)

section 3, they nonetheless provide additional value for wind forecasts in the RUC.

In the vertical profile for 3-h wind forecast error (RMS of the vector wind difference between the model and raobs) for March 2008 (Fig. 22), TAMDAR impacts on winds show a double peak, with a maximum at 700 hPa. At this level, the RMS reduction due to TAMDAR is about 0.25 m s$^{-1}$.

The vertical profile for the 3-h wind forecast error (Fig. 23) from the November–December 2006 retrospective period (see section 5) compares the TAMDAR wind impacts with the impacts of all of the aircraft (AMDAR, which includes TAMDAR). The heavy gold curve in Fig. 23 shows the maximum AMDAR wind impact to be at 450–500 hPa, with an RMS error reduction of 0.7 m s$^{-1}$. The TAMDAR impacts peak at about 600 hPa and are about 0.2 m s$^{-1}$. Below 550 hPa, the similarities of the TAMDAR and the AMDAR impact curves (heavy) indicate that TAMDAR is responsible for most of the (small) AMDAR wind impacts in this altitude range. Above 550 hPa, AMDAR jets provide most of the impacts on the RUC 3-h wind forecasts.

### 3) RELATIVE HUMIDITY

A 3-yr history for TAMDAR impacts on lower-tropospheric RH forecasts (RUC dev versus RUC dev2) is shown in Fig. 24. The impacts are generally between 1% and 2% when averaged between the surface and 500 hPa. A change was made on 26 April 2007 to the

TABLE 2. Bias and RMS differences between 10-hPa interpolated and 1-s raob data from the GJT sounding at 0000 UTC 29 Jun 2009. $N$ is the number of observations in each pressure band.

| Pressure (hPa) | $N$ | $T$ bias (RMS) (°C) | RH bias (RMS) (%) | Speed bias (vector wind RMS) (m s$^{-1}$) |
|---|---|---|---|---|
| 1000–800 | 122 | −0.02 (0.02) | −0.00 (0.24) | −0.24 (0.7) |
| 800–700 | 260 | −0.02 (0.02) | −0.52 (0.84) | 0.10 (0.93) |
| 700–600 | 278 | −0.02 (0.02) | 0.37 (0.95) | −0.44 (0.80) |
| 600–500 | 338 | −0.00 (0.01) | −0.57 (2.52) | 0.10 (1.26) |
| 500–400 | 398 | 0.00 (0.01) | −0.30 (0.95) | −1.09 (2.85) |
| 400–300 | 521 | −0.00 (0.01) | 0.09 (0.10) | 0.04 (0.87) |
| 300–200 | 633 | −0.02 (0.03) | −0.18 (0.34) | −0.62 (1.28) |
| 200–100 | 935 | 0.03 (0.06) | 0.07 (0.57) | −0.08 (2.7) |
| 100–0 | 1960 | −0.01 (0.08) | −0.01 (0.59) | −1.35 (3.94) |

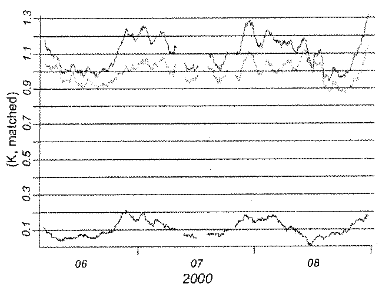



FIG. 18. Time series of 3-h temperature forecast errors (RMS difference from 0000 UTC raobs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and the dev–dev2 difference (black), for the Great Lakes region, in the layer between the surface and 500 hPa. Thirty-day running averages were used. Positive differences indicate a positive TAMDAR impact.

specific observation error for TAMDAR RH (see section 5a). Although we know from reprocessing a 10-day period that the new RH observation error increases TAMDAR's RH impacts, the increase is small enough that it is not clearly evident compared with the seasonal variations shown in Fig. 24.

The corresponding vertical profile for the RH forecast impacts from TAMDAR (Fig. 25) is relatively uniform from the surface to 700 hPa, from 1% to 3%. An enhancement in RH impacts from TAMDAR around 600 hPa is also evident. This enhancement is consistent over the seasons (not shown). We speculate that the surface observations limit the impacts of TAMDAR at

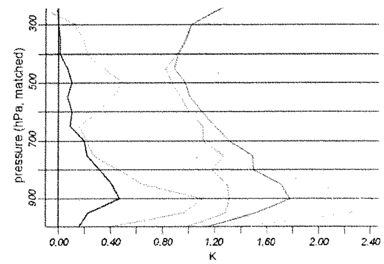



FIG. 20. As in Fig. 19 but for 27 Nov–5 Dec 2006: all-data run, light red; no-TAMDAR run, light blue; no-aircraft run, gold; TAMDAR impact, black; and aircraft impact, heavy gold.

altitudes below this level, and there are relatively few TAMDAR observations above.

#### 4) TAMDAR IMPACTS AS A FRACTION OF ESTIMATED MAXIMUM POTENTIAL IMPROVEMENT (EMPI)

To put these error reductions in perspective, it is worth considering what the minimum model–raob differences ("errors") might be, given a perfect model. Raobs have instrument errors and also exhibit representativeness errors because they provide in situ point observations, whereas a model provides an average over the area of a grid cell (20 $km^2$ in the case of the dev and dev2). To account for these inherent differences between the model and verifying observations, we can take the *analysis* error as an approximate measure of the minimum forecast error to be expected, similar to the normalization of

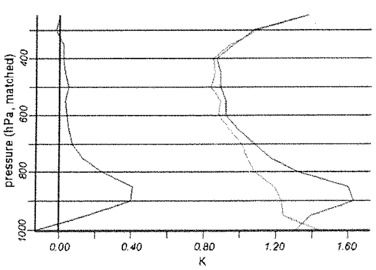



FIG. 19. Vertical profile of 3-h temperature forecast errors (RMS difference from 0000 UTC raobs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and the dev–dev2 difference (black), for the Great Lakes region, during March 2008.

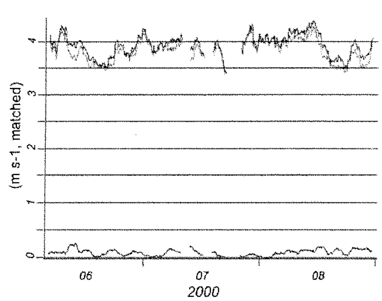



FIG. 21. As in Fig. 18 but for wind forecasts (RMS vector difference from 0000 UTC raobs).

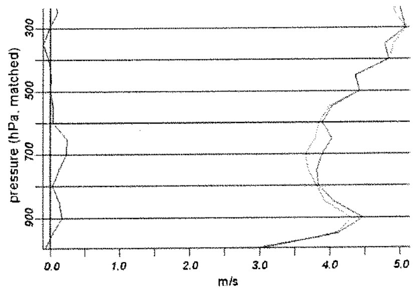



FIG. 22. As in Fig. 19 but for 3-h wind forecasts.

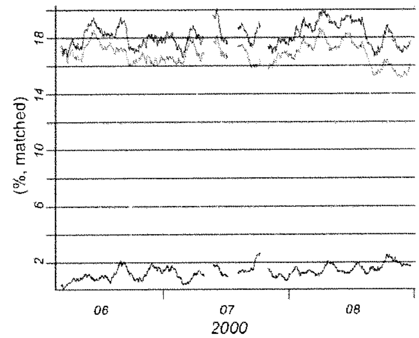



FIG. 24. As in Fig. 18 but for RH forecasts.

forecast impacts shown by Benjamin et al. [(2004c), their Eq. (3)].

As a specific example, Fig. 26 shows profiles of the dev2 and dev 3-h RH forecast errors along with the dev2 *analysis* errors. The RMS for the analysis varies between 6% RH at 950 hPa and about 14% RH at 700 hPa. The *difference between* the dev and dev2 3-h RH forecast error (i.e., the TAMDAR impact) varies between 1% RH and 3% RH. At 600 hPa, the TAMDAR impact is 2.8% RH, and the difference between the dev 3-h forecast curve and the dev2 analysis curve is 5.7% RH. Assuming that this 5.7% RH error reduction at 600 hPa is the best we can hope for (the EMPI), the TAMDAR impact is about 50% of the EMPI. Over all altitudes, TAMDAR provides 15%–50% of the EMPI.

For temperature, we reason similarly. Because the analysis fit to the raob verification data is about 0.5 K, as described in Benjamin et al. (2006a,b, 2007), the maximum possible reduction in RMS error difference would be about 1.1 K (the difference between the ~1.6 K RMS shown for dev in Fig. 19 at 900 hPa and the 0.5-K analysis fit). Therefore, TAMDAR's impact is about 35% of the EMPI for the 3-h temperature forecast error at 900 hPa [35% ≈ 0.4/(1.6–0.5)].

For wind, the analysis fit to the raobs is about 2.2 m $s^{-1}$ near 600 hPa (not shown). Thus, TAMDAR's impact on 3-h wind forecasts in this altitude range is about 15% of the EMPI.

## 5. Further applications of retrospective runs

To study TAMDAR's impacts in more detail, and determine how these new data are best assimilated in the RUC, we saved all data for two 10-day periods: 1200 UTC 26 November–1200 UTC 5 December 2006 and 0000 UTC 15 August–0000 UTC 25 August 2007. We then reran the RUC with a variety of different assimilation schemes and TAMDAR data variations over these periods.

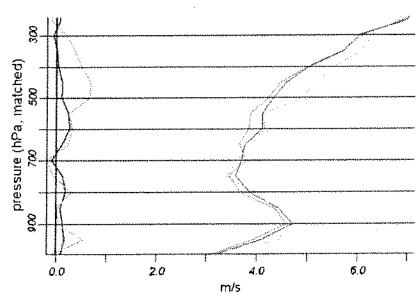



FIG. 23. As in Fig. 20 but for 3-h wind forecasts: all-data run, light red; no-TAMDAR run, light blue; no-aircraft run, light gold; TAMDAR impact, heavy blue; and aircraft impact, heavy gold.

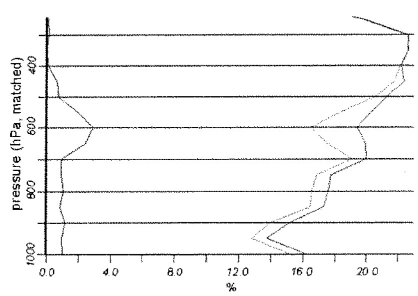



FIG. 25. As in Fig. 19 but for 3-h RH forecasts.

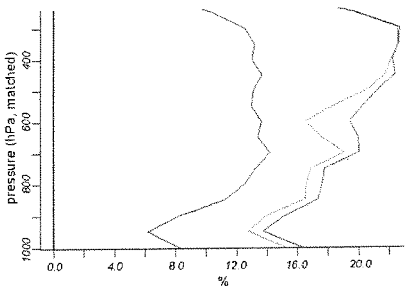



FIG. 26. RMS difference between RUC grids and raobs in the Great Lakes region at 0000 UTC for the dev2 RH analysis (black), dev 3-h forecasts (blue), and dev2 (red) 3-h forecasts, during March 2008.

We chose these periods because they included intense weather events. The 2006 period includes a potent early winter storm that featured a band of heavy snow and ice through the heart of the TAMDAR network, mainly from 30 November through 1 December, and includes more typically moderate weather in the later portion of the period. The August 2007 period includes a variety of weather systems as well. Since results from this summer period generally corroborate the winter results, we do not include them here.

These periods were chosen primarily in support of our TAMDAR investigations. However, they have served as a basis for additional experiments denying other data sources and are discussed in detail by Benjamin et al. (2010).

### *a. Relative humidity observation error specification for assimilation*

Because high temporal and spatial resolution RH measurements have been unavailable in the past, we had no firm guidance for choosing the appropriate error for these observation measurements other than from engineering-based estimates by manufacturers. Both instrument errors and representativeness errors must be accounted for, so that the importance of each observation relative to the model background field is correctly assessed. Estimating an RH observation error that is too large will result in less-than-optimal TAMDAR impacts. Choosing a value that is too small will result in overfitting, causing numerical noise that will degrade forecasts.

We experienced overfitting when, during the fall of 2005, the TAMDAR RH error was inadvertently set to 1% RH. During this period, TAMDAR's impacts on the 3-h RH forecasts were negative (Benjamin et al. 2007, their Figs. 9 and 10). However, for most of the time we that have assimilated TAMDAR's data, we have run the system with RH observation errors for TAMDAR that were between 3% and 12%. With these errors, TAMDAR has had a positive impact of reducing the subsequent RUC RH forecast errors by 1%–3% RH [see section 4b(3)].

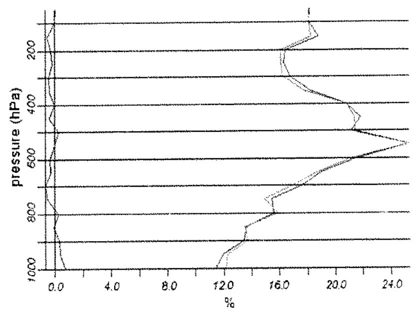



FIG. 27. Vertical profile of 3-h RH forecast errors (RMS difference from 0000 UTC raobs) for "old RH processing" (blue, RH errors divided by 4), and "new RH processing" (RH errors corrected), without TAMDAR data, for the Great Lakes region. The black curve shows the difference; negative values indicate that the new processing has lower RMS errors.

In April 2007, we discovered that the observation errors for all RH observations [TAMDAR, surface observations, raobs, and integrated precipitable water data from the Meteorological Applications of GPS experiment (GPS-Met; Smith et al. 2007)] had been inadvertently set too low since the start of our TAMDAR experiments. We corrected this in a retrospective run and found that the correction (called "new RH processing" below) resulted in slightly increased model skill (decreased RMS) for RH forecasts at nearly all levels, as Fig. 27 shows, even in the absence of TAMDAR.

When TAMDAR data are included, the new processing increased the TAMDAR impact, as shown in Fig. 28.

Each curve in Fig. 28 indicates the difference between the RMS errors of the TAMDAR and no-TAMDAR runs (with respect to 0000 UTC raobs in the Great Lakes verification region shown in Fig. 5). The blue curve shows the impacts under the old RH processing; the red curve shows the impacts with the new RH processing. The larger values for the red curve demonstrate that the TAMDAR impacts in RH forecasts increase substantially at levels between 850 and 450 hPa with the new processing using a more appropriate observation error for the TAMDAR RH observations.

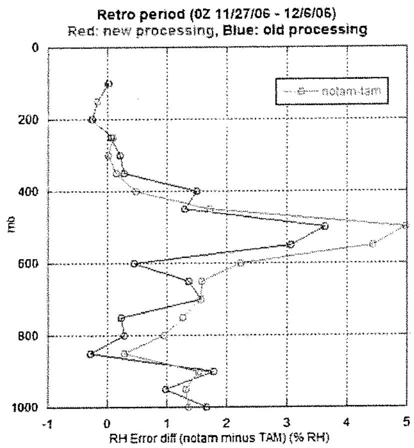



FIG. 28. TAMDAR impacts on 3-h RH forecasts (see text for explanation) for "new RH processing" (12% TAMDAR RH error, red) and "old RH processing" (12%/4 = 3% TAMDAR RH error, blue) for the retrospective time period.

Additional retrospective runs using TAMDAR RH observation errors of 18% and 25% showed that these values resulted in slightly less TAMDAR impact than the 12% value. Therefore, we implemented the 12% RH error, and the correction of the other RH observation errors, in our real-time dev2 runs on 26 April 2007. Although TAMDAR's RH impact was less than it might have been before this date, our long time series show that TAMDAR's impact on RH forecasts was notable even before this change was implemented.

### *b. Indirect relative humidity impacts*

There has been some speculation that improved resolution in temperature and wind data alone will indirectly improve RH forecasts, because better wind and temperature fields will result in better placement of humid areas. We therefore performed a retrospective run in which we included TAMDAR wind and temperature observations, but no TAMDAR RH observations. (All other data were included.)

When TAMDAR RH observations are excluded, TAMDAR has virtually no impact on 3-h forecasts of RH (Fig. 29). However, TAMDAR wind and temperature data alone do have some impact on the longer-range forecasts, such as the 9-h RH forecasts shown in Fig. 30. In that case, the blue curve between 500 and 450 hPa shows RH errors about halfway between the all-TAMDAR

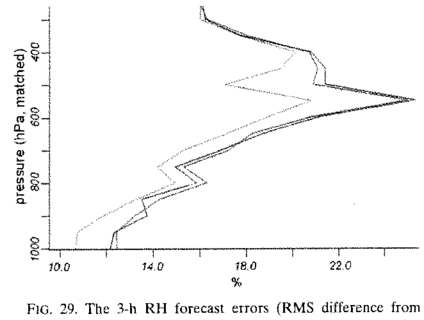



FIG. 29. The 3-h RH forecast errors (RMS difference from 0000 UTC raobs) for the Great Lakes region, for the retrospective period, for three cases: all-TAMDAR data, red; no-TAMDAR data, black; and TAMDAR wind and temperature data only, blue.

(red) and no-TAMDAR (black) runs. Interestingly, this is at a higher altitude than TAMDAR generally flies. This suggests that the model vertical motion is improved by the temperature and wind data, thereby improving the subsequent RH forecasts.

Thus, we can conclude that for 3-h forecasts, RH observations are needed to improve RH forecasts, at least on the 20-km scale of our RUC model runs. However, at longer forecast projections such as 9 h, a small improvement in the RH forecasts is apparent solely from the TAMDAR temperature and wind observations.

### *c. Vertical resolution*

During the retrospective time period, AirDat provided high vertical resolution data [10 hPa in the lowest 200 hPa (for both ascents and descents), and 25 hPa above that]. At other times, to save communication costs, they have provided data at lower vertical resolution. To study

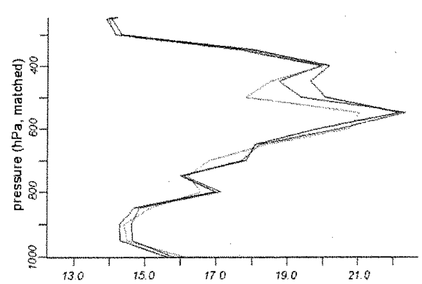



FIG. 30. As in Fig. 29 but for 9-h RH forecasts.

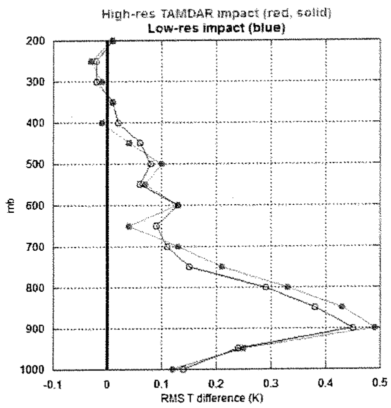



FIG. 31. TAMDAR 3-h temperature forecast impacts (see text for explanation) for the full vertical resolution run (red) and the low-vertical resolution run (blue), for the retrospective period.

the impacts of using different vertical resolutions, we artificially degraded the resolution above the lowest 100 hPa AGL to 50 hPa; we kept the 10-hPa resolution in the lowest 100 hPa. This removed about one-half of the TAMDAR observations.

The curves in Fig. 31 may be compared to the black curve in Fig. 19. That is, each is the difference in the RMS temperature error between an all-TAMDAR run and the no-TAMDAR run. The results indicate that the lowered vertical resolution does indeed reduce TAMDAR's impact on 3-h temperature forecasts below 700 hPa. TAMDAR's impact is reduced by about 10% at 900 hPa, growing to a 30% reduction at 750 hPa. For RH forecasts, reducing the vertical resolution had little consistent impact (not shown). However, for all variables, the impact of reduced vertical resolution is certainly larger in certain situations—often related to adverse weather conditions. We note that higher vertical resolution has been very useful in some critical weather situations for human forecasters who look directly at the TAMDAR soundings (Szoke et al. 2006).

## 6. Recent developments

Recently, additional TAMDAR fleets have started reporting to ESRL/GSD. Currently (fall 2009), the four commercial air carrier fleets providing TAMDAR data are

- Mesaba, data first received in 2004, and reported on above;
- PenAir, data first received in late 2007; PenAir flights connect Anchorage with smaller cities in southwestern Alaska and the Aleutian Islands—a generally data-poor region;
- Chautauqua, data first received in April 2008; this fleet of regional jets flies higher and faster than the turboprops in the other fleets and, therefore, can potentially provide valuable data at higher altitudes than available from turboprops; and
- Horizon, data first received in December 2008.

A more recent (April 2009) horizontal distribution of TAMDAR data reported to ESRL/GSD for a 24-h period is shown in Fig. 32. Reports from the PenAir fleet are evident over Alaska. Horizon reports are over the western United States; Chautauqua reports are now made over Mexico, the lower Midwest, and the east coast. Note the data points coded in light blue, representing data taken above 28 000 ft by Chautauqua jets.

Our initial studies of data from the Chautauqua jets indicate that the quality of the temperature, wind, and relative humidity data is as good or better than that produced by the Mesaba turboprops (not shown). We started ingesting Chautauqua data into the dev2 on 30 April 2008 and have seen a notable increase in TAMDAR's impact—particularly on relative humidity forecasts—since that time.

Figure 33 shows TAMDAR's impact on 3-h relative humidity forecasts for the entire eastern U.S. region (the violet rectangle in Fig. 5). This geographic and altitude (up to 400 hPa) region was not densely covered by the initial TAMDAR Mesaba fleet alone (Fig. 5). The increased TAMDAR impacts on RH forecasts for this region since late April 2008 are evident in the difference curve.

A December 2008 vertical profile of TAMDAR impacts on RH 3-h forecasts (Fig. 34) in the eastern U.S. region includes the effects of the Chautauqua fleet. Comparing this with Fig. 25, which shows the corresponding pre-Chautauqua vertical RH impacts for the Great Lakes region, reveals that TAMDAR's impact now extends higher—to above 300 hPa.

## 7. Summary and a look ahead

The TAMDAR sensor provides meteorological data on a regional scale over the U.S. midwest (and now over most of the United States). By equipping regional aircraft, TAMDAR provides ascent–descent profiles at regional airports for which traditional AMDAR profiles were not available. Moreover, TAMDAR also reports relative humidity, a variable not generally or reliably available previously from commercial aircraft. We have evaluated the impacts of TAMDAR's wind, temperature, and relative

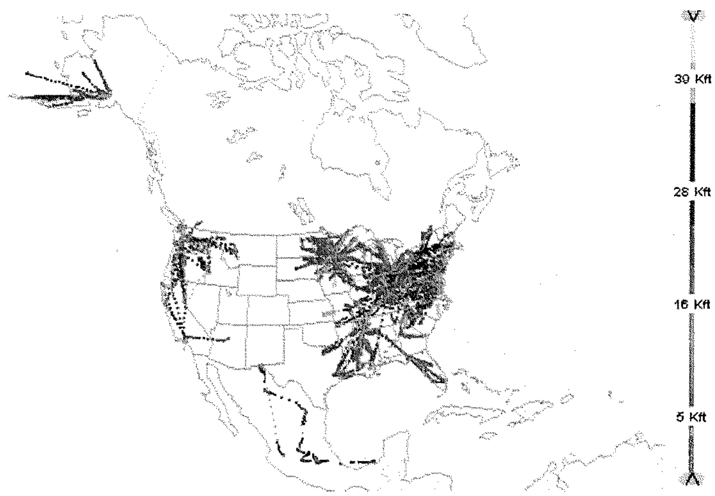



FIG. 32. TAMDAR observation reports received over a 24-h period at ESRL/GSD on 29 Apr 2009. There were 30 877 reports.

humidity data on the RUC model–assimilation system with 1) real-time matched TAMDAR and no-TAMDAR runs for the past 3 yr and 2) retrospective runs over two 10-day active weather periods during the winter of 2006 and summer of 2007.

We have shown that assimilation of TAMDAR observations improves 3-h RUC forecasts in the region and altitude range in which TAMDAR flies. We estimate the TAMDAR's impact as follows:

- The 3-h temperature forecast errors are reduced by up to 0.4 K, dependent on vertical level.
- The 3-h wind forecast errors are reduced by up to $0.25 \text{ m s}^{-1}$.
- The 3-h relative humidity forecast errors are reduced by up to 3% RH.

As discussed in section 4b(4), we can cast these error reductions into fractions of the *estimated maximum potential improvement* (EMPI). In these terms, TAMDAR results in these impacts:

- The 3-h temperature forecast errors are reduced by up to 35% of the EMPI.
- The 3-h wind forecast errors are reduced by up to 15% of the EMPI.
- The 3-h relative humidity forecast errors are reduced by 15% to 50% of the EMPI.

Retrospective runs have revealed the following:

- The optimal TAMDAR RH observational error specification is 12% for assimilation impacts. Both lower and higher values resulted in lower RH forecast impacts.

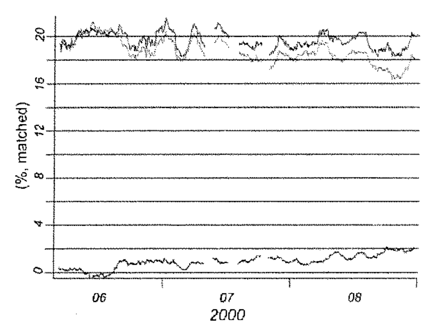



FIG. 33. Time series of 3-h RH forecast errors (RMS difference from 0000 UTC raobs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and the dev–dev2 difference (black), for the eastern U.S. region, in the layer between the surface and 400 hPa. Thirty-day running averages were used. Positive differences indicate a positive TAMDAR impact.

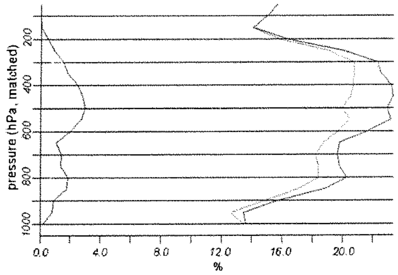



FIG. 34. Vertical profile of 3-h RH forecast errors (RMS difference from 0000 UTC raobs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and the dev-dev2 difference (black), for the eastern U.S. region, during December 2008.

The 12% RH error is now being used in real-time RUC cycles.

- RH observations are generally required to improve 3-h forecast skill. However, for longer forecasts, wind and temperature observations alone, at sufficiently fine resolution, can improve the RH forecasts indirectly.
- Lowered vertical resolution reduces the TAMDAR-related forecast improvement from 10% to 30% for temperature forecasts, but in individual cases this reduced accuracy may cause important meteorological conditions to be unobserved or inadequately resolved.

*Acknowledgments.* This research is in response to requirements and funding by the Federal Aviation Administration (FAA) under Interagency Agreement DTFAWA-03-X-02000. The views expressed are those of the authors and do not necessarily represent the official policy or position of the FAA or NASA. We thank Bradley Ballish (NWS/NCEP), John M. Brown (ESRL/GSD), and an anonymous reviewer for their very helpful comments and suggestions. We also thank Annie Reiser (ESRL/GSD) for her careful editing.

## REFERENCES

Benjamin, S. G., G. A. Grell, J. M. Brown, T. G. Smirnova, and R. Bleck, 2004a: Mesoscale weather prediction with the RUC hybrid isentropic–terrain-following coordinate model. *Mon. Wea. Rev.*, **132**, 473–494.

——, and Coauthors, 2004b: An hourly assimilation–forecast cycle: The RUC. *Mon. Wea. Rev.*, **132**, 495–518.

——, B. E. Schwartz, E. J. Szoke, and S. E. Koch, 2004c: The value of wind profiler data in U.S. weather forecasting. *Bull. Amer. Meteor. Soc.*, **85**, 1871–1886.

——, W. R. Moninger, T. L. Smith, B. D. Jamison, and B. E. Schwartz, 2006a: TAMDAR aircraft impact experiments with the Rapid Update Cycle. Preprints, *10th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, Atlanta, GA, Amer. Meteor. Soc., 9.8. [Available online at http://ams.confex.com/ams/pdfpapers/105064.pdf.]

