Coastal Circulation and Water-Column Properties off Kalaupapa National Historical Park, Molokai, Hawaii, 2008–2010

By Curt D. Storlazzi, M. Katherine Presto, and Eric K. Brown

Aerial photograph of the Kalaupapa Peninsula on the north coast of Molokai, Hawaii, in 2006.

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Coastal Circulation and Water Column Properties off Kalaupapa National Historical Park, Molokai, Hawaii, 2008–2010

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Abstract

More than 2.2 million measurements of oceanographic forcing and the resulting water-column properties were made off U.S. National Park Service's Kalaupapa National Historical Park on the north shore of Molokai, Hawaii, between 2008 and 2010 to understand the role of oceanographic processes on the health and sustainability of the area's marine resources. The tides off the Kalaupapa Peninsula are mixed semidiurnal. The wave climate is dominated by two end-members: large northwest Pacific winter swell that directly impacts the study site, and smaller, shorter-period northeast trade-wind waves that have to refract around the peninsula, resulting in a more northerly direction before propagating over the study site. The currents primarily are alongshore and are faster at the surface than close to the seabed; large wave events, however, tend to drive flow in a more cross-shore orientation. The tidal currents flood to the north and ebb to the south. The waters off the peninsula appear to be a mix of cooler, more saline, deeper oceanic waters and shallow, warmer, lower-salinity nearshore waters, with intermittent injections of freshwater, generally during the winters. Overall, the turbidity levels were low, except during large wave events. The low overall turbidity levels and rapid return to pre-event background levels following the cessation of forcing suggest that there is little fine-grained material. Large wave events likely inhibit the settlement of fine-grained sediment at the site. A number of phenomena were observed that indicate the complexity of coastal circulation and water-column properties in the area and may help scientists and resource managers to better understand the implications of the processes on marine ecosystem health.

Introduction

Statement of the Problem

Oceanographic forces (tides, waves, and currents) and water-column properties (temperature, salinity, and turbidity) influence coastal and marine natural resources in all U.S. National Park Service (NPS) Pacific Island National Parks and also impact culturally significant resources for parks in the NPS Pacific Islands Network (PACN) that have marine boundaries. An understanding of oceanographic characteristics in nearshore park waters is critical to understanding ecosystem processes, such as larval transport, wave dynamics, and sedimentation that structure coral-reef ecosystems within park boundaries. This becomes especially relevant in the face of global climate change, as some parameters (for example, temperature) will be highly influential in shaping the marine resources within the park. Consequently, marine resource managers need baseline information on the spatial and temporal variability of these parameters. In particular, it is important to document the rate of change of such parameters, as these will dictate the timeliness of the management response.

Oceanographic data have been collected in Kalaupapa National Historical Park (KALA) in PACN since the summer of 2008, and these data represent a broad spectrum of environmental conditions that are likely to influence the coastal and marine resources. KALA staff, however, currently lack the necessary tools and expertise to analyze these data. The timely interpretation of these data is integral in the general management plan (GMP) that KALA currently is undertaking. Such analyses serve not only as a baseline to predict and measure the outcome of future conditions along the coastline, but also will be used to educate the public about factors influencing the coastal and marine natural and cultural resources during the GMP process.

Objective

The objective of this project was for U.S. Geological Survey (USGS) Pacific Coastal and Marine Science Center's (PCMSC) Coral Reef Project personnel to process, analyze, and provide interpretation of physical oceanographic data collected by NPS-KALA staff between the summer of 2008 and early spring of 2010. In addition, USGS-PCMSC personnel were to provide recommendations for instrument setup for future deployments.

Methods

USGS-PCMSC personnel have developed numerical analytical tools to process these types of oceanographic data (for example, Xu and others, 2002). Drawing on a decade of experience with the same oceanographic instruments, USGS-PCMSC Coral Reef Project staff have described the oceanographic characteristics of nearshore waters around the state of Hawaii and have published their results in peer-reviewed journals (for example, Storlazzi and Jaffe, 2008; Storlazzi, Ogston, and others, 2004; Storlazzi, McManus, and others, 2006; Storlazzi, Field, and others, 2009) and USGS peer-reviewed reports for NPS (Storlazzi and Presto, 2005; Storlazzi, Russell, and others, 2005; Storlazzi, Presto, and others, 2009). USGS-PCMSC personnel were to provide NPS-KALA staff with analysis and interpretation of the oceanographic data along the lines of previously published results, providing insight into variations in flow and water-column parameters owing to large wave events, tidal forcing, and seasonality of such forcing and water-column response. Furthermore, USGS-PCMSC Coral Reef Project staff also provided guidelines for future deployments of the different oceanographic sensors.

Instrumentation

NPS-KALA deployed three oceanographic instruments during each measurement period at 21.18962° N, 156.98666° W, approximately 300 m offshore of the town of Kalaupapa at a depth of 17 m (fig. 1), on the north coast of Molokai, Hawaii. These instruments included (1) an RD Instruments 1200 kHz Workhorse Monitor acoustic Doppler current profiler (ADCP) with

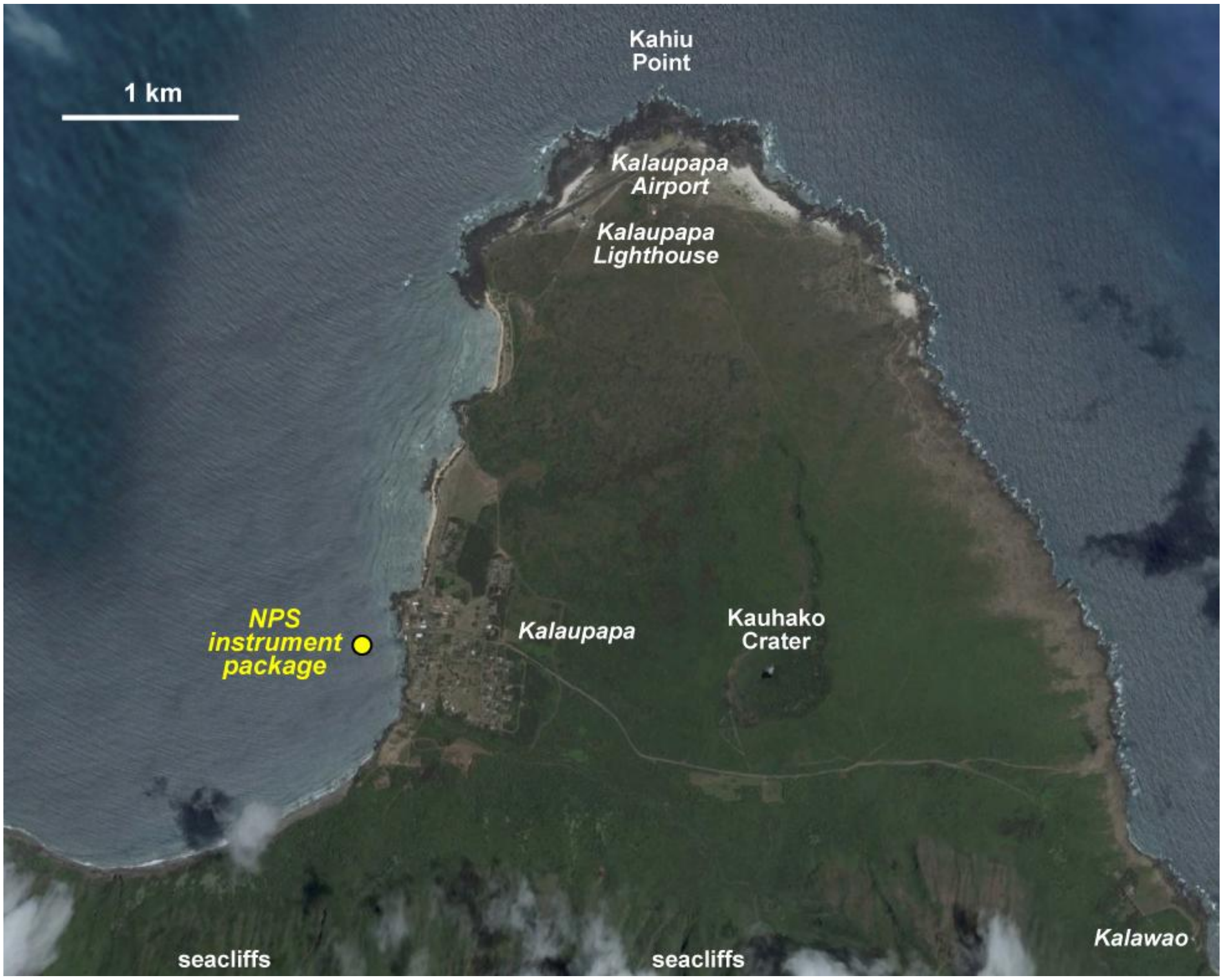

Figure 1. Aerial photograph of the Kalaupapa Peninsula on the north coast of Molokai, Hawaii, showing the location of the National Park Service oceanographic instrument package.

pressure sensor; (2) a SeaBird Microcat SBE-37SMP conductivity and temperature (CT) sensor; and (3) an Aquatec 210-TY logger with Seapoint 880-µm optical backscatter sensor (OBS), as shown in figure 2. The ADCP provided information on tides, waves, currents, and acoustic backscatter. The CT sensor obtained information on water temperature and conductivity, from which salinity was computed, and the OBS provided information on turbidity.

Data Quality

There were a few consistent issues with the ADCP data. The ADCP, a 1200 kHz unit, was deployed at a depth of approximately 17 m. The ADCP was set-up to measure current and acoustic-backscatter profiles in 49 0.5-m bins with approximately 50 pings per ensemble every 5 min and a 2400-sample wave burst at 2 Hz every hour. The excessive number of profile bins and low number of samples per burst resulted in two issues: (1) problems with the wave calculations; and (2) lower than possible resolution of currents. Owing to the large number of bins, the wave calculations were automatically pushed above the ocean surface because the RD Instruments

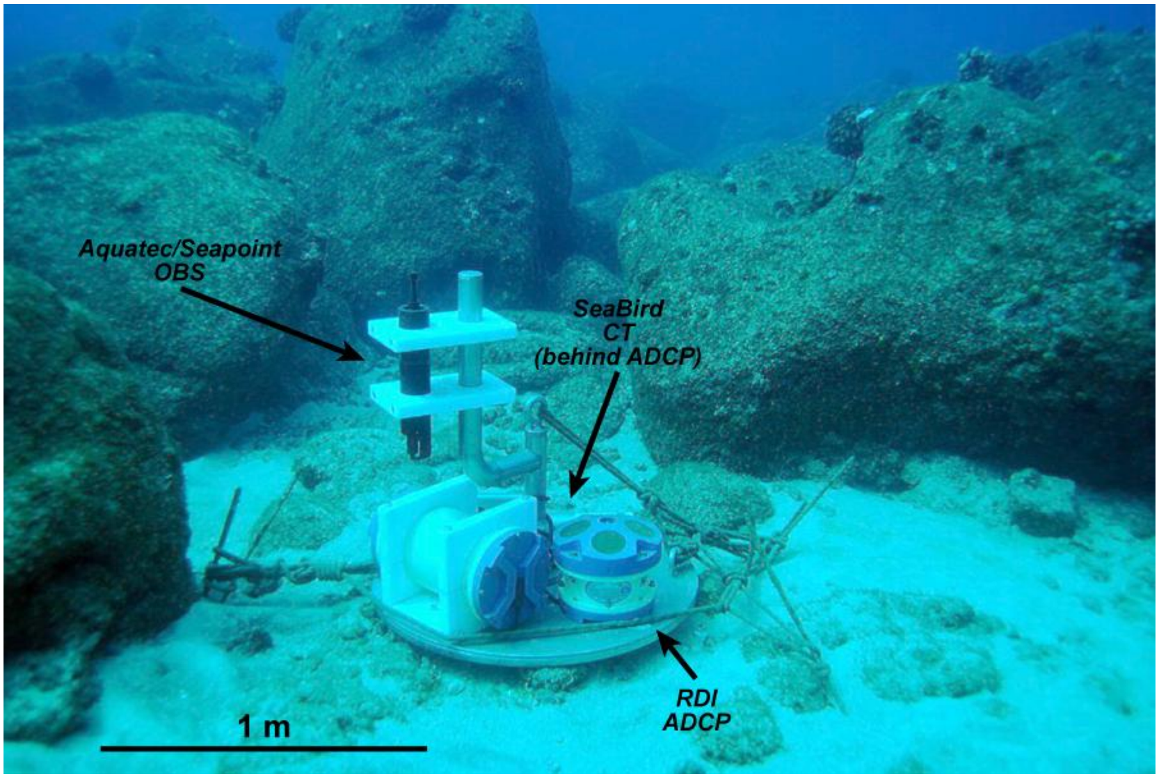

Figure 2. Underwater photograph of instrument package deployed at a depth of 17 m off the Kalaupapa Peninsula.

routines search for bins with good data to use to calculate the wave parameters within a set number of bins from the last bin. The engineers at RD Instruments diagnosed this problem and re-ran the raw data through their WAVES processing software by using valid bins below the ocean surface and thus were able to extract valid wave data. This deployment set-up, using a large number (49) of small (0.5 m) bins in relatively deep (17 m) water for the frequency of the instrument (1200 kHz) resulted in low (<1 cm/s) resolution of the current velocity and thus the resulting speeds and directions. This put the instrument's resolution on order of the average current speeds (1-9 cm/s).

Another problem encountered with the ADCP was the collection of sediment under the pressure sensor's protective cover during the course of multiple deployments, which was not removed during refurbishment before redeployment. This caused errors in the measurements of water depth and resulting wave calculations. Lastly, during one deployment the ADCP was aligned on its mount such that one of the beams was blocked by part of the instrument package, rendering the data from the one beam useless. The RD Instruments engineers rectified this issue by removing the blocked beam's data from the processing routines. The quality of the OBS data was reduced owing to biofouling of the instrument's optics, which commonly happens in warm, clear tropical waters. This issue has hampered numerous USGS-PCMSC studies in the past and resulted in only 5-10 days of high-quality turbidity data for this study before growth on the optics degraded the data. The CT data were of high quality throughout all of the deployments.

