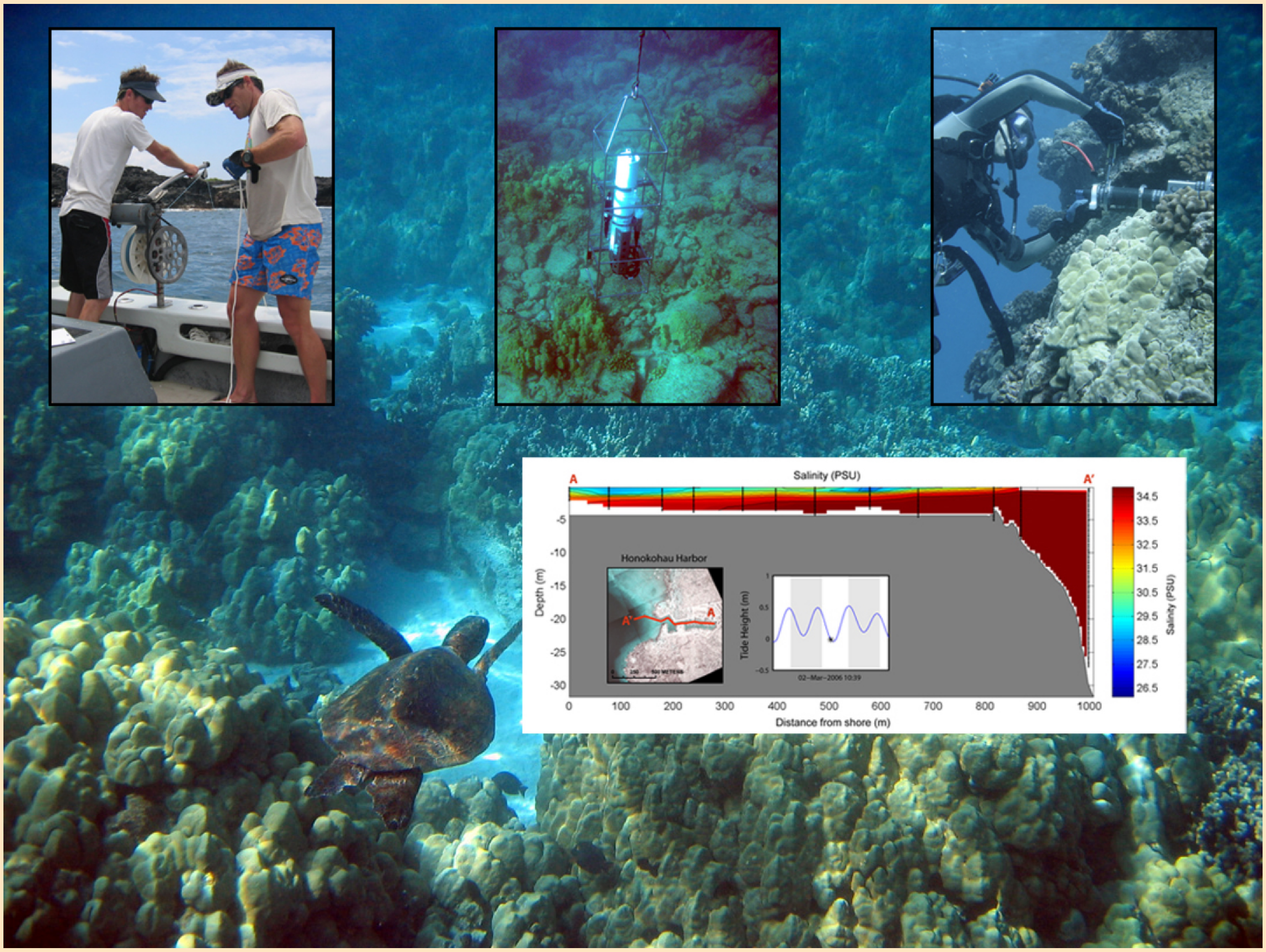
Submarine Groundwater Discharge and Fate Along the Coast of Kaloko-Honokōhau National Historical Park, Island of Hawai‘i

Part 3, Spatial and Temporal Patterns in Nearshore Waters and Coastal Groundwater Plumes, December 2003–April 2006



Scientific Investigations Report 2010-5081

U.S. Department of the Interior
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COVER:
Background photograph of coral reef and turtle with inset images from upper left: USGS scientists profiling water properties from small boat; the profiling equipment underwater; oceanographic instrumentation being installed within reef for temporary time-series deployment; cross-section of salinity derived from measurements through the water column and Honokōhau Small Boat Harbor, Kailua-Kona, Hawai‘i.

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)

Temperature in °Celsius (°C) may be converted to °Fahrenheit (°F) as follows:
°F=(1.8°C)+32
Temperature in °Fahrenheit (°F) may be converted to ° Celsius (°C) as follows:
°C=(°F–32)/1.8

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)

Temperature in °Celsius (°C) may be converted to °Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in °Fahrenheit (°F) may be converted to ° Celsius (°C) as follows:
°C=(°F-32)/1.8

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Abstract

During seven surveys between December 2003 and April 2006, 1,045 depth profiles of surface water temperature and salinity were collected to examine variability in water column properties and the influence of submarine groundwater discharge (SGD) on the nearshore waters and coral reef complex of Kaloko-Honokōhau National Historical Park, Island of Hawai‘i. This effort was made to characterize the variability in nearshore water properties with seasonality and hydrodynamic forcing (tides, winds, and waves) and to determine the spatial and vertical extent of influence of SGD plumes on the Park's marine biological resources. The results of this study reveal that nearshore waters of the Park were persistently influenced by plumes of submarine groundwater discharge that are generally colder, less saline, and more concentrated in nutrients than the surrounding seawater. These plumes extended between 100 and 1,000 m offshore to depths ranging between 1 and 5 m and often contained several million to hundreds of millions of gallons of brackish water. In essence, the Park's nearshore, like much of the arid west coast of Hawai‘i, is estuarine. Although the groundwater plumes were persistent over the years studied, their spatial extent and volume varied tidally, seasonally, and annually. In one season, April 2004, an inverse relation of decreasing salinity with increasing temperature was found in the upper 5 m of the water column, unlike the other seasons, when surface water temperature and salinity were positively correlated.

These data provide the first comprehensive record of nearshore water column properties within the Park boundaries and a baseline for detecting and assessing future conditions. Various resort, industrial, and municipal developments, either planned or under construction around the Park, will require significant groundwater supplies and will likely alter groundwater quantity and quality. The flux and quality of groundwater through the National Park are critical to the rare anchialine (brackish) pool ecosystems and various ecosystem functions of the nearshore waters and coral reefs. Changes in groundwater discharge are expected to have significant impacts to the area's coastal ecosystems, including decreased freshwater outflow to the brackish anchialine pools and coral reefs and increased nutrient and contaminant concentrations. In conjunction with two complementary studies of this series (Parts 1 and 2), these data provide insight into the patterns of influence and fate of SGD in the Park's coastal waters. This information is important for determining water-resource management strategies that balance the needs of the ecosystem with those of human livelihood. This report describes the data, presents the general findings, and gives representative examples of seasonal and tidal variability in water column properties and SGD-fed plumes across the Park's nearshore waters.

Introduction

Along the arid west coast of the Island of Hawai‘i, where streams are absent and surface runoff is rare, groundwater flow across the coastal plain and into the nearshore environment is common. Groundwater is important to the region's coastal ecosystems, including its near-pristine coral reefs and unique brackish "anchialine pools"—tidally influenced groundwater-fed pools without a direct connection to the sea (Holthuis, 1973; Brock and others, 1987; Brock and Kam, 1990). Groundwater is also the principal supply of water for municipal uses in the arid Kailua-Kona region, which is experiencing some the highest rates of development within Hawai‘i (State of Hawai‘i Department of Business, Economic Development and Tourism, 2007). Thermal-infrared survey overflights in 1992 (Wilkens, 1992) and 2005 (Johnson and others, 2008), which imaged cold groundwater plumes flowing across the warmer coastal marine waters at the surface, revealed many groundwater discharge points along the Kailua-Kona coast and provided a snapshot of the patterns of groundwater mixing in the surface ocean layer (uppermost 1-10 mm). Although a qualitative understanding exists that groundwater flow to the coastal ocean is relatively high and is important for multiple ecosystem services, little quantitative information is available on fluxes of groundwater and associated materials (nutrients, pollutants), variability in discharge with land use or climate change, or the fate of these materials in the coastal zone. This information is important for urban and park planning, risk assessments, and science-based decisionmaking with regard to water use and ecosystem management.

This study reports on the findings of measuring water properties during seven surveys between December 2003 and April 2006 to examine variability in water-column properties and the influence of submarine groundwater discharge (SGD) on the nearshore waters and coral reef complex of Kaloko-Honokōhau National Historical Park (NHP) (fig.1). This effort was made to characterize nearshore water properties and their variability associated with seasonal changes and hydrodynamic forcing (tides, winds, and waves). The study was also conducted to determine the spatial and vertical extent of influence of SGD on the Park's biological resources and the processes governing its fate. The results of these efforts contribute to filling three principal data gaps identified by the recent National Park Service (NPS) water resources and biological resource assessment as critical needs (Hoover and Gold, 2005):

1. Characterize groundwater flow dynamics in and around the Park, and its response to existing and planned development (withdrawals and wastewater inputs).
2. Characterize the locations and intensity of groundwater inputs to coastal waters.
3. Characterize water quality, circulation, and dilution processes in coastal waters adjacent to the Honokōhau Small Boat Harbor.

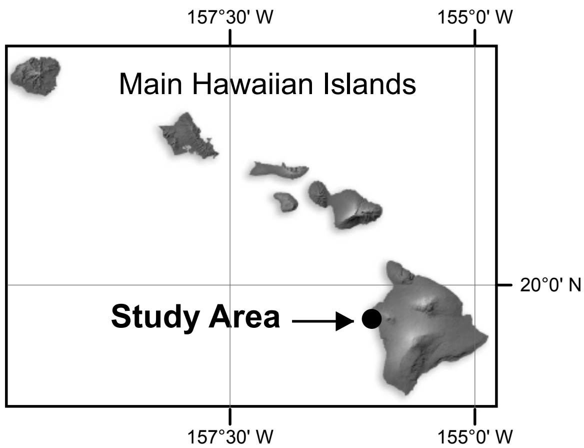
Objectives

The objectives of this study were to (1) determine the spatial extent of influence of submarine groundwater discharge on nearshore benthic habitats of Kaloko-Honokōhau National Historical Park; (2) quantify the volume of submarine groundwater-fed plumes in the nearshore and compare these estimates to complementary measures of SGD flux; and (3) characterize the seasonal and tidal variability in nearshore water quality properties. To accomplish these objectives, researchers from the U.S. Geological Survey, Stanford University, and the National Park Service began a collaborative study in late 2003 to examine the flux and fate of SGD and associated nutrient inputs to the Park's nearshore zone. This work was conducted as part of the U.S. Geological Survey's multidisciplinary Coral Reef Project, which addresses geologic processes and land-use impacts to coral reef systems. This report is the third part of three and addresses the variability of nearshore water properties and the extent and fate of SGD across the nearshore and coral reefs of Kaloko-Honokōhau National Historical Park. The data presented here complement the first two reports, which characterize the inputs of groundwater and associated nutrients to the coast (Knee and others, 2008) and the physical oceanographic processes that distribute those materials through the Park's coastal waters (Presto and others, 2007).