——, ——, ——, ——, and ——, 2006b: Impact of TAMDAR humidity, temperature, and wind observations in RUC parallel experiments. Preprints, *12th Conf. on Aviation, Range, and Aerospace Meteorology*, Atlanta, GA, Amer. Meteor. Soc., 4.5. [Available online at http://ams.confex.com/ams/pdfpapers/105028.pdf.]

——, ——, ——, ——, E. J. Szoke, and T. W. Schlatter, 2007: 2006 TAMDAR impact experiment results for RUC humidity, temperature, and wind forecasts. Preprints, *11th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface*, San Antonio, TX, Amer. Meteor. Soc., 9.2. [Available online at http://ams.confex.com/ams/pdfpapers/119903.pdf.]

——, B. D. Jamison, W. R. Moninger, S. R. Sahm, B. E. Schwartz, and T. W. Schlatter, 2010: Relative short-range forecast impact from aircraft, profiler, radiosonde, VAD, GPS-PW, METAR, and mesonet observations via the RUC hourly assimilation cycle. *Mon. Wea. Rev.*, **138**, 1319–1343.

Daniels, T. S., W. R. Moninger, and R. D. Mamrosh, 2006: Tropospheric Airborne Meteorological Data Reporting (TAMDAR) overview. Preprints, *10th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, Atlanta, GA, Amer. Meteor. Soc., 9.1. [Available online at http://ams.confex.com/ams/pdfpapers/104773.pdf.]

Facundo, J., 2004: Update on the implementation of the National Weather Service's Radiosonde Replacement System. Preprints, *Eighth Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, Seattle, WA, Amer. Meteor. Soc., 3.2. [Available online at http://ams.confex.com/ams/pdfpapers/69730.pdf.]

Helms, D., and Coauthors, 2005: NOAA's deployment of the Water Vapor Sensor System (WVSS II). Preprints, *21st Conf. on Weather Analysis and Forecasting/17th Conf. on Numerical Weather Prediction*, Washington, DC, Amer. Meteor. Soc., P1.45. [Available online at http://www.nws.noaa.gov/ost/wvss/AMS_NWP-WVSSII_Poster_JUL05.pdf.]

Moninger, W. R., R. D. Mamrosh, and P. M. Pauley, 2003: Automated meteorological reports from commercial aircraft. *Bull. Amer. Meteor. Soc.*, **84**, 203–216.

Rogers, E., and Coauthors, 2009: The NCEP North American Mesoscale Modeling System: Recent changes and future plans. Preprints, *23rd Conf. on Weather Analysis and Forecasting/19th Conf. on Numerical Weather Prediction*, Omaha, NE, Amer. Meteor. Soc., 2A.4. [Available online at http://ams.confex.com/ams/pdfpapers/154114.pdf.]

Smith, T. L., S. G. Benjamin, S. I. Gutman, and S. Sahm, 2007: Short-range forecast impact from assimilation of GPS-IPW observations into the Rapid Update Cycle. *Mon. Wea. Rev.*, **135**, 2914–2930.

Szoke, E., R. Collander, B. Jamison, T. Smith, T. Schlatter, S. Benjamin, and W. Moninger, 2006: An evaluation of TAMDAR soundings in severe storm forecasting. Preprints, *23rd Conf. on Severe Local Storms*, St. Louis, MO, Amer. Meteor. Soc., 8.1 [Available online at http://ams.confex.com/ams/23SLS/techprogram/paper_115158.htm.]

——, ——, ——, ——, S. G. Benjamin, W. R. Moninger, T. W. Schlatter, and B. Schwartz, 2007: Impact of TAMDAR data on RUC short-range forecasts. Preprints, *22nd Weather Analysis and Forecasting Conf.*, Park City, UT, Amer. Meteor. Soc., 4A.4. [Available online at http://ams.confex.com/ams/22WAF18NWP/techprogram/paper_124715.htm.]

# Relative Short-Range Forecast Impact from Aircraft, Profiler, Radiosonde, VAD, GPS-PW, METAR, and Mesonet Observations via the RUC Hourly Assimilation Cycle

STANLEY G. BENJAMIN, BRIAN D. JAMISON,* WILLIAM R. MONINGER, SUSAN R. SAHM, BARRY E. SCHWARTZ,+ AND THOMAS W. SCHLATTER#

*NOAA/Earth System Research Laboratory, Boulder, Colorado*

(Manuscript received 15 June 2009, in final form 29 September 2009)

ABSTRACT

An assessment is presented on the relative forecast impact on the performance of a numerical weather prediction model from eight different observation data types: aircraft, profiler, radiosonde, velocity azimuth display (VAD), GPS-derived precipitable water, aviation routine weather report (METAR; surface), surface mesonet, and satellite-based atmospheric motion vectors. A series of observation sensitivity experiments was conducted using the Rapid Update Cycle (RUC) model/assimilation system in which various data sources were denied to assess the relative importance of the different data types for short-range (3–12 h) wind, temperature, and relative humidity forecasts at different vertical levels and near the surface. These experiments were conducted for two 10-day periods, one in November–December 2006 and one in August 2007. These experiments show positive short-range forecast impacts from most of the contributors to the heterogeneous observing system over the RUC domain. In particular, aircraft observations had the largest overall impact for forecasts initialized 3–6 h before 0000 or 1200 UTC, considered over the full depth (1000–100 hPa), followed by radiosonde observations, even though the latter are available only every 12 h. Profiler data (including at a hypothetical 8-km depth), GPS-precipitable water estimates, and surface observations also led to significant improvements in short-range forecast skill.

## 1. Introduction

An increasing number of atmospheric observation systems are used to initialize operational numerical weather prediction (NWP) models. Observation system experiments (OSEs) have been found very useful in determining the impact of particular observation types on operational NWP systems (e.g., Graham et al. 2000; Bouttier and Kelly 2001; Zapotocny et al. 2002, 2007; Lord et al. 2004; Cardinali 2009). OSEs can provide a basis for decisions regarding the design and implementation of current and future observing systems.

Such studies have provided valuable guidance on relative expenditures for different observational systems where expansions of current limited-areal deployments for certain observing systems [e.g., the National Oceanic and Atmospheric Administration (NOAA) Profiler Network (NPN)] might be most helpful toward improved NWP guidance. As heterogeneity of the overall composite observing system increases and as data assimilation and modeling techniques are improved, new OSEs will be needed to evaluate these new configurations.

This study uses a commonly used OSE design, with different observation types being excluded from the data assimilation system for separate experiments to measure effects on subsequent NWP forecasts, with the *control* experiment using all available observation types. This study differs from adjoint-based observation sensitivity experiments (e.g., Cardinali 2009; Zhu and Gelaro 2008; Baker and Daley 2000, among others). As described by Cardinali (2009), the adjoint-based sensitivity method tests the impact of all observations from a given time (or a short time over which a tangent linear model is run). An OSE by comparison shows impact over a longer period

* Additional affiliation: Cooperative Institute for Research in the Atmosphere, Fort Collins, Colorado.

+ Additional affiliation: Systems Research Group, Colorado Springs, Colorado.

# Retired.

*Corresponding author address:* Stanley G. Benjamin, NOAA/ESRL/GSD, 325 Broadway, R/GSD1, Boulder, CO 80304.
E-mail: stan.benjamin@noaa.gov

DOI: 10.1175/2009MWR3097.1

and also requires a much larger number of experiments (a separate experiment for each denial of a given observation type or subset, as done here). In contrast to those experiments mentioned above, this OSE study is performed using a regional model/assimilation system, whereas those previous listed (except for Zapotocny et al. 2002) were performed using global systems. Finally, the OSE data *denial* approach used in this study also differs from a data addition approach using a baseline control with, for instance, radiosondes only and adding other observation types to this control, one at a time.

This new OSE study is also unique in that it considers the very short-range forecast (3–12 h) effects from most of the currently assimilated high-frequency observing systems in a 1-h assimilation cycle, the Rapid Update Cycle (RUC; Benjamin et al. 2004a), which runs at the highest assimilation frequency of operational NWP models operated at the NOAA/National Centers for Environmental Prediction (NCEP). RUC short-range forecasts are heavily used as guidance for aviation, severe weather, energy, and other applications, some applying automated decision support algorithms suitable for hourly-updated NWP systems. Therefore, consideration of observation impact on very short-range (1–12 h) forecasts is important in considering investment in these observation systems, both from regional and global perspectives.

The new study is similar to the previous observation impact experiments also using the RUC reported in Benjamin et al. (2004c), which consider only wind forecast impact from wind profilers over a 13-day winter period. This new impact study is much broader than the previous study; it is now for a greater number of observation types over both summer and winter experiment periods, and for three fields—wind, temperature, and moisture. Other previous work on effects of high-frequency (hourly) observations on short-range forecasts include those reported by Smith et al. (2007) for GPS precipitable water observations and Weygandt et al. (2004) for simulated lidar wind observations [a regional observing system simulation experiment (OSSE)].

The observation sensitivity experiments reported here were carried out using a 2007 version of the RUC, including both assimilation system and forecast model components. The observing systems considered in this study include seven primary wind/temperature observation types over the United States: radiosonde observations (raobs), aircraft (Moninger et al. 2003), aviation routine weather report (METAR; surface), mesonet (automated surface observations from non-METAR networks), wind profilers (Benjamin et al. 2004c), velocity azimuth display (VAD) vertical wind profiles from NOAA Weather Surveillance Radar-1988 Doppler (WSR-88D) radar radial winds, and satellite atmospheric motion vectors (AMVs, sometimes less precisely called cloud-drift winds). All these observing systems except radiosondes provide hourly data. This study also includes the primary tropospheric moisture observation types [radiosondes, GPS ground-based precipitable water (PW; Smith et al. 2007)]. Relative effects of METAR and mesonet surface observations are also considered. We do not consider effects of satellite-measured radiances or retrieved soundings from satellite radiances in this study (neither are assimilated in the RUC; Benjamin et al. 2004b, section 2). Finally, this study also includes the relative impact of actual 16-km (full depth) NOAA profilers versus hypothetical profilers with only an 8-km vertical range.

This paper accompanies a report by Moninger et al. (2010) that focuses on a multiyear data impact study specifically for the (Tropospheric Aircraft Meteorological Data and Recording) TAMDAR-based observations from regional commercial aircraft. The companion paper includes results from a TAMDAR-denial experiment to measure TAMDAR impact during the same test periods used in this paper.

## 2. RUC version used for OSEs

The version of the RUC used in these experiments employs the same code as the 13-km version run operationally at NCEP as of March 2007, including 50 hybrid isentropic-sigma vertical levels and model physical parameterizations as described by Benjamin et al. (2004b), including five-species mixed-phase bulk cloud microphysics, Grell–Devenyi convective parameterization, and RUC–Smirnova land surface model. For computational efficiency, these experiments were run at 20-km resolution with no other modifications except for this resolution modification via a single parameter. The hourly intermittent assimilation cycle in the RUC (Benjamin et al. 2004a) allows full use of hourly observational datasets. The analysis method is the three-dimensional variational (3DVAR) technique implemented in the operational RUC in May 2003 (Devenyi and Benjamin 2003; Benjamin et al. 2004a, section 4), but with subsequent improvements listed below.

The key RUC modifications used in these OSE experiments made since the version of the RUC described by Benjamin et al. (2004a,b) include the following:

- Modification of moisture analysis variable from ln$q$ (natural logarithm of water vapor mixing ratio) to pseudo relative humidity (pseudo-RH), defined as $q/q$-saturation-background (Dee and da Silva 2003). Assimilation of all integrated precipitable water observations [GPS-PW and the Geostationary Operational Environmental Satellite (GOES)] was applied to the

TABLE 1. Observation types assimilated in the RUC for observation system experiments used in this study: pressure ($P$), height ($Z$), temperature ($T$), horizontal wind ($V$), relative humidity (RH), precipitable water (PW), virtual temperature (Tv), and dewpoint temperature (Td).

| Obs data type | Variables measured | Frequency (h) | Approx No. of hourly obs (except 12-hourly radiosondes) |
|---|---|---|---|
| Radiosonde | $P$, $Z$, $T$, $V$, RH | 12 | 80–85 |
| NOAA profilers—404 MHz | $V$ (by $Z$) | 1 | 30 |
| Boundary layer profilers—915 MHz, RASS | $V$ (by $Z$), Tv (by $Z$) | 1, 1 | 25, 14 |
| VAD winds | $V$ | 1 | 100–130 |
| Aircraft (AMDAR, not TAMDAR) | $V$, $T$ | 1 | 1400–7000 |
| TAMDAR aircraft | $V$, $T$, RH | 1 | 0–800 |
| GOES AMVs (cloud-drift winds) | $V$ | 1 | 1000–2500 |
| GOES cloud-top pressure, temp | $P$, $T$ | 1 | 10-km resolution |
| GOES precipitable water | PW | 1 | 10-km resolution–clear areas |
| GPS PW | PW | 1 | 250–300 |
| Surface—METAR | $P$, $T$, $V$, Td | 1 | 1800–2000 |
| Mesonet | $P$, $T$, Td, $V$ | 1 | 7000 |

RUC 3DVAR using a forward model for vertically integrated pseudo-RH with respect to precipitable water (Benjamin et al. 2004d). A small modification in moisture background error specification was made between the winter and summer seasons that did not appear to modify observation impact results (Moninger et al. 2010).

- Assimilation of GPS precipitable water data added in 2005 (Smith et al. 2007).
- Fractional application of lowest temperature analysis increment to top two levels in soil–vegetation–snow model used in RUC.
- Assimilation of METAR ceiling and visibility observations modifying the 3D RUC 3D hydrometeor (five species) and 3D water vapor mixing ratio fields (Benjamin et al. 2004e).
- Assimilation of pseudoresiduals for surface observations distributed within the planetary boundary layer (PBL) using the background (RUC 1-h forecast) PBL depth, using certain constraints (Benjamin et al. 2004f).
- Extension of digital filter initialization (DFI) used in RUC model to a two-pass diabatic DFI.

Changes were also made in RUC model physics using the Thompson mixed-phase cloud microphysics and Grell–Devenyi convective parameterization as described by Benjamin et al. (2004f).

Observational data assimilated in the version of the RUC used in this OSE study are listed in Table 1. GOES-based cloud-top temperature/pressure retrievals, AMVs, and precipitable water are also assimilated in the RUC 1-h cycle.

## 3. Experiment design for observation impact experiments

A series of experiments was conducted using the RUC model/assimilation system in which various data sources were denied to assess relative importance of the different data types for short-range (3–12-h duration) wind, temperature, and relative humidity forecasts at different vertical levels. This assessment was carried out for 10-day periods in cold season (November–December 2006) and warm season (August 2007).

The same boundary conditions were used in all experiments, damping the signal in differences between experiments, more than might be expected in similar OSEs performed with global assimilation and models. The damping effect by lateral boundary conditions becomes stronger as the model/assimilation domain is reduced, and therefore is larger in this study using the RUC domain than that for the (North American Mesoscale) NAM-based (larger regional domain) described by Zapotocny et al. (2002). Nutter et al. (2004) also show a similar effect from lateral boundary conditions limiting the spread of regional ensemble forecasts; the same effect occurs in the OSEs described here limiting variation between experiments more than in global OSEs. In a regional OSSE study for simulated lidar wind observations, Weygandt et al. (2004) found the observational impact from simulated lidar winds interior to the RUC regional domain about equal to that from variations in lateral boundary conditions from associated global OSSE experiments with and without lidar. In this study, the observations considered are generally denser over the United States than over oceans and other land areas, but the actual impact is underestimated in this study because of the common lateral boundary conditions prescribed in these experiments.

### *a. Experiments performed*

A control experiment was performed for each of two seasonal 10-day test periods in which all available observations were used, similar to the operational RUC.

TABLE 2. Observation impact experiments in this study. Those observational variables denied to the RUC are shown for each experiment: pressure ($P$), height ($Z$), temperature ($T$), horizontal wind ($V$), relative humidity (RH), precipitable water (PW), and dewpoint temperature (Td).

| Expt | Variables denied | Carried out for Nov–Dec 2006 | Carried out for Aug 2007 |
|---|---|---|---|
| Control—all observations used | | X | X |
| No radiosonde | $Z$, $T$, $V$, RH | X | X |
| No profiler winds (NOAA network or CAP) | $V$ | X | X |
| No VAD | $V$ | X | X |
| No aircraft (AMDAR or TAMDAR) | $V$, $T$ | X | X |
| No TAMDAR aircraft (in Moninger et al. 2010) | $V$, $T$, RH | X | X |
| No GPS-PW | PW | X | X |
| No surface (METARs, buoy, or mesonet) | $P$, $T$, $V$, Td | X | X |
| No mesonet | $P$, $T$, $V$, Td | X | X |
| All obs but using 8-km NOAA network profilers | $V$ | X | |
| All obs but using 12-km NOAA network profilers | $V$ | X | |
| No GOES atmospheric motion vectors (AMVs; from visible and IR channels, not water vapor) | $V$ | X | |

In subsequent experiments, different observation types were withheld, as shown in Table 2. Most of these observation types were available over the full RUC horizontal domain covering the lower 48 U.S. states and adjacent Canada and Mexico (approximately that shown in Fig. 1). As shown in Fig. 2, some of the observation types (profiler, TAMDAR aircraft) were available only in the midwestern United States, motivating us to also employ a verification subregion in that area, as discussed in the next section. In the RUC, GOES AMVs are assimilated only over oceanic areas, since aircraft data (generally of higher quality) are predominant over land area in the RUC domain. Impact experiments for AMVs, 8-km profilers, and 12-km profilers were performed only for the winter period (Table 2).

Lateral boundary conditions were specified from the NCEP NAM, initialized every 6 h and available with 3-h output frequency. NAM boundary conditions were specified in the same delayed manner as with the operational RUC: RUC model runs at 0000, 0600, 1200, and 1800 UTC use NAM boundary conditions from the previons NAM cycle (1800, 0000, 0600, and 1200 UTC, respectively).

The experiments for the winter and summer 10-day data assimilation periods are shown in Table 3. The November–December 2006 winter period was synoptically active in the northern United States, especially in the upper Midwest and Great Lakes area. An example of surface conditions during this period (1200 UTC 1 December 2006) is shown in Fig. 1, with a strong winter storm centered over Indiana. The 10-day summer experiment period spanned 15–25 August 2007, and was chosen because it included considerable intense weather in the Great Lakes region. The period started with a warm front producing heavy precipitation in that region; later, flooding occurred in Minnesota and Wisconsin. Severe storms continued to appear, and generally move toward the east, throughout the period.

*b. Verification*

We verified model forecasts against conventional, twice-daily radiosonde data over the two domains depicted in Fig. 3. The first domain contains all the radiosonde sites located within the RUC domain; the second (the red rectangle) is a limited area over the data-rich Midwest.

Verification results for the national region reflect the impact of observations over the full RUC domain, covering the lower 48 contiguous U.S. region and significant proportions of Canada and Mexico. The Midwest verification region shown in Fig. 3 has special interest because of the NOAA profiler network (marked in green) and TAMDAR aircraft coverage at that time (see Moninger et al. 2010 for TAMDAR coverage). With the United States considering expenditures for wider deployment of profilers and regional aircraft observations, the Midwest verification domain corresponds to the density that might be expected nationally over the next few to several years.

For each RUC experiment, residuals [forecast minus observed ($f - o$) differences] for temperature ($T$), relative humidity (RH), and wind ($V$) were computed at all radiosonde locations located within each verification domain. These $f - o$ residuals were calculated for 3-, 6-, 9-, and 12-h forecasts. The rms (root-mean-square) difference between forecasts and observations was computed for each 12-h radiosonde verification time (0000 and 1200 UTC). This difference is sometimes referred to below as the "forecast error," or "RMSE," but in fact also contains a contribution from the observation error (including a representativeness "error" from the inability of a grid to resolve subgrid variations sometimes evident in observations).

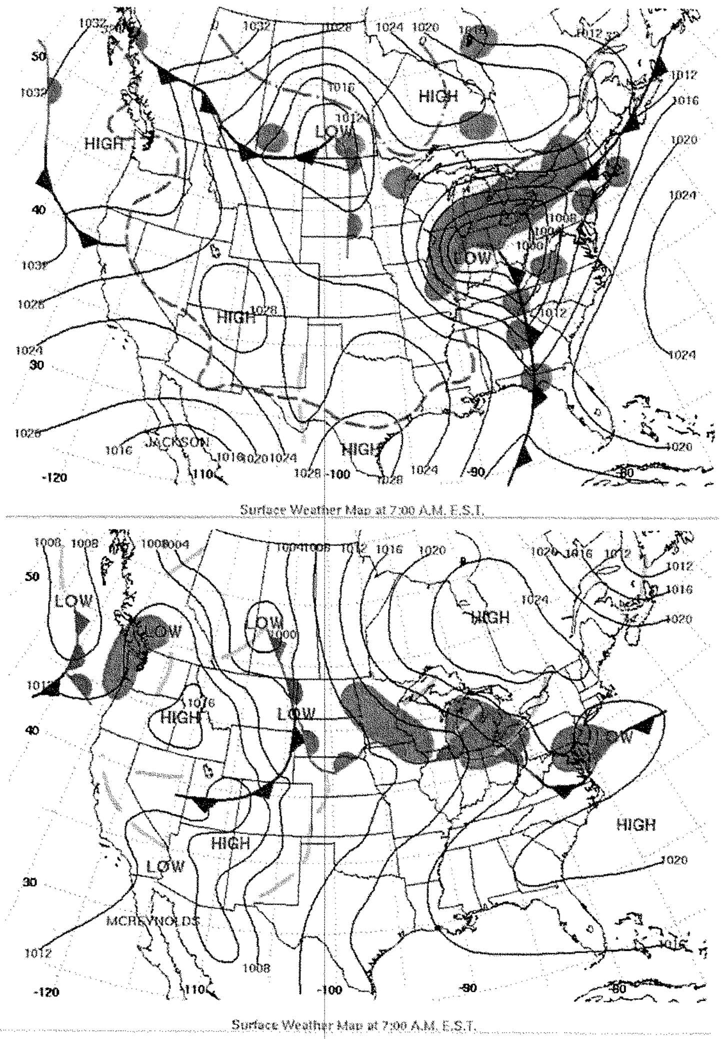



FIG. 1. Surface analyses for (a) 1200 UTC 1 Dec 2006, in middle of winter experiment period, and (b) 1200 UTC 20 Aug 2007, in the middle of the summer experiment period (courtesy of NOAA/NCEP/HPC).

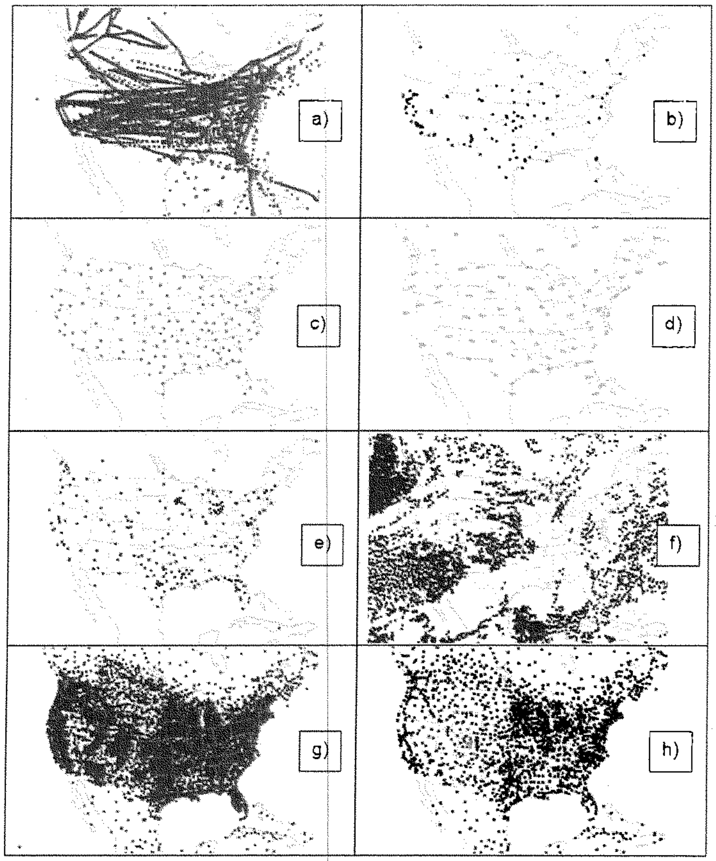



FIG. 2. Distribution of data sources. Sample data from 12 Nov 2009 valid within 1 h of 0000 UTC (data available in retrospective periods is similar, but that TAMDAR data are not shown here). Color coded as in the histogram plots below: (a) AMDAR; (b) profilers (national network plus cooperating agency profilers); (c) VAD, from NEXRAD radars; (d) raobs; (e) GPS; (f) AMV; (g) all surface (METARs plus mesonet); and (h) METAR, color coded by altitude.

In the following results, increase in forecast error from denying a given observation type can be considered equivalent to the added forecast skill when that observation type is added to other existing observations. Benjamin et al. (2004c) explain this verification procedure.

Verification in this paper uses 10-hPa vertical resolution, iucluding significant-level radiosonde observations and native model levels interpolated to that resolution, for calculating $f - o$ differences using a verification capability explained in Moninger et al. (2010). This high vertical resolution of forecast errors allows clearer attribution of differences to physical mechanisms than verifying against radiosonde data only at mandatory levels (e.g., 850, 700, 500, 400, 300, 250, 200, and 150 hPa). For

TABLE 3. Experiment periods.

| Expt period | Beginning | End | Notes |
|---|---|---|---|
| Winter | 26 Nov 2006 | 5 Dec 2006 | Strong winter storm early, moderate winter weather later (in the Midwest) |
| Summer | 15 Aug 2007 | 25 Aug 2007 | Active period for convective storms in Great Lakes region |

example, higher vertical resolution in verification revealed a peak near 900 hPa in temperature forecast error and aircraft impact at that level, subsequently related to boundary layer depth as described by Moninger et al. (2010). The 10-hPa verification also increases the number of $f - o$ data points over what would have been available with mandatory level raob data only, numbering about 5200 for a 200-hPa layer in the Midwest domain (10 days $\times$ 2 times/day $\times$ 13 raob sites $\times$ 20 vertical points) and about 32 000 $f - o$ points for the national domain (80 raobs), increasing significance of results shown later.

For quality control of radiosonde data used in verification, $f - o$ values from the control experiment were subjectively screened for egregiously large values and removed when found. While some erroneous values may have escaped detection, they were used uniformly in verifying all experiments and therefore do not contribute to the *relative* impact results shown below.

We looked for impact on precipitation forecasts in control versus denial experiments for the two observation types most likely to show them, GPS-PW, and TAMDAR aircraft observations, and found only negligible effect. Assimilation of radar reflectivity data, by contrast, has shown a strong effect on RUC precipitation forecasts (Weygandt et al. 2008).

*c. Statistical significance of results*

Results that follow present differences in rms forecast error (RMSE) for model runs with and without specific observation types. Each estimate has an associated uncertainty due, in part, to the small number of days we examined. We present *overall* RMSE differences for each period (winter and summer), but we can estimate the uncertainty in these RMSE differences by considering the variations in RMSE over *each of the 20 raob times* in each seasonal period. The uncertainty on the mean ("standard error") is estimated as

$$\text{Standard Error} = \frac{\sigma}{\sqrt{(n-1)(1-\varphi)}},$$

where $\sigma$ is the standard deviation, $n$ is the number of RMSE forecast values, $x$ is the set of RMSE forecast

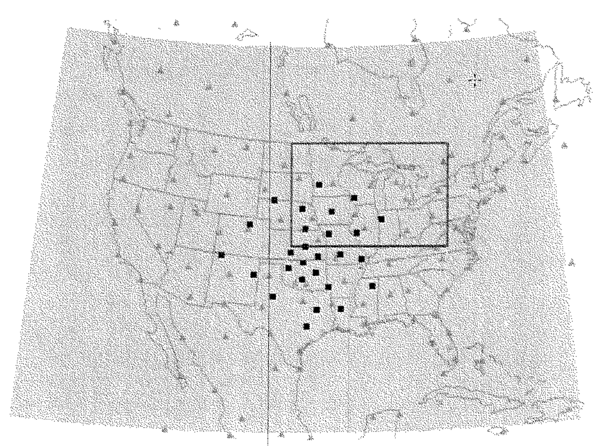


FIG. 3. Midwest–Great Lakes (red rectangle) and national (gray area) verification regions. Also shown is the location of the NOAA profilers (blue rectangles) and verifying raobs (brown triangles).

differences, and $\varphi$ is the lag 1 autocorrelation derived from the time series $x$. This is empirically derived from the RMSE values with the following approximation:

$$\varphi \cong \text{cor}(x_{1\ldots(n-1)}, x_{x\ldots n}).$$

The estimate of the standard error on the mean is distinct and separate from the standard deviation from the sample. The standard error is an estimate of how well we understand the underlying, fundamental differences in RMSE between using the additional data and ignoring the additional data. The standard deviation is an estimate of how far off the mean value any one RMSE forecast may be (Weatherhead et al. 1998). Thus, were our experiment to be repeated in a similar season and for a similar duration, we can say that the mean RMSE difference has a 67% likelihood of being within 1 standard error of our results, and a 95% likelihood of being within 2 standard errors of our results.