Results and Discussion

NPS-KALA staff provided USGS-PCMSC Coral Reef Project personnel with 12 data sets from the three different oceanographic instruments that covered four time periods – two summers and two winters. The four time periods were July-October 2008 (2008 Year Days 198-273), December 2008-February 2009 (2008 Year Days 346-415), August-October 2009 (2009 Year Days 225-282), and December 2009-February 2010 (2009 Year Days 350-419).

Tides

The tides off KALA are mixed, semidiurnal with two uneven high tides and two uneven low tides per day; thus the tides change just over every 6 hours (fig. 3). The mean daily tidal range is roughly 0.6 m, while the minimum and maximum daily tidal ranges are 0.4 m and 0.9 m, respectively.

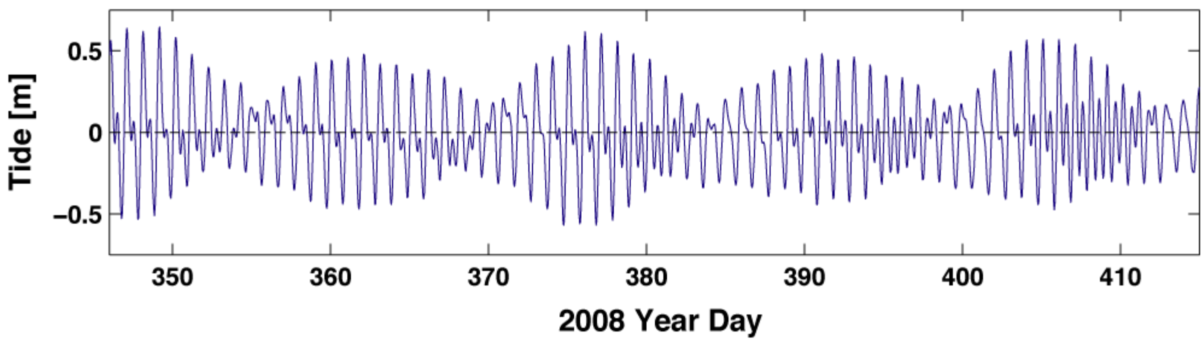

Figure 3. Time-series plot of tidal height, in meters, during the 2008 winter showing the semidiurnal nature of the tides. This time period encompassed five spring-neap tidal cycles.

Waves

The significant wave heights measured off KALA were, on average, almost three times larger and more variable during the two winters than during the two summers (0.38±0.15 m and 1.00±0.47 m, respectively; table 1); they ranged from 0.12-1.41 m during the two summers to 0.25-3.46 m during the two winters (fig. 4; table 1; appendix 1). The dominant wave periods were, on average, almost 3 s longer during the two winters than during the two summers, with little difference in the variability (6.8±2.0 s and 9.7±2.0 s, respectively; table 1); they ranged from 3.1-13.6 s during the two summers to 4.5-16.9 s during the two winters. The mean wave directions during the two summers were slightly more northerly (301±34°) than during the two winters (290±39°). Together, these data show the influence of the two main sources of waves along KALA: (1) larger, longer-period north Pacific winter swell out of the northwest; and (2) shorter, smaller northeast trade-wind waves that refract around the Kalaupapa Peninsula and approach the instrument site from a more northerly direction than the less-refracted north Pacific swell.

Currents

The mean current speeds ± one standard deviation during the two summers were 0.00±0.02 m/s close to the surface and 0.00±0.01 m/s close to the seabed and 0.02±0.05 m/s close to the surface and 0.03±0.03 m/s close to the seabed during the two winters (fig. 5; table 2; appendix 2). The mean current directions ± one standard deviation during the two summers were 35±111° close to the surface and 63±99° close to the seabed; during the two winters they were 62±102° close to the surface and 67±99° to the seabed. These differences in current speeds and

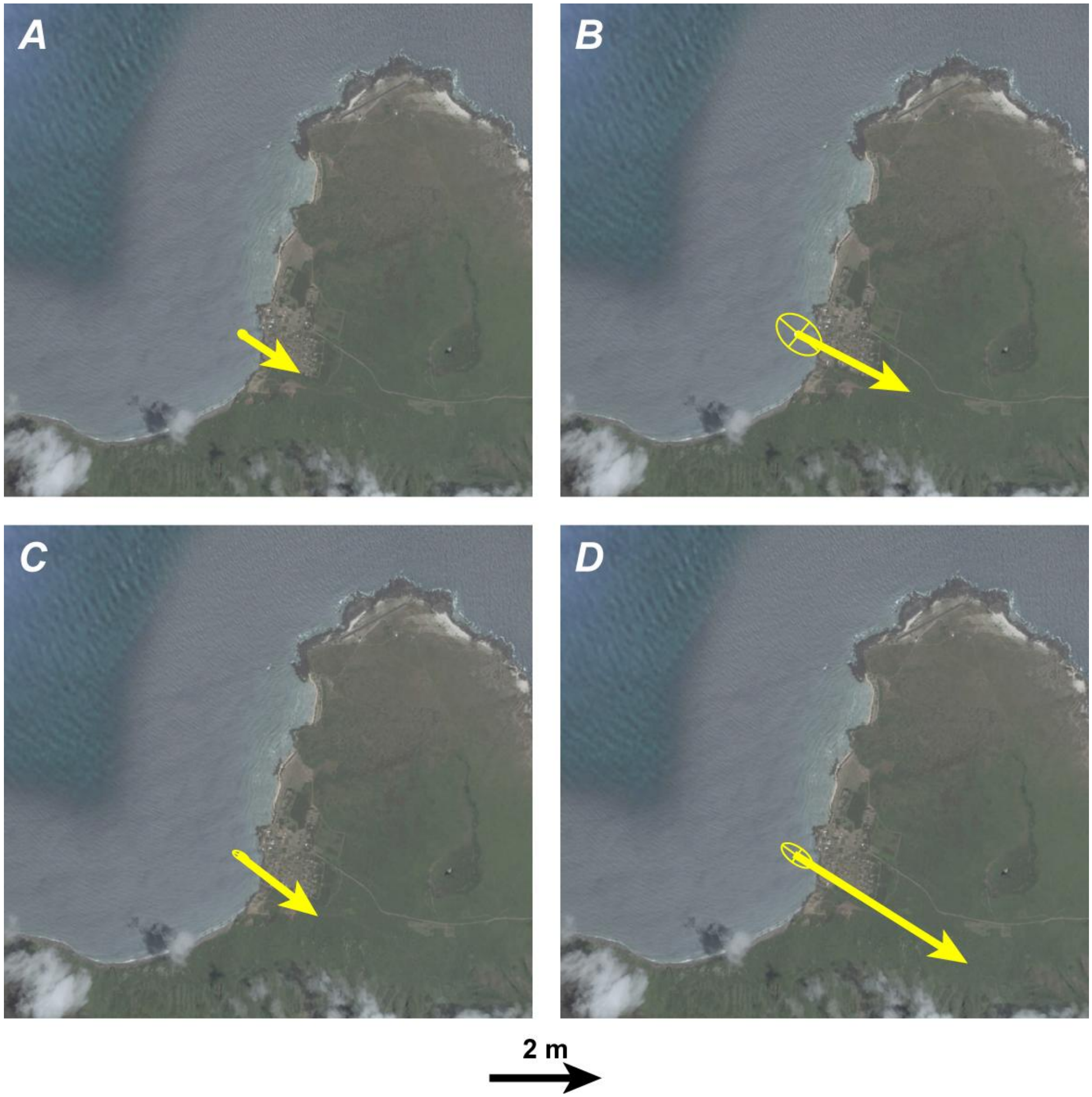

Figure 4. Maps showing the mean (thick vectors) and variability (thin ellipses) in wave heights and directions, in meters from true north, for the different seasons. *A*, 2008 summer. *B*, 2008-2009 winter. *C*, 2009 summer. *D*, 2009-2010 winter. A 2-m vector length is shown for scale.

directions with depth cause velocity shear, and they result in differing directions of material (for example, larvae, sediment, nutrients, and contaminants) flux at different heights above the seabed. Flow primarily was alongshore close to the surface and more cross-shore near the seabed, possibly owing to wave-driven flows. Tidal currents flooded to the north and ebbed to the south, with the near-surface tidal currents faster than those close to the seabed (fig. 6a-b). During large wave events, the near-surface flow primarily was downcoast to the southwest, likely driven by wave-breaking along the shoreline to the north of the instrument package (fig. 6c). Close to the seabed, the currents primarily were onshore during large wave events (fig. 6d),

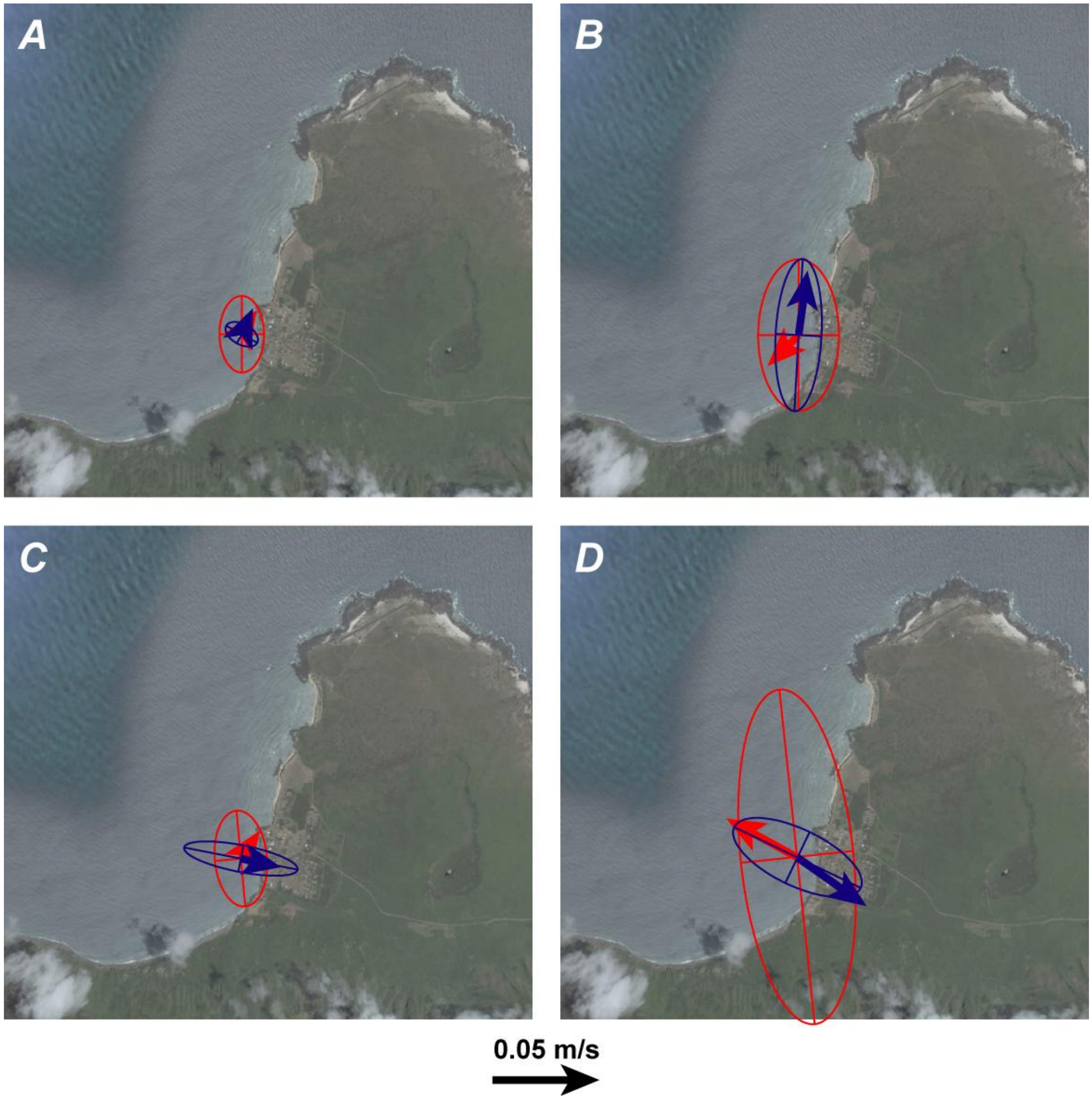

Figure 5. Maps showing the mean (thick vectors) and variability (thin ellipses) in current speeds and directions, in meters from true north, for the different seasons. *A*, 2008 summer. *B*, 2008-2009 winter. *C*, 2009 summer. *D*, 2009-2010 winter. Red denotes near-surface currents; blue denotes near-bed currents. A 0.05-m/s vector length is shown for scale.

possibly owing to wave shoaling over the hydraulically rough boulders and corals in the area (fig. 2).