Study Area

Kaloko-Honokōhau National Historical Park spans 1,276 marine and terrestrial acres on the Kona (west) coast of Hawai'i Island and was established by an act of Congress (Public Law 95-625) in 1978 to preserve, interpret, and perpetuate traditional Native Hawaiian activities and culture. The Park's aquatic resources are culturally significant to Native Hawaiians and are central to the purposes and values for which the park was created. These resources include nearly 200 anchialine pools, two large, historic Hawaiian fishponds, and coral reefs, and they support a diverse range of species of fish, marine mammals, birds, marine reptiles, invertebrates, and plants. Several species supported by these habitats are rare endemics and others have candidate, threatened, or endangered status (http://www.nps.gov/kaho, last accessed Nov. 19, 2009). The sea floor of the Park is generally composed of barren to partially coral-covered lava flows ranging from 10,000 to 1,500 years in age. The corals Pocillopora meandrina and small colonies of P. lobata occur in the shallow depths (< 3 m), a narrow region of dense coral, principally Porites lobata and P. compressa, exists in intermediate depths (5-15 m), and areas of dead coral or sparse carbonate sands are interspersed across all depths (Gibbs and others, 2007). The region is characterized by a bimodal annual rainfall climate, with winter storm precipitation at higher elevations and summer convective rainfall at intermediate elevations (Giambelluca and others, 1986; Juvik and Juvik, 1998). Nearshore circulation is influenced by winter long-period (>15 sec) northwest swell and occasional shorter period (10–12 sec) west-southwest swell from "Kona storms" that produce 3- to 6-m breaking wave heights, and long-period summer south swell (17–22 sec) that produce 2- to 4-m breaking wave heights (Moberly and Chamberlain, 1964).

The Park's aquatic resources and their dependent ecosystems are intimately linked to groundwater. Despite the area's low mean annual rainfall of 50 to 75 cm (Oki and others, 1999) and the absence of perennial streams, most water bodies in the Park are considerably fresher than seawater, indicating the presence of groundwater discharge. This freshwater originates in the rainy central part of the island and, at the intermediate elevations of Hualalai Volcano, flows through the highly porous basalt aquifer and discharges at the coast. Oki and others (1999) showed that increasing groundwater withdrawals for urban development has had the potential to decrease groundwater flux to the coast by 50 percent from 1978 levels (the year the Park was authorized) consistent with an observed drop in the water table. During this same period, contaminants,



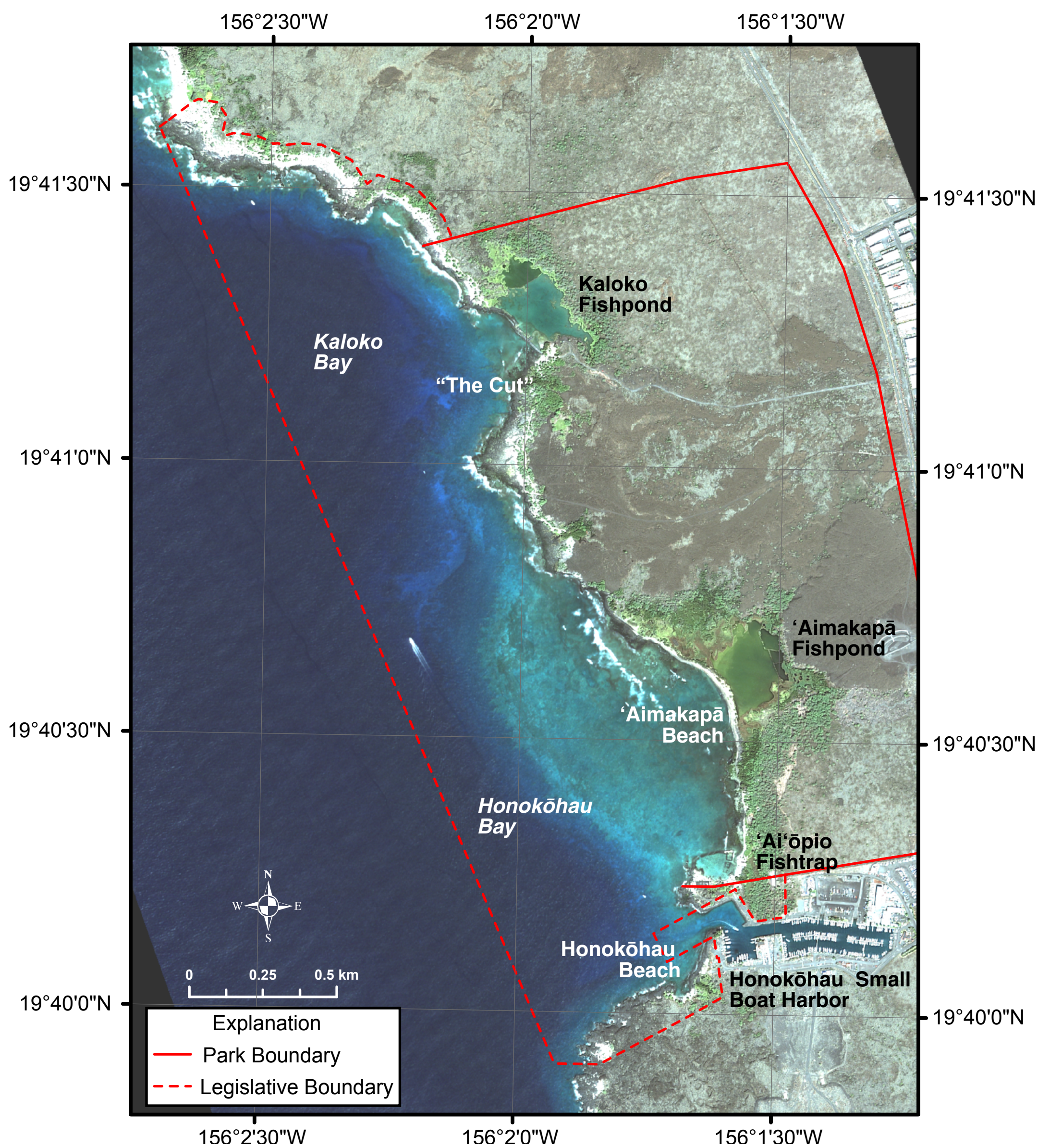


Figure 1. Location map of study area, showing boundary of Kaloko-Honokōhau National Historical Park (KAHO) and other prominent features mentioned in the text, including the Kaloko and 'Aimakapā Fishponds, 'Ai'ōpio Fishtrap, and the Honokōhau Small Boat Harbor.

and residential land use upslope of the park have impacted (or altered) groundwater quality (Oki and others, 1999). Development on the west coast of Hawaiʻi, adjacent to the Park, is ongoing, and more is planned in the near future. In 2008, the waters of Honokōhau Beach and northern Honokōhau Bay near the north edge of the Park were designated as 303(d) impaired water bodies for exceeding state standards for total nitrogen, nitrate+nitrite, total phosphate, and turbidity following Environmental Protection Agency (EPA) standards (Hawaiʻi State Department of Health Clean Water Branch, 2008). The northern Honokōhau Bay waters were also clas sified as 303(d) impaired with respect to chlorophyll-a and enterococci (bacteria).

Submarine Groundwater Discharge (SGD)

SGD occurs when groundwater in the coastal aquifer flows down a hydraulic gradient and enters the ocean (Taniguchi and others, 2002). It can occur in distinct springs and seeps along the shore or below sea level (Church, 1996; Moore, 2003). In the young and porous basalt coast of west Hawaiʻi, groundwater flow can be high and accentuated by fractures, faults, or lava tubes. The quantity of groundwater discharge is influenced by rainfall in aquifer-recharge areas, permeability of the geologic substrate, evapotranspiration, and anthropogenic extraction. The quality of groundwater is influenced by land use and the chemical characteristics of the geologic substrate (Burnett and others, 2006). Human impacts to water quantity and quality, including pumping, which can lead to saltwater intrusion, waste disposal and injection, and runoff and excess use of nutrients, pesticides, and other synthetic materials, are increasingly altering the volume and quality of groundwater discharging to the coast.

SGD can include both fresh and saline groundwater (Moore, 1999; Taniguchi and others, 2002; Kim and others, 2003). On high islands like Hawaiʻi, fresh groundwater tends to be older (years to 100s of years), having flowed underground for long distances from the recharge zones high on the mountain sides. In the Kailua-Kona area, recharge areas occur close to the shore on the flanks of Hualalai Volcano, yet flow paths and traveltimes for groundwater to reach the sea from the recharge zones remain uncertain. In contrast, saline groundwater is generally younger and partly comprises seawater. It is thought that wave-driven and/or tidally driven circulation mixes seawater and groundwater within the coastal aquifer on time scales of days to months. SGD can affect nearshore water properties, including temperature, salinity, and the concentrations of nutrients and other chemicals. In Kaloko-Honokōhau National Historical Park and along most of the arid west coast of Hawaiʻi, SGD is particularly important because it is the only significant hydrologic connection between land and sea. Knowledge of the quantity and quality of SGD and likely future changes to SGD is therefore essential to understanding the region's coastal ecosystem function, including its unique anchialine pools (Brock, 2003a), and to developing effective management plans for anchialine pools (Brock, 2003b) and other coastal ecosystems.

Previous Studies

Although a qualitative understanding of SGD in the vicinity of Kaloko-Honokōhau NHP has been developed from a handful of past studies of anchialine pools along the west Hawaiʻi coast and assessments of nearshore water properties related to the construction of the Honokōhau Small Boat Harbor (Bienfang, 1983; Brock and others, 1987), little quantitative information exists to characterize the quality and variability of the Park's nearshore waters. Bienfang (1983) summarized the results of a decade-long study of changes in water quality immediately following initial construction of the harbor in 1970 and through periodic assessments following expansion in 1978-79. Before the expansion, the harbor circulation was relatively active, characterized by salt-wedge circulation, driven by a seaward-flowing buoyant surface lens of brackish and colder groundwater emanating from the inner harbor. After the 1978-79 expansion, which doubled the surface area of the harbor, the circulation of the inner harbor was reduced, which led to a 10- to 50-fold increase in phytoplankton abundance and elevated turbidity due to increased surface-water residence time. Bienfang (1980) estimated that the flux of SGD through the harbor ranged from 0 to 12 million gallons per day (MGal/d) and had little effect on nearshore waters; however, most of that work was restricted to the harbor and the immediate vicinity of the harbor entrance.

In response to concern about impacts to the Park's biological resources stemming from increased industrial and proposed municipal and resort development around Kaloko-Honokōhau NHP, a study by Oki and others (1999) showed that increased groundwater withdrawals for urban development since 1978 has had the potential to decrease groundwater flux to the coast by 50 percent and is consistent with a measured drop in the water table. During this same time (from 1978 to 1999), the quality of groundwater has been vulnerable to increases in contaminants and additions of nutrients through fertilizers and wastewaters associated with industrial, commercial, and residential use surrounding the Park. Periodic studies since the 1970s have indicated that the water quality of groundwater and the region's anchialine pools has remained relatively pristine. Only a few contaminant impacts from metals, PAHs (polycyclic aromatic hydrocarbons), and other wastewater products have been detected (Oki and others, 1999).