This approach at least partially accommodates the fact that the pairwise differences in RMSE are autocorrelated. Physically, this implies that in some situations, the added data have more influence than others. Those situations can last for more than one day, thus the sequential forecast RMSE differences are not independent estimates of the effect of the added data, but represent an oversampling of the system. The standard error equation above accounts for these. It should be noted that the lag 1 autoregressive assumption in this case refers to a 12-h lag as the most significant approximation to the autocorrelation. It should also be noted that aggregation of 0000 and 1200 UTC results allows for a larger sample size, but may result in combining different physical causes of differences as well as different statistical properties of the time series. These more finescale effects are beyond the scope of the research presented in this paper.

In the figures that follow, standard errors are indicated where relevant. Differences of 1 standard error are significant at the 67% confidence level; differences of 2 standard errors are significant at the 95% confidence level.

### *d. Procedure for 8-km (quarter scale) versus full-scale profiler experiments*

For these experiments, we extracted 8-km (quarter scale) and 12-km profiler data from actual 16-km full-scale profiler data by removing data for all vertical gates higher than 8 km (or 12 km) above station elevation. The hypothetical 8-km profilers provide half the vertical coverage of wind observations compared with the full-scale 404-MHz profilers and approximate data from proposed 8-km 449-MHz profilers. With the 16-km full-scale profilers, winds are available from 36 high-mode gates and 36 low-mode gates, with a slight overlap near 8-km elevation above ground level (AGL). We extracted quarter-scale (8 km) and 12-km profiler data at the 30 profiler sites shown in Fig. 3. In removing winds above 8 km AGL, data were left for 33 low-mode gates, and 5 high-mode gates. We assumed that the observation error in these hypothetical future profilers would be the same as that used for the existing 16-km profilers.

The profiler stations assimilated by the RUC in these experiments included about 21 Cooperative Agency Profiler (CAP) sites operating at 915 MHz with a vertical range of about 4 km, and these data were not truncated in 8- and 12-km profiler experiments. These CAP profilers include 12 in California, 4 in Texas, and 1 each in New Mexico, Arizona, Minnesota, New Jersey, and Nova Scotia), as shown by White et al. (2007, their Fig. 3).

TABLE 4. Verification stratifications for OSEs.

| |
|---|
| Nine expt (control, eight observation denial expt) |
| Control |
| No aircraft (meaning no AMDAR or TAMDAR, no aircraft of any type, listed as noAMDAR—automated aircraft reports) |
| No profiler (no profiler of any kind, NOAA or CAP) |
| No VAD winds |
| No raobs |
| No surface (no surface of any kind; METAR, mesonet or buoy) |
| No GPS precipitable water |
| No satellite AMVs (cloud-drift winds—listed as CDW) |
| No mesonet |
| Two regions |
| U.S. national (data rich) |
| Midwest (very data rich) |
| Four layers |
| 1000–100 hPa (full depth), 1000–400 hPa for RH only |
| 1000–800 hPa (near surface) |
| 800–400 hPa (midtroposphere) |
| 400–100 hPa (upper troposphere, lower stratosphere) |
| Two seasons |
| Winter |
| Summer |
| Forecast duration |
| 3, 6, and 12 h |

## 4. Results for impact from existing observations

### *a. Stratification*

To summarize the complexity of the OSE results from this study, we considered the five verification stratifications: experiment, regions, layers, seasons, and forecast duration, as shown in Table 4. Rather than examine detailed vertical profiles of forecast errors (e.g., Benjamin et al. 2004c; Moninger et al. 2010), we found it effective to break down the full 1000–100-hPa vertical domain into three layers: 1000–800 hPa (dominated by boundary layer and surface effects), 800–400 hPa (middle troposphere), and 400–100 hPa (upper troposphere to lower

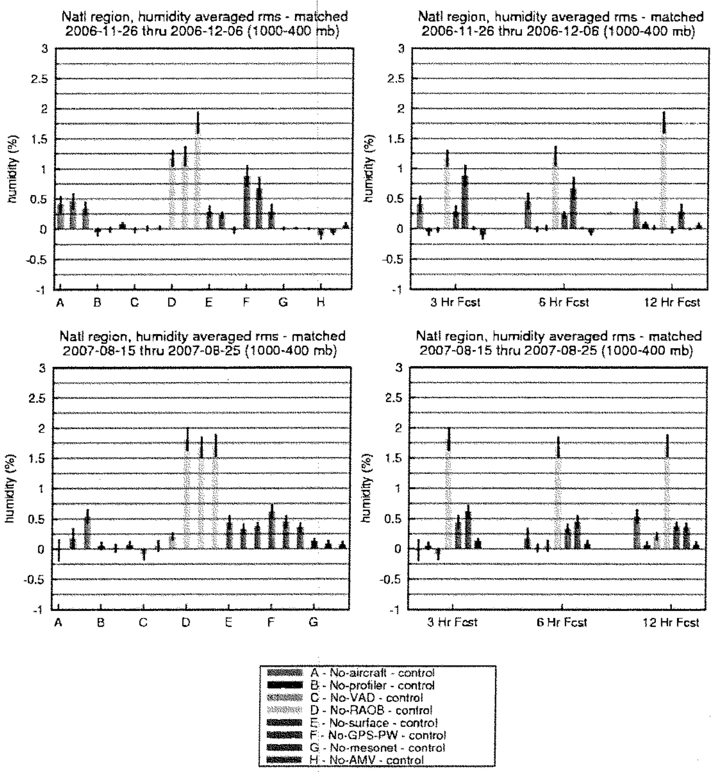



FIG. 4. Differences in rms error (vs radiosonde) between observation denial experiments listed in Table 2 and control run for 1000–400 hPa for relative humidity (% RH) for national domain. Results for each of the eight observational denial experiments are coded with a different color (aircraft: red, profiler: blue, VAD: pink, raob: tan, surface: light blue, GPS-PW: green, mesonet: black, satellite AMV winds: brown). Graphs at top are for winter results; those at bottom are for summer. (left) The three adjacent columns for each OSE are for 3-, 6-, and 12-h forecasts. (right) The same results are organized by observation type for each forecast projection (3, 6, and 12 h). The impact of AMV data was not tested during the summer period. Statistical uncertainties are indicated for each observation denial experiment by narrow black lines showing ±1 standard error from the mean impact.

stratosphere including tropopause and upper-level jet maxima).

We developed a composite graphical format used throughout the rest of this section that is introduced in Fig. 4 to summarize results for all OSE experiments for a given domain (national or Midwest) and vertical layer (1000–100, 1000–800, 800–400, or 400–100 hPa). Because of known raob moisture sensor limitations above approximately 400 hPa, where temperatures are commonly below −30°C, we used 1000–400 hPa for the "full troposphere" results for RH.

### *b. National, full troposphere*

We begin with the broadest view by examining results on the national domain for vertically integrated layers: 1000–100 hPa for temperature and wind, and 1000–400 hPa for RH. In section 4c, we shall show stratifications over different vertical layers, and in section 4d,

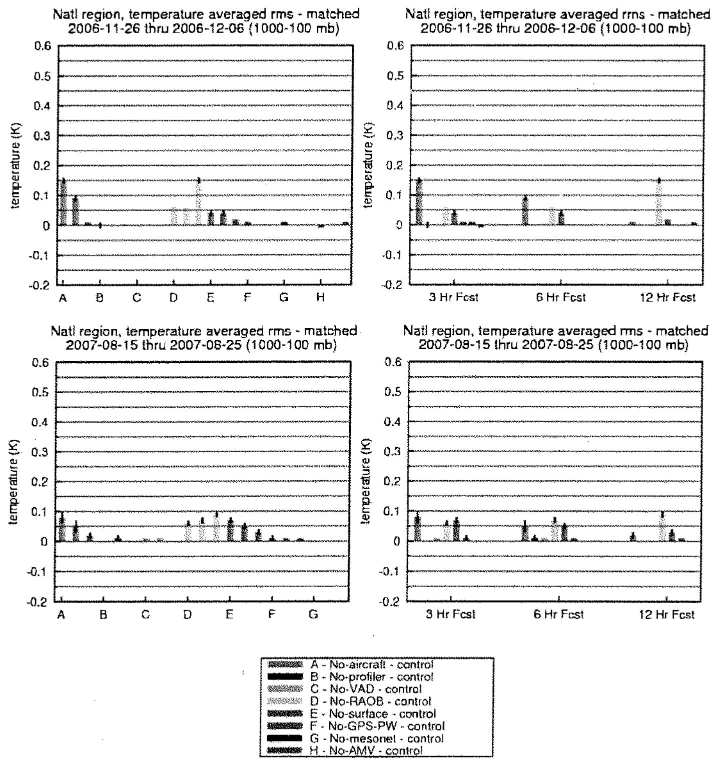



FIG. 5. As in Fig. 4, but for temperature error (K) for 1000–100-hPa layer over national domain.

results specifically from the Midwest region where observations are dense.

In the first graphical composite (Fig. 4), we consider impact results for RH for 1000–400 hPa. Results are for differences between experiments in which various observation types were withheld, as well as the control experiment in which all observations were assimilated (similar to the operational RUC). We use different colors to depict results for each of the eight observation denial experiments. Results in the top graphs are for *winter*; those in the bottom two boxes are for *summer*. For graphs at left, the three adjacent columns for each OSE are for 3-, 6-, and 12-h forecasts, respectively. The graphs on the right show the same information as those on the left, but organized by forecast projection to allow easier interpretation from that perspective. Again, as stated in the last section, increase in forecast error from denying a given observation type can be considered equivalent to the added forecast skill ("forecast impact") when that observation type is added to other existing observations.

The black bars indicate ± one standard error (section 3c) from the forecast impact of each observation type. Differences of 1 standard error are significant at the 67% confidence level; differences of 2 standard errors are significant at the 95% confidence level.

For RH over the 1000–400-hPa layer for 3–12-h RUC forecasts over the full domain (Fig. 4), the observation type with the largest impact is clearly raobs, for which the impact is 1%–2% RH for all forecast durations (3, 6,

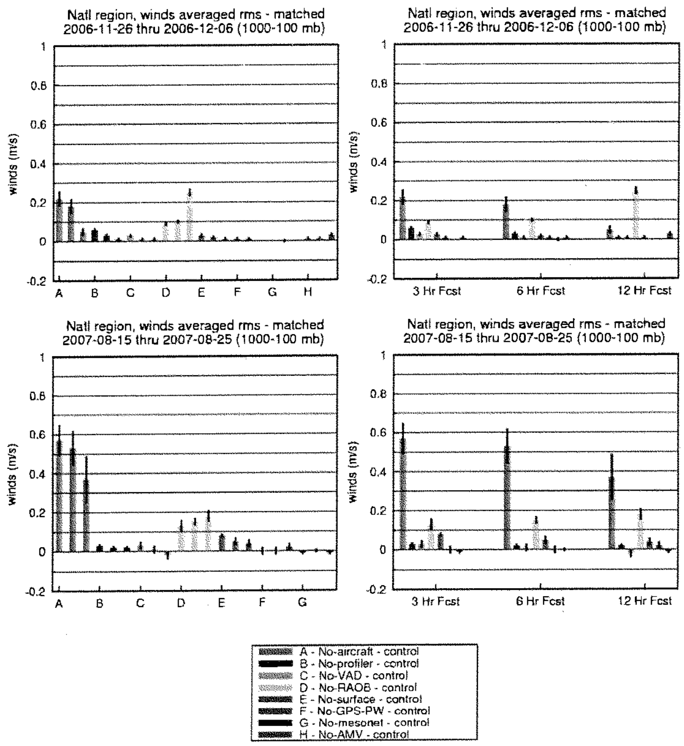



FIG. 6. As in Fig. 4, but for wind vector difference (m $s^{-1}$), still for 1000–100-hPa layer over national domain.

and 12 h) in both summer and winter. GPS-PW (Smith et al. 2007) had the second largest impact especially in winter (0.6%–0.9% for 3- and 6-h forecasts). The third most important observation source is aircraft in winter [<0.5%, presumably primarily from TAMDAR reports (including moisture) in the Midwest] and surface observations in summer. In the summer period, each of the five observation types that provide moisture observations are shown to have varying degrees of at least small positive impacts on the short-range RUC RH forecasts over the full national domain.

The impact of raobs at 12 h on RH forecasts is large, sometimes even larger than that at 3 and 6 h. This is so because 12-h forecasts valid at 0000 and 1200 UTC have the direct benefit of raob data in the initial conditions whereas 3-h and 6-h forecasts do not. Even so, the impact at 3 and 6 h is substantial. We attribute this to the "memory" in the assimilation system of raobs incorporated several cycles before the start of these forecasts.

For temperature forecasts over the full (1000–100 hPa) atmospheric depth (Fig. 5), in winter, on average, raobs and aircraft observations had about equal effect (0.05–0.15 K) on average over 3–6-h impact, more from aircraft at 3 h, equal at 6 h, and much more impact from radiosondes at 12 h. In summer, surface observations have nearly equal impact as both aircraft and raobs over the full 1000–100 hPa. The explanation is that a deeper mixed layer in summer extends the potential vertical influence of surface observations. This PBL effect is accounted for in the RUC 3DVAR design, as discussed in section 2 and in Benjamin et al. (2004f).

For the vector wind difference (Fig. 6), aircraft observations have the strongest overall impact for 3- and 6-h forecast projections for both for the summer (0.3–0.6 m $s^{-1}$) and winter periods (0.15–0.20 m $s^{-1}$) and for 12-h forecasts in the summer season. Radiosondes have the greatest impact for winds at 12 h in winter only. Satellite AMVs provide a small positive impact (<0.05 m $s^{-1}$) at 12 h in winter, in third place after radiosondes and aircraft. All observation types tested showed at least a small positive impact except for VAD winds in summer at 12-h duration (perhaps due to bird migration problems not detected by the RUC bird detection algorithm; Benjamin et al. 2004a, their section 4e) and mesonet observations, which frequently have unrepresentative siting for wind measurement (Benjamin et al. 2007).

Our results indicate that aircraft observation impact (Fig. 6) was stronger in summer (0.3–0.6 m $s^{-1}$ over full layer) than winter (0.15–0.20 m $s^{-1}$), which was surprising to us since upper-level wind forecast errors are usually larger in winter than in summer over the United States. To examine this behavior a bit further, we first looked at seasonal variations of upper-level wind (400–200 hPa) forecast error for the RUC at 9-, 3-, and 1-h forecast duration (Fig. 7, 30-day running mean) over a period from January 2007 to May 2009. For RUC 9-h wind forecasts for the 400–200-hPa layer, error (versus raobs) was about 5.8–6.0 m $s^{-1}$ in winter for 2007–09 and lower, about 5.2–5.3 m $s^{-1}$ on average, in summer for 2007–08. However, the short-range increment in forecast skill (e.g., 9- to 1-h forecast skill difference, bottom in Fig. 7), largely from assimilation of recent observations (Benjamin et al. 2004a), does not vary drastically over season, although the 30-day running mean show some apparent shorter-period regime-dependent variations. Therefore, we consider the larger aircraft impact for wind forecasts in the summer August 2007 period than in winter to be slightly unusual but plausible, consistent with the particular synoptic-scale regimes of those separate 10-day periods.

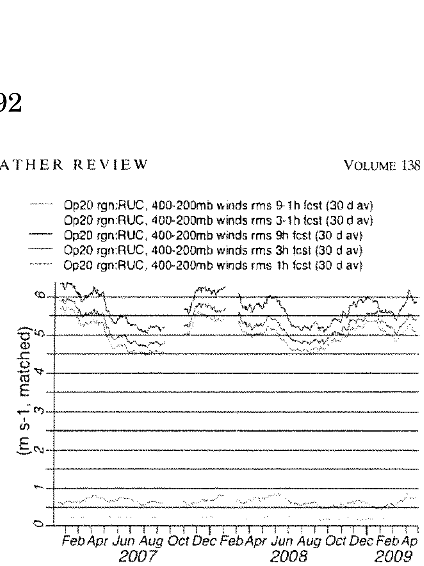



FIG. 7. Vector wind error (vs radiosondes) for RUC 9- (black), 3- (blue), and 1-h (red) forecasts averaged over 400–200-hPa layer and for a 30-day running mean for January 2007–April 2009. Also shown are the forecast error increments (between 0 and 1) from assimilation of recent observations for 9- to 1-h (red, near lower axis) and 3- to 1-h (tan) pairs.

### c. *National, but stratified into three layers (for wind only)*

Next, we stratify the OSE results within three layers as described in section 4a, 1000–800 (near surface), 800–400 (midtroposphere), and 400–100 hPa. We start with the lower tropospheric (1000–800 hPa) layer for wind forecasts (Fig. 8).

For the lower-tropospheric 1000–800-hPa layer (Fig. 8), aircraft, VAD, and surface observations have about equal impact for 3-h wind forecasts in winter, when the PBL is typically shallow and inversions are common. In summer, surface observations have the most impact. We attribute this to deeper PBL mixing and the addition of PBL-depth pseudoresiduals for surface observations in the RUC 3D assimilation (discussed in section 2 and Benjamin et al. 2004f). Mesonet observations were found to add little or no impact to 3- or 6-h lower-tropospheric wind forecasts to other surface observations (primarily METARs) even in summer when stronger effects are shown from surface observations, but have a very small positive effect at 12 h in summer and winter. The increasing impact of aircraft observations with forecast projection in summer may result from better midtropospheric winds (next section) that are mixed down over time in the typically deeper PBL.

For midtroposphere winds over the national verification domain (Fig. 9), aircraft observations had the strongest impact overall, especially in summer (0.25–0.40 m $s^{-1}$), followed by raobs. Raobs had the strongest impact for 12-h forecasts in winter for midtropospheric winds. Profilers, VAD winds, and AMVs all have a small positive effect for midtropospheric winds. The slight positive impact from GOES AMVs shows a slight increase with forecast projection as its offshore effect (assimilated only over water) propagates inland.

Figure 10 indicates that aircraft have a pronounced impact on upper-level wind forecast accuracy in the RUC domain for all forecast projections and both seasons, consistently larger than that for any other observation

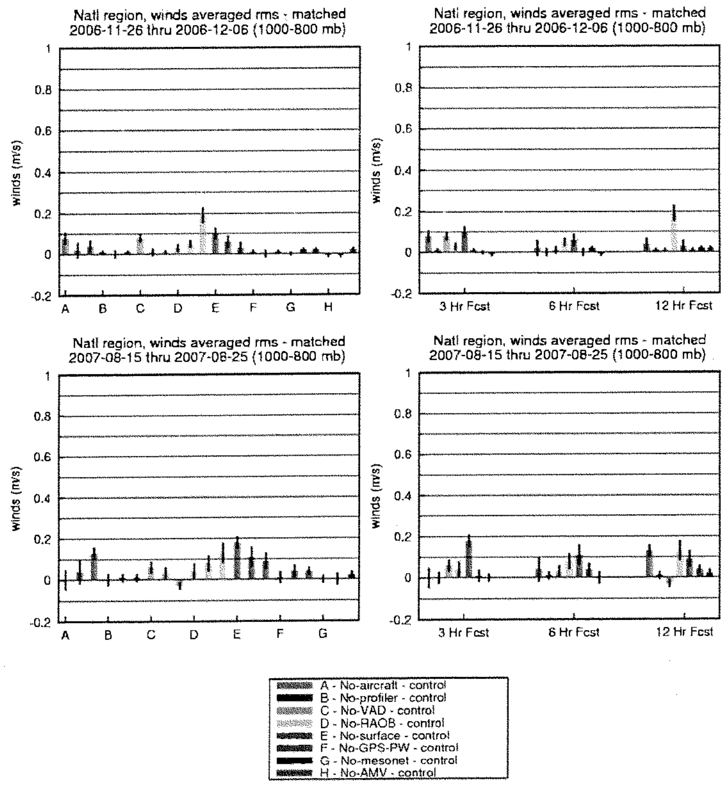



FIG. 8. As in Fig. 6, but for 1000–800-hPa only (still wind, national domain).

type, ~0.3 m s$^{-1}$ in this particular winter period and 0.8–0.9 m s$^{-1}$ in the summer period for 3- and 6-h forecasts. Hourly automated aircraft reports over the United States were the original primary justification for the development and implementation of a rapidly updated data assimilation cycle to improve short-range upper-level wind forecasts (Benjamin et al. 1991). The results depicted in Fig. 10 are still consistent with that justification, despite the addition of many other observation types since 1991. Raob data had the second largest impact on upper-level wind forecasts over the national verification domain, with the profiler also making a very small positive impact over this larger domain. As with the 800–400-hPa layer, AMVs ("cloud drift" winds) had a small but positive effect on upper-level winds, larger at 12 h than at 3 h, again a consequence of their assimilation in RUC only over oceanic regions.

### *d. Midwest (very data rich area)*

The Midwest region has exceptional upper-air observational coverage, denser than any other area in the United States because of the region's proximity to the NOAA profiler network, and the initial deployment of TAMDAR sensors on regional aircraft in this area (see Moninger et al. 2010). Therefore, we considered it useful to examine the relative impact of different observation types for short-range RUC forecasts specifically in this region.

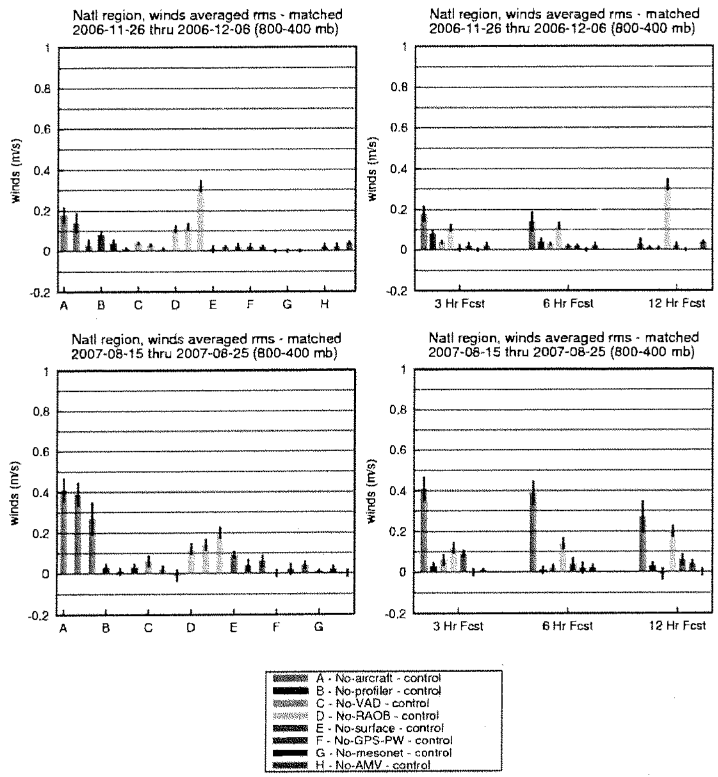



FIG. 9. As in Fig. 8, but for 800–400-hPa layer (still wind, national domain).

### 1) Relative humidity impact in Midwest region

In the Midwest verification region, we start again with the overall observational impact on relative humidity forecasts starting with the 1000–400-hPa layer (Fig. 11). Here, radiosondes still show the largest impact in winter (1%–2% RH), but with nearly equal impact from aircraft observations in summer (all forecast projections) and in winter 3-h forecasts. The availability of aircraft-based moisture observations from TAMDAR clearly contributed strongly in this region, comparing Fig. 11 with corresponding RH impact for the national domain (Fig. 4) showing much less aircraft impact. OSE results (control–noTAMDAR) in Moninger et al. (2010) confirm its very large impact, averaging about 2% for the 1000–400-hPa layer in both the November–December 2006 winter period and from fall 2008 onward. The RH impact from GPS-PW observations followed closely that from aircraft data in both summer and winter test periods. Even profilers made a positive contribution to RH forecasts (0.2%–0.5%) although they do not measure moisture, presumably because of improved vertical motion and horizontal transport fields.

### 2) Temperature forecast impact over the Midwest domain

For temperature impact over the full depth (1000–100 hPa) in the Midwest region (Fig. 12), results were similar to those shown in Fig. 5 for the national domain,

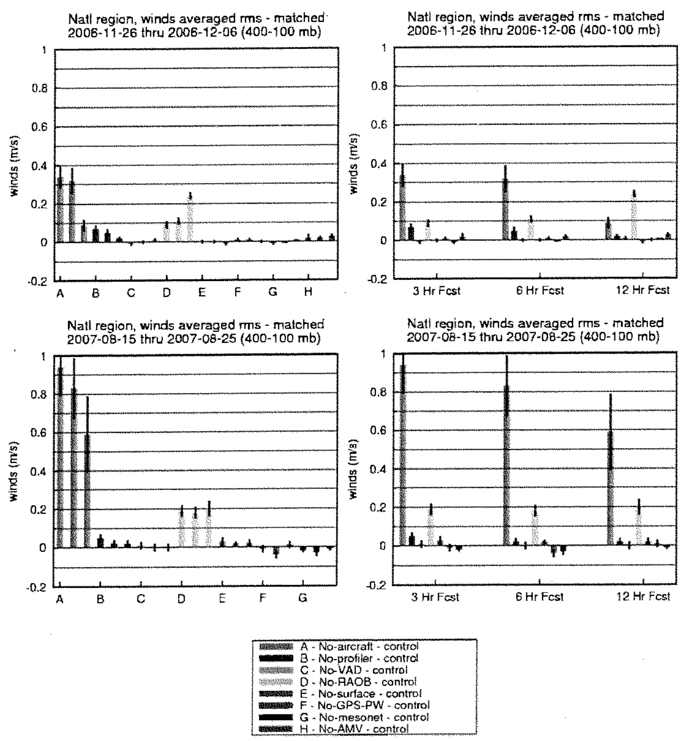



FIG. 10. As in Fig. 8, but for 400–100-hPa layer (still winds for national domain).

with aircraft showing the greatest impact for 3- and 6-h temperature forecasts in both winter and summer. However, the average impact from assimilation of aircraft observations in winter in 3-h temperature forecasts was significantly stronger in the Midwest (0.25 K) than over the full national domain (0.15 K), likely due to the higher density of aircraft data in this region.

Regarding temperature forecasts in the lower troposphere (1000–800 hPa, Fig. 13), aircraft reports have the strongest impact (0.3–0.56 K) by far in winter for 3–6-h forecasts. In summer, the aircraft data have a slightly but significantly larger impact (0.12–0.20 K) than surface observations. The extra spatial density provided by TAMDAR aircraft observations, which include data from frequent ascents and descents into regional airports (Moninger et al. 2010), contributes to the forecast impact for lower-tropospheric temperatures, and especially during periods of wintertime lower-tropospheric temperature inversions.

Aircraft observations also exhibit the largest impact in the midtroposphere for both winter and summer seasons (Fig. 14), although the impact for all observation types is quite low in summer (<0.1 K for all types, all forecast projections), presumably due to a relatively low thermal stability and a general absence of midlevel frontal zones.