Temperature

Water temperatures off the peninsula ranged from 22.25 to 26.54°C, with a mean temperature ± one standard deviation of 25.54±0.35°C during the two summers and 23.76±0.53°C during the two winters (table 3; appendix 3). Water temperatures generally rose

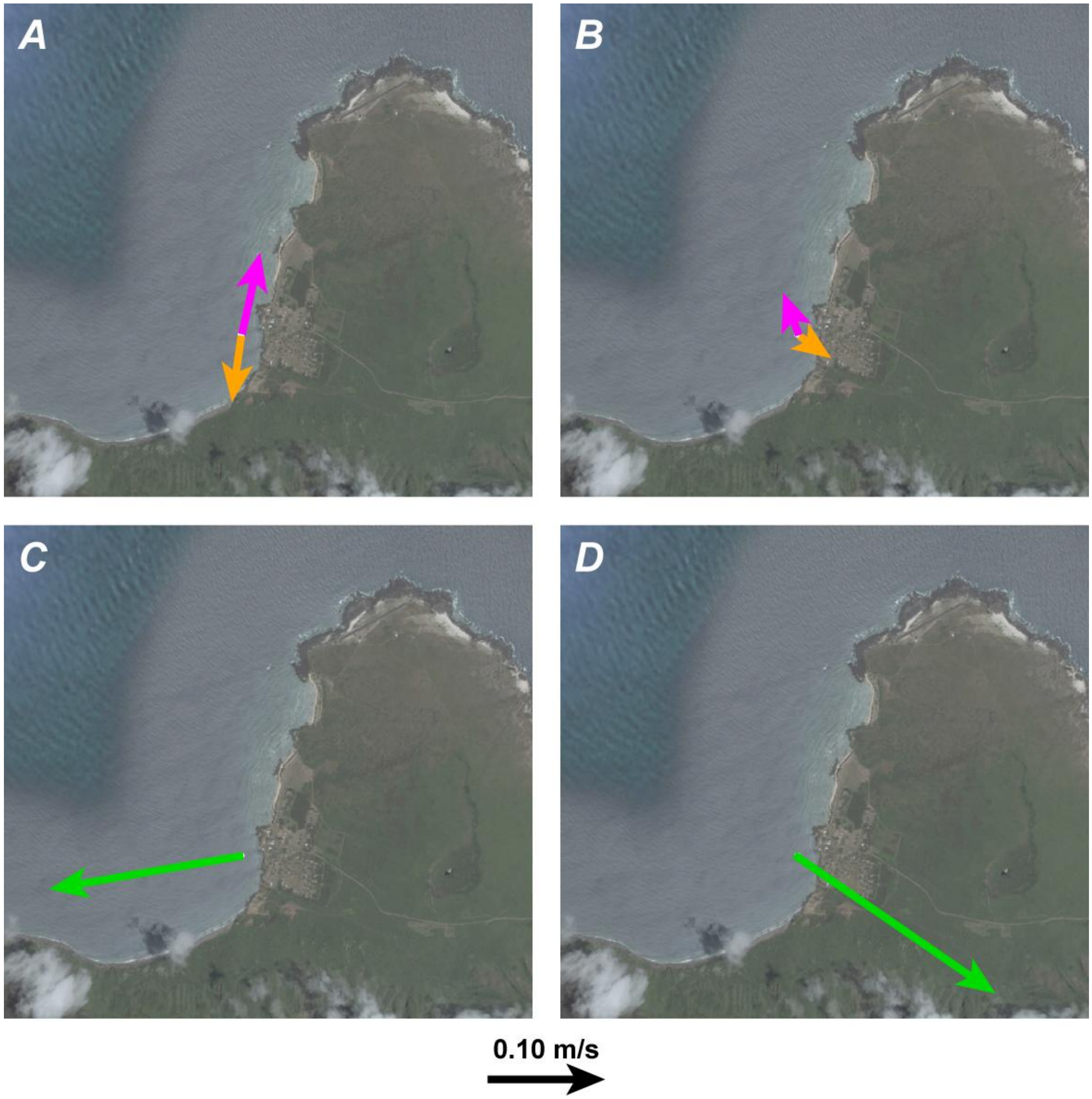

Figure 6. Maps showing the relative magnitude and direction of currents during different forcing conditions. *A*, Near-surface tidal currents, in meters per second from true north. Magenta is flood tide and orange is ebb tide. *B*, Near-bed tidal currents, in meters per second from true north. Magenta is flood tide and orange is ebb tide. *C*, Near-surface currents during a large wave event (January 2009), in meters per second from true north. *D*, Near-bed currents during a large wave event (January 2009), in meters per second from true north. A 0.10-m/s vector length is shown for scale.

0.2°C during the day, owing to insolation, and cooled during the night (fig. 7). The seasonal trend shows fairly constant temperatures throughout the summer, with slight warming towards the end of the deployments (appendix 3.1, 3.3). The decreasing temperature trend during the winters shows less warming because of insolation, and the larger variations may be the result of increased water column mixing from the large wave events during this season (appendix 3.2,

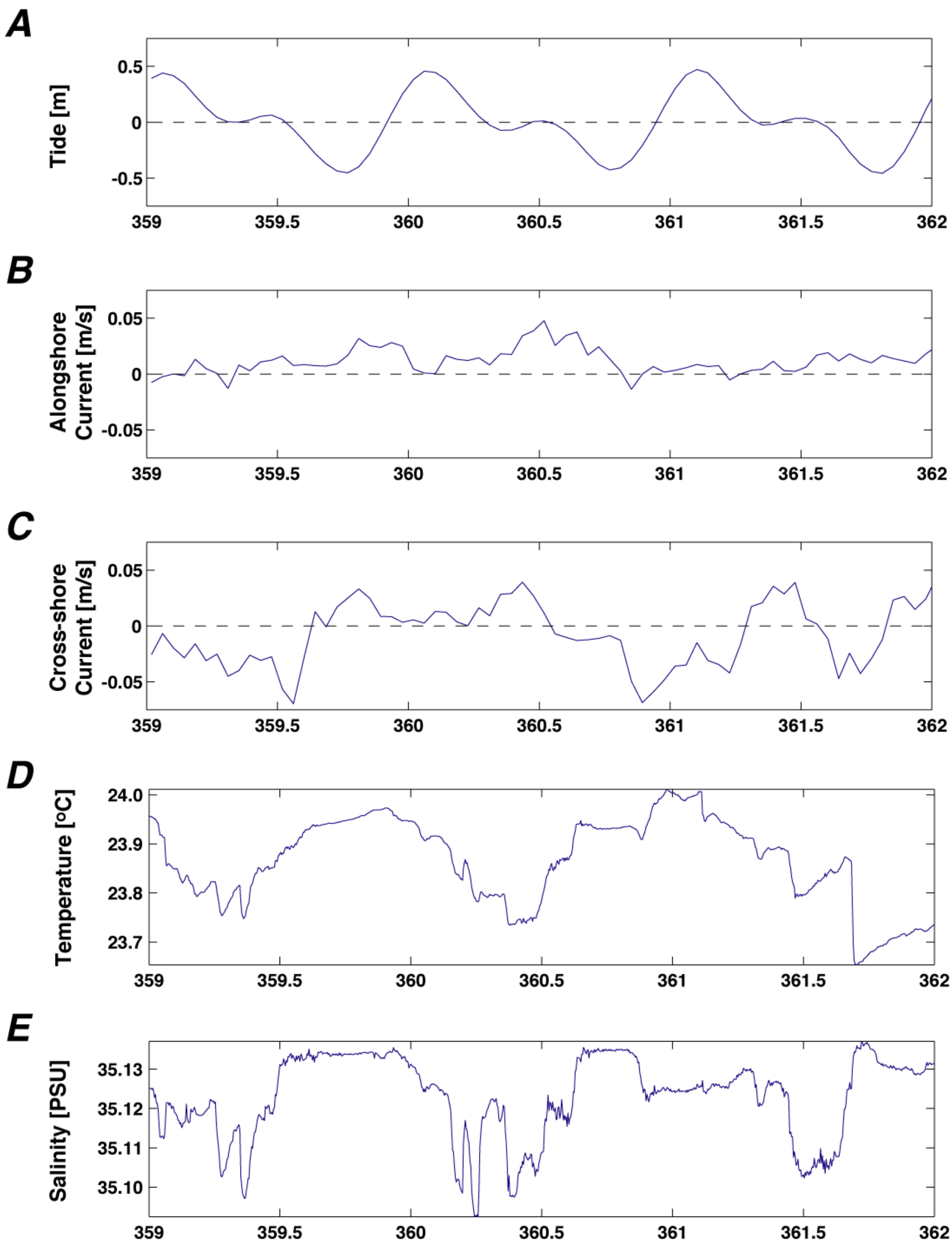

Figure 7. Time-series plots showing the relationships between tides, currents, water temperature, and salinity. *A*, Tidal height, in meters. *B*, Cross-shore current velocities, in meters per second. *C*, Alongshore current velocities, in meters per second. *D*, Water temperature, in degrees Celsius. *E*, Salinity, in Practical Salinity Units (PSU).

3.4). Water temperature generally decreased during ebb tides because cooler water close to shore was advected to the south by the falling tide (fig. 7).

Salinity

Salinity measurements off the peninsula ranged from 34.94 to 35.35 PSU, with a mean salinity ± one standard deviation of 35.16±0.07 PSU during the two summers and 35.12±0.05 PSU during the two winters (table 4; appendix 3). Salinity generally rose during flood tides because more saline offshore water was advected onshore and to the north by the rising tide (fig. 7). The greatest variability in temperature and salinity occurs during higher low tide. There seems to be a depletion of nearshore waters by the time the lower low tide occurs. In addition, the shallow water of the lower low tide allows for higher insolation and greater influence from higher salinity water offshore. The seasonal trend in salinity during the summer deployments shows fairly constant salinity with little overall variation (<0.3 PSU; appendix 3.1). The small perturbations in the salinity signal may be the result of internal waves, as discussed further below. The seasonal trend during winter deployments also shows fairly constant salinity with decreases (~0.2 to 0.5 PSU) during rainfall/storm events (appendix 3.2 and 3.4)

The co-variation of temp and salinity show the two main controls on variations in salinity at the study site (fig. 8). The trend between low temperature–high salinity and high temperature–low salinity shows the mixing of what appears to be cooler, more saline, deeper oceanic waters and shallow, warmer, lower-salinity nearshore waters. The large variation in salinity at a constant temperature of approximately 24.8°C appears to be the result of an influx of freshwater, either from adjacent streams or submarine groundwater discharge, close to the site around 2008 Year Day 350 (appendix 3.2).

The high-frequency (order of 10s of min) concurrent variations in both temperature and salinity, which can be seen throughout the two summer periods and between large wave events during the two winters (appendix 3), appear to be caused by the propagation of high-frequency internal waves past the instrument site. Similar motions have been observed along shallow reefs elsewhere in Hawaii (Storlazzi and Presto, 2005; Storlazzi and Jaffe, 2008) and the western Pacific (Storlazzi, Presto, and others, 2009) and may be important for coral reef ecosystem health.

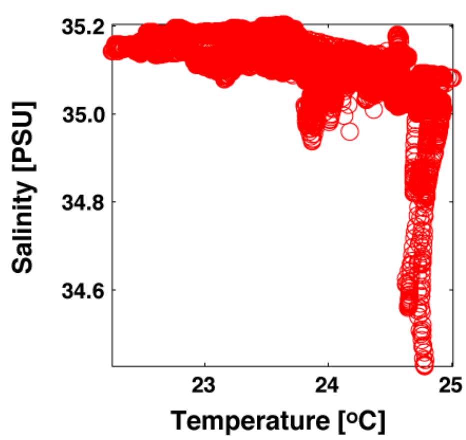

Figure 8. Scatter plot showing the relationship between water temperature, in degrees Celsius, and salinity, in Practical Salinity Units (PSU).

Turbidity

High-resolution turbidity data free from the effects of biofouling were only available from approximately the first 5-10 days of each deployment (appendix 4). During the short time period when the OBS's optics were clear, the turbidity in the study area ranged from 0.13 to 116.48 NTU, with a mean turbidity ± one standard deviation of 0.33±0.12 NTU (table 5) during the summer deployments and a mean turbidity ± one standard deviation of 0.95±3.03 NTU during the winter deployments (table 5).

Although the turbidity records were limited in length, the influence of large waves on turbidity was evident in the 2008-2009 winter dataset (fig. 9). When the wave height exceeded approximately 0.8 m at the study site, turbidity was above baseline levels (<1 NTU), with instantaneous turbidity levels exceeding 5 NTUs. The turbidity levels returned to background levels within hours when the wave height dropped below 0.8 m. The low overall turbidity levels during this large wave event, in conjunction with the rapid return to pre-event background levels following the cessation of forcing, suggest either that currents rapidly advected the material away from the study site, or more likely, that fine-grained material is absent at the site owing to the exposure to large wave events that inhibit the settlement of fine-grained sediment.

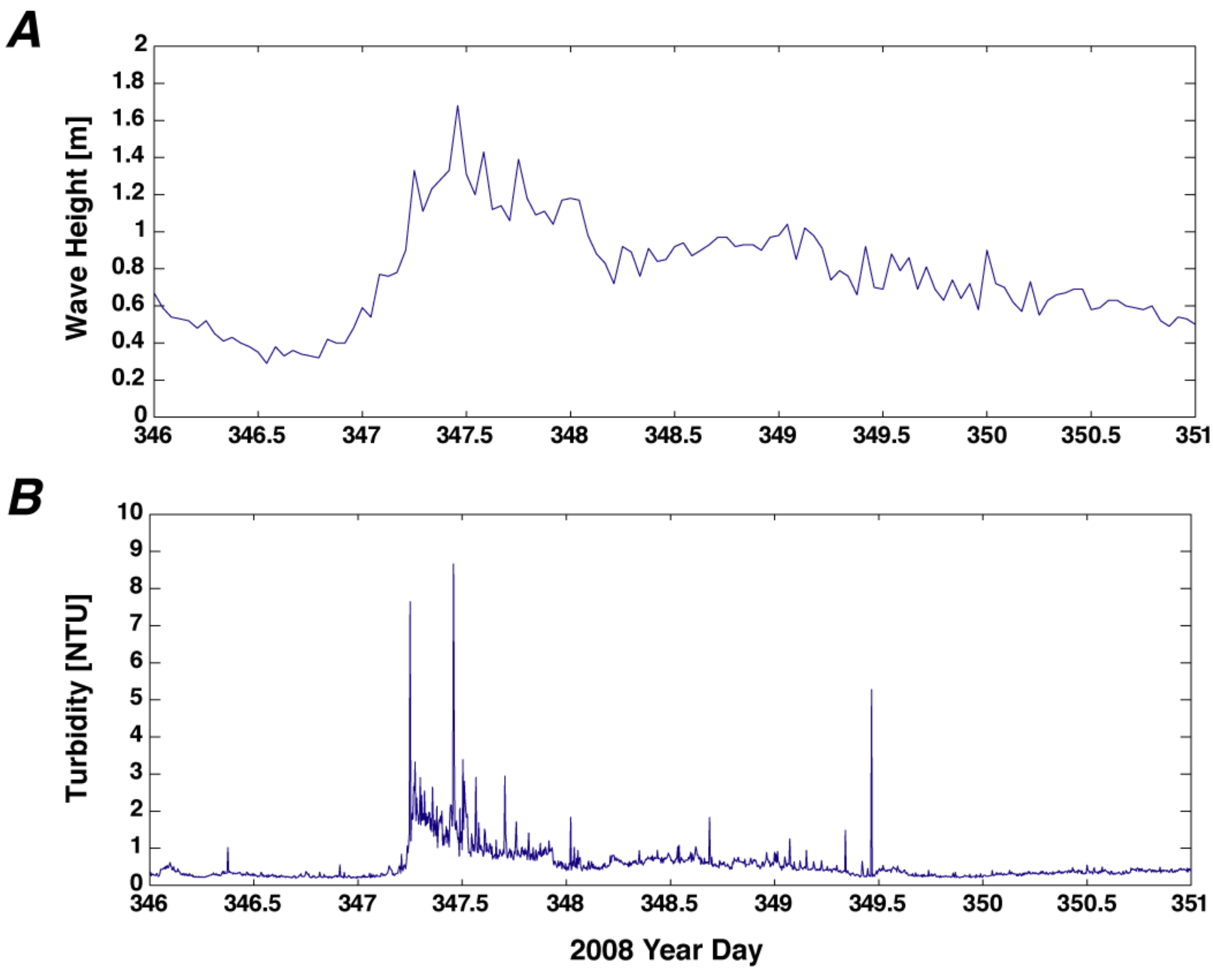

Figure 9. Time-series plots showing the relationship between wave height and turbidity during early December 2008. *A*, Wave height, in meters. *B*, Turbidity, in National Turbidity Units (NTU).