As part of the present study, Knee and others (2008) quantified the flux of SGD and the associated nutrient load through the Kaloko-Honokōhau coastal zone to the nearshore waters using radium isotope chemistry and analyses of transported nutrients. Knee and others (2008) estimated that SGD fluxes from several discharge points along the Park, most notably ʻAimakapā Beach, ʻAiʻōpio Fishtrap, and Kaloko Fishpond, ranged from 1 to 22 m^3 (264 to 5,812 Gal) per day per meter of shoreline between December 2003 and April 2006. SGD through the harbor was considerably larger, ranging from 7,800 to 12,000 m^3 (2 to 3 MGal) per day per meter of shoreline over the same period. Of this discharge, 16-26 percent was calculated to originate as freshwater. Both fresh and saline

SGD were found to be sources of nitrate+nitrite (N+N), phosphate (PO_4^{3-}), and silica (Si); fluxes from fresh SGD reached up to 31, 2.1, and 260 mol per day per meter of shoreline, respectively, while contributions from saline SGD reached up to 46, 9.3, and 110 mol per day per meter of shoreline, respectively (Knee and others, 2008). These results agreed with a collaborative study by Johnson and others (2008), who imaged the surface layer of the SGD plumes with thermal infrared spectrometry and estimated nutrient additions to the coastal waters through a modeled relation between measured nutrient concentrations, salinity, and temperature. Parsons and others (2008) also estimated relatively high additions of nutrients to the coast through groundwater and found that biologic uptake by phytoplankton was high and efficient, which minimized the buildup of excess nutrient on the benthos. No systematic studies have been conducted to examine changes in nearshore water quality and biologic resources stemming from land use and/or climate change; however, the previously mentioned studies and the current study provide important baseline information with which to detect possible future impacts.

Operations

Study Design

This study was designed to quantify the spatial extent of influence of SGD on the biological resources of Kaloko-Honokōhau National Historical Park and expand knowledge of the depths and zones that SGD plumes influence benthic marine resources within the Park. The study was also designed to characterize the variability in nearshore water properties associated with seasonality, tides, and wind- and wave-driven circulation. Measurements of water-quality parameters were made with depth at stations across the nearshore, principally at low tides, to identify the maximum spatial influence of submarine groundwater that occurs with the greatest hydraulic gradient. Initial surveys targeted a regularly spaced 100-m grid in water depths between 1 and 40 m to develop an understanding of the general pattern of SGD plume interaction with Park nearshore waters (fig. 2). Subsequent surveys targeted repeat sampling along specific crossshore and alongshore transects where SGD plumes were identified in thermal infrared imagery (Wilkins, 1992; Johnson and others, 2008), at stations of hydrodynamic instrument deployments (Presto and others, 2007), and at select control sites.

Principal study transects were located within and offshore of the Honokōhau Small Boat Harbor (south), offshore of Kaloko Fishpond (north), and in the region known by the Park as "The Cut"—a narrow reentrant located in the blocky coastal lava flows ~0.25 km south of Kaloko Fishpond (north). Additional study transects were located in ʻAiʻōpio Fishtrap and offshore of ʻAimakapā Fishpond. These crossshore and alongshore transects were sampled to examine the offshore and shore-parallel gradients in SGD and mixing. Measurements were made at stations with fixed instruments that collected time-series measurements of tides, waves, currents, water temperature, salinity, and turbidity (Presto and others, 2007) to improve understanding of temporal variability in water properties. Control sites were located along the 10-m isobath between the two transects to characterize ambient conditions and to detect migration of SGD plumes during high discharge or transport events. Several control sites more than 1 km offshore were sampled to characterize background "marine" water quality conditions. Three surveys were conducted concurrently with comprehensive surveys of SGD and associated nutrient flux using radioisotopes of radium (Knee and others, 2008) and radon (Johnson and others, 2008).

Equipment Review

Seven surveys were conducted between December 2003 and April 2006 (table 1) using a Seabird 19-Plus profiling conductivity, temperature, depth sensor (CTD) to measure variations in water temperature and salinity with depth (fig. 3; individual survey maps are included in appendix 1). Additional parameters, including turbidity, dissolved oxygen, photosynthetically available radiation (PAR), and chlorophyll-a, were also measured in five of the surveys (not shown). Early surveys also included a down-looking color video camera with two lasers for scale to map substrate, coral cover, and species composition. Measurements were made by small boat and kayak. Generally, at least two scientists were present, along with a boat captain. Position information was collected with a handheld global positioning system (GPS) with an accuracy ranging from 3 to 10 m.

Profiling with a Conductivity, Temperature, Depth Sensor (CTD)

Profiles of water temperature and salinity were made with a Seabird 19-Plus profiling CTD operating at 4 Hz (fig. 4; appendix 2). Although data were collected on both downcasts and upcasts, only data from downcasts are presented in this report. Profiles were made by priming the pump for more than 30 s before casting down at a rate of approximately 10-30 cm/s. This rate furnished between 8 and 24 samples per meter of water column. The profiler was lowered to just above the sea floor before recovery. Occasionally, high waves, strong winds, and boat wakes made conditions challenging and led to variations in rate of profiling and number of samples per meter.

Profile data were downloaded and processed using Seabird Seaterm and SBEDataProcessing software. The processing included soak (priming) corrections and bin averaging at 0.25-m depth intervals. A second set of processed data were also generated using Matlab to skip Seabird's Loop Edit Minimum Velocity Correction (on older versions of SBEDataProcessing Software) that automatically deleted desired data on casts with high downcast rates when using the soak correction. This procedure retained data where they were scarce (for example, rapid downcasts). These data were subject to the same processing steps otherwise suggested by Seabird (http://www.seabird.com, accessed November 19, 2009). Following bin averaging, the data were output as ASCII files, and samples were linked to position by times recorded on the instrument and GPS. Information on tidal height and weather conditions (when available) were then merged with these data and read into a Matlab structured-array dataset, where general statistics, queries around target stations, and analyses of water properties were made. Cross sections of individual parameters were plotted in Matlab, while gridded surface maps and cross sections were made in ArcGIS from flat data files output from the Matlab structured arrays.

The initial survey activities A-8-03-HW, A-4-04-HW, and A-6-04-HW (table 1) targeted the initial 100-m sampling grid (fig. 2). However, breaking waves, shallow conditions, rocks, and other hazards made many target sites of the initial grid inaccessible. Later surveys focused in on the study transects of the north and south areas and select control sites along the 10-m depth contour offshore of the central Kaloko-Honokōhau reef.

Weather Station

Meteorological data were acquired from two sources. For surveys occurring after December 2004, data were acquired from the NPS Remote Automatic Weather Station (RAWS) located in the southeast portion of the Park (http://mesowest.utah.edu/cgi-bin/droman/meso_base.cgi?stn=KHOH1&product=&time=LOCAL, accessed November 19, 2009). For surveys

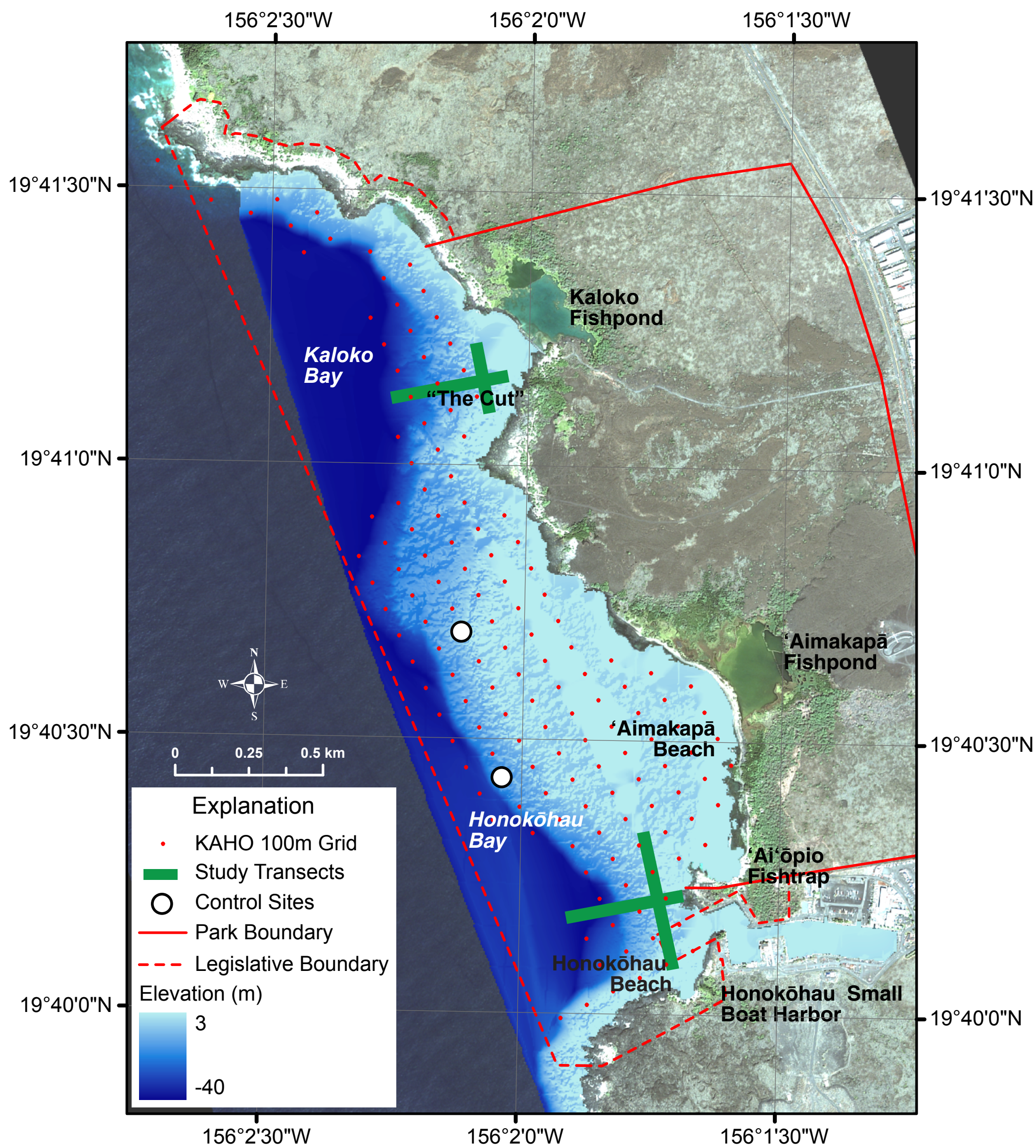


Figure 2. Map showing the 100-m sampling grid, locations of focused study transects, and controls sites for this study.

Table 1. List of sampling activities, dates and samples collected.

Information for the surveys (USGS Infobank Activities) are provided at the following websites.