### 3) WIND FORECAST IMPACT OVER THE MIDWEST DOMAIN

The observation impact results for winds integrated over the full 1000–100-hPa layer within the data-rich Midwest

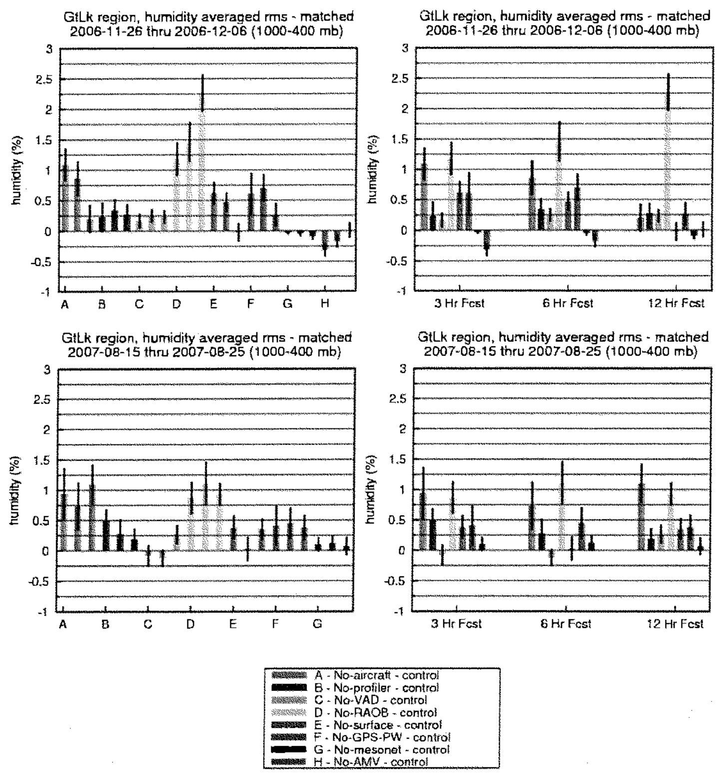



FIG. 11. As in Fig. 4, but for the Midwest (or Great Lakes) regional verification domain.

domain is shown in Fig. 15, indicating a nearly equal impact for aircraft and profiler observations in winter at 3 and 6 h (0.13–0.20 m $s^{-1}$). In summer, aircraft observations had the greatest overall impact at 3 h (0.35 m $s^{-1}$) and 6 h (0.25 m $s^{-1}$), followed by profiler, surface, and raobs, all with about the same effect. Note that surface observations have such a large effect on the fully integrated 1000–100-hPa layer, again indicating their representativeness in the deeper summertime boundary layer and the effectiveness of the RUC PBL-based pseudoresidual assimilation technique. The addition of mesonet observations, by contrast, had a slight negative effect on 1000–100-hPa 3-h wind forecasts in both winter and summer, again presumably due to widespread siting issues.

For lower-tropospheric (1000–800 hPa) wind forecasts in the Midwest domain (Fig. 16), it is not surprising that surface observations had the largest positive effect on both 3- and 6-h forecasts in both winter and summer periods. After surface observations, the largest effects in lower-tropospheric 3-h wind forecasts were from aircraft in winter, and from profiler in summer. As with the national domain (Fig. 9), aircraft data have very little effect in summer near-surface (1000–800 hPa) winds for 3- and 6-h duration, but have the largest effect by 12 h. VAD wind observations had the third-largest impact at 3 h in summer and for 3–6 h in winter.

The lowest gate in NOAA profilers is 500 m AGL, and sites within the Midwest verification domain are at 170–300-m elevation, limiting the profiler impact below

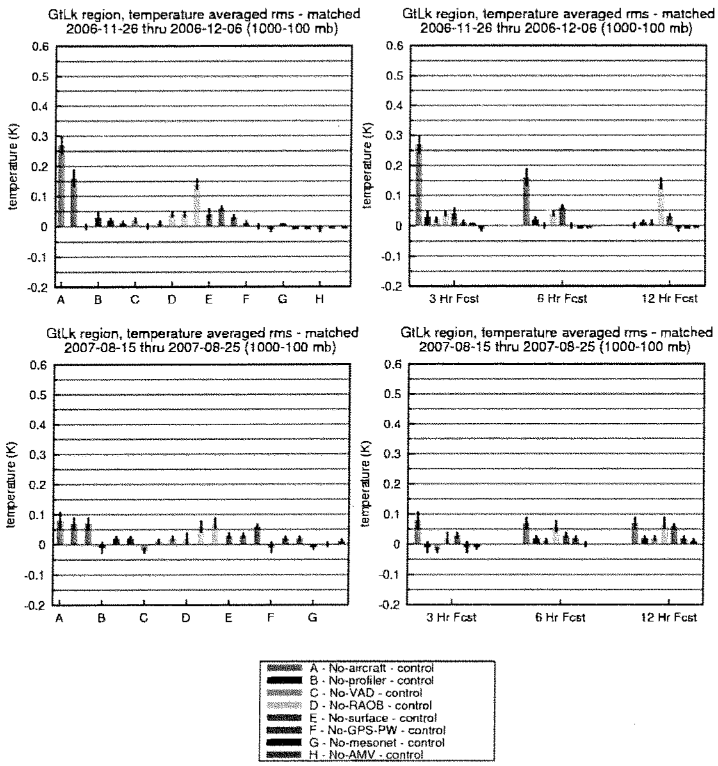



FIG. 12. As in Fig. 5, but for the Midwest verification region.

800 hPa, and perhaps contributing to negligible impact in winter in this layer. Over a different regional domain centered directly on the NOAA profiler network but using a similar RUC observation impact strategy for a profiler-only OSE with a 14-day test period in February 2001, Benjamin et al. (2004c) showed a larger 0.3 m $s^{-1}$ impact from assimilation of profiler winds for 3-h wind forecasts at 850 hPa and a 0.1 m $s^{-1}$ impact over a larger eastern U.S. verification domain. The smaller impact in this study is attributed to a shift in the Midwest domain not centered on the NPN (Fig. 3) and averaging over the 1000–800-hPa layer, essentially down to the surface.

For midtropospheric (800–400 hPa; Fig. 17) wind forecasts in the data-rich Midwest verification domain, aircraft, followed by profiler observations had the greatest impact. Clearly, these two observation types in the Midwest are not redundant, but together produce a larger reduction in forecast error. For upper-level winds (400–100 hPa; Fig. 18), profiler observations had the largest positive impact (reduction in forecast error) in winter at 3 and 6 h, followed by aircraft observations in winter. In the summer period, the opposite was true, with aircraft showing the greatest effect (e.g., >0.5 m $s^{-1}$ at 3 h), followed by radiosondes and profilers at 3 h. At 6 h, aircraft had the most impact, with profiler and raobs second. Profiler impact for the NPN-centered verification domain shown by Benjamin et al. (2004c) from the February 2001 period was approximately 0.5 m $s^{-1}$ for the 800–400-hPa layer for 3-h forecasts and about 0.1 m $s^{-1}$ for 12-h forecasts. We are unable to explain the small

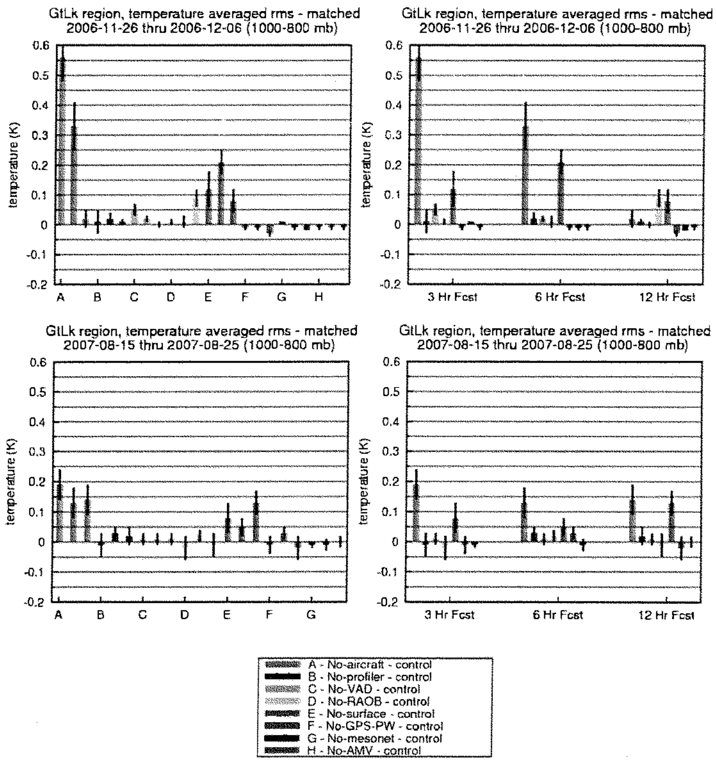



FIG. 13. As in Fig. 12, but for the 1000–800-hPa layer only.

negative impact at 12 h from aircraft in the Midwest layer for the 400–100-hPa layer evident in both winter and summer periods, except that it may be a sampling anomaly. The dropoff of profiler impact with projection time is attributed to propagation of that impact quickly outside of the limited extent of the NOAA profiler network (Fig. 3). A similar dropoff with time was shown in Benjamin et al. (2004c) for profiler impact.

## 5. Results from profiler height experiments—Impact from vertically truncated profiler heights

We added two additional experiments (Table 2), involving hypothetical 8- and 12-km profilers, referring to the vertical reach of the profiler antenna. The additional experiments give us a quantitative measure of the impacts that potential reduction in the vertical reach of existing NOAA network profilers will have on forecast accuracy. The operating frequency of network profilers must soon be changed from 404 to 449 MHz. Larger (and more expensive) antennas are required to reach 16 km than to reach lower altitudes. The experiment also relates to the cost of a possible expansion of the current network from the mid-United States to the entire lower 48 states.

The 8-km profilers have half the vertical reach of the full-scale (16 km) network profilers. The former are often called "quarter-scale profilers" because their antennas occupy only one quarter of the area. To manufacture data

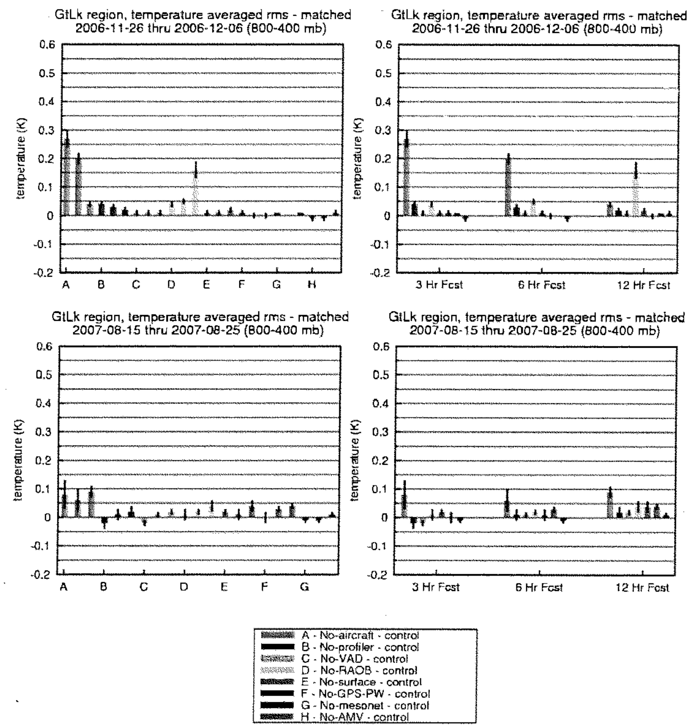



FIG. 14. As in Fig. 12, (temperature, Midwest domain), but for the 800–400-hPa layer.

from quarter-scale wind profilers, we merely extracted actual data (surface to 8 km AGL) from the full-scale profilers.

The results for these experiments are depicted in Figs. 19–21 for both 3- and 6-h forecast projections in the Midwest region for the 10-day winter period (Table 2). The vector wind error difference, No-Profiler minus Control (N-C, blue line in figures), shows the impact of profiler data themselves (equivalent to degradation if profiler data are missing). When profiler data are denied for the 10-day test period, 3-h forecasts of winds aloft (Fig. 19) from 600 to 300 hPa are worse by ~0.4 m s$^{-1}$ in the Midwest region and by 0.2–0.3 m s$^{-1}$ for the same layer for 6-h forecasts (Fig. 20). The greatest improvement from the inclusion of profiler winds for 3-h wind forecasts was ~0.55 m s$^{-1}$ at 350 hPa (Fig. 19). These results are similar to those shown by Benjamin et al. (2004c) in a previous profiler impact study for the profiler (Midwest) domain and downscale domains, respectively.

The vector wind error difference, Quarter-scale minus Control (Q − C, red line in Figs. 19 and 20), shows the value of using 16-km full-scale profilers versus 8-km quarter-scale profilers. The Q − C difference is near zero at most altitudes, indicating that most of the value added to tropospheric wind forecasts from full-scale profilers is also added by quarter-scale profilers up to the jet levels where aircraft data are plentiful. Only at 200 hPa and above do full-scale profilers show value added (more accurate 3-h forecasts) that are not available with 8-km profilers. Quarter-scale profilers actually

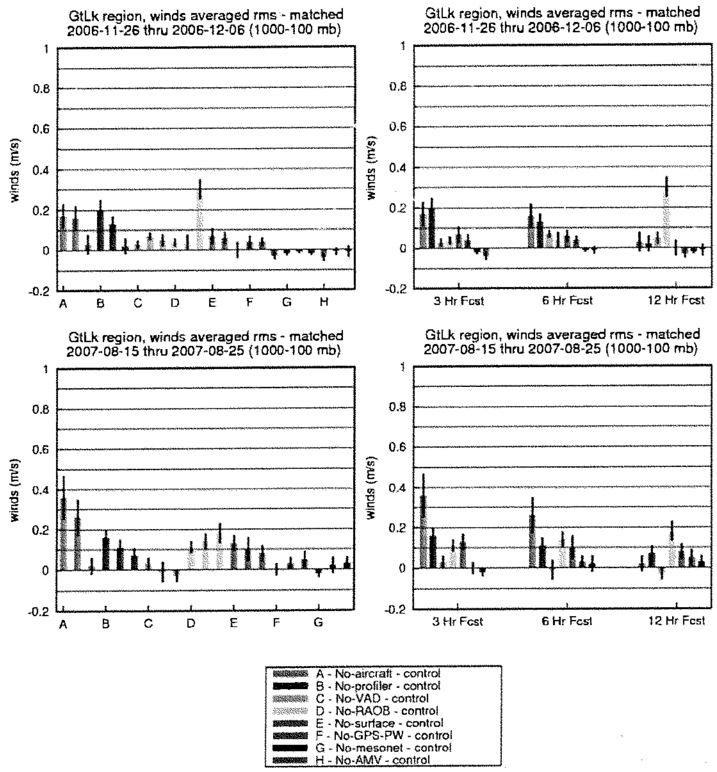



FIG. 15. As in Fig. 6, but for the Midwest domain.

delivered somewhat better 3-h wind forecasts in the 900–750-hPa layer than full-scale profilers, possibly resulting from less lower-tropospheric geostrophic wind adjustment without the stratospheric (200 hPa and above) wind observations available only with 16-km profilers.

The final experiment was performed to simulate the inclusion of 12-km profilers, extracted from the actual 16-km profiler data. The results for 12-km profilers in Fig. 21 are very similar to those for the 8-km (quarter scale) profilers up to the 250-hPa level. However, as might be expected, the 12-km profilers do add forecast skill improvement over 8-km profilers for 3-h wind forecasts for the 150–200-hPa layer. The 12-km profilers do not capture the extra improvement in the 50–100-hPa layer available from the full 16-km profilers.

## 6. Conclusions

We performed extensive observation system experiments (OSEs) involving data denial for two 10-day periods, one in winter and one in summer, using the hourly-updating Rapid Update Cycle model/assimilation system. We examined forecast impact for relative humidity, temperature, and wind at 3, 6, 9, and 12 h.

We conclude from these experiments that the heterogeneous atmospheric observing system in the United States is effective for short-range (3–12 h) 1000–100-hPa forecasts for all three variables studied: relative humidity, temperature, and wind.

Overall, aircraft data were found to have the most impact on reducing error in short-range forecasts over the

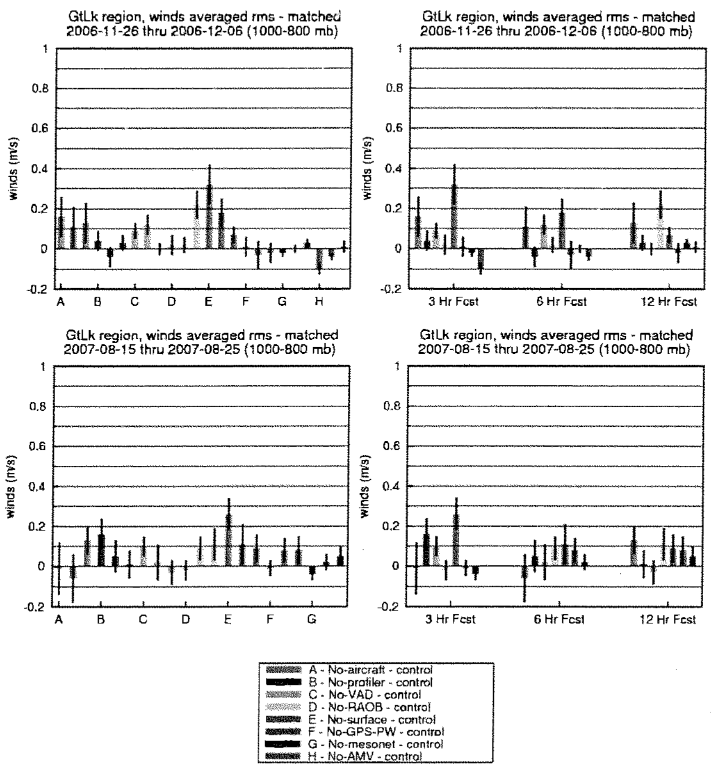



FIG. 16. As in Fig. 15, but for the 1000–800-hPa layer.

United States from the lower stratosphere down to the surface, but they are strongly and necessarily augmented by other observing systems. As shown by Moninger et al. (2010) in a companion article, TAMDAR aircraft observations (also including moisture) clearly improved forecast accuracy in the Midwest and eastern U.S. area when added to all other observations in a complementary experiment to those shown in this paper.

Radiosonde observations were second in importance overall, within the parameters defining this OSE for 3–6 h, and arguably most important for 12-h forecast impact on the national scale followed closely by aircraft. GPS-PW, surface, profiler, and VAD all provided value added to forecast accuracy, in roughly that order. GPS-PW was similar to raob contributions for short-range RH forecasts. Given that surface observations showed a significant additional value to lower-tropospheric forecasts, especially for the 1000–800-hPa layer and in summertime, we conclude that the RUC assimilation and use of PBL depth for pseudoresiduals is effective for 3D assimilation of these surface variables. The impact of profiler wind data was notably higher in the Midwest domain, where the NOAA network is located, than in the national domain, where their effect is heavily diluted. The relatively small impact from AMVs (used only over ocean areas) is attributable to the relatively small extent of the RUC domain over oceanic areas, limiting the possible AMV-related effect. Generally, the relative impact for profiler, aircraft, and raobs in this experiment was similar to that shown by Schwartz and

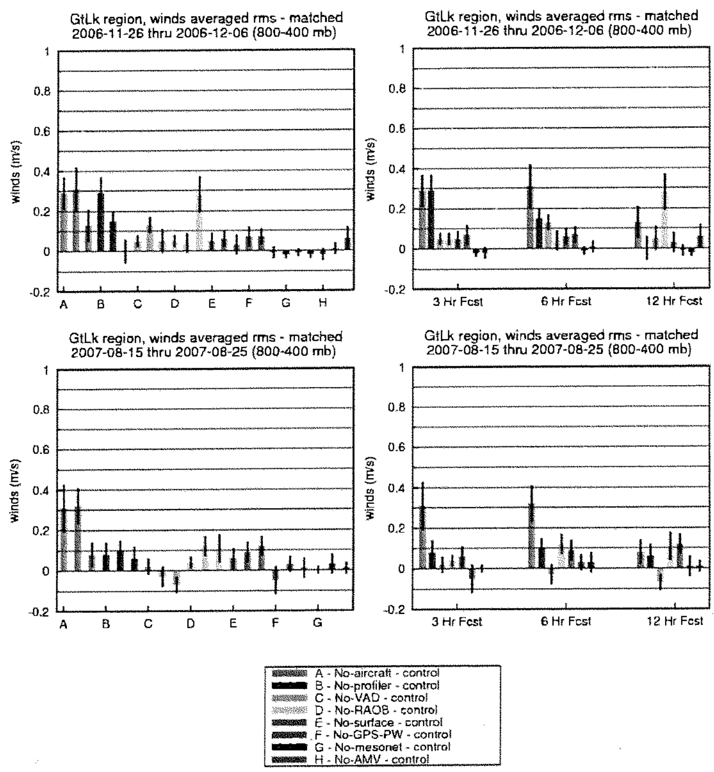



FIG. 17. As in Fig. 15, but for the 800–400-hPa layer.

Benjamin (2004) for an OSE using an earlier version of the RUC for a February 2001 test period. Midtroposphere wind forecast impact from profiler data in that earlier study was larger with a verification domain centered directly over the NOAA profiler network than in this study for the Midwest verification domain, shifted from the NPN area.

Experiments using hypothetical vertically truncated profiler data (with a vertical reach of 8- and 12-km AGL) were performed for the winter (November–December 2006) period. These experiments showed that 8-km (quarter scale) profilers provide 3- and 6-h wind forecast improvement about equal to that from full-scale (16 km) profilers from the surface up to 250 hPa, suggesting that 8-km profilers would complement aircraft data for short-range tropospheric forecasts.

We note once again that the magnitude of forecast impacts from different observation denial experiments is damped by the same lateral boundary conditions used in all experiments for the regional RUC domain. The 10-day periods used in this study for winter and summer seasons are barely long enough for robust results, but were limited by the logistics for the 1-h update cycle environment (unique to this study) and available computing and storage resources. These limitations were partially mitigated by performing verification every 10-hPa using full significant level radiosonde data, adding considerable data points. Standard error calculations for

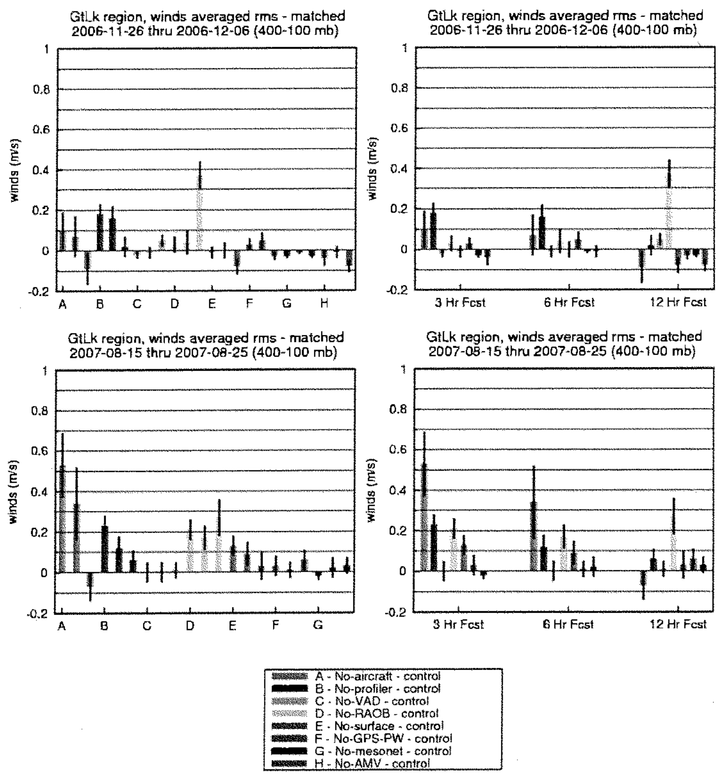



FIG. 18. As in Fig. 15, but for the 400–100-hPa layer.

each experiment indicate that, even for our relatively short 10-day summer and winter periods, results are statistically robust, witb many forecast impacts being significant at more than the 95% confidence level.

The observation impact results in this study often showed a decrease with forecast projection (see the example in Fig. 15). This was evident, in general, for aircraft and profiler data, for which this effect was enhanced by regional concentrations of those observations (aircraft enhanced by TAMDAR in Midwest area, profiler primarily in the NOAA profiler network). The impact of raob data was a prominent exception, showing an apparent increase with time, a statistical quirk from our verification only at 0000 and 1200 UTC for forecasts valid at those times, initialized at 0900 and 2100 for 3-h forecasts, for instance. Of course, in general, raobs are available only every 12 h, so their impact on the analyses that create the less-than-12-h forecasts valid at 0000 and 1200 UTC is indirect (only through the hourly-cycled background field) and degrades as the analysis time moves away from 0000 and 1200 UTC. Also, the overall impact of high-frequency observations is somewhat larger at analysis times when not competing with raobs.

Conducting OSEs can sometimes reveal flaws in the assimilation system from forward models or observation-error specification. In this study, relatively consistent positive (sometimes very small) or near-zero impacts were shown for nearly all observation types, presumably indicating no major flaws in treatment in the RUC for any observation types. But in initial experiments performed

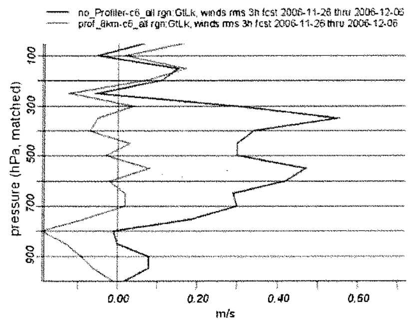



FIG. 19. Differences in 3-h vector wind errors between No-profile minus Control (N − C, blue line) and 8-km (quarter-scale) minus Control (8 − C, red line) over the Midwest region.

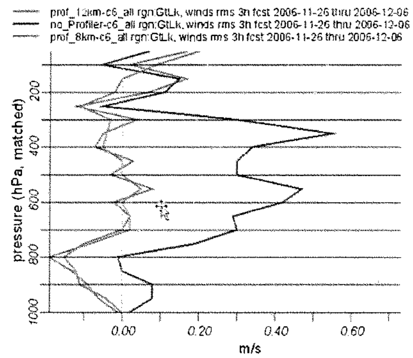



FIG. 21. As in Fig. 20, but for 3-h wind forecast impact in the Midwest domain, but with results added for 12-km profilers. Green line (12 − C) is for difference between experiments with 12-km profilers (12) vs Control (C).

for this OSE, some counterintuitive results arose, leading to detection of assimilation design flaws for aircraft moisture observation error, moisture assimilation design, and too-small observation errors specified for radiosonde RH and wind observations. The results shown in this paper are dependent, for better or for worse, on the design of the RUC 3D variational analysis and modeling system as described in section 2, and we cannot rule out remaining design flaws or outright errors.

This OSE study included vertically stratified results for the data-rich Midwest verification domain. Even here, nearly all observation types contributed positive impact, with clear, positive, and complementary effects from profiler and aircraft data, indicating that this region is not oversampled by observations. A strong positive effect from surface observations over surprisingly deep layers was shown, especially but not solely in summer, for temperature, wind, and RH, but very little positive impact was showu when mesonet observations were added to METAR observations.

We intend to add new observation impact experiments using high-frequency assimilation of radar reflectivity (Weygandt et al. 2008), added to the operational RUC at NCEP in November 2008, and using hydrometeor assimilation from GOES and METAR cloud/visibility data (Benjamin et al. 2004e). We also intend to identify diurnal variations in observation impact (1200 versus 0000 UTC) and repeat similar OSEs with the upcoming Rapid Refresh soon replacing the RUC hourly assimilation/model cycle at NCEP.