Another wave event during the winter of 2009-2010 also demonstrated the lack of available fine-grained sediment at the study site (fig. 10). The large increases in turbidity occurred once the wave heights reached 1.5 m, and only during sustained large wave heights (>2 m) did the elevation in turbidity increase to more than 10 NTU. During this time the turbidity values were highly variable, indicating that the sediment probably was sand-sized or coarser with high settling velocities that required greater sheer stresses (wave-orbital velocities) to keep the sediment in suspension. The quick return (order of hours) to pre-event turbidity levels also suggests that the sediment in suspension was coarser-grained material that settled rapidly following the cessation of forcing.

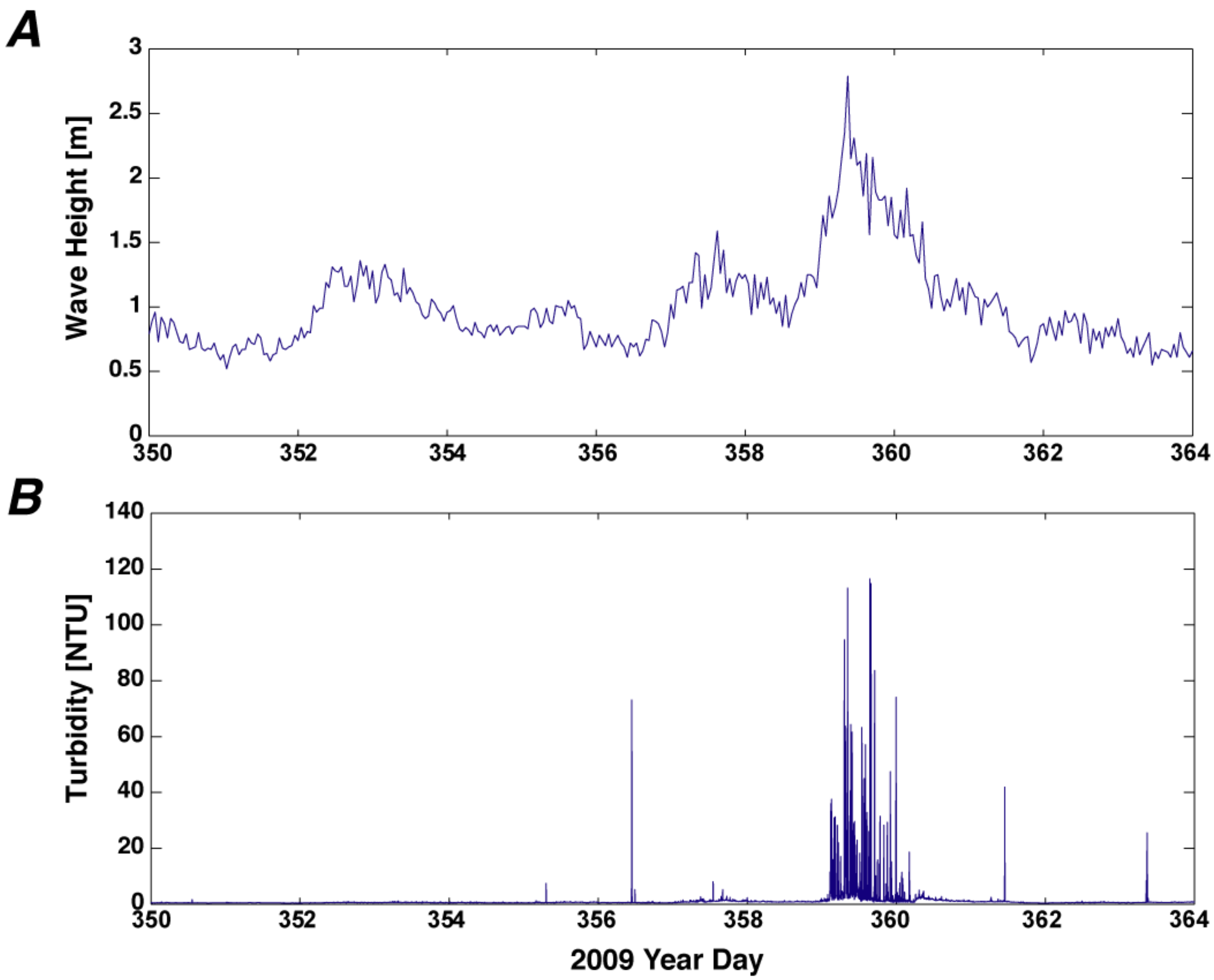

Figure 10. Time-series plots showing the relationship between wave height and turbidity during early December 2009. *A*, Wave height, in meters. *B*, Turbidity, in National Turbidity Units (NTU).

The State of Hawaii Department of Health's Administrative Rules, Title 11, Chapter 54, Water Quality Standards for "open ocean out to 600 foot depth", as defined on page 54-44 of that report (Department of Health, 2004), sets the maximum allowable "dry" and "wet" mean turbidity levels at 0.20 and 0.50 NTU, respectively. The mean turbidity values for the 4 periods of study exceeded the dry threshold, and the mean turbidity values during the 2008-2009 and 2009-2010 winters exceeded the wet threshold (table 5).

Conclusions

More than 2.2 million measurements of oceanographic forcing and the resulting water-column properties were made off KALA between 2008 and 2010. Key findings from these measurements and analyses include the following:

(1) The tides are mixed, semidiurnal, with a mean daily tidal range of 0.6 m and minimum and maximum daily tidal range of 0.4 m and 0.9 m, respectively.

(2) The wave climate is dominated by two end-members: large northwest Pacific winter swell that directly impacts the study site, and smaller, shorter-period northeast trade-wind waves that have to refract around the peninsula resulting in a more northerly direction before propagating over the study site.

(3) The currents primarily are alongshore and are faster at the surface then close to the seabed; large wave events, however, tend to drive flow in a more cross-shore orientation. The tidal currents flood to the north and ebb to the south. Velocity shear throughout the water column result in different directions of material (for example, larvae, sediment, nutrients, and contaminants) flux at different heights above the seabed.

(4) The waters appear to be a mix of cooler, more saline, deeper oceanic waters and shallow, warmer, lower-salinity nearshore waters, with intermittent injections of freshwater, generally during the winters. During the summers, high-frequency internal waves appear to have propagated past the instrument site; these may be important for coral-reef ecosystem health by advecting deep, cool, more nutrient-rich waters up into the warm, oligotrophic surface waters.

(5) Overall, the turbidity levels were low, except during large wave events. The low overall turbidity levels and rapid return to pre-event background levels following the cessation of forcing suggest that there is little fine-grained material at the site owing to winnowing by large wave events.

These data provide information on the nature and controls on flow and water-column properties off the Kalaupapa Peninsula, Molokai. A number of phenomena were observed that indicate the complexity of coastal circulation and water-column properties in the area and may help scientists and resource managers to better understand the implications of the processes on coral-reef ecosystem health.

Recommendations

Per the NPS-USGS Interagency Agreement, we are providing a few recommendations for future NPS instrument deployments.

(1) The RD Instruments ADCP should be set up differently based on the water depth and current speeds at the study site. Because of the high frequency (1200 kHz) of the instrument, the bin size should be increased to 1 m, and the number of pings per ensemble should be increased to 100 to provide better resolution of the current measurements. These changes will make the measurement error on the order of the observed current speeds. If continued deployments are desired, a better option would be to switch with one of the other NPS-PACN parks to deploy a RDI 600 kHz ADCP, which is better suited for deployment at a depth of 14 m. See appendix 5 for suggested deployment parameters for the NPS RD Instruments ADCP.

(2) There were no detectable issues with the SeaBird Microcat's deployment scheme. As requested, we did provide suggested deployment parameters in appendix 6, which are similar to the existing ones used by NPS.

(3) The Aquatec/Seapoint OBS should be set up differently to take advantage of the burst-sampling mode of the instrument; this will increase the resolution of the resulting data. See appendix 7 for suggested deployment parameters for the NPS Aquatec/Seapoint OBS. The rapid biofouling of the instrument's optics, however, needs to be addressed in order to provide long-term, high-quality measurements to determine how turbidity at KALA compares to State of Hawaii water-quality standards. The biofouling can be minimized by frequent cleaning of the instrument's optics, which can be accomplished by two potential methods: scuba diver or mechanical wiper. Because the OBS's optics off KALA frequently fouled within 5-10 days, 8-16 scuba dives would be required to clean the optics by hand during a 3-month deployment; this would be difficult in the wintertime when large waves would likely make these operations dangerous. The other option, a mechanical wiper, comes at a high initial cost (~$1500), but most run on common alkaline AA batteries and can wipe twice per day for up 6 months. USGS PCMSC staff have dealt with similar issues and determined that for their studies, mechanical wipers, such as ZebraTech's Hydro-Wipers (*http://www.zebra-tech.co.nz/Hydro-Wiper*), were the most cost-efficient long-term solution.

Acknowledgments

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For more information on the U.S. Geological Survey's Pacific Coastal and Marine Science Center's Coral Reef Project, please see:
http://coralreefs.wr.usgs.gov/

Direct Contact Information

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Table 1. Wave Statistics.

Wave direction is "From".

Time (Year Days)	Parameter	Mean ± 1 Std Deviation	Minimum	Maximum
Summer 2008 (198-273)	Height [m]	0.30±0.10	0.12	0.76
	Period [s]	6.3±1.5	3.5	12.3
	Direction [^{o}]	297±40	0	356
Winter 2008-2009 (346-415)	Height [m]	0.82 ±0.48	0.25	2.92
	Period [s]	8.9±2.0	3.7	15.5
	Direction [^{o}]	277±65	1	358
Summer 2009 (225-282)	Height [m]	0.47±0.20	0.17	1.41
	Period [s]	7.3±2.4	2.7	14.8
	Direction [^{o}]	305±29	1	358
Winter 2009-2010 (350-419)	Height [m]	1.17±0.46	0.17	3.46
	Period [s]	10.5±1.9	5.2	18.2
	Direction [^{o}]	302±13	7	359

Table 2. Current Statistics.

Current direction is "Going to".
N.S. = Near-surface observation.
N.B. = Near-seabed observation.

Time (Year Days)	Parameter	Depth [m]	Mean ± 1 Std Deviation	Minimum	Maximum
Summer 2008 (198-273)	Speed [m/s]	2.0 (N.S.)	0.00±0.01	0.00	0.10
	Direction [^{o}]	2.0 (N.S.)	36±109	0	359
	Speed [m/s]	15.5 (N.B.)	0.00±0.01	0.00	0.05
	Direction [^{o}]	15.5 (N.B.)	25±105	0	359
Winter 2008-2009 (346-415)	Speed [m/s]	2.0 (N.S.)	0.01±0.03	0.00	0.22
	Direction [^{o}]	2.0 (N.S.)	225±102	0	359
	Speed [m/s]	15.5 (N.B.)	0.02±0.03	0.00	0.20
	Direction [^{o}]	15.5 (N.B.)	8±130	0	359
Summer 2009 (225-282)	Speed [m/s]	2.0 (N.S.)	0.00±0.02	0.00	0.10
	Direction [^{o}]	2.0 (N.S.)	35±114	0	359
	Speed [m/s]	15.5 (N.B.)	0.01±0.02	0.00	0.15
	Direction [^{o}]	15.5 (N.B.)	102±92	0	359
Winter 2009-2010 (350-419)	Speed [m/s]	2.0 (N.S.)	0.03±0.07	0.00	0.45
	Direction [^{o}]	2.0 (N.S.)	299±101	0	359
	Speed [m/s]	15.5 (N.B.)	0.04±0.03	0.00	0.20
	Direction [^{o}]	15.5 (N.B.)	125±68	0	359

Table 3. Temperature Statistics.

Time (Year Days)	Mean ± 1 Std Deviation [^{o}C]	Minimum [^{o}C]	Maximum [^{o}C]
Summer 2008 (198-273)	25.38±0.32	24.51	26.54
Winter 2008-2009 (346-415)	23.80±0.56	22.25	25.01
Summer 2009 (225-282)	25.71±0.38	24.32	26.50
Winter 2009-2010 (350-419)	23.72±0.51	22.25	24.93

Table 4. Salinity Statistics.