Activity	Date	Samples	Metadata URL
A-8-03-HW	Dec 2003	150	http://walrus.wr.usgs.gov/infobank/a/a803hw/html/a-8-03-hw.meta.html
A-4-04-HW	Apr 2004	166	http://walrus.wr.usgs.gov/infobank/a/a404hw/html/a-4-04-hw.meta.html
A-6-04-HW	Aug 2004	86	http://walrus.wr.usgs.gov/infobank/a/a604hw/html/a-6-04-hw.meta.html
A-1-05-HW	Aug 2005	143	http://walrus.wr.usgs.gov/infobank/a/a105hw/html/a-1-05-hw.meta.html
W-1-05-HW	Nov 2005	12	http://walrus.wr.usgs.gov/infobank/w/w105hw/html/w-1-05-hw.meta.html
W-1-06-HW	Feb–Mar 2006	276	http://walrus.wr.usgs.gov/infobank/w/w106hw/html/w-1-06-hw.meta.html
W-2-06-HW	Apr 2006	212	http://walrus.wr.usgs.gov/infobank/w/w206hw/html/w-2-06-hw.meta.html

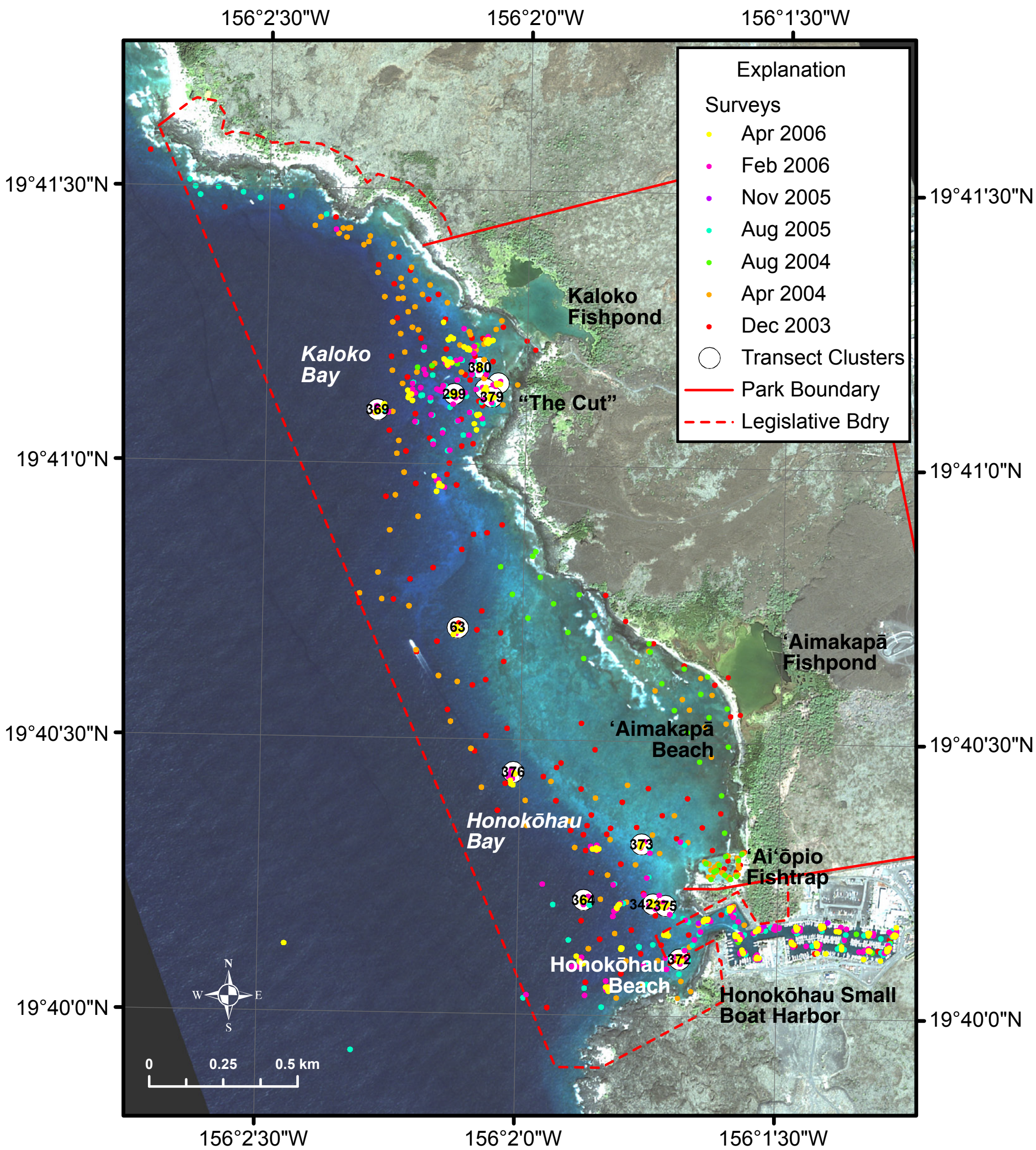


Figure 3. Map showing locations of CTD profiles collected during all 7 sampling activities, north and south transect clusters, and two control sites (see Appendix I for maps of individual surveys).

conducted before December 2004, meteorological data were acquired from the NOAA Automated Surface Observation System (ASOS) at the Kona International Airport (KOA) located roughly 5 km north of the Park (http://weather.noaa.gov/weather/current/PHKO.html, accessed November 19, 2009).

Data Acquisition and Quality

One thousand and forty-five (1,045) individual profiles of temperature and salinity were collected across the Park's nearshore waters and deemed suitable for analyses. The profiles measured temperature and salinity in water depths of 0.5 to 45 m between the shoreline and 1 km offshore. Seawater end-members were measured as much as 3 km offshore. To analyze temporal differences in water properties at individual sites over the different survey activities and tidal conditions, individual casts were grouped into cluster stations of a 20-m radius (fig. 5A, B) to account for navigation errors, hazards from large breaking waves, and strong currents that made repeat measurements at a given location challenging. Therefore resulting analyses for clustered data represent conditions within a 20-m radius.

Data were acquired during seven surveys under a range of different tidal stages and wind conditions. Most surveys were intended to map the maximum excursion of groundwater discharge into the coastal ocean and therefore targeted low-tide conditions. Several surveys were made to characterize differences at high tides and between flooding and ebbing tides and to determine associated fluxes of SGD ocurring between tidal states.

In December 2003 (USGS Infobank Activity ID A-8-03-HW), surveys were made during spring-tide conditions and spanned high and low tide states (fig. 6). Winds during the survey were generally low (<5 m/s) but increased to approximately 10 m/s on the last survey day. Winds blew generally offshore (from the ENE) in the early morning and onshore (from the SW) by the middle of the day. On the last survey day, the stronger winds blew from the north. Air temperatures ranged from 21ºC at night and early morning to 27 to 28ºC in the early afternoons. On the first survey day (December 11) the temperature reached 30ºC. This survey was conducted during an unusually dry period. The total rainfall for the preceding month of November was 5 mm, nearly 27 mm below the mean precipitation for that same month during the period from 1981 to 2000 (http://www.soest.hawaii.edu/MET/Hsco/ppt.htm, accessed November 19, 2009). Only a trace of precipitation was recorded during the survey at the Kona International Airport ASOS station during the early morning on the last day of the survey.

In April 2004 (A-4-04-HW), surveys were conducted during a transition from neap to spring tides and measurements were made mostly at low tides, except on the first day, when data included flooding and high-tide conditions (fig. 7). Winds during the survey were generally low (<5 m/s) except for the last survey day, when they exceeded approximately 10 m/s. Winds blew generally offshore (from the ESE) at night and in the early morning and onshore (from the WSW) by the middle of the day. During the last survey day, stronger winds blew from the north. Air temperatures ranged from 22ºC at night and early morning to 27 to 28ºC in the early afternoon. This survey was conducted during an unusually wet period. The total precipitation for April 2004 was 44 mm, much greater than the mean precipitation of 15 mm for the same month in the time period between 1981 and 2000. Roughly 35.5 mm of that precipitation occurred during the survey, mostly during the nighttime and early morning hours. On the morning of the second day of surveys (April 21, 2004), 18.5 mm of rain fell in a 4-hour period ending roughly 1.5 hours before the first CTD cast was performed that day.

In August 2004 (A-6-04-HW), surveys were conducted during a transition from spring to neap tides, and measurements were made mostly during middle to high tides (fig. 8). Winds during the survey varied from southerly in the early morning to westerly in the middle part of the day, to northerly in the later afternoon and were between 5 and 10 m/s. Air temperatures ranged from 23 to 26ºC at night and early morning to 30 to 32ºC in the late afternoon. This survey occurred during a period that was somewhat drier than normal. During the preceding month of July, 5 mm of precipitation accumulated, compared to a mean of 20 mm for the month of July in the period between 1981 and 2000. In the early morning of the second day of the survey (August 3, 2004), a burst of precipitation occurred, with 15.5 mm of rain falling within a 6-hour period ending roughly 3.5 hours from the first cast of the day.

In August 2005 (A-1-05-HW), surveys were conducted during the end of spring tides and measurements were made during low tides, flooding, and high tides (fig. 9). Winds during the survey were generally low (<5 m/s) and blew onshore or from the south, except for brief periods in the late night and early morning hours. Air temperatures ranged from 22ºC at

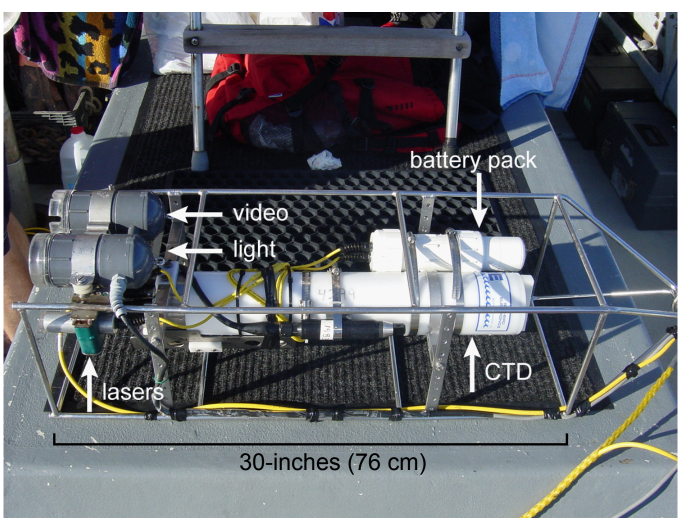
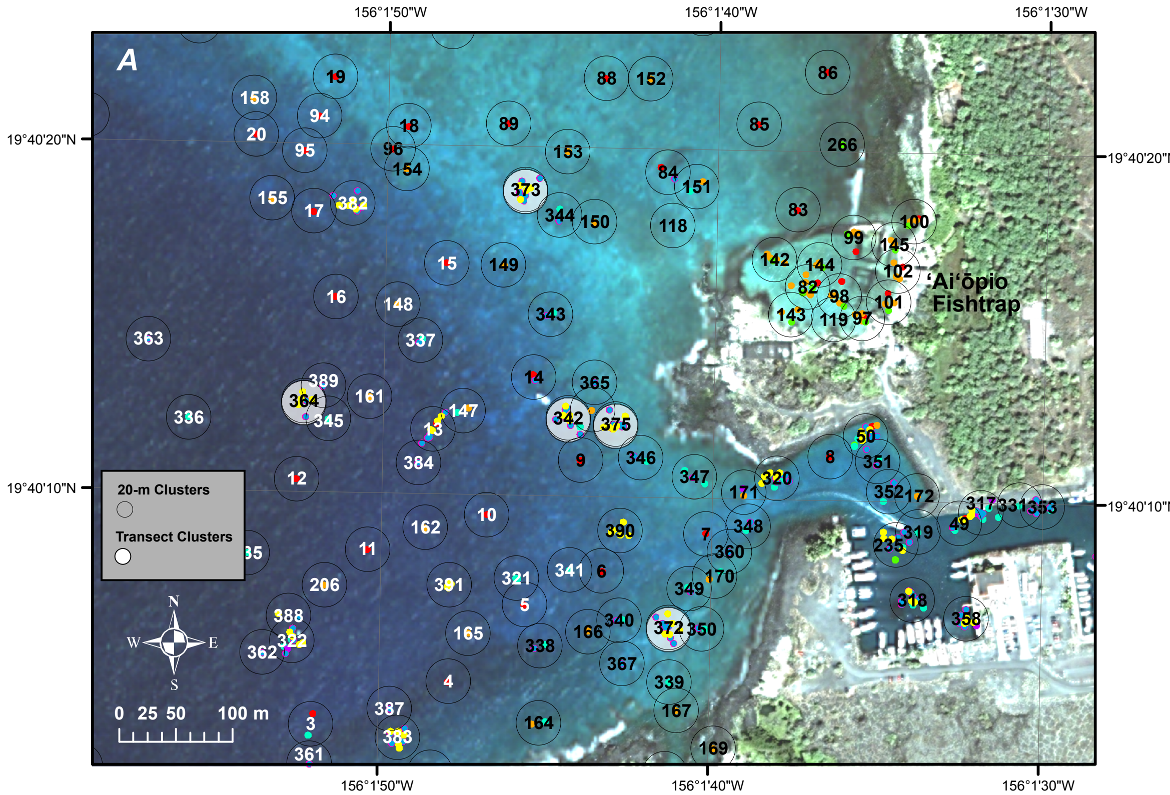


Figure 4. Photograph of Seabird CTD with underwater video camera configuration. Sensor specification are provided in Appendix II.