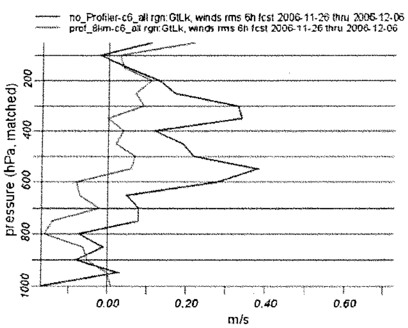



FIG. 20. As in Fig. 19, but for 6-h forecasts instead of 3-h forecasts.

*Acknowledgments.* We thank Betsy Weatherhead of NOAA/ESRL/GSD for her thoughtful and effective analysis of the statistical significance of our results. We also thank Annie Reiser and Dezso Devenyi of NOAA/ESRL/GSD for their excellent reviews of this manuscript.

REFERENCES

Baker, N. L., and R. Daley, 2000: Observation and background adjoint sensitivity in the adaptive observation-targeting problem. *Quart. J. Roy. Meteor. Soc.*, **126**, 1431–1454.

Benjamin, S. G., K. A. Brewster, R. L. Brummer, B. F. Jewett, T. W. Schlatter, T. L. Smith, and P. A. Stamus, 1991: An isentropic 3-hourly data assimilation system using ACARS aircraft observations. *Mon. Wea. Rev.*, **119**, 888–906.

——, and Coauthors, 2004a: An hourly assimilation/forecast cycle: The RUC. *Mon. Wea. Rev.*, **132,** 495–518.

——, G. A. Grell, J. M. Brown, T. G. Smirnova, and R. Bleck, 2004b: Mesoscale weather prediction with the RUC hybrid isentropic/terrain-following coordinate model. *Mon. Wea. Rev.*, **132,** 473–494.

——, B. E. Schwartz, E. J. Szoke, and S. E. Koch, 2004c: The value of wind profiler data in U.S. weather forecasting. *Bull. Amer. Meteor. Soc.*, **85,** 1871–1886.

——, and Coauthors, 2004d: A 13-km RUC and beyond: Recent developments and future plans. Preprints, *11th Conf. on Aviation, Range, and Aerospace*, Hyannis, MA, Amer. Meteor. Soc., J1.6.

——, J. M. Brown, S. S. Weygandt, T. L. Smith, B. Schwartz, and W. R. Moninger, 2004e: Assimilation of surface cloud, visibility, and current weather observations in the RUC. Preprints, *16th Conf. on Numerical Weather Prediction*, Seattle, WA, Amer. Meteor. Soc., P1.47.

——, S. Weygandt, D. Devenyi, J. M. Brown, G. Manikin, T. L. Smith, and T. Smirnova, 2004f: Improved moisture and PBL initialization in the RUC using METAR data. Preprints, *11th Conf. on Aviation, Range, and Aerospace*, Hyannis, MA, Amer. Meteor. Soc., 17.3.

——, W. R. Moninger, S. R. Sahm, and T. L. Smith, 2007: Mesonet wind quality monitoring allowing assimilation in the RUC and other NCEP models. Preprints, *22nd Conf. on Weather Analysis and Forecasting/18th Conf. on Numerical Weather Prediction*, Park City, UT, Amer. Meteor. Soc., P1.33.

Bouttier, F., and G. Kelly, 2001: Observing-system experiments in the ECMWF 4D-Var data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **127,** 1469–1488.

Cardinali, C., 2009: Monitoring the observation impact on the short-range forecast. *Quart. J. Roy. Meteor. Soc.*, **135,** 239–258.

Dee, D. P., and A. M. da Silva, 2003: The choice of variable for atmospheric moisture analysis. *Mon. Wea. Rev.*, **131,** 155–171.

Devenyi, D., and S. G. Benjamin, 2003: A variational assimilation technique in a hybrid isentropic-sigma coordinate. *Meteor. Atmos. Phys.*, **82,** 245–257.

Graham, R. J., S. R. Anderson, and M. J. Bader, 2000: The relative utility of current observations systems to global-scale NWP forecasts. *Quart. J. Roy. Meteor. Soc.*, **126,** 2435–2460.

Lord, S. J., T. Zapotocny, and J. Jung, 2004: Observing system experiments with NCEP's Global Forecast System. *Proc. Third WMO Workshop on Impact of Various Observing Systems on Numerical Weather Prediction*, WMO/TD 1228, Alpbach, Austria, WMO, 56–62.

Moninger, W. R., R. D. Mamrosh, and P. M. Pauley, 2003: Automated meteorological reports from commercial aircraft. *Bull. Amer. Meteor. Soc.*, **84,** 203–216.

——, S. G. Benjamin, B. D. Jamison, T. W. Schlatter, T. L. Smith, and E. J. Szoke, 2010: Evaluation of regional aircraft observations using TAMDAR. *Wea. Forecasting*, in press.

Nutter, P., D. Stensrud, and M. Xue, 2004: Effects of coarsely resolved and temporally interpolated lateral boundary conditions on the dispersion of limited-area ensemble forecasts. *Mon. Wea. Rev.*, **132,** 2358–2377.

Schwartz, B., and S. Benjamin, 2004: Observation sensitivity experiments using the Rapid Update Cycle. Preprints, *Eighth Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, Seattle, WA, Amer. Meteor. Soc., 6.3.

Smith, T. L., S. G. Benjamin, S. I. Gutman, and S. Sahm, 2007: Short-range forecast impact from assimilation of GPS-IPW observations into the Rapid Update Cycle. *Mon. Wea. Rev.*, **135,** 2914–2930.

Weatherhead, E. C., and Coauthors, 1998: Factors affecting the detection of trends: Statistical considerations and applications to environmental data. *J. Geophys. Res.*, **103,** 17 149–17 161.

Weygandt, S. S., and Coauthors, 2004: Potential forecast impacts from space-based lidar winds: Results from a regional observing system simulation experiments. Preprints, *Eighth Symp. on Integrated Observing Systems*, Seattle, WA, Amer. Meteor. Soc., 6.4.

——, S. G. Benjamin, T. G. Smirnova, and J. M. Brown, 2008: Assimilation of radar reflectivity data using a diabatic digital filter within the Rapid Update Cycle. Preprints, *12th Conf. on IOAS-AOLS*, New Orleans, LA, Amer. Meteor. Soc., 8.4.

White, A. B., F. M. Ralph, J. R. Jordan, C. W. King, D. J. Gottas, P. J. Neiman, L. Bianco, and D. E. White, 2007: Expanding the NOAA Profiler Network: Technology evaluation and new applications for the coastal environment. Preprints, *Seventh Conf. on Coastal Atmospheric and Oceanic Prediction and Processes*, San Diego, CA, Amer. Meteor. Soc., 8.6.

Zapotocny, T. H., W. P. Menzel, J. P. Nelson, and J. A. Jung, 2002: An impact study of five remotely sensed and five in situ data types in the Eta Data Assimilation System. *Wea. Forecasting*, **17,** 263–285.

——, J. Jung, J. Le Marshall, and R. Treadon, 2007: A two-season impact study of satellite and in situ data in the NCEP Global Data Assimilation System. *Wea. Forecasting*, **22,** 887–909.

Zhu, Y., and R. Gelaro, 2008: Observation sensitivity calculations using the adjoint of the Gridpoint Statistical Interpolation (GSI) analysis system. *Mon. Wea. Rev.*, **136,** 335–351.

**Attachment A (including PPT slides)**

The first 3 slides after the title slide are showing observing system impact over the US by withholding various obs. **RAOBs or "weather balloons" (mustard) and aircraft data (bright red) dominate the impact in the model.** Keep in mind NOAA has very few balloons/RAOB sites with large space-time gaps. They were also using a very small subset of the full TAMDAR feed.

Notice also:

**- AMV (dark red, atmospheric motion vectors = satellite winds) has virtually no impact.**

**- Mesonet (dark blue) has no detectable impact either.**

Slide 4 (slide 5 including title slide) shows global impact. AMSUA, which are satellite obs comes in #1 (I'll explain below), RAOBS/balloons #2, Aircraft #3. Keep in mind, this is global, and there is a lot more ocean than land.

If you look at plot 2 (same slide), you see impact per observation.

RAOB/Balloons= #1. Ship/buoy are #2 because there is only 1 per several 100,000 square miles. Notice the sat obs drop way back. Keep in mind again that this is "global".

Slide 5 (slide 6 including title slide):

**This is the key slide. The only reason sat obs show up in the "global" model impact is because they are practically the only observing system in the Southern Hemisphere (green; bottom left).**

**Yet, the SH weather is essentially detached from the Northern Hemisphere.**

**Systems do not cross back and forth, so contribution to the SH is irrelevant to impact in the NH.**

**To forecast severe convection at a high resolution over the US, contribution from sat obs over the open ocean in the NH are practically just as irrelevant as SH.**

The entire PPT can be found here:
http://www.ofcm.gov/odw/2011/Presentations/

Two slides from a different NOAA PPT follow a blank slide.

**The take home message of this slide comes from the plot on the right. Out of the 100% of data NOAA receives for each model run, only 7% is selected. The other 93% is rejected by a gross quality control filter. Then, a second line of screening rejects another 5%, so that only 2% of the initial 100% of the observations actually make it into the forecast model.**

**Of this 98% of rejected data, almost all of it comes from satellite. Ms. Kicza stated in her testimony that 96% of the data used by the models was from satellites. While it is true that 96% or more of the "received" data volume comes from satellites, the majority of it is rejected by the model during assimilation.**

# Cliff Mass Weather Blog

This blog provides updated forecasts and comments on current weather or other topics

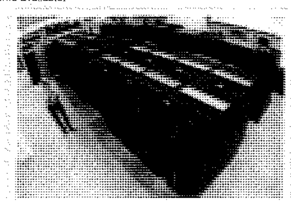
## The U.S. Has Fallen Behind in Numerical Weather Prediction: Part I

**Part II found** here.

**It's a national embarrassment.** It has resulted in large unnecessary costs for the U.S. economy and needless endangerment of our citizens. *And it shouldn't be occurring.*

*What am I talking about?* **The third rate status of numerical weather prediction in the U.S.** It is a huge story, an important story, but one the media has not touched, probably from lack of familiarity with a highly technical subject. And the truth has been buried or unavailable to those not intimately involved in the U.S. weather prediction enterprise. This is an issue I have mentioned briefly in previous blogs, and one many of you have asked to learn more about. It's time to discuss it.

Weather forecasting today is dependent on numerical weather prediction, the numerical solution of the equations that describe the atmosphere. The technology of weather prediction has improved dramatically during the past decades as faster computers, better models, and much more data (mainly satellites) have become available.



Supercomputers are used for numerical weather prediction

U.S. numerical weather prediction has fallen to third or fourth place worldwide, with the clear leader in global numerical weather prediction (NWP) being the European Center for Medium Range Weather Forecasting (ECMWF). And we have also fallen behind in ensembles (using many models to give probabilistic prediction) and high-resolution operational forecasting. We used to be the world leader decades ago in numerical weather prediction: NWP began and was perfected here in the U.S. Ironically, we have the largest weather research community in the world and the largest collection of universities doing cutting-edge NWP research (like the University of Washington!). Something is very, very wrong and I will talk about some of the issues here. And our nation needs to fix it.

But to understand the problem, you have to understand the competition and the players. And let me apologize upfront for the acronyms.

In the U.S., numerical weather prediction mainly takes place at the National Weather Service's Environmental Modeling Center (**EMC**), a part of **NCEP** (National Centers for Environmental Prediction). They run a global model (**GFS**) and regional models (e.g., **NAM**).

The Europeans banded together decades ago to form the European Center for Medium-Range Forecasting (ECMWF), which runs a very good global model. Several European countries run regional models as well.

**For the Local Weather Enthusiast**


Click on Picture for More Info

**Help Support UW Weather Prediction Research**

**Contributions provide needed support for UW weather prediction research** and studies of Northwest weather that make this blog possible. You can help by clicking **here.**

**Total Pageviews**

**8,793,881**

**My Weather Segment is on KPLU!**

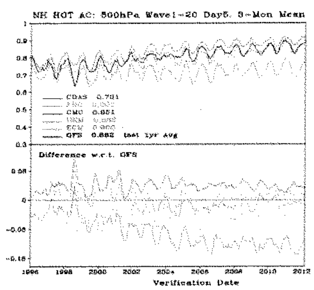
Friday's at 9 AM right after Birdnote. 88.5 in the Puget Sound area. KPLU Web Site. Want to ask a question I can answer during the show? Click here

The United Kingdom Met Office (**UKMET**) runs an excellent global model and regional models. So does the Canadian Meteorological Center (**CMC**).

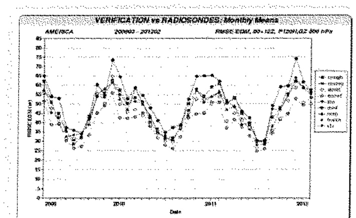
There are other major global NWP centers such as the Japanese Meteorological Agency (**JMA**), the U.S. Navy (**FNMOC**), the Australian center, one in Beijing, among others. All of these centers collect worldwide data and do global NWP.

The problem is that both objective and subjective comparisons indicate that the U.S. global model is number 3 or number 4 in quality, resulting in our forecasts being noticeably inferior to the competition. Let me show you a rather technical graph (produced by the NWS) that illustrates this. This figure shows the quality of the 500hPa forecast (about halfway up in the troposphere--approximately 18,000 ft) for the day 5 forecast. The top graph is a measure of forecast skill (closer to 1 is better) from 1996 to 2012 for several models (U.S.--black, GFS; ECMWF-red, Canadian: CMC-blue, UKMET: green, Navy: FNG, orange). The bottom graph shows the difference between the U.S. and other nation's model skill.

You first notice that forecasts are all getting better. That's good. But you will notice that the most skillful forecast (closest to one) is clearly the red one...the European Center. The second best is the UKMET office. The U.S. (GFS model) is third...roughly tied with the Canadians.




Here is a global model comparison done by the Canadian Meteorological Center, for various global models from 2009-2012 for the 120 h forecast. This is a plot of error (RMSE, root mean square error) again for 500 hPa, and only for North America. Guess who is best again (lowest error)?--the European Center (green circle). UKMET is next best, and the U.S. (NCEP, blue triangle) is back in the pack.




Lets looks at short-term errors. Here is a plot from a paper by Garrett Wedam, Lynn McMurdie and myself comparing various models at 24, 48, and 72 hr for sea level pressure along the West Coast.

### Some of My Presentations on Video

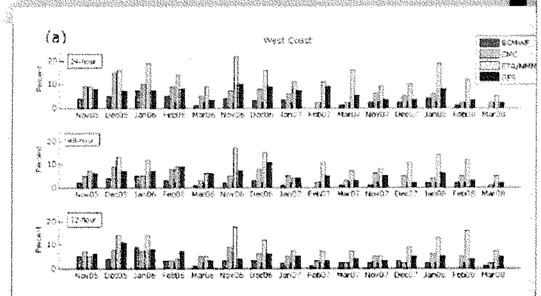
- Climate Talk-1
- Climate Talk-2
- NW Windstorms-Science Cafe-1
- NW Windstorms-Science Cafe-2
- NW Windstorms-Science Cafe-3
- Windstorm Talk at City Hall

### Favorite Weather Websites

- Seattle Weather Forecast
- UW Radar Viewer
- Scott Sistek Weather Blog
- National Weather Service, Seattle
- Probcast Probabilisitic Forecasts

### Blog Archive

Bigger bar means more error. Guess who has the lowest errors by far? You guessed it, ECMWF.




I could show you a hundred of these plots, but the answers are very consistent. ECMWF is the worldwide gold standard in global prediction, with the British (UKMET) second. We are third or fourth (with the Canadians). One way to describe this, is that the ECWMF model is not only better at the short range, but has about one day of additional predictability: their 8 day forecast is about as skillful as our 7 day forecast. Another way to look at it is that with the current upward trend in skill they are 5-7 years ahead of the U.S.

Most forecasters understand the frequent superiority of the ECMWF model. If you read the NWS forecast discussion, which is available online, you will frequently read how they often depend not on the U.S. model, but the ECMWF. And during the January western WA snowstorm, it was the ECMWF model that first indicated the correct solution. Recently, I talked to the CEO of a weather/climate related firm that was moving up to Seattle. I asked them what model they were using: the U.S. GFS? He laughed, of course not...they were using the ECMWF.

A lot of U.S. firms are using the ECMWF and this is very costly, because the Europeans charge a lot to gain access to their gridded forecasts (hundreds of thousands of dollars per year). Can you imagine how many millions of dollars are being spent by U.S. companies to secure ECMWF predictions? But the cost of the inferior NWS forecasts are far greater than that, because many users cannot afford the ECMWF grids and the NWS uses their global predictions to drive the higher-resolution regional models--which are NOT duplicated by the Europeans. All of U.S. NWP is dragged down by these second-rate forecasts and the costs for the nation has to be huge, since so much of our economy is weather sensitive. Inferior NWP must be costing billions of dollars, perhaps many billions.

The question all of you must be wondering is why this bad situation exists. How did the most technologically advanced country in the world, with the largest atmospheric sciences community, end up with third-rate global weather forecasts? I believe I can tell you...in fact, I have been working on this issue for several decades (with little to show for it). Some reasons:

1. **The U.S. has inadequate computer power available for numerical weather prediction.** The ECMWF is running models with substantially higher resolution than ours because they have more resources available for NWP. This is simply ridiculous--the U.S. can afford the processors and disk space it would take. We are talking about millions or tens of millions of dollars at most to have the hardware we need. A part of the problem has been NWS procurement, that is not forward-leaning, using heavy metal IBM machines at very high costs.

2. **The U.S. has used inferior data assimilation.** A key aspect of NWP is to assimilate the observations to create a good description of the atmosphere. The European Center, the UKMET Office, and the Canadians using 4DVAR, an advanced approach that requires lots of computer power. We used an older, inferior approach (3DVAR). The Europeans have been using 4DVAR for 20 years! Right now, the U.S. is working on another advanced approach (ensemble-based data assimilation), but it is not operational yet.

3. **The NWS numerical weather prediction effort has been isolated and has not taken advantage**



**My Dog is Still Lost in Brier/Mountlake Terrace: Let Me Know If You See Her**

Female, 9 yr old, Cockapoo, Mainly Black with White Markings, Spotted in Brier and Mountlake Terrace, Click Image for Info

**Subscribe To**

Posts

Comments

**of the research community.** NCEP's Environmental Modeling Center (EMC) is well known for its isolation and "not invented here" attitude. While the European Center has lots of visitors and workshops, such things are a rarity at EMC. Interactions with the university community have been limited and EMC has been reluctant to use the models and approaches developed by the U.S. research community. (True story: some of the advances in probabilistic weather prediction at the UW has been adopted by the Canadians, while the NWS had little interest). The National Weather Service has invested very little in extramural research and when their budget is under pressure, university research is the first thing they reduce. And the U.S. NWP center has been housed in a decaying building outside of D.C.,one too small for their needs as well. (Good news... a new building should be available soon).

4. **The NWS approach to weather related research has been ineffective and divided.** The governmnent weather research is NOT in the NWS, but rather in NOAA. Thus, the head of the NWS and his leadership team do not have authority over folks doing research in support of his mission. This has been an extraordinarily ineffective and wasteful system, with the NOAA research teams doing work that often has a marginal benefit for the NWS.

**5. Lack of leadership.** This is the key issue. The folks in NCEP, NWS, and NOAA leadership have been willing to accept third-class status, providing lots of excuses, but not making the fundamental changes in organization and priority that could deal with the problem. Lack of resources for NWP is another issue...but that is a decision made by NOAA/NWS/Dept of Commerce leadership.

This note is getting long, so I will wait to talk about the other problems in the NWS weather modeling efforts, such as our very poor ensemble (probabilistic) prediction systems. One could write a paper on this...end I may.

I should stress that I am not alone in saying these things. A blue-ribbon panel did a review of NCEP in 2009 and came to similar conclusions (found here). And these issues are frequently noted at conferences, workshops, and meetings.

Let me note that the above is about the modeling aspects of the NWS, NOT the many people in the local forecast offices. This part of the NWS is first-rate. They suffer from inferior U.S. guidance and fortunately have access to the ECMWF global forecasts. And there are some very good people at NCEP that have lacked the resources required and suitable organization necessary to push forward effectively.

This problem at the National Weather Service is not a weather prediction problem alone, but an example of a deeper national maleise. It is related to other U.S. issues, like our inferior K-12 education system. Our nation, gaining world leadership in almost all areas, became smug, self-satisfied, and a bit lazy. We lost the impetus to be the best. We were satisfied to coast. And this attitude must end...in weather prediction, education, and everything else... or we will see our nation sink into mediocrity.

The U.S. can reclaim leadership in weather prediction, but I am not hopeful that things will change quickly without pressure from outside of the NWS. The various weather user communities and our congressional representatives must deliver a strong message to the NWS that enough is enough, that the time for accepting mediocrity is over. And the Weather Service requires the resources to be first rate, something it does not have at this point.

Part II will discuss the problems with ensemble and high-resolution numerical weather prediction in the U.S.

Posted by Cliff Mass Weather Blog at 11:49 AM

+13 Recommend this on Google

## 28 comments:

**Kolya said...**

Would it make more sense (from a financial perspective) overall to use a third party (specifically Amazon EC2) for the compute infrastructure?

March 18, 2012 1:07 PM

**mdeh said...**

Cliff, Thanks for bringing this to our attention. Politics is funny...you never know when or how an article catches fire and starts the process of change. I have often likened our

**Statistics**

18835592

**Access the blog using your IPhone/IPod**


Click on image to access this app from the Itunes store.

# Estimation of TAMDAR Observational Error and Assimilation Experiments

FENG GAO

*National Center for Atmospheric Research, Boulder, Colorado, and Nanjing University of Information Science and Technology, Nanjing, Jiangsu, China*

XIAOYAN ZHANG

*National Center for Atmospheric Research, Boulder, Colorado*

NEIL A. JACOBS

*AirDat LLC, Morrisville, North Carolina*

XIANG-YU HUANG AND XIN ZHANG

*National Center for Atmospheric Research, Boulder, Colorado*

PETER P. CHILDS

*AirDat LLC, Morrisville, North Carolina*

(Manuscript received 8 October 2011, in final form 16 March 2012)

ABSTRACT

Tropospheric Airborne Meteorological Data Reporting (TAMDAR) observations are becoming a major data source for numerical weather prediction (NWP) because of the advantages of their high spatiotemporal resolution and humidity measurements. In this study, the estimation of TAMDAR observational errors, and the impacts of TAMDAR observations with new error statistics on short-term forecasts are presented. The observational errors are estimated by a three-way collocated statistical comparison. This method employs collocated meteorological reports from three data sources: TAMDAR, radiosondes, and the 6-h forecast from a Weather Research and Forecasting Model (WRF). The performance of TAMDAR observations with the new error statistics was then evaluated based on this model, and the WRF Data Assimilation (WRFDA) three-dimensional variational data assimilation (3DVAR) system. The analysis was conducted for both January and June of 2010. The experiments assimilate TAMDAR, as well as other conventional data with the exception of non-TAMDAR aircraft observations; every 6 h, and a 24-h forecast is produced. The standard deviation of the observational error of TAMDAR, which has relatively stable values regardless of season, is comparable to radiosondes for temperature, and slightly smaller than that of a radiosonde for relative humidity. The observational errors in wind direction significantly depend on wind speeds. In general, at low wind speeds, the error in TAMDAR is greater than that of radiosondes; however, the opposite is true for higher wind speeds. The impact of TAMDAR observations on both the 6- and 24-h WRF forecasts during the studied period is positive when using the default observational aircraft weather report (AIREP) error statistics. The new TAMDAR error statistics presented here bring additional improvement over the default error.

## 1. Introduction

Aircraft observations, which have been significantly increasing in volume over the past few years due to the expansion of aircraft-based observing systems, as well as the increase in commercial air travel, are becoming an important part in the global observing system (Benjamin et al. 1999, 2010). Operational numerical prediction centers have begun to ingest automated aircraft reports from the Aircraft Communications Addressing and Reporting System (ACARS), which is a digital datalink system for transmission of small messages between aircraft and

*Corresponding author address:* Xiang-Yu Huang, National Center for Atmospheric Research, 3450 Mitchell Ln., Boulder, CO 80301.
E-mail: huangx@ucar.edu

DOI: 10.1175/WAF-D-11-00120.1

ground stations via VHF radio. This is the primary system employed by the Aircraft Meteorological Data Relay (AMDAR) program of the World Meteorological Organization (WMO) into regional and global data assimilation systems (Schwartz and Benjamin 1995; Drüe et al. 2008).

DiMego et al. (1992) reported forecast improvements from using aircraft data at the National Centers for Environmental Prediction (NCEP). Smith and Benjamin (1994) showed that ACARS reports improved short-range forecasts of upper-level winds and temperatures when added to wind profiler data over the central United States. However, the absence of humidity observations, as well as the high cruise heights, are two shortfalls of the current aircraft observation sets (Moninger et al. 2010). Other than scattered radiosonde soundings (RAOBs), there is a significant lack of routinely collected in situ observations, particularly humidity, from within the region below the tropopause, where the majority of moisture resides and where convective activity originates (Daniels et al. 2006).

To supplement existing technologies, a low-cost sensor called Tropospheric Airborne Meteorological Data Reporting (TAMDAR) was deployed by AirDat, under the sponsorship of a joint National Aeronautics and Space Administration (NASA) and Federal Aviation Administration (FAA) project as part of Aviation Safety and Security Program, according to requirements defined by the FAA, the Global Systems Division (GSD) of the National Oceanic and Atmospheric Administration (NOAA), and WMO. The TAMDAR sensor network has been providing a continuous stream of real-time observations on regional airlines since December 2004. Aircraft equipped with TAMDAR provide coverage over North America, including Alaska, Hawaii, and Mexico, and generate data from locations and times not available from any other observing system. TAMDAR produces thousands of high-frequency daily observations of humidity, icing, and turbulence, as well as conventional temperature, pressure, and winds aloft along with GPS-based coordinates in near-real time. Although TAMDAR will work on any airframe from a transoceanic 777 to a small unmanned aerial vehicle (UAV), commercial regional airlines have been the primary focus because those planes make more daily flights into a greater number of smaller airports, while still serving the major hubs. As a result, a larger number of soundings from a more geographically diverse set of airports are obtained. TAMDAR observations are rapidly becoming a major source of critical data utilized by various assimilation systems for the improvement of mesoscale NWP and the overall safety of aviation in the future (Fischer 2006).

A crucial step in the process of extracting maximal value from this new observation source is to correctly estimate the observational error of TAMDAR measurements. This will provide weighting information among different types of observations and background fields in the data assimilation system in order to obtain a statistically optimal estimated value of the true variables (Lorenc 1986; Benjamin et al. 1999; Barker et al. 2004).

Several previous investigations have addressed various methods for estimating observational error (e.g., Hollingsworth and Lönnberg 1986; Desroziers and Ivanov 2001; Desroziers et al. 2005). Typically, observational error includes instrument error, reporting error (i.e., measurement error), and representativeness error (Daley 1991; Schwartz and Benjamin 1995). Richner and Phillips (1981) used three ascents with two sondes on the same balloon to take simultaneous measurements of the same air mass. The results showed that the deviations between two sondes fell within the accuracies specified by the manufacturer with respect to the instrument error. As previously stated, this is not the only source of error in an observing system; therefore, when a comparison is made between two observations, or a single observation and forecast or model analysis, representativeness error must be taken into account.

Sullivan et al. (1993) updated temperature error statistics for *NOAA-10* when the retrieval system in National Meteorological Center (NMC, since renamed the National Centers for Environmental Prediction, or NCEP) changed from a statistical to a physical algorithm. In their study, radiosonde soundings were considered the reference value, and the space–time proximity (i.e., 4 h and 330 km) between those soundings and satellite reports was the constraint. Their research provided an initial methodology regarding the estimation of observational error; however, by the inherent nature of the comparison, it was subject to greater representativeness error because of the large space–time collocation threshold.