Time (Year Days)	Mean ± 1 Std Deviation [PSU]	Minimum [PSU]	Maximum [PSU]
Summer 2008 (198-273)	35.112±0.089	34.953	35.258
Winter 2008-2009 (346-415)	35.113±0.059	34.427	35.203
Summer 2009 (225-282)	35.20±0.07	35.08	35.35
Winter 2009-2010 (350-415)	35.12±0.04	34.94	35.20

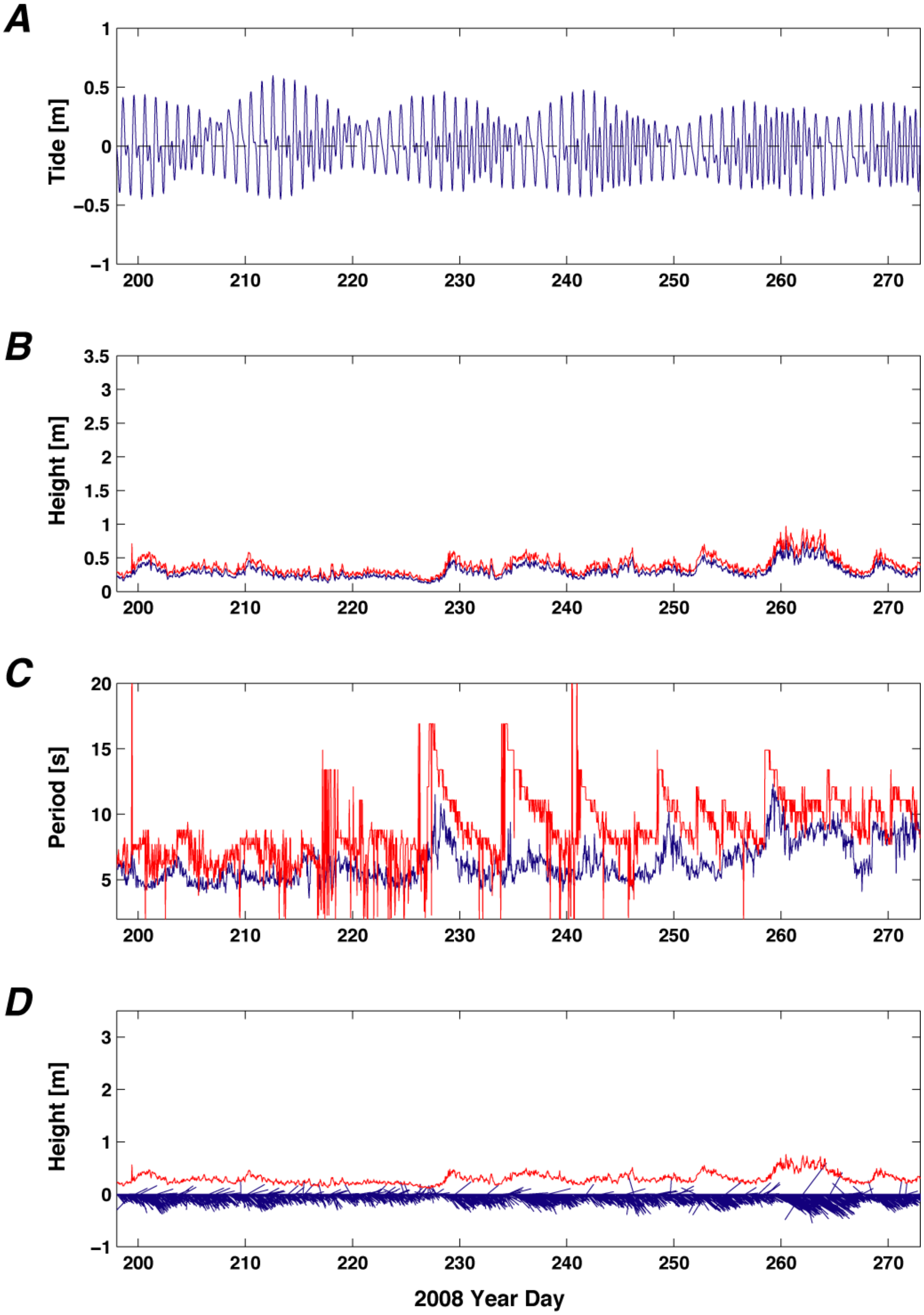
Table 5. Turbidity Statistics.

Time (Year Days)	Mean ± 1 Std Deviation [NTU]	Minimum [NTU]	Maximum [NTU]
Summer 2008* (198-205)	0.32±0.10	0.24	1.00
Winter 2008-2009* (346-351)	0.55±0.51	0.19	8.66
Summer 2009* (225-230)	0.33±0.14	0.13	1.24
Winter 2009-2010* (350-363)	1.35±5.55	0.35	116.48

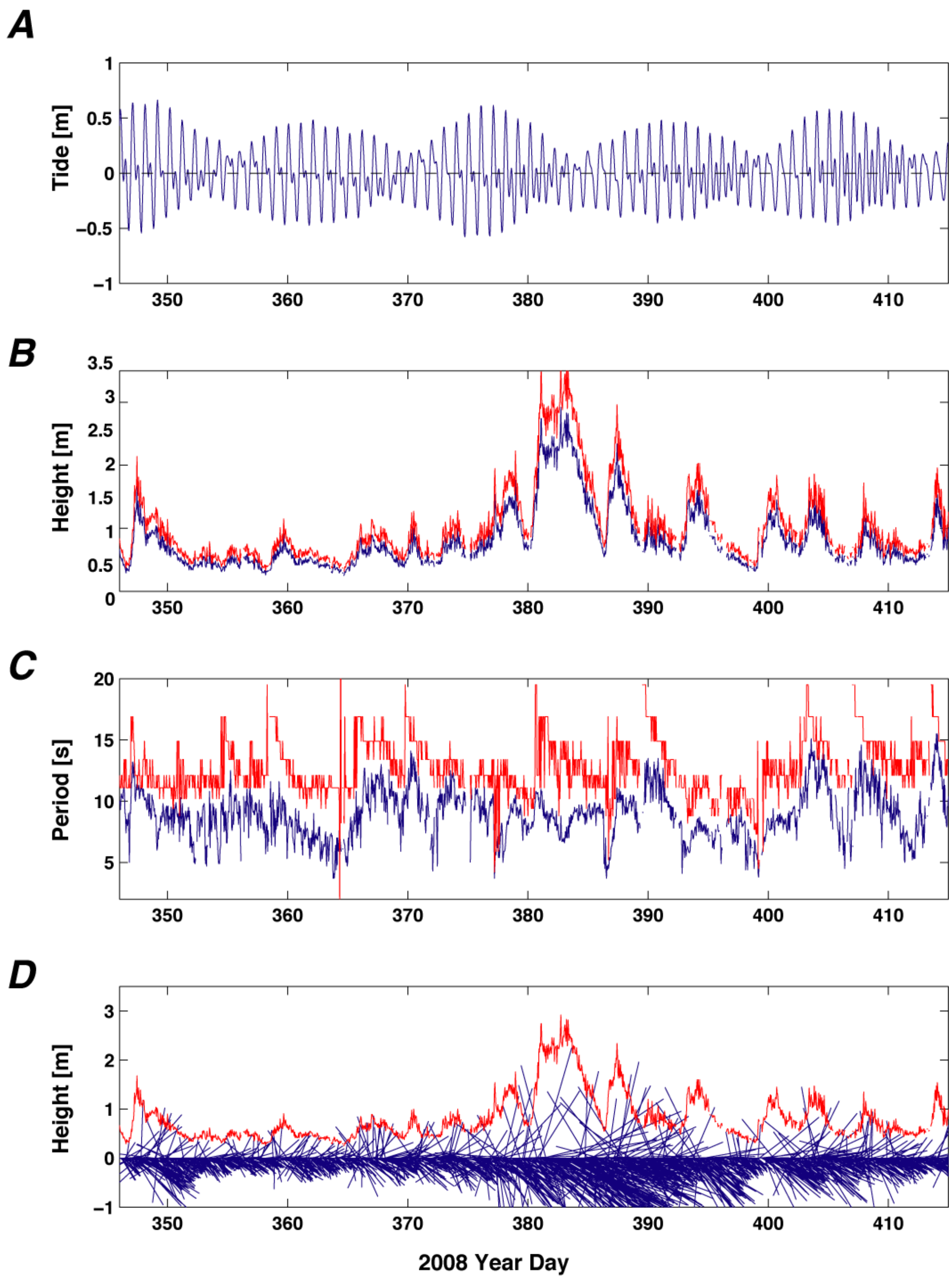
*Statistics are for short time periods owing to biofouling of the sensor's optics.

Appendixes

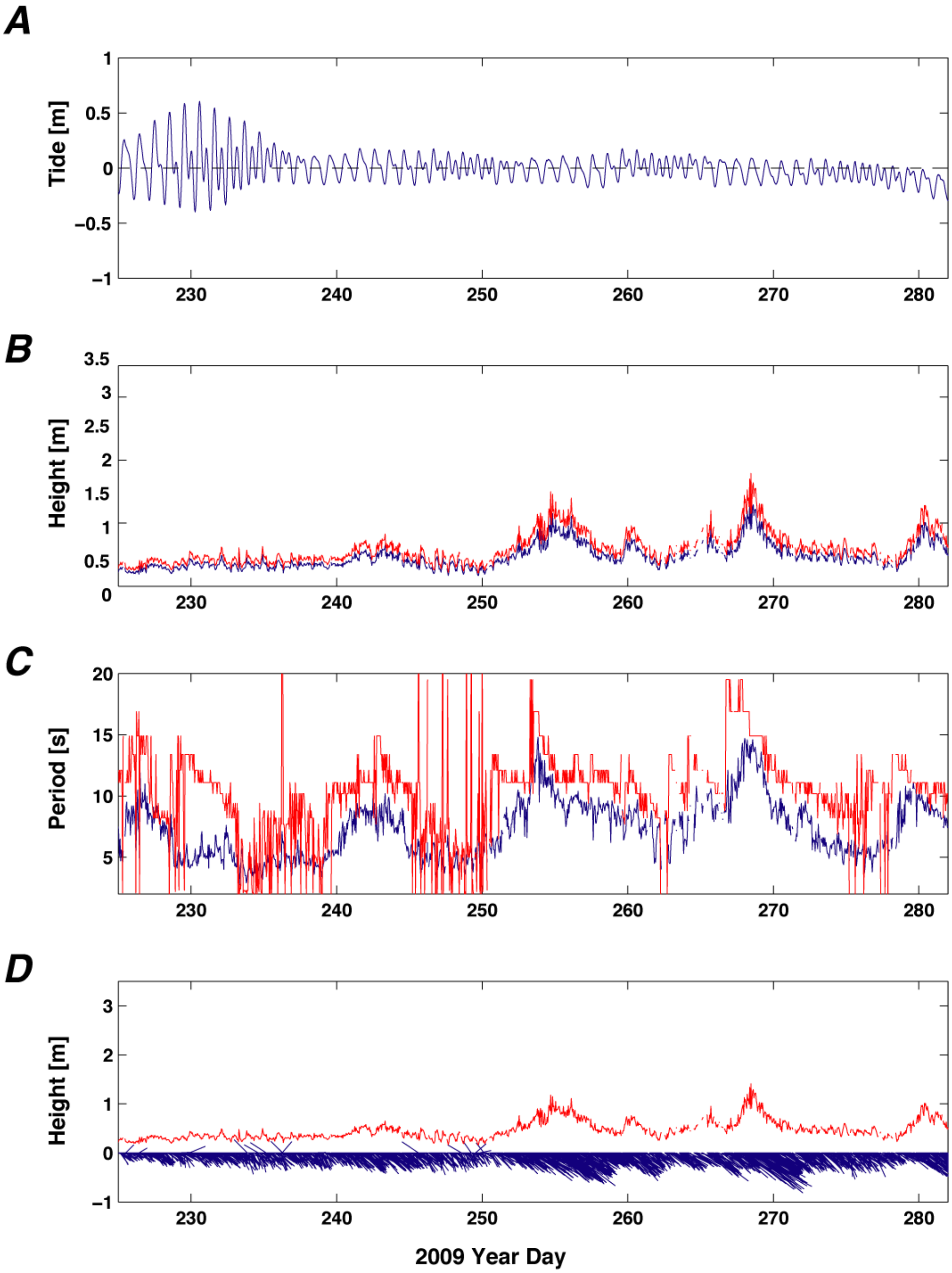
Appendix 1. Time series plots of variations in water level and wave heights, periods, and directions through time from the acoustic Doppler current profiler (ADCP).



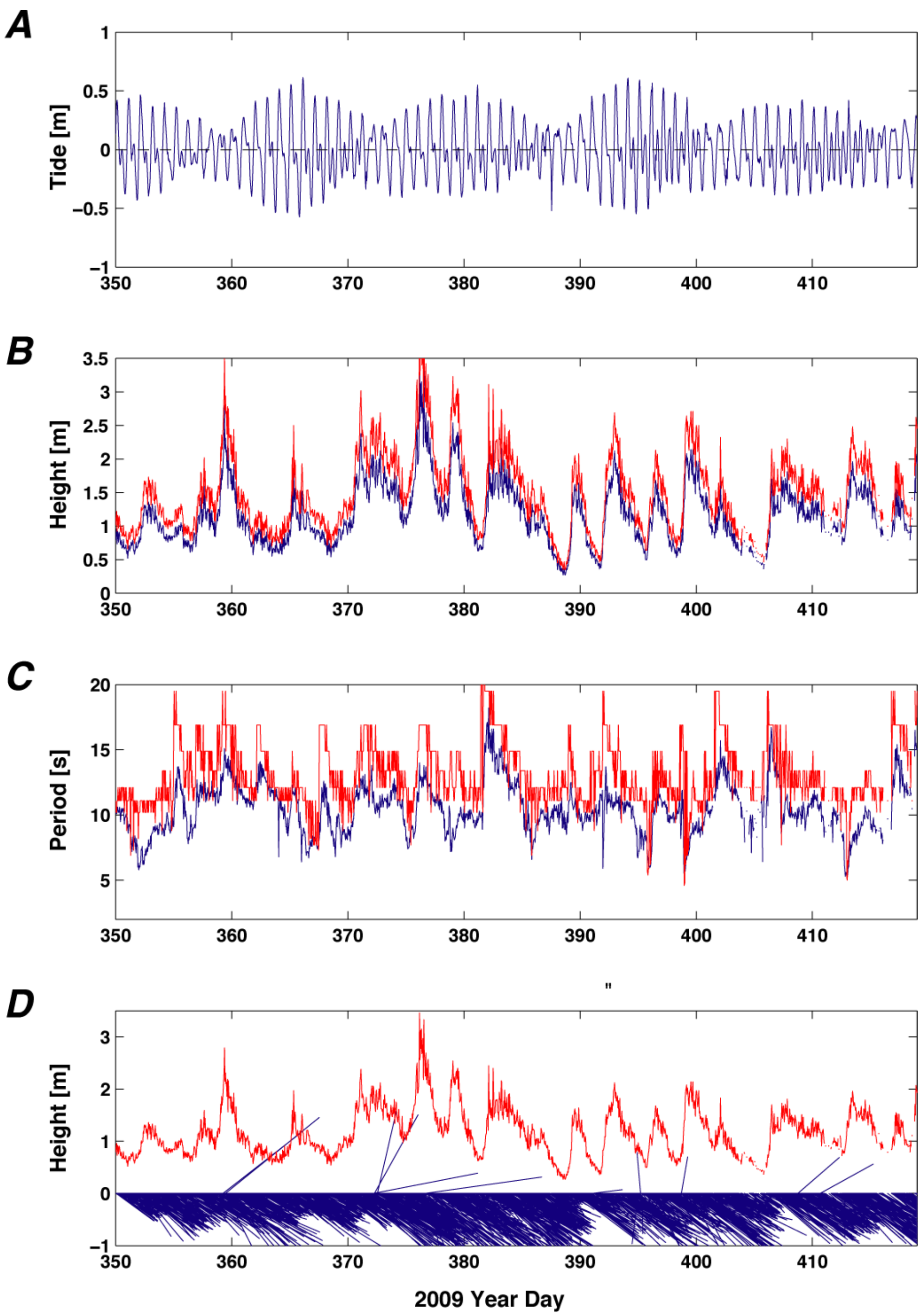
Appendix 1.1. Tide and wave data for the 2008 summer from the ADCP. *A*, Tidal height, in meters. *B*, Wave height, in meters, with significant wave height in blue and maximum wave height in red. *C*, Wave period, in seconds, with mean wave period in blue and peak wave period in red. *D*, Wave height, in meters, in red and wave height and direction, in meters from true north, in blue.