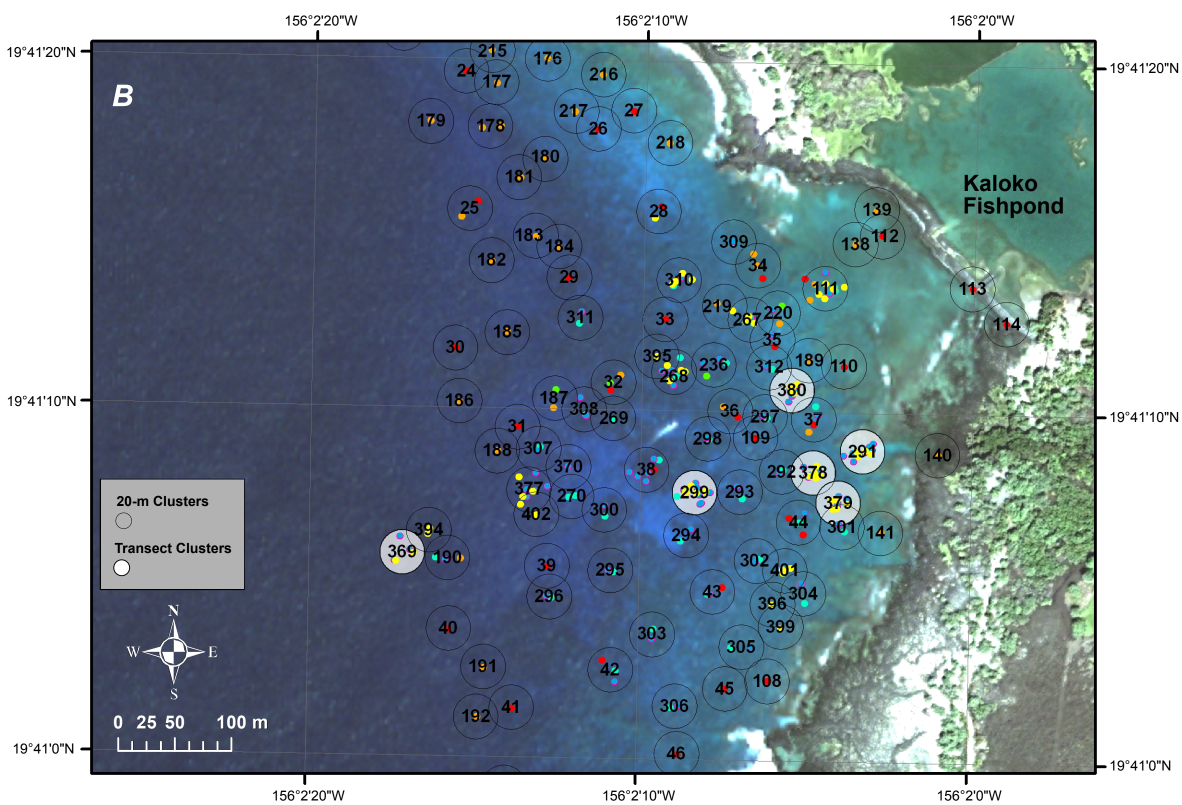


Figure 5. Maps of the harbor entrance area (*A*) and area offshore of Kaloko Fishpond (*B*) showing 20-m cluster stations.

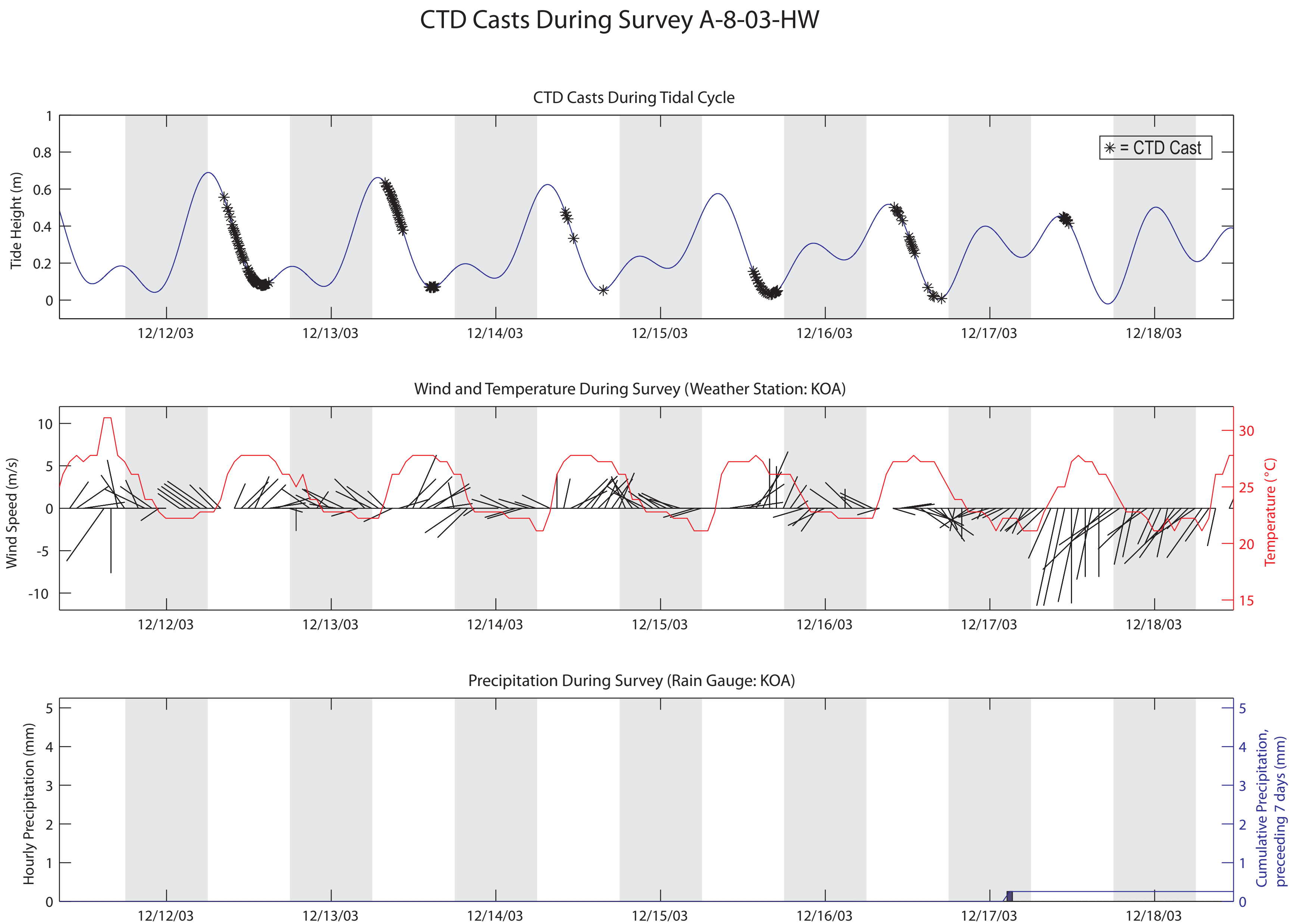


Figure 6. Environmental conditions during December 2003 surveys, including tidal stage, wind speed, temperature, and precipitation.

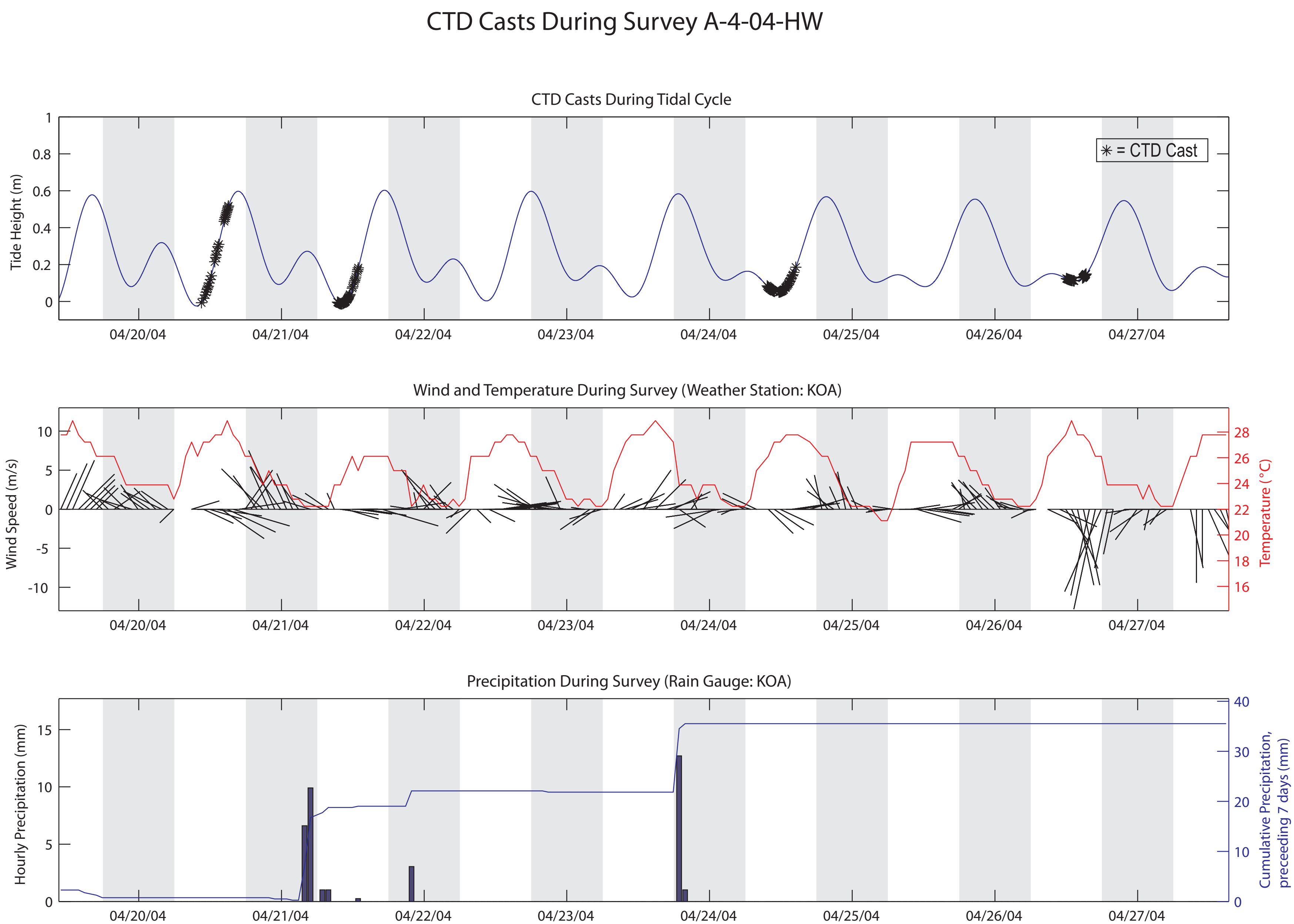


Figure 7. Environmental conditions during April 2004 surveys, including tidal stage, wind speed, temperature, and precipitation.