In light of an ever-growing wealth of aircraft observations to be included as input for generating initial conditions in NWP, the quality of the data has been subject to several studies. Schwartz and Benjamin (1995) gave statistical characteristics of the difference between radiosonde observations (RAOBs) and ACARS data surrounding the Denver, Colorado, airport as a function of time and distance separation. A standard deviation of 0.97 K in temperature was reduced to 0.59 K through using a more strict collocation match constraint from 150 km and 90 min to 25 km and 15 min, which primarily arose based on the representativeness error decreasing. As a result, this study provided an upper bound on the combined error of ACARS and RAOB data with small representativeness error. Additionally, the authors speculated that the large direction difference was related to mesoscale variability, especially from turbulence in the boundary layer.

In a subsequent study to obtain the independent observation error of ACARS, Benjamin et al. (1999) reported on a collocation study of ACARS reports with different tail numbers to estimate observational error, assuming an equivalent expected error from each aircraft, and the minimization of the representativeness error by a strict match condition of 1.25 km and 2 min and no vertical separation. They reported a temperature root-mean-square error (RMSE) of 0.69–1.09 K and wind vector error of 1.6–2.5 m $s^{-1}$ in a vertical distribution, which were comparable to RAOB data. The methodology and assumptions employed by Benjamin et al. (1999) are reasonable; however, since TAMDAR-equipped planes frequently fly into airports that do not have operational radiosonde launches, it is difficult to get enough data for a robust statistical comparison, while retaining similar strict collocation constraints.

More recently, Moninger et al. (2010) provide error characteristics of TAMDAR by comparing the data to the Rapid Update Cycle (RUC) 1- and 3-h forecasts with a model grid spacing of 20 km. In this study, the RUC 1-h forecast is not considered to be "truth" but is treated as a common denominator by which various aircraft fleets are compared. The results show the RMS difference of 1 K, 8%–20%, and RMS vector difference 4–6 m $s^{-1}$ in temperature, RH, and wind observations, respectively. Since the Moninger et al. (2010) study, a procedure was implemented to correct for magnetic deviation errors that were degrading the wind observations (Jacobs et al. 2010), and the results reduced the RMS vector difference by 1.3 m $s^{-1}$ for planes using this type of heading instrumentation. As with previous studies, the RMS difference reported by Moninger et al. (2010) includes the TAMDAR observation error, representativeness error, as well as the RUC 1-h forecast error.

When examining previous studies for the purpose of constructing a methodology for estimating observational error of TAMDAR, two issues become apparent.

### a. *Collocated observational error sources are typically combined in error statistics*

Prior collocation studies consider radiosonde data as truth, and while the uncertainty can be addressed to a limited degree by dual-sensor sonde launches in field experiments (e.g., Schwartz and Benjamin 1995), or by systematic bias adjustments (e.g., Ballish and Kumar 2008; Miloshevich et al. 2009), automated evaluation of TAMDAR observations, as well as TAMDAR-related forecast impacts, for the purposes of deriving error statistics, inherently include radiosonde observational error (Moninger et al. 2010). Ballish and Kumar (2008) highlighted differences between radiosonde temperature and traditional AMDAR data, and suggested correcting temperature biases based on statistics derived against the model background. While this approach may mitigate systematic temperature biases, it is still subject to individual observing system uncertainty and does not address similar issues with wind and moisture observations.

### b. *The wind error is based on vector notation*

There are two areas of interest with respect to the error associated with the assimilation of aircraft wind observations. First, in the Weather Research and Forecasting Model (WRF) data assimilation system (WRFDA; Huang 2009), both the instrumentation error file, as well as the error calculation, use a constant instrumentation error value of 3.6 m $s^{-1}$ at all levels for aircraft weather reports (AIREPs), which includes TAMDAR. This is not the case for RAOBs, which vary the instrumentation error with height above 800 hPa for vector wind. Second, previous collocation studies that analyze wind error compare the vector wind (e.g., Benjamin et al. 1999; Schwartz et al. 2000; Moninger et al. 2010), which inherently includes both the observed speed error, as well as the directional error embedded in the vector component value. It should be noted that WRFDA and the gridpoint statistical interpolation (GSI) handle wind observations in a slightly different way. In this study, we only address WRFDA, where the observational error of wind speed is assigned as a single error value for both $u$ and $v$, and can only be defined by level.

The observed wind vector, $\mathbf{V}_{W_{\text{TAM}}}$, is computed by taking the difference between the ground track vector (i.e., aircraft motion with respect to Earth), $\mathbf{V}_G$, and the aircraft track vector, $\mathbf{V}_A$:

$$\mathbf{V}_{W_{\text{TAM}}} = \mathbf{V}_G - \mathbf{V}_A. \qquad (1)$$

The TAMDAR ground track vector is determined by a very accurate Garmin GPS system, and the associated error is at least two orders of magnitude less than the error in $\mathbf{V}_A$. The aircraft track vector is calculated from the true airspeed (TAS) and the heading angle. The TAS is derived from the difference between the dynamic pressure of the pitot tube and the static pressure. The heading angle is determined by either a laser gyro, or magnetic flux valve, heading system.

This means that there are two primary sources for potential instrumentation error in the wind observation: the TAS and the heading angle. The pitot tube system, which determines TAS, and the heading system, which determines the angle, are essentially two unrelated observing systems. They both provide information to calculate the wind observation, which is then broken down into its $u$ and $v$ components. Once this step has occurred, it is not possible to determine if the error in $u$ or $v$ originated from the TAS (i.e., speed) or the heading (i.e., direction). The uncertainty largely depends on the precision of the heading instrumentation, and older magnetic flux gate systems are subject to large deviations that can impact the observed wind accuracy (Moninger et al. 2010). Mulally and Anderson (2011) introduced a magnetic deviation bias filter that corrects this error, and results in wind observations that are comparable to those reported by aircraft with more sophisticated heading instrumentation.

Small errors in the TAS can result in larger observed wind errors due to the sensitivity of the equation to minor fluctuations in dynamic pressure as seen by the pitot tube. Additionally, the assumption is made that the aircraft is in perfect inertial alignment (i.e., no roll, pitch, or yaw), and since this is almost never the case, there is a small angle-based error introduced in addition to the TAS-based speed error (Painting 2003). The latter can be flagged and filtered based on acceptable thresholds as described in Moninger et al. (2003). Schwartz et al. (2000) explained that the RMS differences depend upon the observed wind speeds, and as wind speed increases, so does the RMS vector difference. They state that one of the reasons for this increase is that small directional differences can have a significant impact on vector components when the magnitude of the wind vector is large. Schwartz et al. (2000) showed this by stratifying the mean RMS vector differences by increments in the observed wind speed.

O'Carroll et al. (2008) developed a statistical method for calculating the standard deviation of the observational error for each of three different observation types under the assumption that the observational error of different systems is uncorrelated, which is typically a reasonable assumption in error theory. We revisit this problem with TAMDAR data, but for this study, we characterize the observational error in its original speed and direction notation. We hypothesize that it may be beneficial to define the error in terms of both direction and speed, as opposed to the magnitude of a single vector component, because of the inverse nature of the relationship between the angle and magnitude. In this study, we employ the O'Carroll et al. (2008) method of estimating the TAMDAR observational error in temperature, RH, wind speed, and wind direction. We further analyze the error in both wind speed, as well as direction, as a function of the speed itself. Additionally, we follow strict collocation match conditions as described in Benjamin et al. (1999) for the purpose of minimizing the representativeness error; however, even with this protocol, any time a numerical model representation of the atmosphere is constructed based on observations, an associated space–time representativeness error of that observation will be introduced.

The rest of this paper is laid out as follows. In section 2, the error statistics methodology and the data sources are introduced. Section 3 presents the error statistics results, which include the difference and vertical distribution of observational error. A brief description of the WRFDA system and WRF model configuration is presented in section 4. In section 5, we discuss assimilation sensitivity experiments that compare the default error to the new error statistics. Conclusions and plans for future work are described in section 6.

## 2. Methodology

### *a. Error analysis*

Following the simultaneous equations for three-way collocation statistics given by O'Carroll et al. (2008), where the observation $x$ is expressed as the sum of the true value of the variable, $x_T$, the bias, or mean error, $b$, and the random error $\varepsilon$, which has a mean of zero by definition, we begin with

$$x = b + \varepsilon + x_T. \tag{2}$$

For a set of three collocated observation types $i$, $j$, and $k$, the following set of equations are obtained:

$$\begin{aligned} x_i &= b_i + \varepsilon_i + x_T \\ x_j &= b_j + \varepsilon_j + x_T \\ x_k &= b_k + \varepsilon_k + x_T. \end{aligned} \tag{3}$$

The variance of the difference, $V$, between two observation types can be expressed as

$$\begin{aligned} V_{ij} &= \sigma_i^2 + \sigma_j^2 - 2r_{ij}\sigma_i\sigma_j \\ V_{jk} &= \sigma_j^2 + \sigma_k^2 - 2r_{jk}\sigma_j\sigma_k \\ V_{ki} &= \sigma_k^2 + \sigma_i^2 - 2r_{ki}\sigma_k\sigma_i, \end{aligned} \tag{4}$$

where $\sigma$ is the standard deviation, $\sigma^2$ is the variance, and $r_{ij}$ is the correlation coefficient. Solving this set of equations allows the error variance of each observation type to be estimated from the statistics of the differences between the three types, which can be expressed as

$$\begin{aligned} \sigma_i^2 &= \frac{1}{2}(V_{ij} - V_{jk} + V_{ki}) \\ \sigma_j^2 &= \frac{1}{2}(V_{jk} - V_{ki} + V_{ij}) \\ \sigma_k^2 &= \frac{1}{2}(V_{ki} - V_{ij} + V_{jk}). \end{aligned} \tag{5}$$

A complete derivation of Eq. (5) is presented in the appendix.

If the representativeness error is taken into consideration, $\sigma_i^2$ from Eq. (5) can be expressed as

$$\sigma_i^2 = \frac{1}{2}(V_{ij} - V_{jk} + V_{ki} - \sigma^2_{\mathrm{rep}_{ij}} + \sigma^2_{\mathrm{rep}_{jk}} - \sigma^2_{\mathrm{rep}_{ki}}), \tag{6}$$

where $\sigma^2_{\mathrm{rep}}$ is the variance of the representativeness error, which is inherent when comparing any two observation types in different space–time locations. If the collocation match conditions between any type (e.g., $k = fg$; WRF 6-h forecast) and two other types (e.g., $i$ = TAMDAR and $j$ = RAOB) are met, we can assume $\sigma^2_{\mathrm{rep}_{\mathrm{RAOB}-fg}} \approx \sigma^2_{\mathrm{rep}_{fg-\mathrm{TAMDAR}}}$, where $fg$ has a constant resolution based on the model grid spacing. Thus, in terms of the representativeness error of TAMDAR and RAOB data, Eq. (5) will give an upper bound of error calculated in Eq. (6). The assumption discussed above eliminates two terms in Eq. (6); however, the contribution from the fourth term, in this case $\sigma^2_{\mathrm{rep}_{\mathrm{TAMDAR}-\mathrm{RAOB}}}$, may still be apparent, and is discussed below. Additionally, for this study, it is assumed that the short-term forecast error of a nonlinear numerical model is uncorrelated to the error of subsequent observations of any observing system.

### *b. Data*

Based on the methodology discussed in the previous section, TAMDAR, RAOB, and WRF 6-h forecasts are selected as the three sources of data employed to estimate the TAMDAR observational error.

#### 1) TAMDAR

The high-frequency TAMDAR observations, which number in the tens of thousands daily, are collected with multifunction in situ atmospheric sensors on aircraft (Daniels et al. 2004; Moninger et al. 2010). In addition to the conventional measurements of temperature and winds aloft, the observations contain measurements of humidity, pressure, icing, and turbulence, along with GPS-derived coordinates.

For humidity, the fundamental physical parameter that the TAMDAR capacitive sensor technology responds to is the density of $H_2O$ molecules. The sensor uses a polymer material that either absorbs or desorbs water molecules based on the RH with respect to water. This in turn affects the capacitance; the relationship is monotonic, so in principle, a given capacitance, which can be measured and turned into a voltage, represents a certain RH.

The observations are relayed via satellite in real time to a ground-based network operations center where they are received, processed, quality controlled, and available for distribution or model assimilation in less than a minute from the sampling time. These observations are reported at 10-hPa pressure intervals up to 200 hPa, with the largest time-based interval during cruise being no more than 3 min.

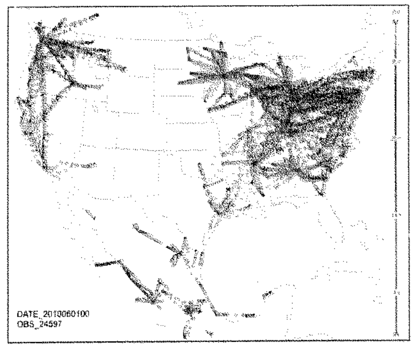



FIG. 1. The distribution of TAMDAR observations on 1 Jun 2010; colors represent thousands of feet. The lower-left corner is the observation number. The distribution and number do not include TAMDAR observations in the AK area.

From 2005 through 2011, NOAA/GSD played a central role in the distribution, evaluation, and initial quality control (i.e., reports formatting or units error) of TAMDAR data. In this study, TAMDAR observations are collected via the Meteorological Assimilation Data Ingest System (MADIS) dataset from NOAA/GSD. The TAMDAR observations used in this study came from fleets that covered most of the airports in the east-central and northwest continental United States (CONUS; Fig. 1). The dataset in this study uses a winter month (January) and a summer month (1–25 June) in 2010. The time series of TAMDAR observation counts are displayed in Fig. 2. The wind observations are fewer than those for RH, which is less than for the temperature. This is because the wind observation requires an accurate aircraft heading reading, so whenever the plane is banking or rolling in a turn over a frame-specific threshold, the wind data are flagged. On occasion, RH data will also be flagged, which typically happens during brief icing events; these data were withheld based on the current quality control flagging system.

#### 2) RADIOSONDE

The radiosonde observations are transmitted to a receiving station where the height of the package is sequentially computed in incremental layers at each reporting level using the hypsometric equation. The drift speed aud direction at various levels are determined from the ground-based radio antenna that tracks the instrument package as it is carried by the wind during the ascent. These observations are processed, tabulated, and encoded for transmission over various communication networks. The National Weather Service launches radiosondes from 92

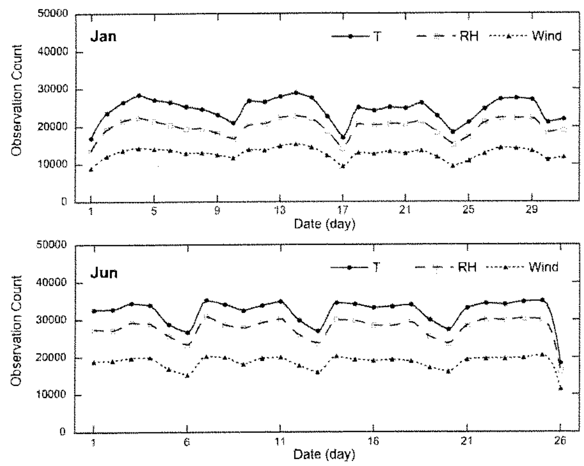



FIG. 2. Time series of the observation count of the experiment period for temperature, RH, and wind from TAMDAR during (top) January and (bottom) June 2010.

stations in North America and the Pacific Islands twice daily. Nearly all routine launches occur approximately 45 min before the official observation times of 0000 and 1200 UTC to allow time for a relaunch should there be a mechanical failure. Therefore, the only observations that are truly sampled at these synoptic hours are in the middle of the profile. In this study, both the TAMDAR and RAOB data were selected over the same time windows from the National Center for Atmospheric Research (NCAR) database, which is routinely transmitted over the Global Telecommunication System (GTS).

The comparison described below was tested with and without a drift applied to the radiosonde using ascent rate statistics from Seidel et al. (2011). For the highest level one would expect to see in TAMDAR observations, the average drift was 16 km in June and 26 km in January with a standard deviation of roughly 12 km. Below 450 hPa, which would include the majority of the TAMDAR observations, the mean drift results were approximately 7 and 10 km for June and January, respectively. In general, the number of matched pairs remained unchanged when considering drift for these cases. Presently, WRFDA does not account for radiosonde drift during the assimilation. One would expect accounting for drift to still improve the accuracy slightly at lower levels; however, when considering the mean statistics over a 1-month period, it was not significant enough to alter the error values to the present decimal place used by WRFDA.

### 3) WRF FORECAST

When using tight constraints for the collocation, there are no other real observations besides RAOB and TAMDAR that share this small window of three-dimensional space over the same time. Thus, the third data source employed for this three-way collocation methodology during January and June of 2010 is the 6-h forecast from the Advanced Research core of the WRF (WRF-ARW; Skamarock et al. 2008). The configuration of the WRF 6-h forecast is discussed in section 4.

### 4) DATA COLLOCATION

According to Eq. (5), the standard deviation of the TAMDAR observational error ($\sigma_T$) can be expressed as

$$\sigma_T = \left[\frac{1}{2}(V_{T-R} - V_{R-F} + V_{F-T})\right]^{1/2}, \qquad (7)$$

where $T$, $R$, and $F$ stand for TAMDAR, RAOB, and WRF 6-h forecast, respectively, and $V$ is the variance of the difference between two observation types. Therefore, data pairs between any two observation types must be calculated first to determine the value of $V$ in Eq. (7).

To compare with both TAMDAR and WRF, the RAOB data are interpolated to every 5 hPa. The data pairs between TAMDAR and RAOB were created for every TAMDAR observation that occurred within

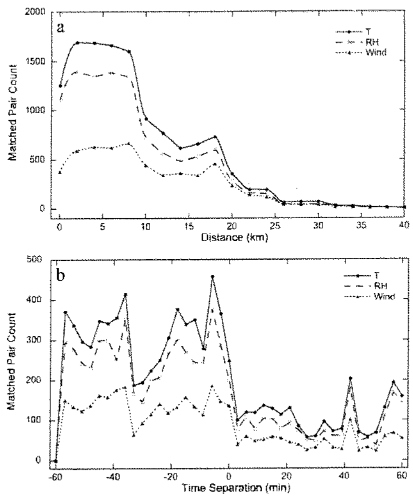



FIG. 3. The distribution of matched pairs by (a) horizontal distance and (b) time separation between TAMDAR and RAOB observations according to the match conditions.

a certain space–time interval of a RAOB report. This means that both data types are assumed to represent the mean value of a small volume of air within a certain spatial and temporal range. To assure confidence in the quality of data pairs, as well as to decrease the effect of representativeness error, different collocation match conditions are applied on different levels for the purpose of maintaining statistically significant matched-pair volume counts. A maximum temporal (vertical spatial) separation difference of 1 h (25 m) was applied in conjunction with three horizontal spatial separation limits of 10 km below 775 hPa, 20 km between 775 and 450 hPa, and 30 km above 450 hPa. The main reason why the collocation matches become fewer with height is that the number of TAMDAR measurements decreases with height because not all flights achieve maximum cruise altitude.

When applying these constraints over the study window, 23 551 matched data pairs were obtained. Despite having less strict horizontal collocation criteria for upper levels (i.e., 30 km), most of the data pairs still fell into the <10-km bin, similar to the lower levels. Figure 3 depicts the distribution of these pairs by distance and time separation. Approximately 70%, 71%, and 61% of TAMDAR–RAOB matched pairs for temperature, RH, and wind, respectively, have a spatial separation of less than 10 km.

As discussed for Fig. 2, more wind data (RH data) were withheld because of aircraft maneuvering (icing). This is also evident in Fig. 3a, where for a collocation threshold below 10 km, despite more net matched pairs, there are fewer matched wind observations. This is because most RAOB sites are located at airports, and during the final approach, aircraft tend to make more banking maneuvers, which result in flagged wind data on descents near airports (i.e., near RAOB launch sites). There is also a notable increase in matched pairs in Fig. 3b in the 60 min prior to 0000 and 1200 UTC, and fewer after, which is a function of RAOB launch time and ascent rate, and the flight schedules, which are routed to avoid passing too close to the ascending balloon during the cruise phase of flight. The data pairs between the WRF 6-h forecast and both RAOB and TAMDAR are easily obtained by gridpoint interpolation to the observation location.

Figure 4 presents the RMSE difference of the data pairs based on the spatial and temporal separation. Generally, the data-pair difference for temperature (Fig. 4a) and RH (Fig. 4b) steadily increases, as the space–time separation grows, which is expected according to the representativeness error. The RH values above 400 hPa do not appear to follow this trend. This is likely a result of the numerically small mixing ratio values; however, based on the low correlation, any meaningful trend would be hard to identify. The order of the lines based on RMSE difference is consistent with temperature becoming more homogeneous with height, and larger RH RMSE resulting from very dry air at higher levels.

Conversely, the wind vectors can be significantly affected by synoptic flow patterns. The wind speed (Fig. 4c) follows the same trend as the previously mentioned scalars with the exception of the lowest level, which still increases, but not at the same rate. This may be a result of the more chaotic flow observed closer to the surface combined with smaller speed magnitudes.

In Fig. 4d, there is greater directional error closer to the surface, and the magnitude of the directional error decreases with height. As we will discuss below, higher speeds typically have less directional error associated with them despite having larger speed error. Thus, it is somewhat expected to see the direction error from the three layers stratified in opposite order of the speed error in Fig. 4c.

The small decrease in error for the middle layer may be related to the amount of RAOB drift. The top of this layer is high enough to be slightly affected by drift, but still low enough that it lacks the homogeneity of the upper-most layer, which can offset this variability. Since we are using the launch position of the radiosonde site for the spatial coordinate, rapidly drifting sondes should have a lower wind direction error. Another possible cause may occur when large spatial collocation match conditions are employed. In

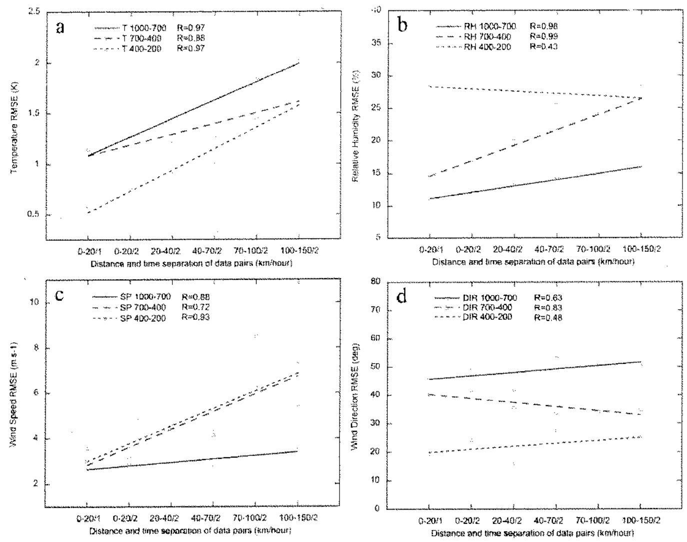



FIG. 4. The RMSE difference of the data pairs based on the spatial and temporal separation for (a) temperature, (b) RH, (c) wind speed, and (d) wind direction.

this case, similar wind directions may be obtained; however, the actual observations are a full wavelength apart. Either situation can greatly increase the variance of the representativeness error term $\sigma^2_{\text{rep-TAMDAR-RAOB}}$ discussed above, and as a result, we employed strict collocation match conditions, described in the beginning of this section, to minimize the impact of this term.

## 3. Error estimation analysis

### *a. Difference distribution*

Figures 5 and 6 present the collocated matched-pair Gaussian-like distribution patterns between TAMDAR and RAOBs, and TAMDAR and WRF 6-h forecasts, respectively. The dotted line is the Gaussian distribution according to the mean value and standard deviation of the difference. Observation pairs with a difference more than 7 K, 40%, 10 m s$^{-1}$, and 60° in the temperature, RH, speed, and direction variables, respectively, are rejected, since abnormal differences are often a result of representativeness error or mesoscale perturbations. In both Figs. 5 and 6, the matched-pair counts approach zero well before the error threshold limits are encountered; therefore, only clear outliers would fall beyond this limit and, as such, would be caught by the upstream in-line quality control procedure. The statistics of the differences are shown in Table 1, which includes bias ($B$), standard deviation ($\sigma$), and confidence intervals of 68%, 90%, and 99% (i.e., 1, 1.64, and 2.58$\sigma$) of the normal Gaussian distribution.

In general, TAMDAR data quality is comparable to RAOBs data based on the biases ($\sim$0.1$\sigma$) with the exception of direction (Table 1). One standard deviation away from the mean, the differences between all the metrics are more than 68.3%, which means that the collocated matched pairs exceeded the normal distribution threshold while maintaining comparable quality. Both difference distributions also follow a similar trend at the 1.64$\sigma$ confidence interval, and have a percent area of around 90%, which shows that the three observation types have a reasonable error range.

It is expected that mesoscale perturbations will lead to some observation pairs with abnormal differences, which lie outside 2.58$\sigma$; however, the collocated data pairs with large differences resulting from either coarse match conditions, or the occasional bad observation that slipped

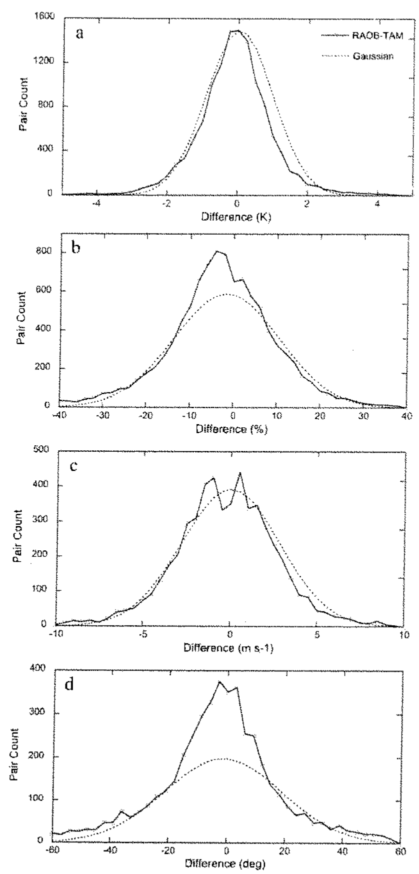



FIG. 5. The difference in (a) temperature, (b) RH, (c) wind speed, and (d) wind direction between TAMDAR observations and RAOB. The dotted line is the Gaussian distribution according to the RAOB-TAM mean value and standard deviation of the difference.

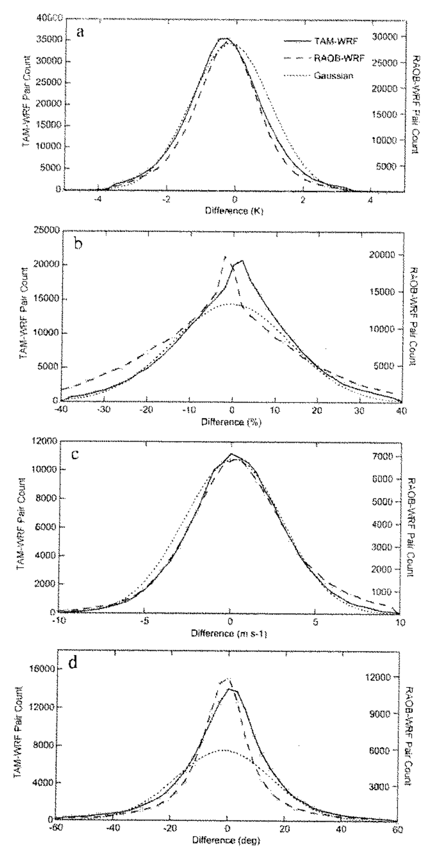



FIG. 6. The difference in (a) temperature, (b) RH, (c) wind speed, and (d) wind direction between TAMDAR and RAOB observations and WRF 6-h forecasts. The dotted line is the Gaussian distribution according to the TAM-WRF mean value and standard deviation of the difference.

through the quality control filter, are rare enough so as not to significantly affect the error estimation of the observations. In this respect, variables such as RH, wind speed, and direction should be closely monitored by quality control and gross error check procedures during operational preprocessing. The total $\sigma$ of observed RH is typically smaller in the critical lower levels because the error in the upper levels increases remarkably based on the very low water vapor values. An inherent characteristic of the wind observations is that the direction error feeds back into the wind vector observations. As a result, mesoscale variability and fluctuations in accurate heading information can cause larger directional error at lower wind speeds, which can increase the frequency of bad observations.