Appendix 1.2. Tide and wave data for the 2008-2009 winter from the ADCP. *A*, Tidal height, in meters. *B*, Wave height, in meters, with significant wave height in blue and maximum wave height in red. *C*, Wave period, in seconds, with mean wave period in blue and peak wave period in red. *D*, Wave height, in meters, in red and wave height and direction, in meters from true north, in blue.

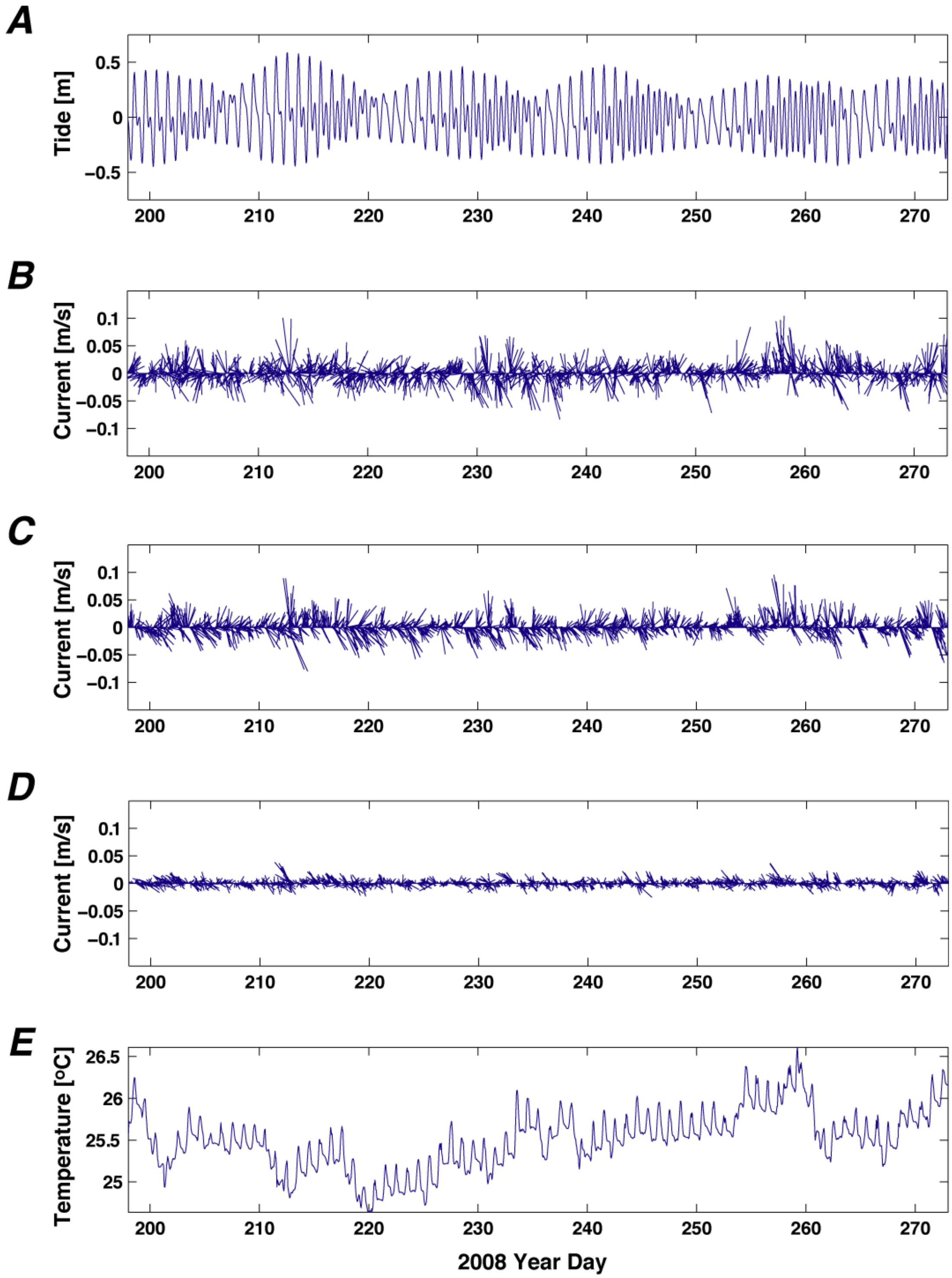


Appendix 1.3. Tide and wave data for the 2009 summer from the ADCP. *A*, Tidal height, in meters. *B*, Wave height, in meters, with significant wave height in blue and maximum wave height in red. *C*, Wave period, in seconds, with mean wave period in blue and peak wave period in red. *D*, Wave height, in meters, in red and wave height and direction, in meters from true north, in blue. The odd pressure signal was likely caused by material (for example, sediment) stuck in the pressure sensor.

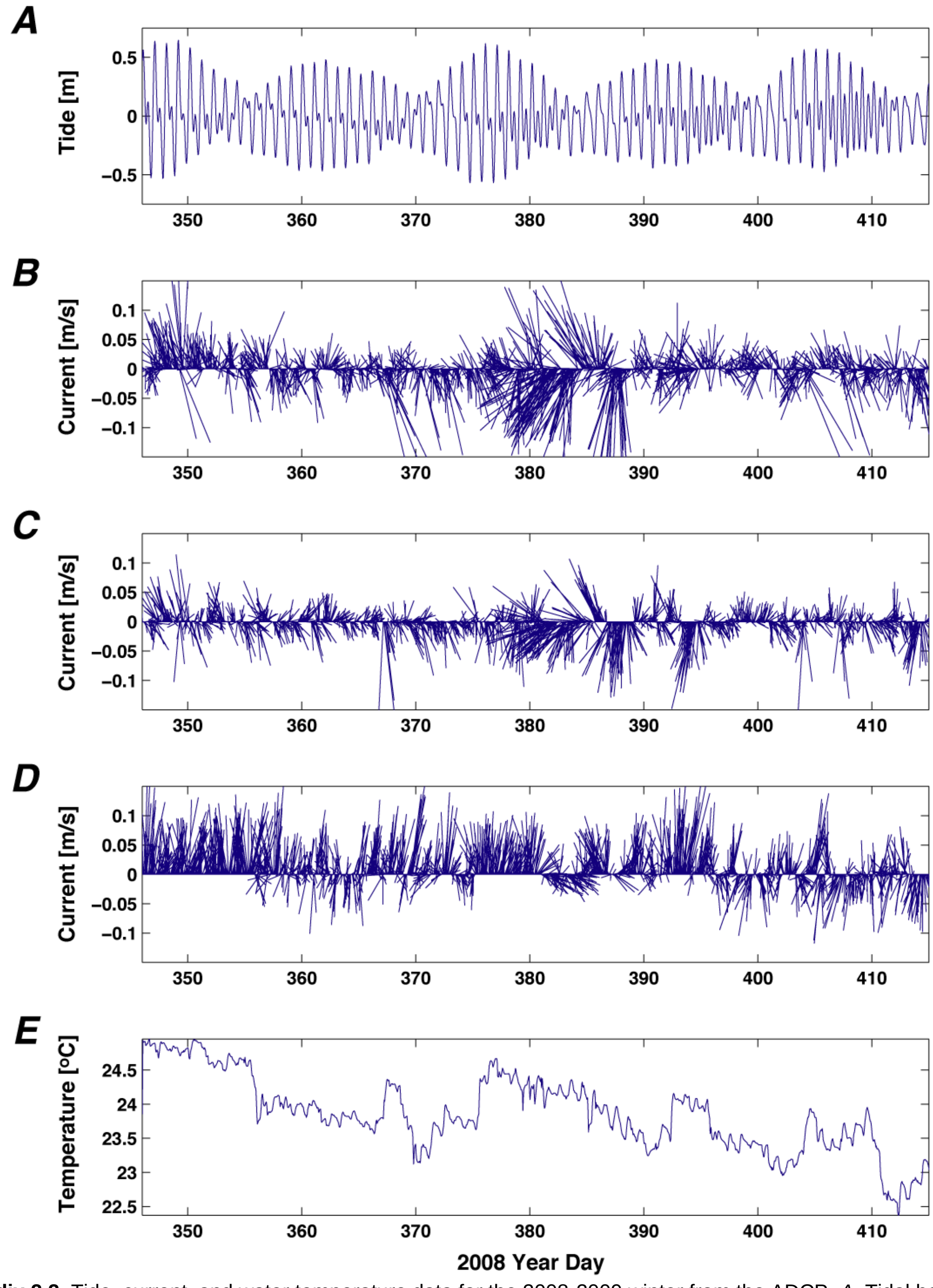


Appendix 1.4. Tide and wave data for the 2009-2010 winter from the ADCP. *A*, Tidal height, in meters. *B*, Wave height, in meters, with significant wave height in blue and maximum wave height in red. *C*, Wave period, in seconds, with mean wave period in blue and peak wave period in red. *D*, Wave height, in meters, in red and wave height and direction, in meters from true north, in blue.

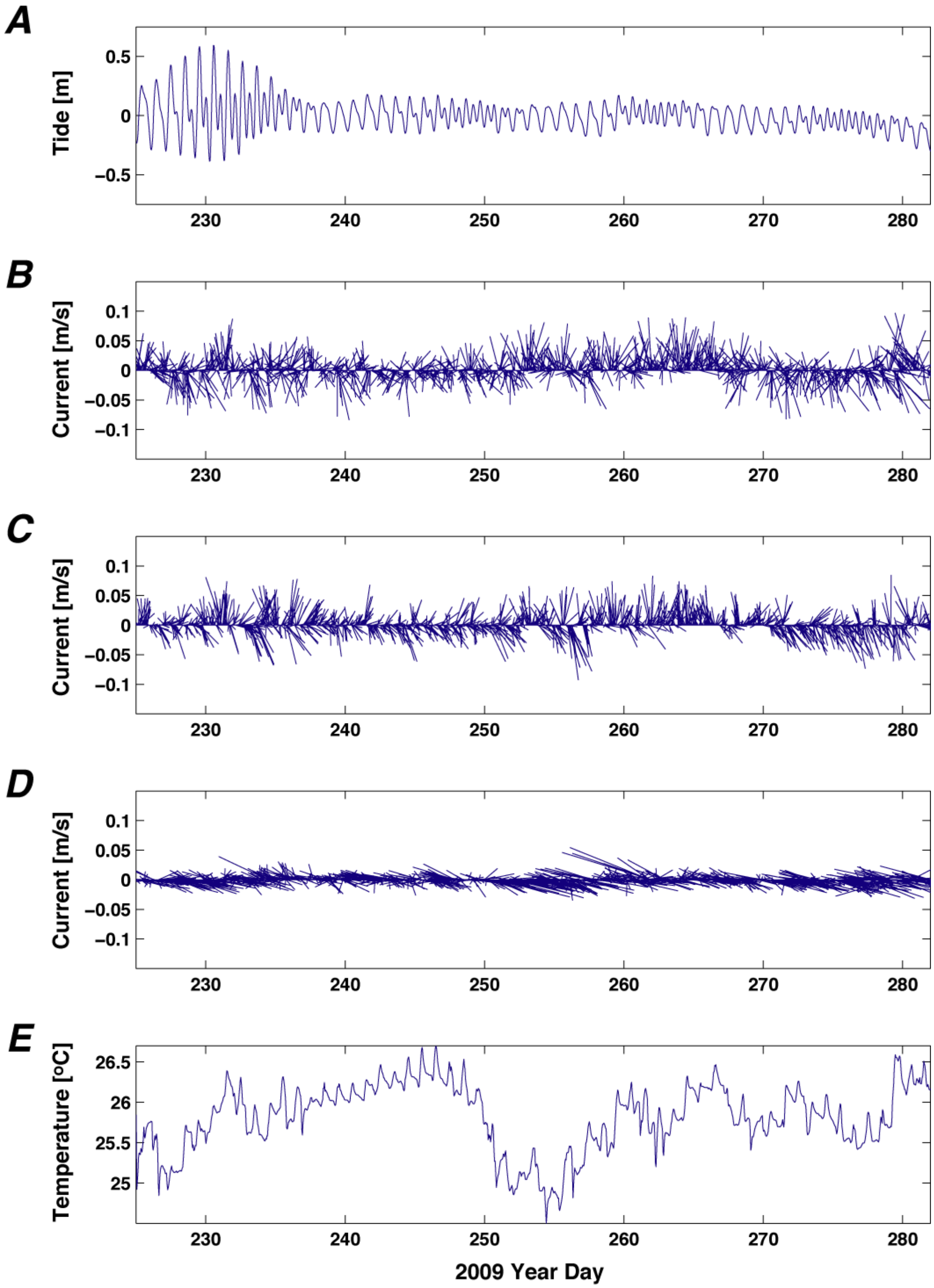
Appendix 2. Time series plots of variations in water level, currents, and temperature through time from the acoustic Doppler current profiler (ADCP).