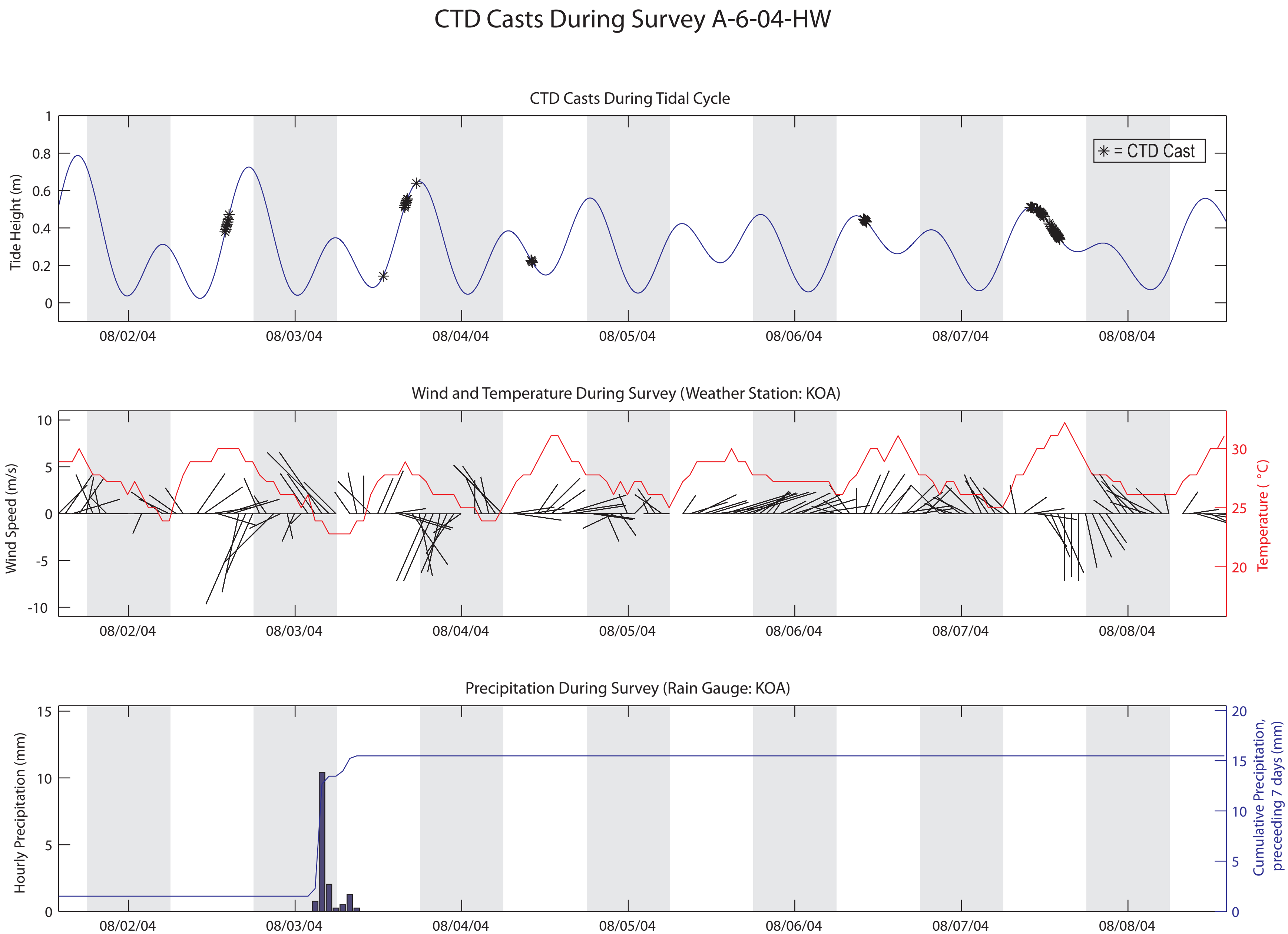


Figure 8. Environmental conditions during August 2004 surveys, including tidal stage, wind speed, temperature, and precipitation.

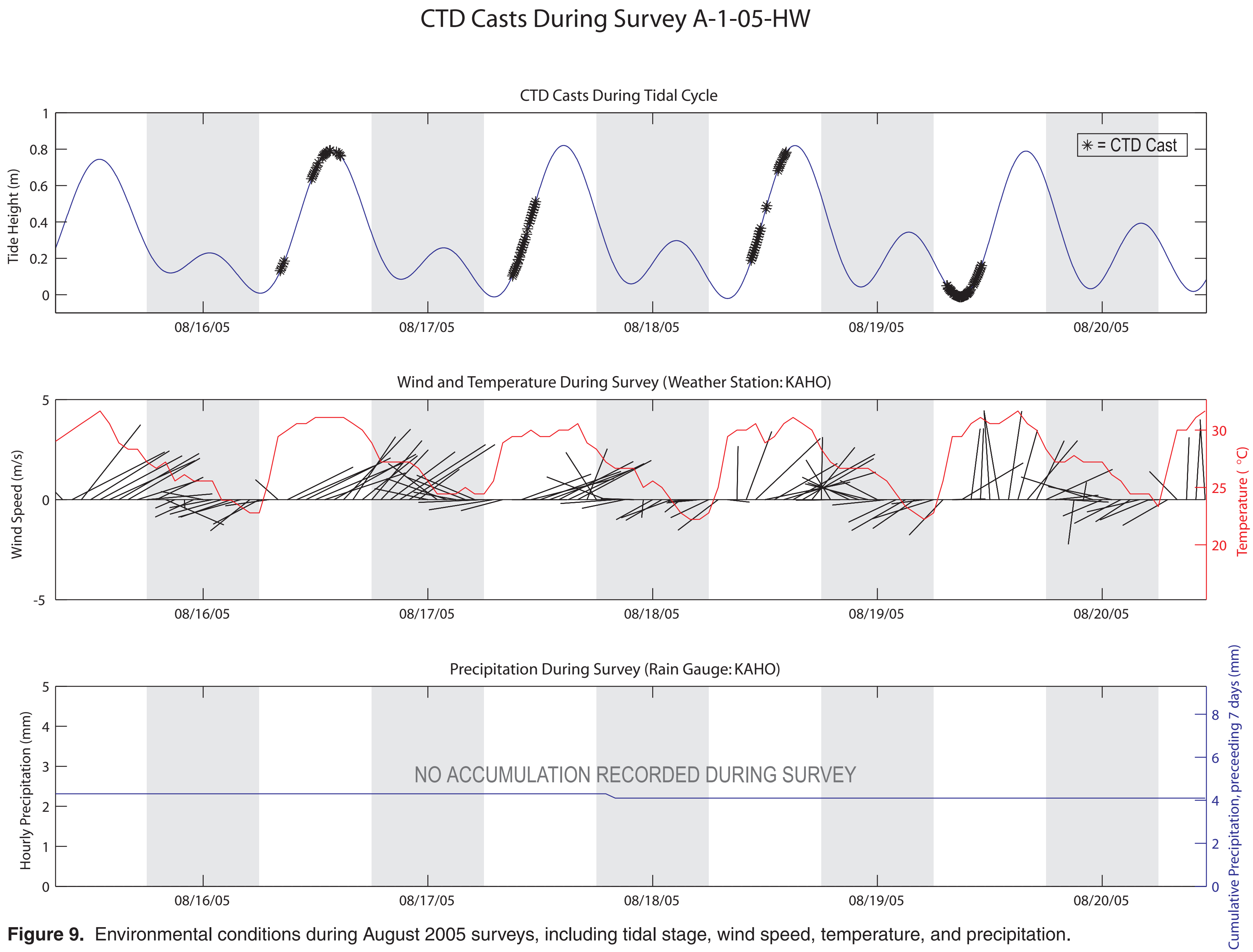


Figure 9. Environmental conditions during August 2005 surveys, including tidal stage, wind speed, temperature, and precipitation.

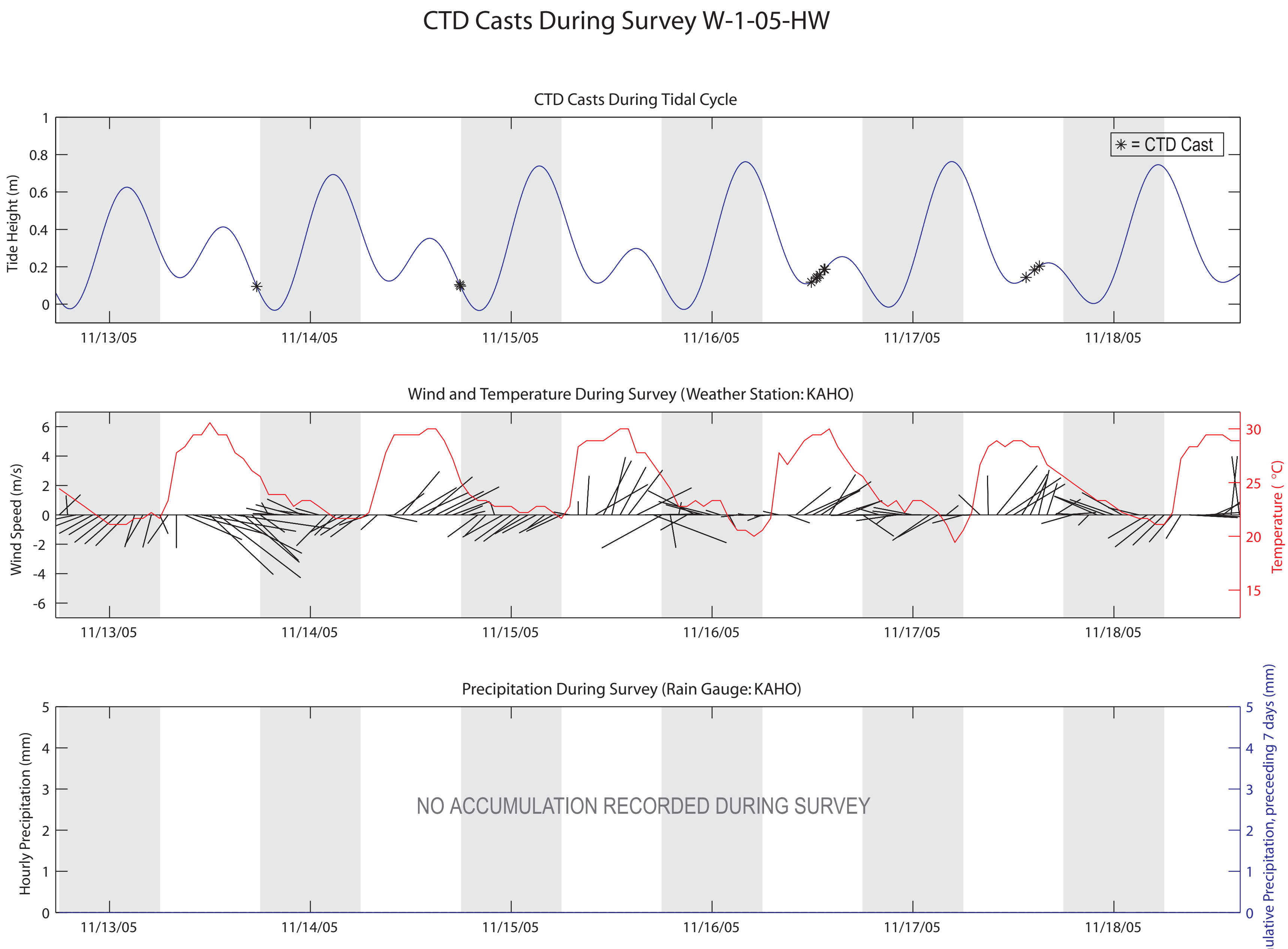


Figure 10. Environmental conditions during November 2005 surveys, including tidal stage, wind speed, temperature, and precipitation.