TABLE 1. The statistics of the differences between TAMDAR and RAOB, and TAMDAR and WRF 6-h forecasts.

| | RAOB–TAMDAR | | | | TAMDAR–Forecast | | | |
|---|---|---|---|---|---|---|---|---|
| | RH | $T$ | Speed | Direction | RH | $T$ | Speed | Direction |
| $N$ | 9994 | 12 549 | 5384 | 4810 | 284 586 | 374 198 | 149 044 | 143 572 |
| $B$ | −1.57 (%) | 0.04 (K) | −0.004 (m $s^{-1}$) | −1.22 (°) | −0.37 (%) | −0.16 (K) | 0.15 (m $s^{-1}$) | −1.39 (°) |
| $\sigma$ | 12.18 (%) | 1.06 (K) | 2.83 (m $s^{-1}$) | 20.13 (°) | 13.81 (%) | 1.16 (K) | 2.88 (m $s^{-1}$) | 16.83 (°) |
| $1\sigma$ | 72.10% | 74.90% | 71.50% | 73.60% | 69.80% | 70.10% | 70.10% | 74.30% |
| $1.64\sigma$ | 89.30% | 90.70% | 89.80% | 87.70% | 88.80% | 89.10% | 89.60% | 89.50% |
| $2.58\sigma$ | 97.80% | 97.50% | 97.50% | 97.80% | 98.30% | 98.30% | 98.50% | 97.10% |

### *b. Vertical distribution of observational error*

#### 1) TEMPERATURE

The standard deviation of the temperature errors of TAMDAR and RAOB data in January and June are shown in Fig. 7. The temperature error for TAMDAR is 0.6–0.9 K depending on the level. It is comparable to RAOB data below 700 hPa for the June period and slightly smaller than RAOB data for the January period. The maximum difference of about 0.15 K occurs around 500 hPa in Juue, and around 700 hPa in January. Based on the vertical distribution described in the following section, higher impacts between 850 and 700 hPa are expected. The difference seen at 500 hPa in June may be related to the increased frequency of small-scale perturbations from the convective mixed layer during this time of year.

The instrument error, as specified by the manufacturers of both TAMDAR and the radiosondes, is 0.5 K, and anything above this is likely representativeness error, which must always be taken into account when comparing two data sources within an assimilation system.

#### 2) WIND

Wind error can be affected by multiple factors such as mesoscale perturbations, aircraft heading information, and even as a function of the wind speed itself. According to the wind speed observation statistics in Fig. 8, the RAOB error is about 0.5–1.0 m $s^{-1}$ less than for TAMDAR; however, the average error of 2.0–2.5 m $s^{-1}$ is still quite small. It is also interesting to note that the results shown in Fig. 8 for RAOBs appear to validate the default RAOB error in WRFDA. The wind direction error can be seen in Fig. 9. Both RAOB and TAMDAR have a significant decrease in error with height, and the magnitude of the error in the lower levels is quite large. Three possible reasons for these large error statistics are presented:

- The TAMDAR wind observations are dependent on the accuracy of the heading information supplied by the aircraft instrumentation, and even the most accurate avionics will still introduce an additional source of error. This error source would have more impact on lower wind speeds.
- The error of the wind speed and direction changing as a function of wind speed is a typical characteristic of wind observations.
- The frequeucy of TAMDAR is weighted toward the 1800 and 0000 UTC cycles, whereas the RAOB data have equal numbers for both 0000 and 1200 UTC. Au increase in diurnal instability tends to be more prevalent in the 0000 UTC cycle, compared to 1200 UTC, especially during the summer months because of the heating and length of day.

Figure 10 further illustrates this error dependence on wind speed. Both the wind direction error and the wind speed error for the TAMDAR and RAOB data are plotted based on bins of wind speed magnitude. In general, wind speed (direction) error increases (decreases) with wind speed. RAOBs have less error than TAMDAR for speeds below 15 m $s^{-1}$, while the opposite is true for speeds above 15 m $s^{-1}$, but the differences typically remain less than 0.5 m $s^{-1}$.

Recent improvements in correcting the heading bias seen on some aircraft are discussed in Jacobs et al. (2010) and Mulally and Anderson (2011). The error is reduced by approximately 2 kt, or 1 m $s^{-1}$, which is roughly a 45% decrease in error for this subset of magnetic-heading-equipped planes, and briugs the quality of the data in line with the remainder of the fleet. It should also be mentioned that this subset of planes makes up a small fraction (i.e., 15 out of more than 250) of the expanding TAMDAR fleet, which typically rely on more sophisticated avionics.

#### 3) RELATIVE HUMIDITY

The abundant RH observations of TAMDAR should provide a substantial supplement to present observation types. The quality of TAMDAR RH observations can be seen in Fig. 11, where during the month of January the error of 7%–9% was similar to the RAOB result. In June, the TAMDAR error ranged from 6% near the

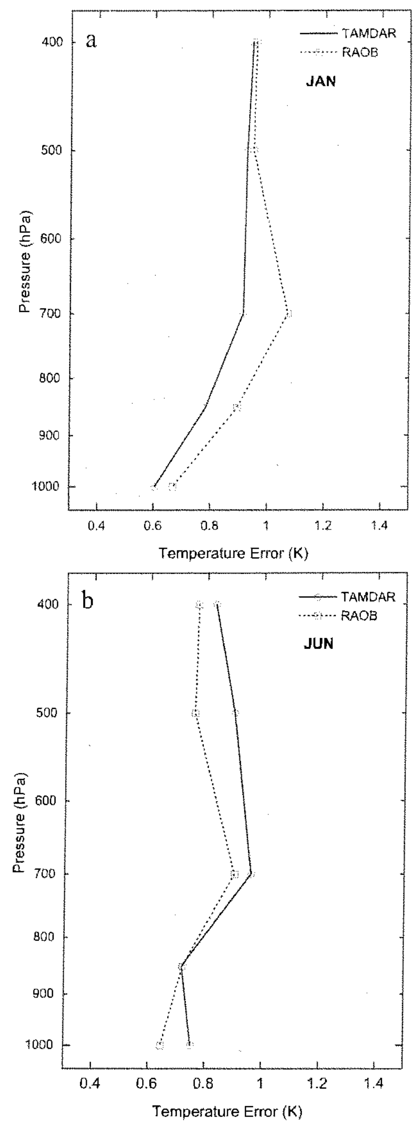



FIG. 7. The standard deviation of temperature error for TAMDAR and RAOB in (a) January and (b) June.

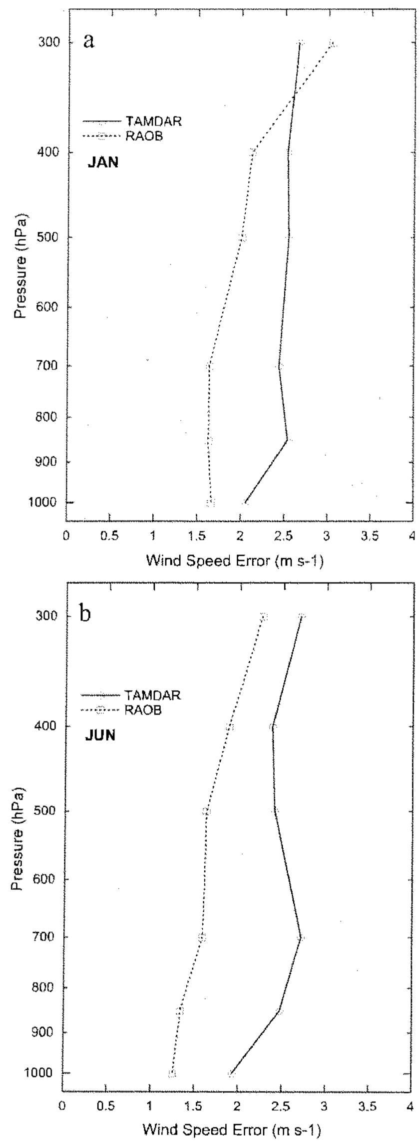



FIG. 8. As in Fig. 7, but for wind speed error.

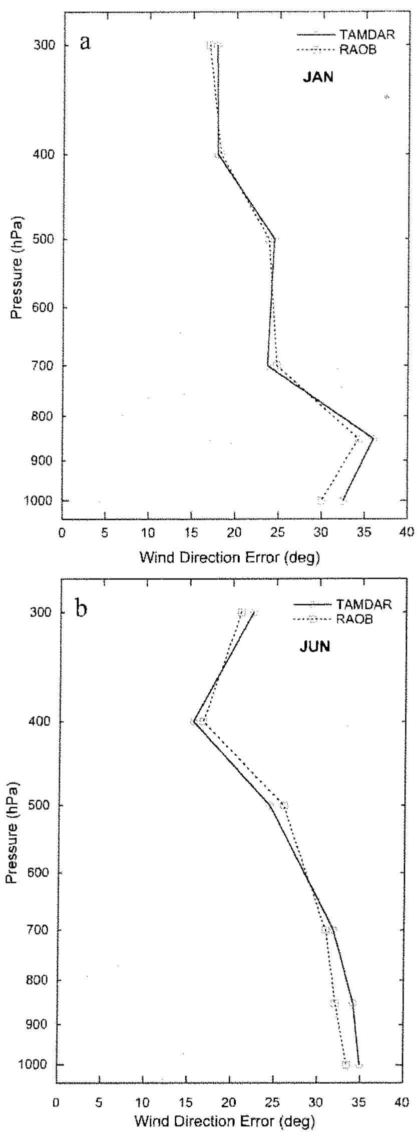



FIG. 9. As in Fig. 7, but for wind direction error.

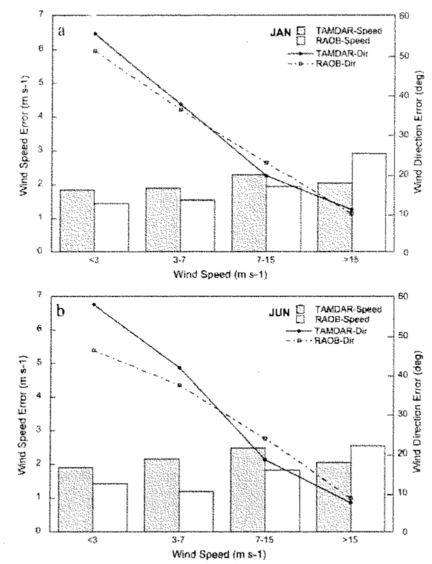



FIG. 10. The standard deviation of the wind speed (bars) and wind direction (lines) error as a function of wind speed magnitude thresholds for TAMDAR and RAOB in (a) January and (b) June.

surface to 8% above 400 hPa, and had a maximum reduction in error of 3% RH compared to RAOB at 500 hPa. The estimated error range is consistent with the findings of 5%–10% from Daniels et al. (2006).

## 4. Model configuration and experiment design

To evaluate the performance of TAMDAR with the observational error estimated above, three parallel experiments are conducted. These experiments were performed during June 2010, and are based on WRFDA three-dimensional variational data assimilation (3DVAR) and the WRF ARW (version 3.2).

In the present WRFDA system, the AIREP error is the default table for any type of observation collected by an aircraft regardless of airframe, phase of flight, or instrumentation type. Since TAMDAR is based on different operating principles compared to traditional AIREPs, it is not realistic to assume it possesses similar error characteristics. The TAMDAR error statistics derived above will be used in the following assimilation experiment as a substitute for the default AIREP error. Both the original default AIREP error, and the new

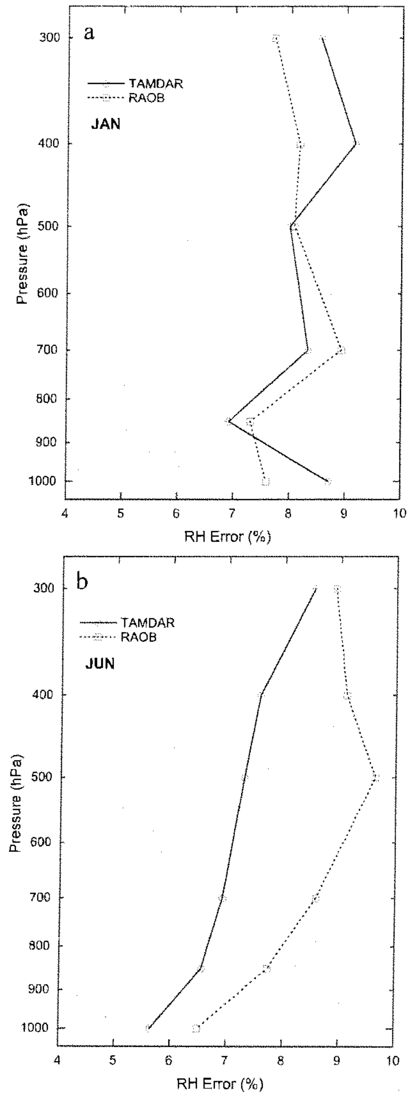



FIG. 11. The standard deviation of RH error for TAMDAR and RAOB in (a) January and (b) June.

TAMDAR-specific error, are presented in Table 2. The WRFDA error file contains values that correspond to levels up to 10 hPa. Since TAMDAR data would never appear above 200 hPa, any value entered in the table above this height would merely serve as a placeholder.

In section 3, both the wind speed error and the wind direction error were characterized. However, in this part, only the wind speed error (Fig. 8) was employed to modify the WRFDA observational error statistics in Table 2. The results from Figs. 9 and 10 help shed light on some of the error-related trends, but those results were not applied to the error table for the NEWerr_T run, as this would require a modification to the observation operator discussed in the following section.

## a. *WRF ARW and WRFDA 3DVAR*

The WRF-ARW is a fully compressible and Euler nonhydrostatic model with a vertical coordinate of terrain-following hydrostatic pressure, and features time-split integration using a third-order Runge–Kutta scheme with a smaller time step for acoustic and gravity wave modes and multiple dynamical cores with high-order numerics to improve accuracy. A detailed description of the model can found in Skamarock et al. (2008).

The WRFDA 3DVAR system originates from the 3DVAR system in the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5) developed by Barker et al. (2004), and based on an incremental formulation (Courtier et al. 1994). Following Lorenc et al. (2000), the control variables are the streamfunction, unbalanced velocity potential, unbalanced temperature, unbalanced surface pressure, and pseudo RH, which are used in the minimization process of the first term of Eq. (8) below.

The basic goal of 3DVAR is to obtain statistically optimal estimated values of the true atmospheric state at a desired analysis time through an iterative minimization of the prescribed cost function (Ide et al. 1997):

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}_b)^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_b) + \frac{1}{2}[\mathbf{y}_0 - H(\mathbf{x})]^{\mathrm{T}}\mathbf{R}^{-1}[\mathbf{y}_0 - H(\mathbf{x})], \qquad (8)$$

where $\mathbf{B}$ is the background error covariance matrix, $\mathbf{x}_b$ is the background state, $H$ is the nonlinear observation operator, $\mathbf{y}$ is the data vector, $\mathbf{R}$ is the observation error covariance matrix, and the state vector is defined as

$$\mathbf{x} = [\mathbf{u}^{\mathrm{T}}, \mathbf{v}^{\mathrm{T}}, \mathbf{T}^{\mathrm{T}}, \mathbf{q}^{\mathrm{T}}, \mathbf{p}_s^{\mathrm{T}}]^{\mathrm{T}}. \qquad (9)$$

If an iterative solution can be found from Eq. (9) that minimizes Eq. (8), the result represents a minimum

TABLE 2. The new (TAMDAR) and default (AIREP) errors from the WRFDA error file.

| Level (RH,T) | New RH (%) | New T (K) | Default RH (%) | Default T (K) | Level (wind) | New wind (m $s^{-1}$) | Default wind (m $s^{-1}$) |
|---|---|---|---|---|---|---|---|
| 200 | 8.00 | 0.8 | 10.00 | 1.0 | 200 | 2.7 | 3.6 |
| 250 | 8.00 | 0.8 | 10.00 | 1.0 | 250 | 2.7 | 3.6 |
| 300 | 8.00 | 0.8 | 10.00 | 1.0 | 300 | 2.7 | 3.6 |
| 400 | 7.50 | 0.8 | 10.00 | 1.0 | 350 | 2.6 | 3.6 |
| 500 | 7.00 | 0.9 | 10.00 | 1.0 | 400 | 2.5 | 3.6 |
| 700 | 7.00 | 0.9 | 10.00 | 1.0 | 450 | 2.5 | 3.6 |
| 850 | 6.50 | 0.7 | 10.00 | 1.0 | 500 | 2.5 | 3.6 |
| 1000 | 5.50 | 0.7 | 15.00 | 1.0 | 550 | 2.5 | 3.6 |
| | | | | | 600 | 2.5 | 3.6 |
| | | | | | 650 | 2.5 | 3.6 |
| | | | | | 700 | 2.5 | 3.6 |
| | | | | | 750 | 2.5 | 3.6 |
| | | | | | 800 | 2.5 | 3.6 |
| | | | | | 850 | 2.5 | 3.6 |
| | | | | | 900 | 2.3 | 3.6 |
| | | | | | 950 | 2.1 | 3.6 |
| | | | | | 1000 | 2.0 | 3.6 |

variance estimate of the true atmospheric state given the background $\mathbf{x}_b$ and observations $\mathbf{y}_0$, as well as $\mathbf{B}$ and $\mathbf{R}$ (Lorenc 1986). The conjugate gradient method is used to minimize the incremental cost function. A detailed description of this system can be found in Barker et al. (2004), as well as at the WRFDA web site (http://www.mmm.ucar.edu/wrf/users/wrfda/pub-doc.html). Additional background on TAMDAR assimilation by WRFDA can also be found in Wang et al. (2009).

### b. Model configuration

The data assimilation experiments and WRF forecasts were performed on a single 400 × 250 grid with 20-km spacing that covered the United States and surrounding oceanic regions. There were 35 vertical levels with a top of 50 hPa. The model produced a 24-h forecast. While this configuration is not necessarily optimal for assimilation of high-resolution asynoptic data like TAMDAR, it was sufficient to reach conclusions and illustrate the necessity to consider other methods of determining wind observation error statistics.

In this study, the Kain–Fritsch cumulus parameterization was employed (Kain 2004), along with the Goddard cloud microphysics scheme, and the Yonsei University (YSU) planetary boundary layer parameterization (Hong et al. 2006).

### c. Experiment design

Three parallel WRF runs were performed during 1–20 June 2010·

- 'DEFerr_noT' is used as a control run, conventionally assimilating GTS data with default error statistics in WRFDA, including surface synoptic observations (SYNOP), aviation routine weather reports (METARs), PROFILER, RAOB, ground-based GPS precipitable water, SHIP, and BUOY, but excluding all non-TAMDAR automated aircraft data (e.g., the Meteorological Data Collection and Reporting System, MDCRS);
- 'DEFerr_T' is identical to 'DEFerr_noT' in every way except that it also assimilates TAMDAR wind, temperature, and RH observations; in this run, the default AIREP error is applied to the TAMDAR observations; and
- 'NEWerr_T' is identical to 'DEFerr_T' in every way except it uses the TAMDAR error statistics introduced in section 3 and Table 2 instead of the default AIREP error.

The cycling process employed here begins with a 6-h WRF forecast based on the GFS at the four analysis times (i.e., 0000, 0600, 1200, and 1800 UTC) for initial background and lateral boundary conditions (LBCs), after which, the 6-h WRF forecasts are used as the background or first guess for all three runs in the experiment. The LBCs are updated on every run by the latest GFS. All three assimilation versions produce eighty 24-h forecasts over the 20-day period during June 2010. The window of time for the 3D-Var data assimilation process is 2 h on either side of the analysis time; thus, TAMDAR data from 0300, 0900, 1500, and 2100 UTC were not included. Ideally, a more rapid cycling 3DVAR (or 4DVAR) assimilation process would be able to extract greater value from the asynoptic observations, but the objective of this study was only to derive and test the error statistics.

Before assimilation, a basic quality control procedure, which includes a vertical consistency check (superadiabatic

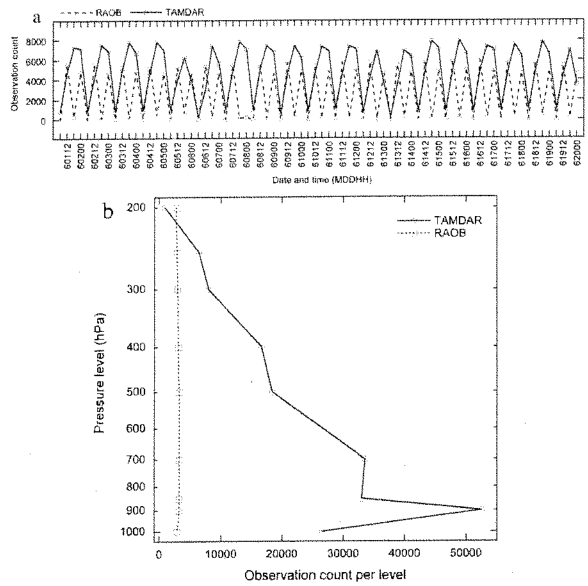



FIG. 12. The (a) time series and (b) vertical profile distribution per mandatory level of the temperature observation numbers for RAOB and TAMDAR.

check and wind shear check), and dry convective adjustment, is performed on all observations including TAMDAR. This is following the initial quality assurance protocol performed by AirDat on the TAMDAR data when it is sampled (Anderson 2006). Additionally, observations that differ from the background by more than 5 times the observational error are also rejected.

The NMC method (Parrish and Derber 1992) was applied over a period of 1 month prior to each study window to generate the background error covariances using monthly statistics of differences between WRF 24- and 12-h daily forecasts. The verifications presented here are from both the 6- and 24-h forecasts, and are based on the average results of the 80 forecast cycles.

## 5. New TAMDAR error statistics in WRFDA

### *a. Previous studies*

Several studies have been conducted on the TAMDAR dataset, which underwent a lengthy operational evaluation during the Great Lakes Fleet Experiment (GLFE; e.g., Mamrosh et al. 2006; Jacobs et al. 2008; Moninger et al. 2010). Mamrosh et al. (2006) found that TAMDAR, with high spatial and temporal resolution, was valuable when used in marine (lake breeze) forecasting, convective forecasting, and aviation forecasting. Moninger et al. (2010) conducted a detailed analysis of the additional forecast skill provided by TAMDAR to the Rapid Update Cycle (RUC) model over a period of more than three years. The estimated temperature, wind, and RH 3-h forecast errors in RUC were reduced by up to 0.4 K, 0.25 m s$^{-1}$, and 3%, respectively, by assimilating TAMDAR, which corresponds to an estimated maximum potential improvement in RUC of 35%, 15%, and 50% for temperature, winds, and RH, respectively. These experiments were conducted during the initial phase of installation of the sensors, so the improvements seen as time progresses are a function of additional sensors being deployed in the field.

### *b. Observations assimilated*

Figure 12 presents the time series and vertical profile of RAOB and TAMDAR temperature observation counts used in assimilation experiments. RAOBs are routinely launched twice daily at 0000 and 1200 UTC in the CONUS, which leaves a void of upper-air observational data to initialize the 0600 and 1800 UTC forecast cycles. Supplementing both the spatial gaps, as well as the temporal gaps, is critical for improving forecast skill. It is evident in Fig. 12a that TAMDAR not only is coincident with the 0000 and 1200 UTC cycles, but also peaks in data volume during the 1800 UTC cycle. The daily mean observation count for TAMDAR over the study period for the 0600 and 1800 UTC cycles, respectively, is 798 and 7402 for temperature, 756 and 6409 for RH, and 230 and 2145 for wind. Figure 12b presents the observation count per mandatory level for the duration of the study period. It is hypothesized that these extra observations will make a statistically significant contribution to forecast skill.

### *c. Results analysis*

The TAMDAR error in the DEFerr_T run is based on the default AIREP error statistics (i.e., generic aircraft data) in the obsproc program within WRFDA. The default errors, especially the wind observational error, which is a constant 3.6 m $s^{-1}$, are larger than the new error statistics. In this situation, TAMDAR will receive unreasonably small weight among the other observation types and background. The new error statistics derived here will correct this issue.

Because we wanted to highlight the difference in TAMDAR impact using the default (DEFerr_T) versus new errors (NEWerr_T), we withheld MDCRS data, which would be assimilated as a default AIREP in WRFDA. If the MDCRS data were included as a default AIREP, we would expect the relative impact of TAMDAR, especially for wind and temperature, to be noticeably reduced.

To evaluate the impact of the new error statistics, the root-mean-square errors (RMSEs) of the 6- and 24-h forecast are calculated using mainly radiosondes, as well as various near-surface observation types (e.g., SYNOP and METAR) available between the surface and 200 hPa as verification over the entire CONUS domain. Since the verification package referenced all of the conventional observations distributed by NCEP over the GTS, a small fraction of the TAMDAR feed (~2.7%) was also present in this database. The percentage of improvement is calculated by $\%\mathrm{IMP} = -(\alpha - \beta)/\beta \times 100$, where simulation $\alpha$ is compared to simulation $\beta$, and appears contextually below as an improvement of $\alpha$ over $\beta$ (Brooks and Doswell 1996).

#### 1) TEMPERATURE

The average impact of the TAMDAR temperature observations on the 6- and 24-h WRF forecasts are presented in Fig. 13. In general, temperature error decreases with elevation through the troposphere, and the inaccuracy of

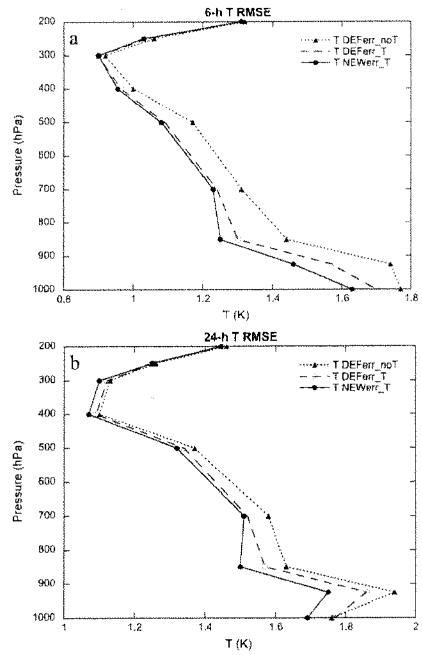



FIG. 13. The RMSEs of WRF (a) 6- and (b) 24-h temperature forecasts for DEFerr_noT (dotted), DEFerr_T (dashed), and NEWerr_T (solid).

forecasted temperatures associated with errors within the planetary boundary layer are greatest between 1000 and 900 hPa for a 24-h forecast. In Fig. 13b, the vertical profile of 24-h forecast error has a maximum around 925 hPa, which is consistent with the results from Moninger et al. (2010) discussed in section 1.