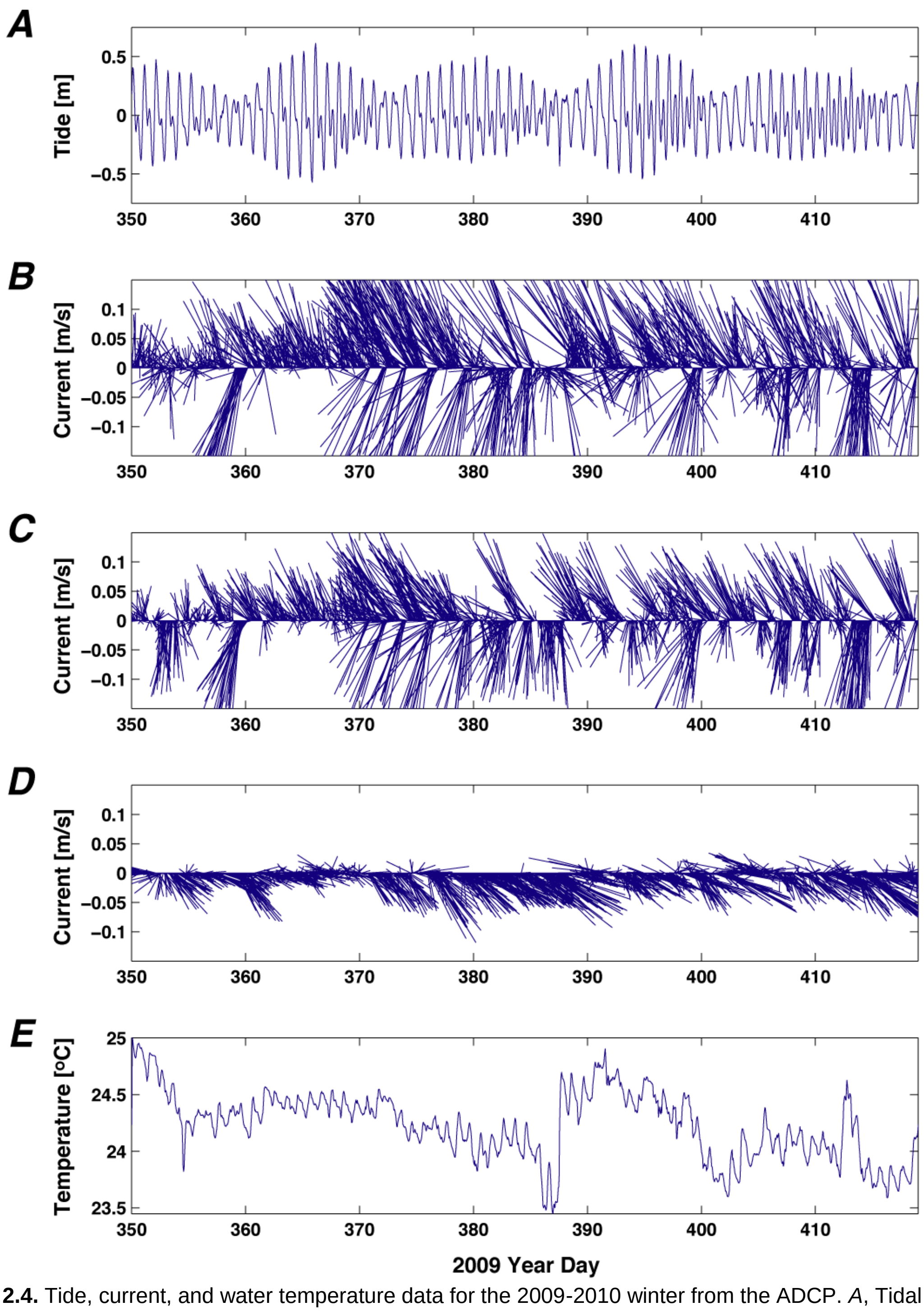
Appendix 2.1. Tide, current, and water temperature data for the 2008 summer from the ADCP. *A*, Tidal height, in meters. *B*, Near-surface current speeds and directions, in meters per second from true north. *C*, Mid-depth current speeds and directions, in meters per second from true north. *D*, Near-bed current speeds and directions, in meters per second from true north. *E*, Water temperature, in degrees Celsius.



Appendix 2.2. Tide, current, and water temperature data for the 2008-2009 winter from the ADCP. *A*, Tidal height, in meters. *B*, Near-surface current speeds and directions, in meters per second from true north. *C*, Mid-depth current speeds and directions, in meters per second from true north. *D*, Near-bed current speeds and directions, in meters per second from true north. *E*, Water temperature, in degrees Celsius.

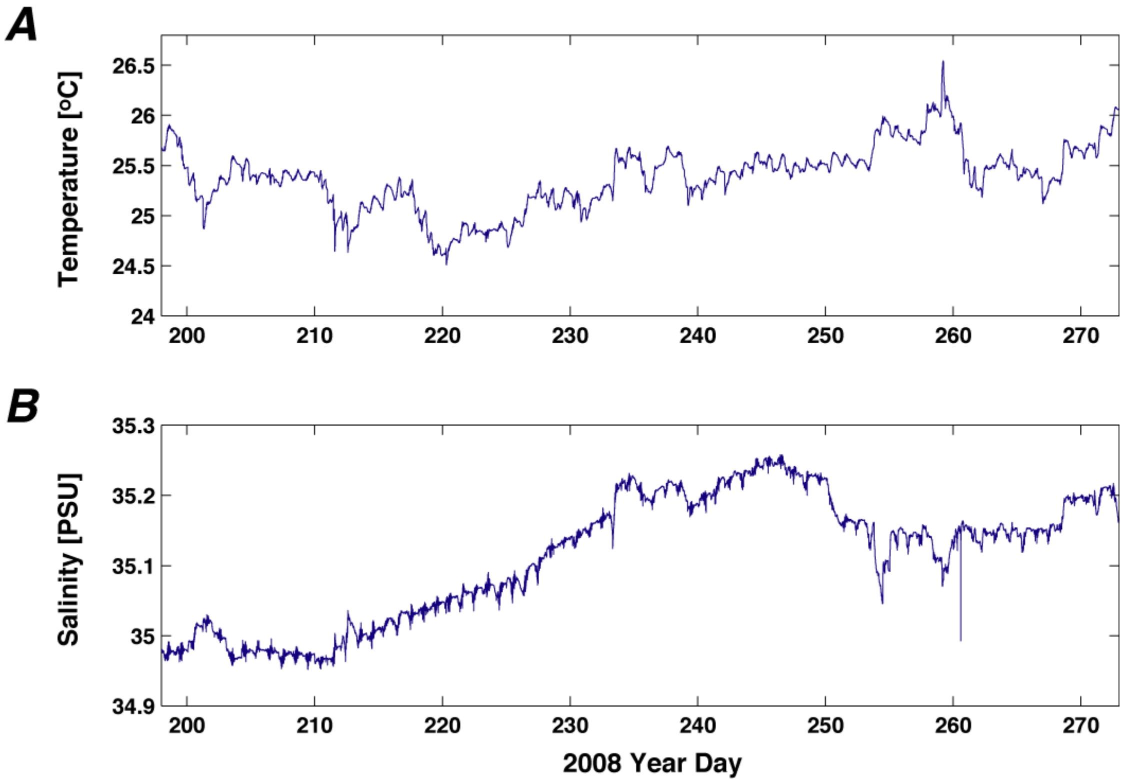


Appendix 2.3. Tide, current, and water temperature data for the 2009 summer from the ADCP. *A*, Tidal height, in meters. *B*, Near-surface current speeds and directions, in meters per second from true north. *C*, Mid-depth current speeds and directions, in meters per second from true north. *D*, Near-bed current speeds and directions, in meters per second from true north. *E*, Water temperature, in degrees Celsius.

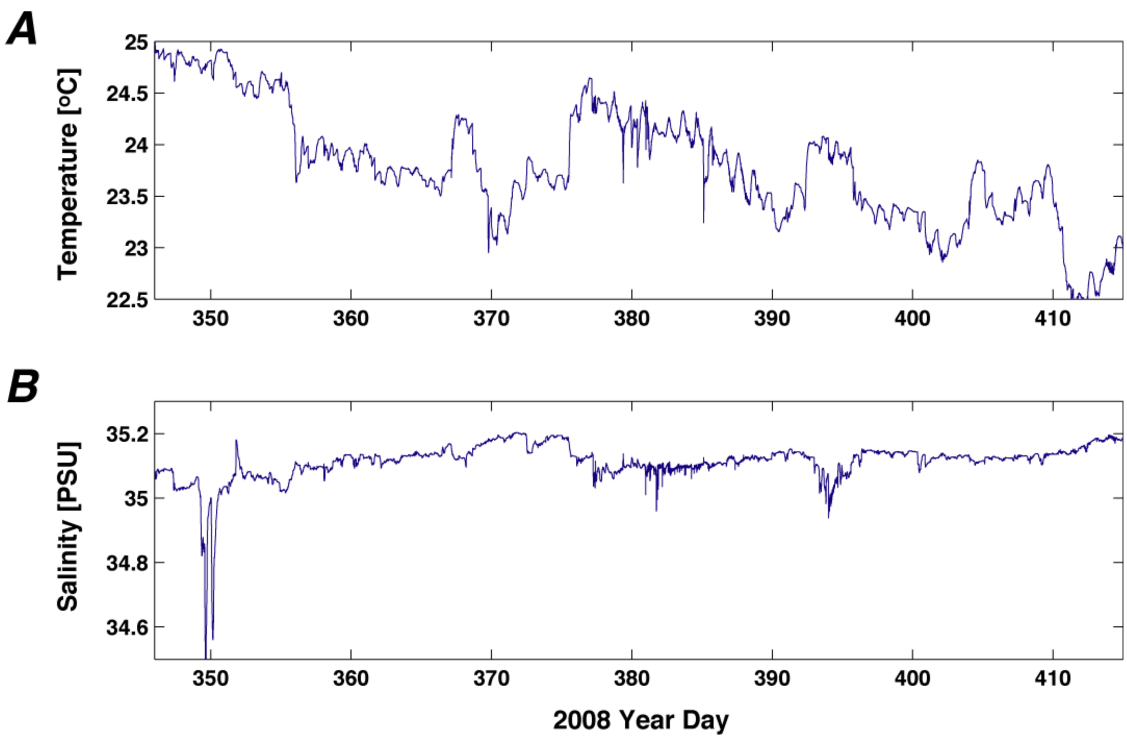


Appendix 2.4. Tide, current, and water temperature data for the 2009-2010 winter from the ADCP. *A*, Tidal height, in meters. *B*, Near-surface current speeds and directions, in meters per second from true north. *C*, Mid-depth current speeds and directions, in meters per second from true north. *D*, Near-bed current speeds and directions, in meters per second from true north. *E*, Water temperature, in degrees Celsius.

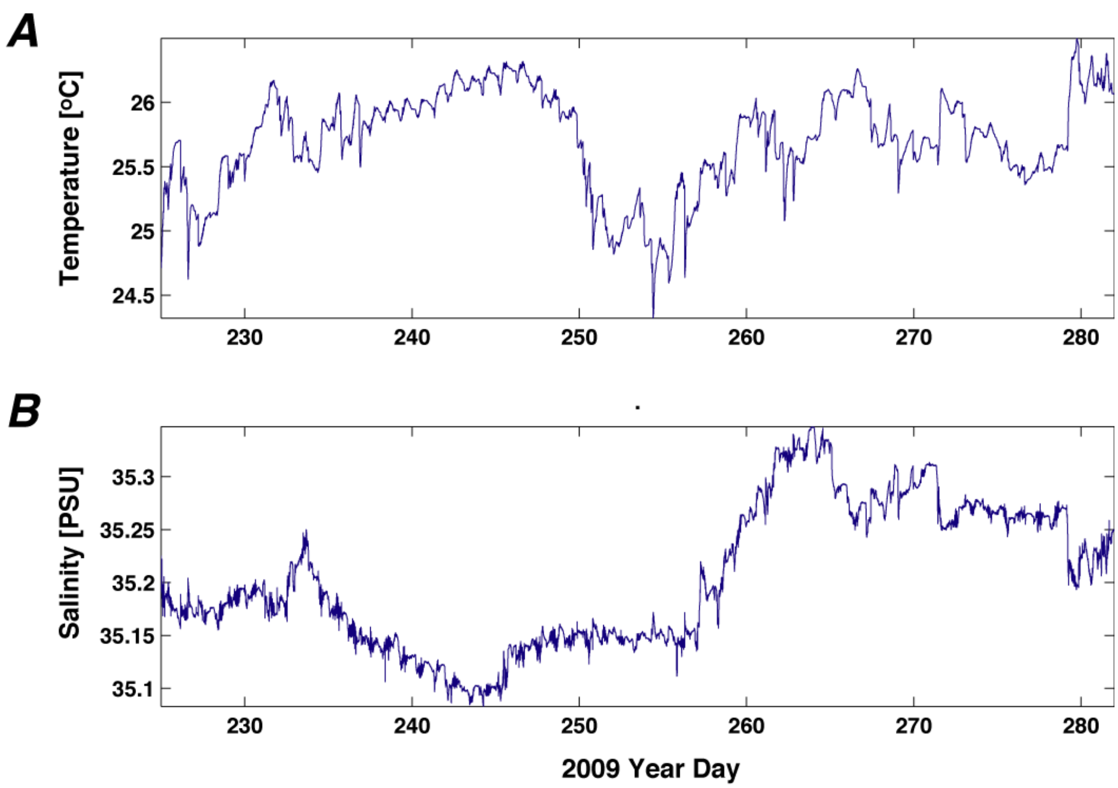
Appendix 3. Time series plots of variations in water temperature and salinity through time from the conductivity and temperature (CT) sensor.