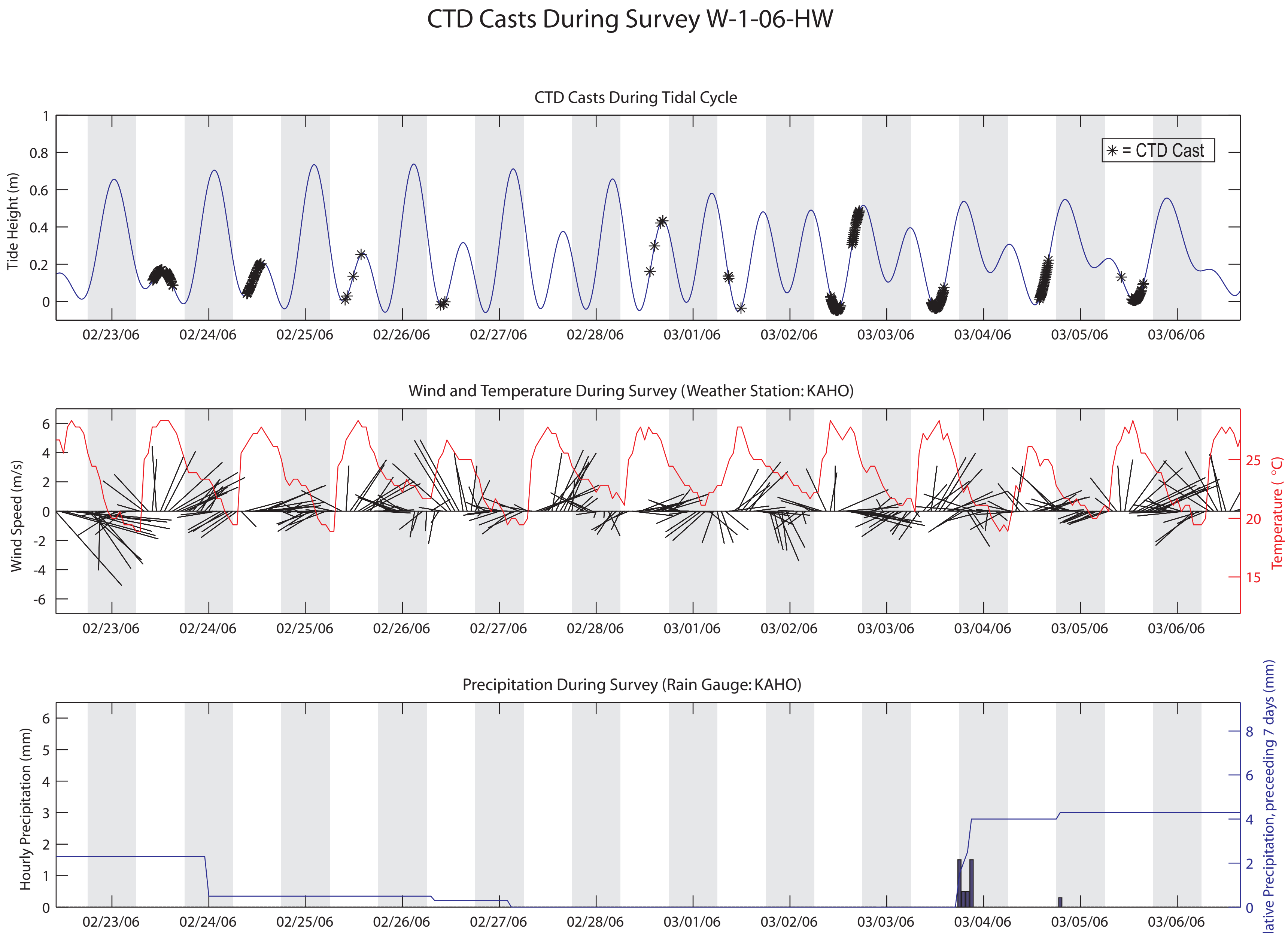


Figure 11. Environmental conditions during November 2006 surveys, including tidal stage, wind speed, temperature, and precipitation.

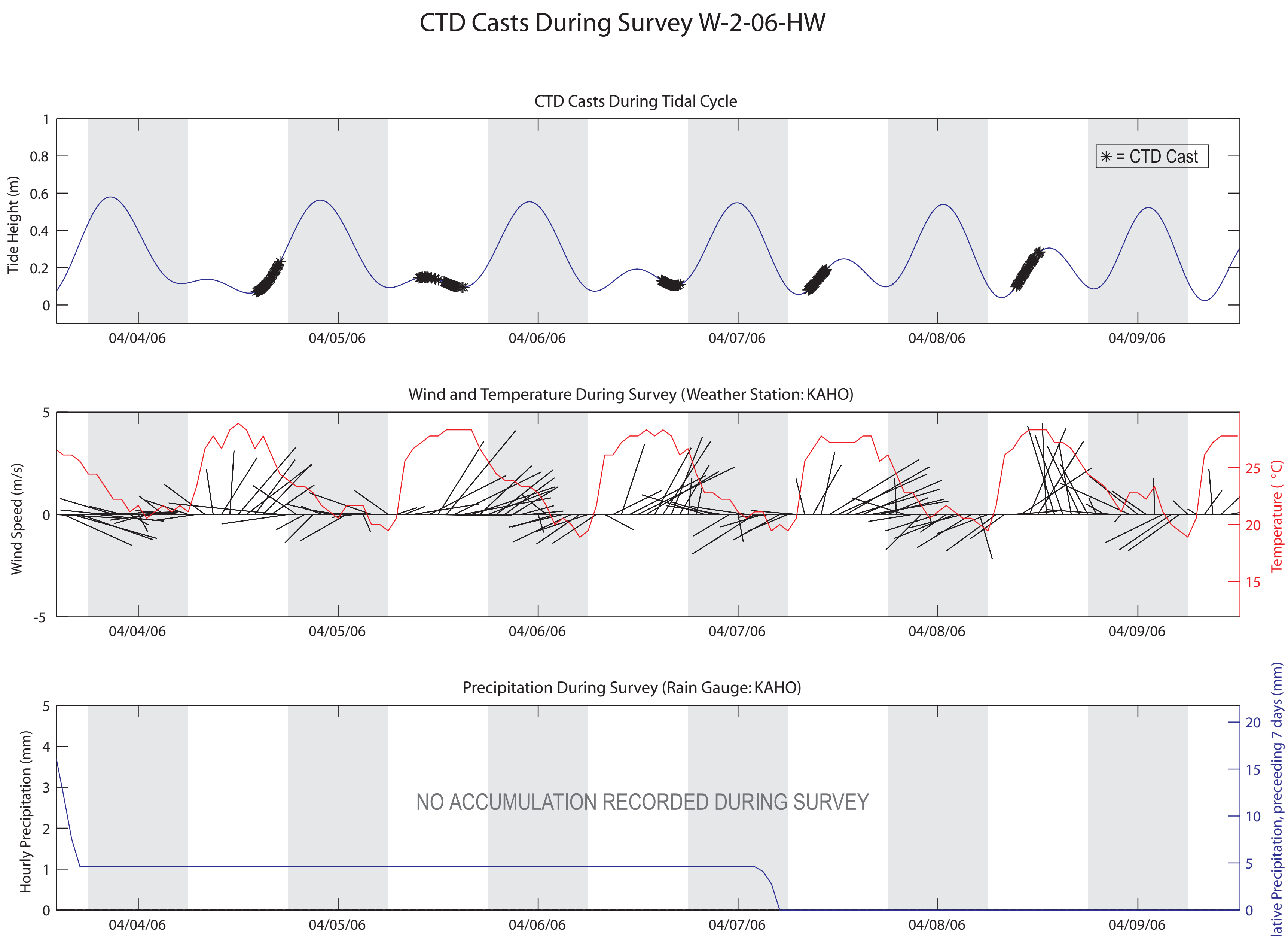


Figure 12. Environmental conditions during February/March 2006 surveys, including tidal stage, wind speed, temperature, and precipitation.

night and early morning to 31 to 32ºC in the middle afternoon. No precipitation was recorded during this survey at the Park RAWS meteorological station. The survey was conducted during a period that was slightly wetter than the mean. During July and August of 2005, the cumulative precipitation recorded was 28.5 mm and 34.25 mm respectively, compared to an average of 16 mm and 20 mm for those months during the time period between 1981 and 2000 (measured at the Kona International Airport, Keahole Point (KOA)).

In November 2005 (W-1-05-HW), surveys were conducted during low tides near the end of a neap tide cycle (fig. 10). Large swell prohibited profiling for several days, and as a result, fewer samples were collected. Winds during the survey were generally low (<3 m/s), blew offshore (from the ENE) at night and early morning, and blew onshore (from the WSW) in the afternoons. Air temperatures ranged from 20ºC at night and early morning to 30ºC in the middle afternoon. This survey was conducted during a drier than normal period. No precipitation was recorded during our survey at the Park RAWS meteorological station. Total precipitation for October and November of 2005 were 6.5 mm and 2.75 mm of precipition, compared to an average of 19 mm and 33 mm for those months during the time period between 1981 and 2000.

In February and March 2006 (W-1-06-HW), surveys were conducted during the lower of spring high tides early in the survey and over low, flooding, and near-high tides in the neap tide cycle near the end of the survey (fig. 11). Winds during the survey ranged 3-5 m/s and blew offshore (from the NNE) or from the north at night and early morning and onshore (from the WSW) in the afternoons. Air temperatures ranged from 20ºC at night and early morning to 28ºC in the middle afternoon. A small precipitation event occurred during the later part of this survey: 4 mm of precipitation occurred during a 4-hour period on the afternoon of March 3, 2004. A trace of precipitation occurred during the evening of the following day also. In the preceding month of February, the Park RAWS station recorded 2.25 mm of accumulated precipitation, compared to an average of 26.2 mm for the month of February in the period between 1981 and 2000.

In April 2006 (W-2-06-HW), surveys were conducted mostly during low tides near the end of a spring cycle and on flooding tides early in the following neap tide cycle (fig. 12). Winds during the survey ranged from 3 to 5 m/s and blew offshore (from the NNE) at night and early morning, from the south in the middle morning, and onshore (from the SSW) in the afternoons. Air temperatures ranged from 20ºC at night and early morning to 28ºC in the middle afternoon. In the preceding month of March, 77.25 mm of precipitation accumulated. Athough no precipitation was recorded during the survey, 4.75 mm accumulated during the preceding week.

Results and Discussion

This section reviews the data collected and examines the spatial and temporal variability in surface water temperature and salinity, the spatial patterns and changes in SGD plumes, and their relation to estimates of SGD flux into the coastal ocean, in order to explore the fate of SGD and associated nutrients discharged into the Park's nearshore waters. The entire data set of CTD profiles may be downloaded from the report website (http://www.usgs.gov/sir/2010/5081/) and on CD (upon request). Representative examples of key features of the nearshore water properties are presented in detail below.