Both the DEFerr_T and NEWerr_T results have noticeably less error when compared to DEFerr_noT, particularly below 500 hPa, which is not surprising given the vertical distribution of the TAMDAR observations (cf. Figs. 12b and 13). The maximum difference in the 6-h forecast RMSE between DEFerr_noT and DEFerr_T is 0.15 K at 925 hPa, and 0.09 K at the same level for the 24-h forecast. The NEWerr_T simulation further reduces the error, and this reduction is attributed to the new error statistics. The profile pattern is similar, but for the 6-h forecast RMSE the maximum difference between NEWerr_T and DEFerr_noT is 0.27 K, which is a 44%

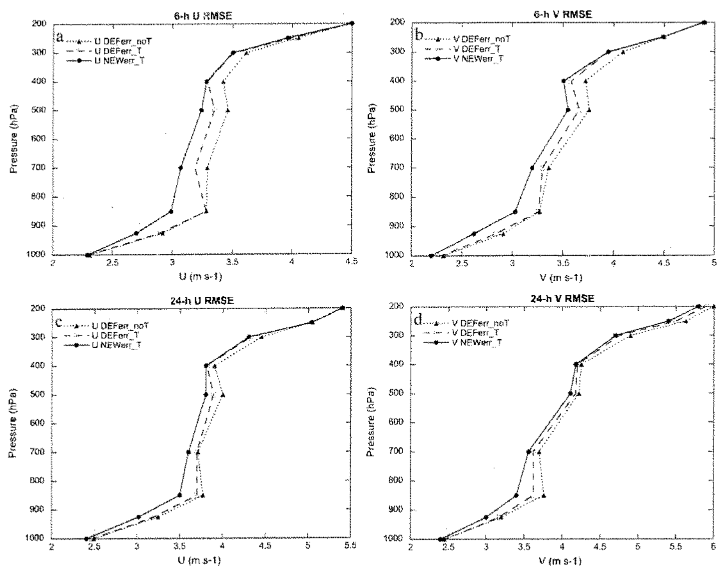



FIG. 14. The RMSEs of WRF 6-h (a) $U$ and (b) $V$ forecasts and 24-h (c) $U$ and (d) $V$ forecasts for DEFerr_noT (dotted), DEFerr_T (dashed), and NEWerr_T (solid).

improvement over the DEFerr_T run. For the 24-h forecast (Fig. 13b), the maximum difference between the NEWerr_T and DEFerr_noT is 0.2 K, which is roughly a 55% improvement over the DEFerr_T run at the same level.

### 2) Wind

Despite having a wind observation error larger than a radiosonde, the TAMDAR wind data still produce a notable improvement in forecast skill. In Fig. 14, there are two interesting comparisons that are observed. First, both the DEFerr_T and NEWerr_T simulations produce a similar decrease in RMSE around 400 hPa. This is more easily seen in Fig. 14a for the 6-h forecast, and is a combination of a larger volume of data compared to 300 and 200 hPa and similar error statistics.

However, below 900 hPa, the $U$ and $V$ wind RMSEs of the DEFerr_T run do not improve much, if any, over the DEFerr_noT run. This is largely a result of the error statistics in the default error file, which employ a constant value of 3.6 m $s^{-1}$ for every level. While this is acceptable for levels around 400 hPa and higher, it is likely too large for levels below 800 hPa, especially when dealing with observations of lower wind speed or aircraft maneuvering on the final approach of the descent. As a result, fewer observations are rejected at lower levels. Adjustments made to the error statistics in the NEWerr_T run mitigate this problem, and as a result, the $U$ and $V$ wind forecast RMSEs are reduced. This serves as an alternative to withholding all of the descent wind observations. A maximum reduction in error of roughly 0.25 m $s^{-1}$ is observed around 850 hPa.

### 3) Humidity

The positive impacts of the TAMDAR RH observations can be seen in Fig. 15. For the 6-h forecast, the magnitude of the impact below 500 hPa is approximately 0.1 g $kg^{-1}$; however, above 500 hPa, there is the improvement is much less clear, which converges to undetectable above 200 hPa. This is partly because the volume of TAMDAR decreases with height, but it is primarily a function of the water vapor magnitudes approaching very small numerical values, as height increases above 500 hPa. A similar trend is seen for the 24-h

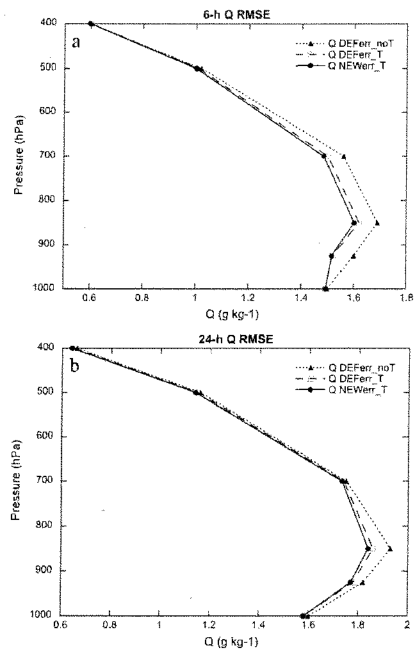



FIG. 15. The RMSEs of WRF (a) 6- and (b) 24-h specific humidity forecasts for DEFerr_noT (dotted), DEFerr_T (dashed), and NEWerr_T (solid).

forecast. The impacts of the new error statistics are positive but small with the exception of those at the 850-hPa level. Although the TAMDAR RH error in the NEWerr_T run was changed, the observations impacted by the change based on RAOB data and the model background remained similar, so that in the window examined here, the positive impact from the new error statistics is relatively small. This is likely a function of atmospheric variability, as well as dynamic events and seasonal fluctuations, which may produce larger differences.

## 6. Summary and outlook

The TAMDAR sensor network provides abundant meteorological data with high spatial and temporal resolution over most of North America. The large diversity of regional airport coverage, real-time reporting, adjustable vertical resolution, as well as humidity measurements are some of the advantages that this dataset provides above traditional aircraft observations (e.g., the Aircraft Communication, Addressing, and Reporting System, ACARS), which have ascents and descents only at larger airport hubs. We have estimated the TAMDAR observational error and evaluated the subsequent impacts when employing the new error statistics in WRF through three assimilation experiments. The error estimation results are summarized as follows:

- The observational error of the TAMDAR RH is approximately 5.5%–9.0%, which is comparable to RAOB in winter months, and smaller than RAOB during summer months.
- The TAMDAR temperature error of 0.6–1.0 K is comparable to RAOB. The largest difference between RAOB and TAMDAR error at any time or level was 0.15 K.
- With respect to wind observations, the RAOB data have less error for speeds below 15 m $s^{-1}$, while the opposite is true for speeds above this threshold. The differences typically remained less than 0.5 m $s^{-1}$, with June producing slightly larger variance. The average magnitude of the TAMDAR wind error was approximately 2 m $s^{-1}$. In general, for both RAOB and TAMDAR, a slight increase in speed error was seen as a function of increasing wind speed; however, with this same increase in wind speed came a notable decrease in direction error from more than 40° for winds <3 m $s^{-1}$ to roughly 10° for winds >15 m $s^{-1}$.

Improvements in forecast skill are seen in both the 6- and 24-h forecasts throughout the altitude range where the TAMDAR data are collected. Additionally, greater gains, sometimes exceeding 50%, are achieved when the new error statistics are applied. As mentioned previously, because we wanted to highlight the difference in TAMDAR impact using the new error statistics, we withheld MDCRS data, which wonld be assimilated as a default AIREP in WRFDA. If the MDCRS data were included as a default AIREP, we would expect the relative impact of TAMDAR and the improvements discussed below, especially for wind and temperature, to be noticeably reduced.

- The 6-h (24-h) temperature forecast errors are reduced by up to 0.27 K (0.2 K), and the new error statistics are responsible for as much as 0.1 K of that difference (~37%).
- The impact of the TAMDAR wind observations was largest at 850 hPa, where it reduced the RMSE by 0.25 m $s^{-1}$. Nearly all of this rednction was a result of the new error statistics at this level. Across the entire profile, average reductions between 0.1 and 0.2 m $s^{-1}$ were noted, and approximately 50%–75% of that was attributable to the revised error.

- Based on the evidence that the new error statistics play a leading role in the improvement in wind forecast skill below 500 hPa, it is concluded that the default AIREP wind error is large enough to inhibit the contribution of the TAMDAR wind observations. Thus, unique level-specific error statistics are warranted.
- The impact of TAMDAR RH is generally close to 0.1 g $kg^{-1}$ from 925 to 700 hPa for the 6-h forecast. The maximum difference of either with-TAMDAR run over DEFerr_noT was 0.1 g $kg^{-1}$ at 850 hPa. In the case of water vapor, the revised error statistics produced only a slight positive impact, which is not unexpected. In terms of RH, this change was approximately 2% for the 6-h forecast, which is consistent with the findings presented in Moninger et al. (2010), where the RH error reduction in the 3-h RUC forecast that was attributed to TAMDAR varied between 1% and 3% RH. With an analysis RMSE of roughly 5%–6% RH, the improvement of 2% RH, according to the estimated maximum potential improvement (EMPI; Moninger et al. 2010), would be approximately 35%–40%.

Due to the high temporal and spatial resolution of the TAMDAR data, real-time changes in the boundary layer and midtroposphere with respect to temperature and humidity, several stability parameters can be monitored (Szoke et al. 2006; Fischer 2006), and positive impacts on quantitative precipitation forecast (QPF) are achieved (Liu et al. 2010).

Future work will focus on refining the ability of the data assimilation methodology to extract the maximum benefit of the RH observations for the purpose of improving QPF skill. Additionally, significant work will be performed on characterizing the wind errors based on the phase of flight, space–time position in the atmosphere, and the observed wind direction and magnitude.

*Acknowledgments.* The authors thank Yong-Run Guo (NCAR), Daniel Mulally (AirDat), and three anonymous reviewers for their valuable comments and suggestions. We are grateful for the code support of TAMDAR assimilation provided by Hongli Wang (NCAR). The National Center for Atmospheric Research is sponsored by the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

## APPENDIX

### Error Analysis for Three-Way Collocation Statistics

Following the methodology presented by O'Carroll et al. (2008), below is the complete derivation of the set of equations used for obtaining the three-way collocation statistics. For a set of three collocated observation types $i$, $j$, and $k$, the following set of equations is obtained:

$$\begin{aligned} x_i &= b_i + \varepsilon_i + x_T \\ x_j &= b_j + \varepsilon_j + x_T \\ x_k &= b_k + \varepsilon_k + x_T, \end{aligned} \tag{A1}$$

where the observation $x$ is expressed as the sum of the true value of the variable, $x_T$; the bias, or mean error, $b$; and the random error $\varepsilon$, which, over a reasonable sample size, has a mean of zero by definition. The mean difference between two observation types (e.g., $i$ and $j$) is

$$\overline{x}_i - \overline{x}_j = \overline{b}_i - \overline{b}_j + \overline{\varepsilon}_i - \overline{\varepsilon}_j + \overline{b}_{\mathrm{rep}_{ij}} + \overline{\varepsilon}_{\mathrm{rep}_{ij}}, \tag{A2}$$

where the representativeness error, which is always present when comparing two observation types, is broken into its mean ($b_{\mathrm{rep}}$) and random ($\varepsilon_{\mathrm{rep}}$) components. Because it is assumed that $\varepsilon$ has a mean of zero, and the mean of $b$ is just $b$, Eq. (A2) can be written as

$$\overline{x}_i - \overline{x}_j = \overline{b}_i - \overline{b}_j + \overline{b}_{\mathrm{rep}_{ij}} = b_i - b_j + b_{\mathrm{rep}_{ij}}. \tag{A3}$$

Using Eqs. (A2) and (A3), we can express the difference between these two observation types as

$$x_i - x_j = \overline{x}_i - \overline{x}_j + \varepsilon_i - \varepsilon_j + \varepsilon_{\mathrm{rep}_{ij}}. \tag{A4}$$

After rearranging (A4), sqnaring both sides, and expanding the terms, we obtain

$$\begin{aligned} &(x_i - \overline{x}_i)^2 + (x_j - \overline{x}_j)^2 - 2(x_j - \overline{x}_j)(x_i - \overline{x}_i) \\ &= (\varepsilon_i - \varepsilon_j + \varepsilon_{\mathrm{rep}_{ij}})^2. \end{aligned} \tag{A5}$$

If we apply Eq. (A5) to a sample size of $N$ collocated observations, we can express the equation as

$$\begin{aligned} &\frac{1}{N}\sum_{k=1}^{N}(x_{i_k} - \overline{x}_i)^2 + \frac{1}{N}\sum_{k=1}^{N}(x_{j_k} - \overline{x}_j)^2 \\ &- \frac{2}{N}\sum_{k=1}^{N}(x_{j_k} - \overline{x}_j)(x_{i_k} - \overline{x}_i) \\ &= \frac{1}{N}\sum_{k=1}^{N}(\varepsilon_{i_k} - \varepsilon_{j_k} + \varepsilon_{\mathrm{rep}_{ijk}})^2, \end{aligned} \tag{A6}$$

where the first two terms in (A6) are tbe variances of $i$ and $j$,

$$\sigma_i^2 = \frac{1}{N}\sum_{k=1}^{N}(x_{i_k} - \overline{x}_i)^2, \quad \sigma_j^2 = \frac{1}{N}\sum_{k=1}^{N}(x_{j_k} - \overline{x}_j)^2, \tag{A7}$$

and term three in (A6) is the covariance of $i$ and $j$, which can be expressed in terms of the standard deviation of $i$ and $j$:

$$\sigma_{ij} = \frac{1}{N}\sum_{k=1}^{N}(x_{j_k} - \overline{x}_j)(x_{i_k} - \overline{x}_i) = r_{ij}\sigma_i\sigma_j, \tag{A8}$$

where $r_{ij}$ is the correlation coefficient. Applying Eqs. (A7) and (A8) to Eq. (A6) yields

$$\begin{aligned}\frac{1}{N}\sum_{k=1}^{N}(\varepsilon_{i_k} - \varepsilon_{j_k} + \varepsilon_{\mathrm{rep}_{ij_k}})^2 &= \overline{\varepsilon_i^2} + \overline{\varepsilon_j^2} + \overline{\varepsilon_{\mathrm{rep}_{ij}}^2} + \overline{2\varepsilon_i\varepsilon_{\mathrm{rep}_{ij}}} - \overline{2\varepsilon_j\varepsilon_{\mathrm{rep}_{ij}}} - \overline{2\varepsilon_i\varepsilon_j}\\ &= \sigma_i^2 + \sigma_j^2 + \sigma_{\mathrm{rep}_{ij}}^2 + 2r_{i-\mathrm{rep}_{ij}}\sigma_i\sigma_{\mathrm{rep}_{ij}} - 2r_{j-\mathrm{rep}_{ij}}\sigma_j\sigma_{\mathrm{rep}_{ij}} - 2r_{ij}\sigma_i\sigma_j.\end{aligned} \tag{A9}$$

Therefore, the variance of the difference between observation types $i$ and $j$, which is defined as

$$V_{ij} = \mathrm{var}(i - j) = \mathrm{var}(i) + \mathrm{var}(j) - 2\mathrm{cov}(i, j), \tag{A10}$$

can be written in terms of (A9), and applied to a three-way comparison between observation types $i$, $j$, and $k$ to obtain the following set of equations:

$$\begin{aligned}V_{ij} &= \sigma_i^2 + \sigma_j^2 + \sigma_{\mathrm{rep}_{ij}}^2 + 2r_{i-\mathrm{rep}_{ij}}\sigma_i\sigma_{\mathrm{rep}_{ij}}\\ &\quad - 2r_{j-\mathrm{rep}_{ij}}\sigma_j\sigma_{\mathrm{rep}_{ij}} - 2r_{ij}\sigma_i\sigma_j\\ V_{jk} &= \sigma_j^2 + \sigma_k^2 + \sigma_{\mathrm{rep}_{jk}}^2 + 2r_{j-\mathrm{rep}_{jk}}\sigma_j\sigma_{\mathrm{rep}_{jk}}\\ &\quad - 2r_{k-\mathrm{rep}_{jk}}\sigma_k\sigma_{\mathrm{rep}_{jk}} - 2r_{jk}\sigma_j\sigma_k\\ V_{ki} &= \sigma_k^2 + \sigma_i^2 + \sigma_{\mathrm{rep}_{ki}}^2 + 2r_{k-\mathrm{rep}_{ki}}\sigma_k\sigma_{\mathrm{rep}_{ki}}\\ &\quad - 2r_{i-\mathrm{rep}_{ki}}\sigma_i\sigma_{\mathrm{rep}_{ki}} - 2r_{ki}\sigma_k\sigma_i.\end{aligned} \tag{A11}$$

The reasonable assumption is made that the instrumentation error produced by completely independent techniques will be independent, and the instrumentation error is also independent of the representativeness error; thus, $r = 0$, and we obtain

$$\begin{aligned}V_{ij} &= \sigma_i^2 + \sigma_j^2 + \sigma_{\mathrm{rep}_{ij}}^2\\ V_{jk} &= \sigma_j^2 + \sigma_k^2 + \sigma_{\mathrm{rep}_{jk}}^2\\ V_{ki} &= \sigma_k^2 + \sigma_i^2 + \sigma_{\mathrm{rep}_{ki}}^2.\end{aligned} \tag{A12}$$

Solving this system of equations for the variance of error for each of the three observation types yields

$$\begin{aligned}\sigma_i^2 &= \frac{1}{2}(V_{ij} - V_{jk} + V_{ki} - \sigma_{\mathrm{rep}_{ij}}^2 + \sigma_{\mathrm{rep}_{jk}}^2 - \sigma_{\mathrm{rep}_{ki}}^2)\\ \sigma_j^2 &= \frac{1}{2}(V_{jk} - V_{ki} + V_{ij} - \sigma_{\mathrm{rep}_{jk}}^2 + \sigma_{\mathrm{rep}_{ki}}^2 - \sigma_{\mathrm{rep}_{ij}}^2)\\ \sigma_k^2 &= \frac{1}{2}(V_{ki} - V_{ij} + V_{jk} - \sigma_{\mathrm{rep}_{ki}}^2 + \sigma_{\mathrm{rep}_{ij}}^2 - \sigma_{\mathrm{rep}_{jk}}^2).\end{aligned} \tag{A13}$$

If strict collocation match conditions are met, as discussed in section 2, the variance of the representativeness error terms will be very small, and (A13) can be reduced to

$$\begin{aligned}\sigma_i &= \left[\frac{1}{2}(V_{ij} - V_{jk} + V_{ki})\right]^{1/2}\\ \sigma_j &= \left[\frac{1}{2}(V_{jk} - V_{ki} + V_{ij})\right]^{1/2}\\ \sigma_k &= \left[\frac{1}{2}(V_{ki} - V_{ij} + V_{jk})\right]^{1/2}.\end{aligned} \tag{A14}$$

REFERENCES


Anderson, A., 2006: AirDat system for ensuring TAMDAR data quality. Preprints, *10th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface,* Atlanta, GA, Amer. Meteor. Soc., 9.3. [Available online at http://ams.confex.com/ams/pdfpapers/101342.pdf.]

Ballish, B. A., and K. V. Kumar, 2008: Systematic differences in aircraft and radiosonde temperatures. *Bull. Amer. Meteor. Soc.,* **89,** 1689–1707.

Barker, D. M., W. Huang, Y.-R. Guo, A. J. Bourgeois, and Q. N. Xiao, 2004: A three-dimensional variational data assimilation system for MM5: Implementation and initial results. *Mon. Wea. Rev.,* **132,** 897–914.

Benjamin, S. G., B. E. Schwartz, and R. E. Cole, 1999: Accuracy of ACARS wind and temperature observations determined by collocation. *Wea. Forecasting,* **14,** 1032–1038.

——, B. D. Jamison, W. R. Moninger, S. R. Sahm, B. E. Schwartz, and T. W. Schlatter, 2010: Relative short-range forecast impact from aircraft, profiler, radiosonde, VAD, GPS-PW, METAR, and mesonet observations via the RUC hourly assimilation cycle. *Mon. Wea. Rev.,* **138,** 1319–1343.

Brooks, H. E., and C. A. Doswell III, 1996: A comparison of measures-oriented and distributions-oriented approaches to forecast verification. *Wea. Forecasting,* **11,** 288–303.

Courtier, P., J.-N. Thépaut, and A. Hollingsworth, 1994: A strategy for operational implementation of 4D-Var, using an incremental approach. *Quart. J. Roy. Meteor. Soc.,* **120,** 1367–1387.

Daley, R., 1991: *Atmospheric Data Analysis.* Cambridge University Press, 457 pp.

Daniels, T. S., G. Tsoucalas, M. Anderson, D. Mulally, W. Moninger, and R. Mamrosh, 2004: Tropospheric Airborne Meteorological

Data Reporting (TAMDAR) sensor development. Preprints, *11th Conf. on Aviation, Range, and Aerospace Meteorology,* Hyannis, MA, Amer. Meteor. Soc., 7.6. [Available online at http://ams.confex.com/ams/pdfpapers/81841.pdf.]

——, W. R. Moninger, and R. D. Mamrosh, 2006: Tropospheric Airborne Meteorological Data Reporting (TAMDAR) overview. Preprints, *10th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface,* Atlanta, GA, Amer. Meteor. Soc., 9.1. [Available online at http://ams.confex.com/ams/pdfpapers/104773.pdf.]

Desroziers, G., and S. Ivanov, 2001: Diagnosis and adaptive tuning of information error parameters in a variational assimilation. *Quart. J. Roy. Meteor. Soc.,* **127,** 1433–1452.

——, L. Berre, B. Chapnik, and P. Poli, 2005: Diagnosis of observation, background and analysis error statistics. *Quart. J. Roy. Meteor. Soc.,* **131,** 3385–3396.

DiMego, G. J., K. E. Mitchell, R. A. Petersen, J. E. Hoke, J. P. Gerrity, J. J. Tuccillo, R. L. Wobus, and H.-M. Juang, 1992: Changes to NMC's Regional Analysis and Forecast System. *Wea. Forecasting,* **7,** 185–198.

Drüe, C., W. Frey, A. Hoff, and T. Hauf, 2008: Aircraft type-specific errors in AMDAR weather reports from commercial aircraft. *Quart. J. Roy. Meteor. Soc.,* **134,** 229–239.

Fischer, A., 2006: The use of TAMDAR (Tropospheric Airborne Meteorological Data Reporting) as a convective forecasting supplement in the northern plains and upper Midwest. Preprints, *10th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface,* Atlanta, GA, Amer. Meteor. Soc., 9.6. [Available online at http://ams.confex.com/ams/pdfpapers/104888.pdf.]

Hollingsworth, A., and P. Lönnberg, 1986: The statistical structure of short-range forecast errors as determined from radiosonde data. Part I: The wind field. *Tellus,* **38A,** 111–136.

Hong, S.-Y., Y. Noh, and J. Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev.,* **134,** 2318–2341.

Huang, X.-Y., 2009: The 2009 WRFDA overview. *Extended Abstracts, WMO Data Assimilation Symp.,* Melbourne, WMO. [Available online at http://www.cawcr.gov.au/staff/pxs/wmoda5/ExtendedAbstracts/Huang.pdf.]

Ide, K., P. Courtier, M. Ghil, and A. C. Lorenc, 1997: Unified notation for data assimilation: Operational, sequential and variational. *J. Meteor. Soc. Japan,* **75,** 181–189.

Jacobs, N., P. Childs, M. Croke, and Y. Liu, 2008: The effects of horizontal grid spacing and vertical resolution on TAMDAR data assimilation in short-range mesoscale forecasts. Preprints, *12th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface,* New Orleans, LA, Amer. Meteor. Soc., 15B.6. [Available online at http://ams.confex.com/ams/pdfpapers/132091.pdf.]

——, ——, ——, ——, and X. Y. Huang, 2010: An update on the TAMDAR sensor network deployment. Preprints, *14th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface,* Atlanta, GA, Amer. Meteor. Soc., 8.3. [Available online at http://ams.confex.com/ams/pdfpapers/164835.pdf.]

Kain, J. S., 2004: The Kain–Fritsch convective parameterization: An update. *J. Appl. Meteor.,* **43,** 170–181.

Liu, Y., and Coauthors, 2010: Evaluation of TAMDAR data impact on predicting warm-season convection using the NCAR-AirDat WRF-based RTFDDA system. Preprints, *14th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface,* Atlanta, GA, Amer. Meteor. Soc., 8.6. [Available online at http://ams.confex.com/ams/pdfpapers/165099.pdf.]

Lorenc, A. C., 1986: Analysis methods for numerical weather prediction. *Quart. J. Roy. Meteor. Soc.,* **112,** 1177–1194.

——, and Coauthors, 2000: The Met. Office global three-dimensional variational data assimilation scheme. *Quart. J. Roy. Meteor. Soc.,* **126,** 2991–3012.

Mamrosh, R. D., E. S. Brusky, J. K. Last, E. J. Szoke, W. R. Moninger, and T. S. Daniels, 2006: Applications of TAMDAR aircraft data reports in NWS forecast offices. Preprints, *14th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface,* Atlanta, GA, Amer. Meteor. Soc., 9.4. [Available online at http://ams.confex.com/ams/pdfpapers/104842.pdf.]

Miloshevich, L. M., H. Vömel, D. N. Whiteman, and T. Leblanc, 2009: Accuracy assessment and correction of Vaisala RS92 radiosonde water vapor measurements. *J. Geophys. Res.,* **114,** D11305, doi:10.1029/2008JD011565.

Moninger, W. R., R. D. Mamrosh, and P. M. Pauley, 2003: Automated meteorological reports from commercial aircraft. *Bull. Amer. Meteor. Soc.,* **84,** 203–216.

——, S. G. Benjamin, B. D. Jamison, T. W. Schlatter, T. L. Smith, and E. J. Szoke, 2010: Evaluation of regional aircraft observations using TAMDAR. *Wea. Forecasting,* **25,** 627–645.

Mulally, D., and A. Anderson, 2011: Correction of aircraft flux valve based heading for two-dimensional winds aloft calculations using weather model comparisons. Preprints, *15th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface,* Seattle, WA, Amer. Meteor. Soc., 5.6. [Available online at http://ams.confex.com/ams/91Annual/webprogram/Paper184928.html.]

O'Carroll, A. G., J. R. Eyre, and R. W. Saunders, 2008: Three-way error analysis between AATSR, AMSR-E, and in situ sea surface temperature observations. *J. Atmos. Oceanic Technol.,* **25,** 1197–1207.

Painting, D. J., 2003: AMDAR reference manual. WMO, 84 pp. [Available online at http://amdar.wmo.int/Publications/AMDAR_Reference_Manual_2003.pdf.]

Parrish, D. F., and J. C. Derber, 1992: The National Meteorological Center's spectral statistical-interpolation analysis system. *Mon. Wea. Rev.,* **120,** 1747–1763.

Richner, H., and P. D. Phillips, 1981: Reproducibility of VIZ radiosonde data and some sources of error. *J. Appl. Meteor.,* **20,** 954–962.

Schwartz, B. E., and S. G. Benjamin, 1995: A comparison of temperature and wind measurements from ACARS-equipped aircraft and rawinsondes. *Wea. Forecasting,* **10,** 528–544.

——, ——, S. M. Green, and M. R. Jardin, 2000: Accuracy of RUC-1 and RUC-2 wind and aircraft trajectory forecasts by comparison with ACARS observations. *Wea. Forecasting,* **15,** 313–326.

Seidel, D. J., B. Sun, M. Pettey, and A. Reale, 2011: Global radiosonde balloon drift statistics. *J. Geophys. Res.,* **116,** D07102, doi:10.1029/2010JD014891.

Skamarock, W. C., and Coauthors, 2008: A description of the Advanced Research WRF version 3. NCAR Tech. Note NCAR/TN-475+STR, 113 pp.

Smith, T. L., and S. G. Benjamin, 1994: Relative impact of data sources on a data assimilation system. Preprints, *10th Conf. on Numerical Weather Prediction,* Portland, OR, Amer. Meteor. Soc., 491–493.

Sullivan, J., L. Gandin, A. Gruber, and W. Baker, 1993: Observation error statistics for *NOAA-10* temperature and height retrievals. *Mon. Wea. Rev.*, **121,** 2578–2587.

Szoke, E., B. D. Jamison, W. R. Moninger, S. Benjamin, B. Schwartz, and T. L. Smith, 2006: Impact of TAMDAR on RUC forecasts: Case studies. Preprints, *10th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface,* Atlanta, GA, Amer. Meteor. Soc., 9.9. [Available online at http://ams.confex.com/ams/pdfpapers/104059.pdf.]

Wang, H., X.-Y. Huang, Y. Chen, X. Zhang, D. Stark, and P. Childs, 2009: The impact of TAMDAR observations on Hurricane Ike (2008) forecast using WRFDA system. *10th WRF Users' Workshop,* Boulder, CO, NCAR, P2A.6. [Available online at http://www.mmm.ucar.edu/wrf/users/workshops/WS2009/abstracts/P2A-06.pdf.]