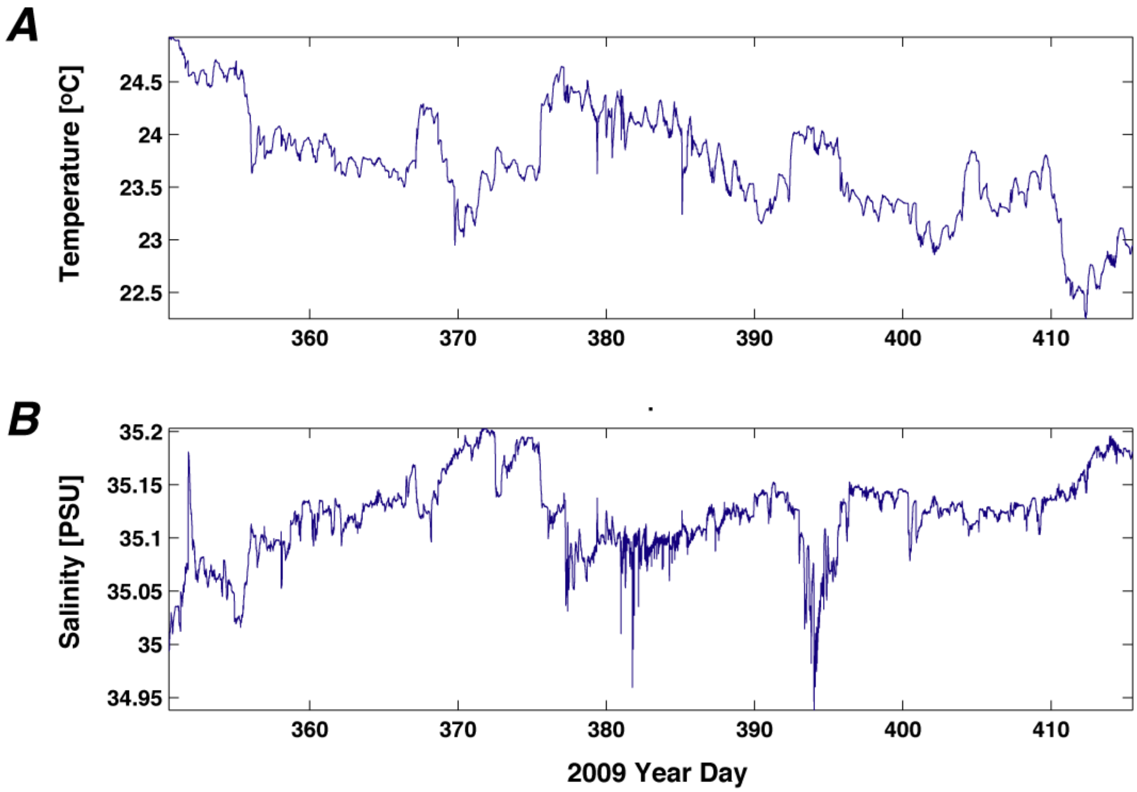
Appendix 3.1. Water temperature and salinity data for the 2008 summer from the CT. *A*, Water temperature, in degrees Celsius. *B*, Salinity, in Practical Salinity Units (PSU).



Appendix 3.2. Water temperature and salinity data for the 2008-2009 winter from the CT. *A*, Water temperature, in degrees Celsius. *B*, Salinity, in Practical Salinity Units (PSU).

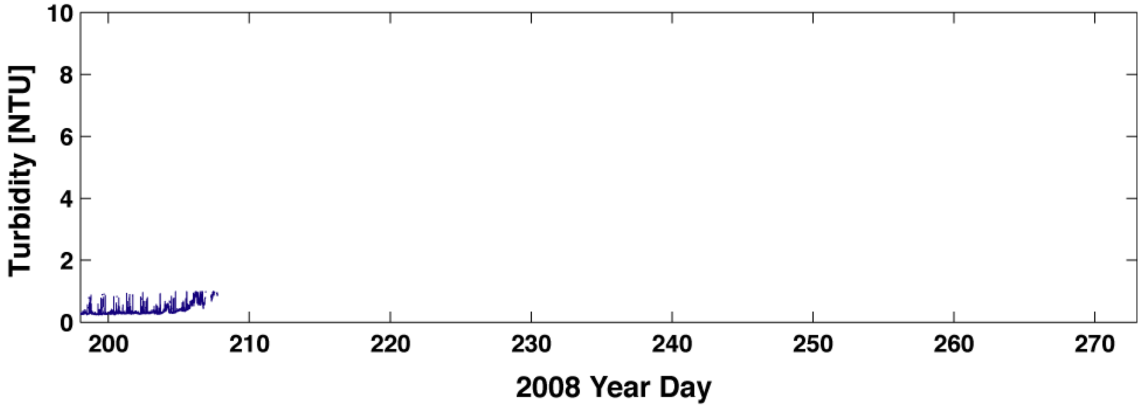


Appendix 3.3. Water temperature and salinity data for the 2009 summer from the CT. *A*, Water temperature, in degrees Celsius. *B*, Salinity, in Practical Salinity Units (PSU).

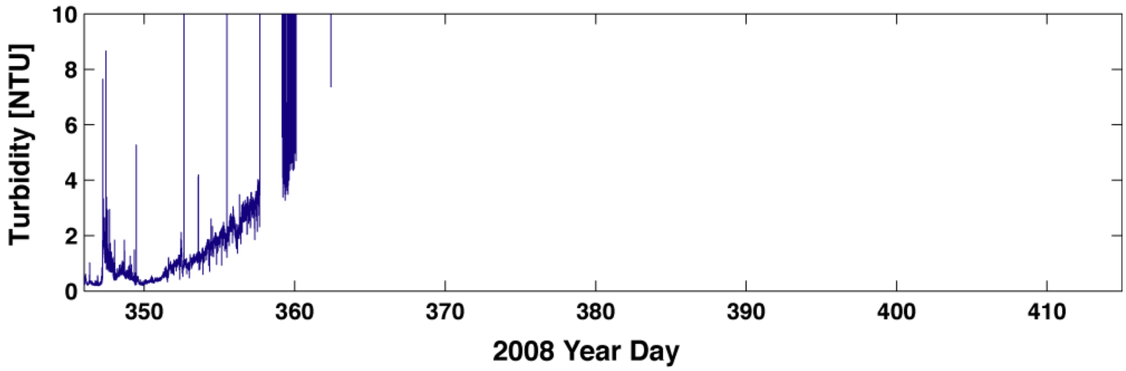


Appendix 3.4. Water temperature and salinity data for the 2009-2010 winter from the CT. *A*, Water temperature, in degrees Celsius. *B*, Salinity, in Practical Salinity Units (PSU).

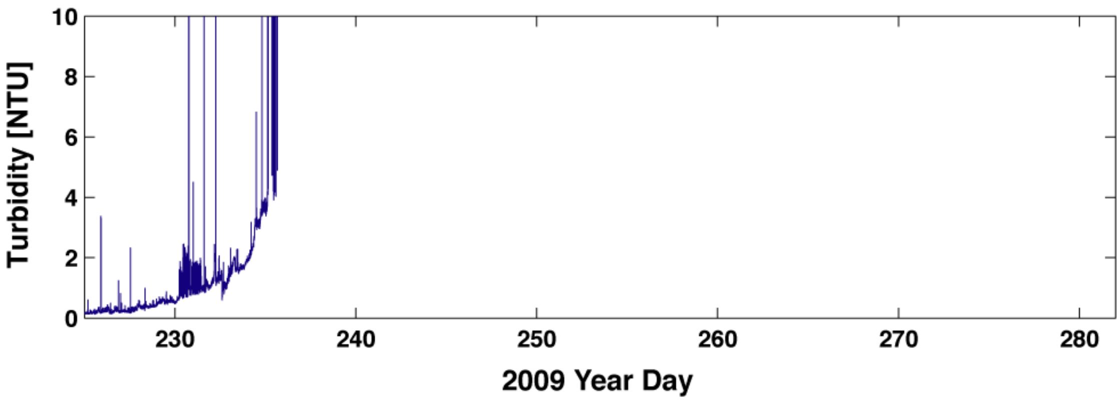
Appendix 4. Time series plots of variations in turbidity through time from the optical backscatter sensor (OBS).



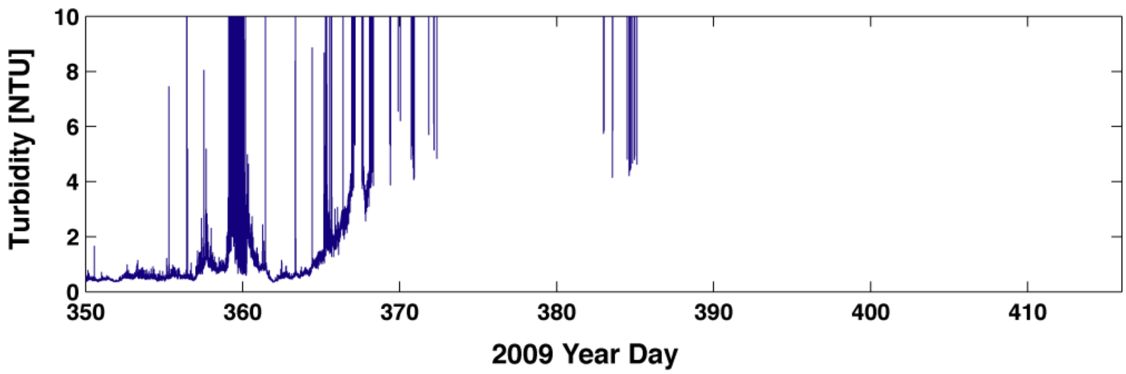
Appendix 4.1. Turbidity data for the 2008 summer from the OBS, in National Turbidity Units (NTU).



Appendix 4.2. Turbidity data for the 2008-2009 winter from the OBS, in National Turbidity Units (NTU).



Appendix 4.3. Turbidity data for the 2009 summer from the OBS, in National Turbidity Units (NTU).



Appendix 4.4. Turbidity data for the 2009-2010 winter from the OBS, in National Turbidity Units (NTU).

Appendix 5. Suggested RD Instruments 1200 kHz ADCP deployment parameters for Kalaupapa National Historical Park.

RD Instruments 1200 kHz Workhorse Monitor upward-looking acoustic Doppler current profiler

What to enter in RD Instruments' "PlanADCP" software under the "ADVANCED" tab:

ENVIRONMENT SET-UP	
Depth of Transducer:	17 m
Salinity:	35 ppt
Magnetic Variation:	10 deg
Temperature:	20 deg (this is only used for battery calculations)
DEPLOYMENT TIMING SET-UP	
Deployment Duration:	90 days
Ensemble Interval:	0:05:00.00
Ping Interval:	Auto
Ping Immediately After Deployment:	unchecked
First Ping Date:	DD-MMM-YYYY (start MMDDYY)
First Ping Time:	HH:MM:SS (start HHMMSS)***

***-best to start at some round fraction of a day, for example, 00:00. 06:00, 12:00, 18:00

PROFILING TIMING SET-UP	
Pings per Ensemble:	100
Number of Depth Cells:	20
Depth Cell Size:	1 m
Mode:	1 (static, waves)
WAVES SET-UP	
Burst Duration:	10 min
Time Between Bursts:	60 min
EXPERT SET-UP	
Blank:	0.44 m
Ambiguity Velocity:	1.75 m/s

What should result in RD Instruments' "PlanADCP" file:

First Cell Range:	1.54 m
Last Cell Range:	20.54 m
Standard Deviation:	0.35 cm/s
Battery Pack Usage:	1.9
Samples per Wave Burst:	1200
Min. Observ. Wave Period (non-dir):	2.11 s
Min. Observ. Wave Period (dir):	3.25 s

Appendix 6. Suggested SeaBird Micorcat SBE-37SMP CT deployment parameters for Kalaupapa National Historical Park.

SeaBird Microcat SBE-37SMP pumped conductivity and temperature sensor

What to enter in SeaBird's "Terminal" software:

interval:	300 (sample interval, in seconds)
samplenum:	0 (clears memory)
txrealtime:	n (no real-time time output)
outputsal:	n (no real-time salinity output)
outputsv:	n (no real-time sound velocity output)
storetime:	y (log time)
navg:	4 (average 4 samples per burst)
refpress:	17 (reference pressure for salinity calculations)
syncmode:	n (not synced to other sensors)
pumpinstalled:	y (pump installed)
mmddyy:	XXXXXX (current MMDDYY)
hhmmss:	XXXXXX (current HHMMSS)
startmmddyy:	XXXXXX (start MMDDYY)
starthhmmss:	XXXXXX (start HHMMSS)***
ds	(to check settings, see below)
startlater	(initiate deployment)

***-best to start at some round fraction of a day, for example, 00:00. 06:00, 12:00, 18:00

What SeaBird's "Terminal" should display following DS command:

SBE37-SMP V X.XX SERIAL NO. XXXX   DD MMM YYYY HH:MM:SS
logging not started
sample interval = 300 seconds
samplenumber = 0, free = XXXXXX
do not transmit real-time data
do not output salinity with each sample
do not output sound velocity with each sample
store time with each sample
number of samples to average = 4
reference pressure = 17.0 db
serial sync mode disabled
internal pump installed

Appendix 7. Suggested Aquatec/Seapoint 210-TY OBS deployment parameters for Kalaupapa National Historical Park.

Aquatec/Seapoint 210-TY self-logging optical backscatter sensor

What to enter in Aquatec's "AQUAtalk" software under the "Deploy" tab:

Set Date and Time:	set via computer time
Logging Start:	XX:XX (start HH:MM)***
Channels:	select "Turbidity" and "Battery"
Averaging:	do not select
Gain:	auto
Enable Burst Sampling:	Checked
Sampling Interval:	5 minutes
Samples per Burst:	8
Sampling Frequency:	every 1 second

***-best to start at some round fraction of a day, for example, 00:00. 06:00, 12:00, 18:00