Profiles of Temperature and Salinity with Depth

The typical profile of temperature and salinity with depth in nearshore waters where SGD is present has lower salinity and generally lower temperature (than offshore) at the surface above a prominent inflection point in salinity and often temperature (fig. 13A). Below the inflection, salinity generally remains uniform or increases slightly with increasing depth, while temperature generally decreases steadily with increasing depth. The salinity inflection point marks the depth at which the buoyant, less dense, fresh-to-brackish groundwater floats on top of and mixes with the deeper, more saline marine water. The temperature inflection may occur with the salinity inflection or vary in depth, depending on localized warming or cooling in response to changes in insolation or mixing. The inflection point becomes less pronounced and shallower (plume thickness decreases) with distance offshore as the groundwater-fed surface lens mixes and diffuses with offshore marine water. The "marine" end-member water mass offshore has a profile of temperature and salinity with depth that is generally characterized by uniform salinity and either uniform or steadily decreasing temperature with increasing depth (fig. 13B). This uniformity likely reflects thorough mixing with depth and the influence of solar insolation having preferentially warmed the surface waters. In some cases, more than one inflection point in temperature and/or salinity occurrs, indicating more than one unique water mass at depth.

The depth at which the inflection point occurrs marks the thickness of the upper water mass, and for the present study this depth is used to calculate the thickness, characterize the temperature and salinity, and determine the spatial and temporal extent and variability of the SGD plumes. The SGD plumes observed between 2003 and 2006 ranged in thickness from 1 to 5 m, with an typical thickness of 2.0 to 2.5 m, and extended between several m to approximately 1,000 m from shore.

Variation in Water Properties at Principal Study Transects and Control Sites

Water properties across the nearshore of Kaloko-Honokōhau NHP are characterized by a prominent brackish groundwater plume close to shore, ranging from 1 to 5 m thick, off of Honokōhau Small Boat Harbor and the ʻAiʻōpio Fishtrap area in the south and Kaloko Fishpond in the north. The plumes gradually thin offshore.

South Study Transect

At the landward central station (cluster 375, fig. 5A) located in 3- to 5-m water depth, temperatures ranged from 24.0 to 25.5ºC and salinities ranged from 31 to 35 practical salinity units (PSU) (fig. 14). During each of the 11 surveys within cluster 375, a surface plume of lower salinity water that ranged between 1.0 and 2.5 m thick was observed. Most often temperature was positively correlated with salinity through the water column, but occasionally the surface plume had higher temperature than observed at depth, perhaps as a result of daily insolation or mixing with warmer waters advected from elsewhere (fig. 14B, D). At the furthest landward station in the south (cluster 372, fig. 5B) in water depths of 3 to 4 m, a surface plume of brackish water was evident on all surveys and ranged from 0.5 to 2.5 m thick (fig. 15). The temperatures in this surface plume ranged from 23.8 to 25.5ºC, and salinities ranged from 25 to 35 PSU. This site showed slightly more brackish conditions and greater variability in temperature within the surface plume than cluster 375 to the north. The most landward station on the north end of this transect (cluster 373, fig. 5A), in water depths of 3 to 8 m, had temperatures ranging from 24.0 to 25.5ºC and salinities ranging from 28 to 35 PSU (fig. 16), slightly fresher than cluster 375 and slightly more saline than cluster 372. The surface plumes in this northern area ranged from 0.5 to 2.0 m thick and were present in each survey except one, when strong west to northwest winds occurred and presumably mixed the water column thoroughly (fig. 16C). At the central station (cluster 342, fig. 5A) located in water depths of 3.0 to 7.5 m, temperatures ranged from 24 to 28ºC, and salinities ranged from 31 to 35 PSU (fig. 17). A surface plume was present here during all surveys and ranged from 0.5 to 3.5 m thick. Generally, temperature was positively correlated with salinity, except in a few cases (fig. 17C, E, I) when slightly higher temperatures occurred with lower salinity. On average, cluster 342 was slightly more saline than the other more landward clusters. At the most

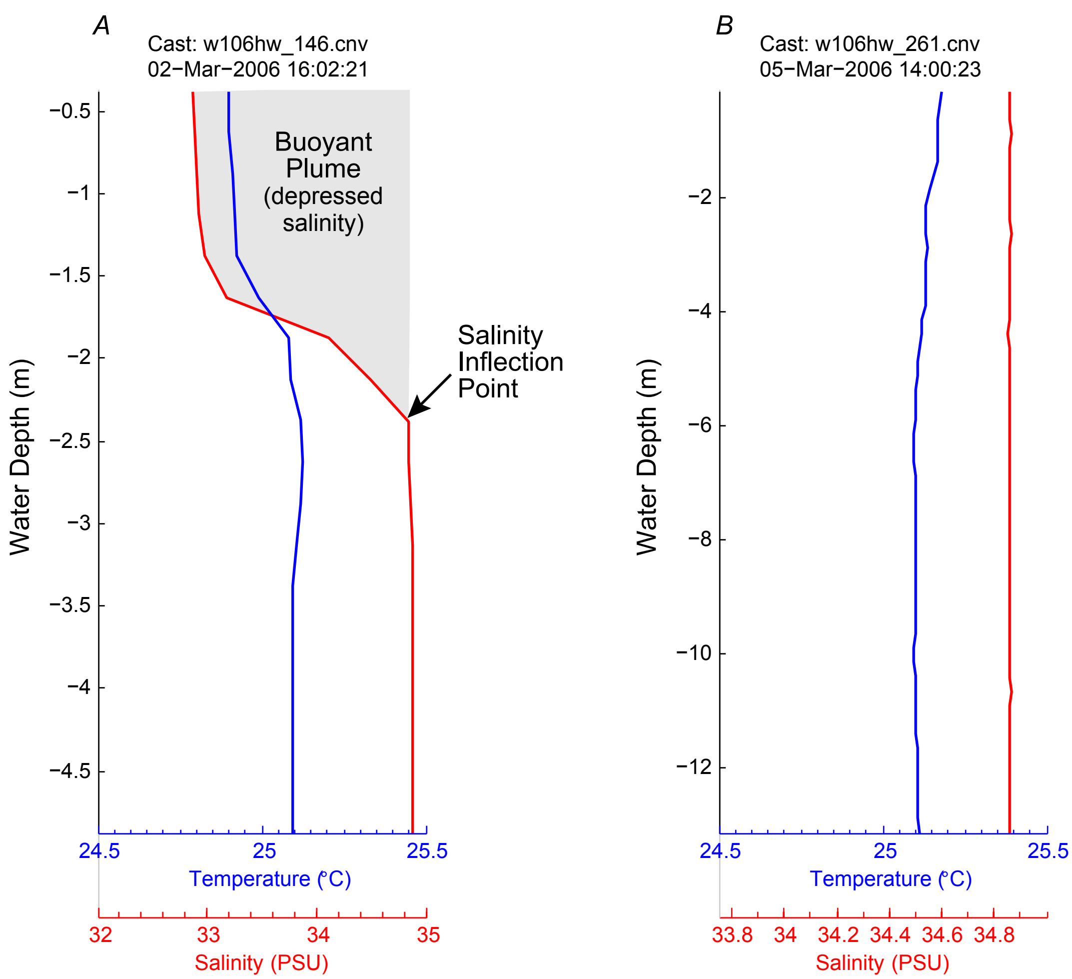


Figure 13. Examples of typical temperature and salinity profiles. (*A*) Example profile showing brackish surface lens, prominent salinity inflection point, and interpreted plume. (*B*) Example profile from offshore marine endmember.

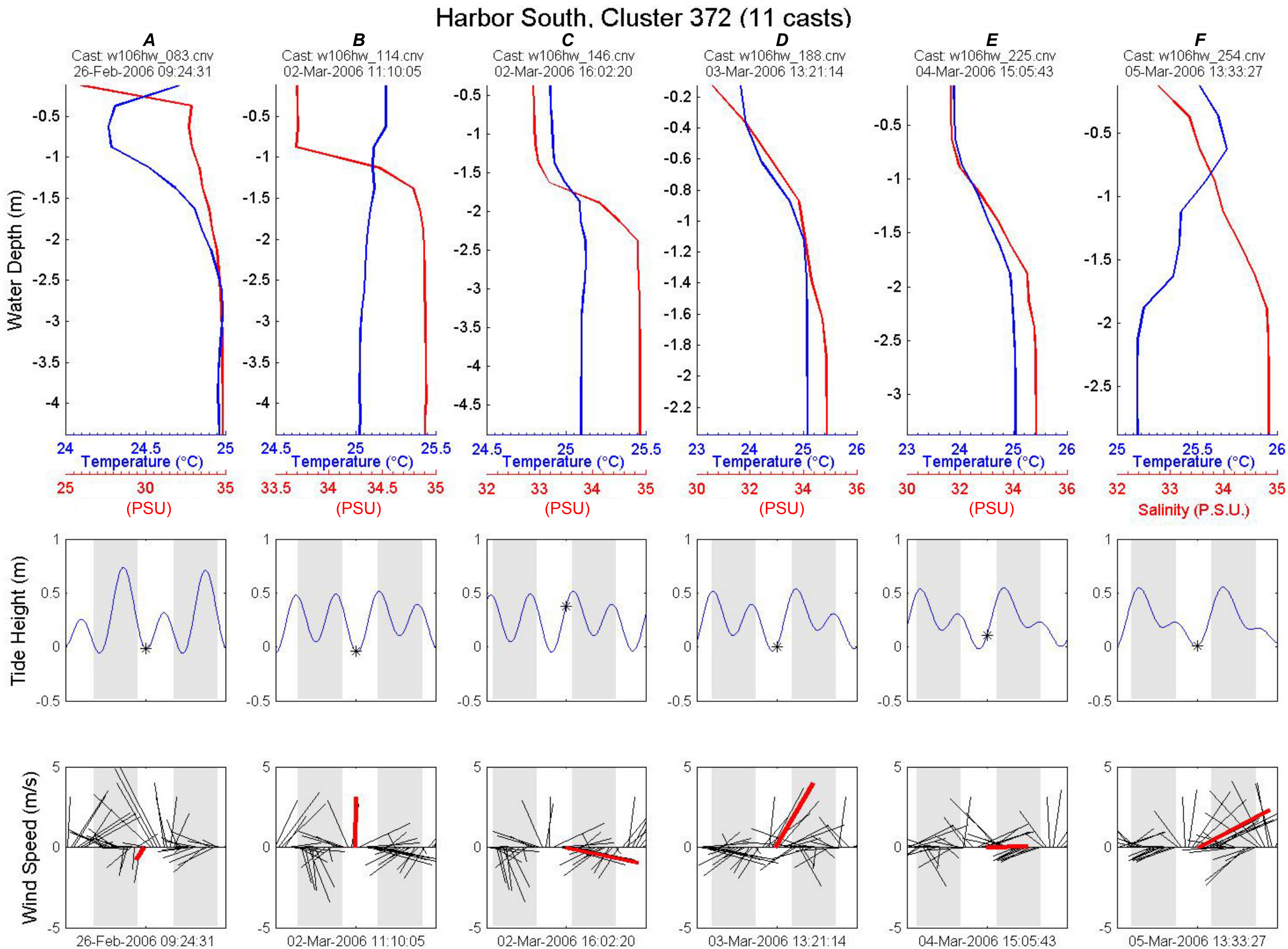
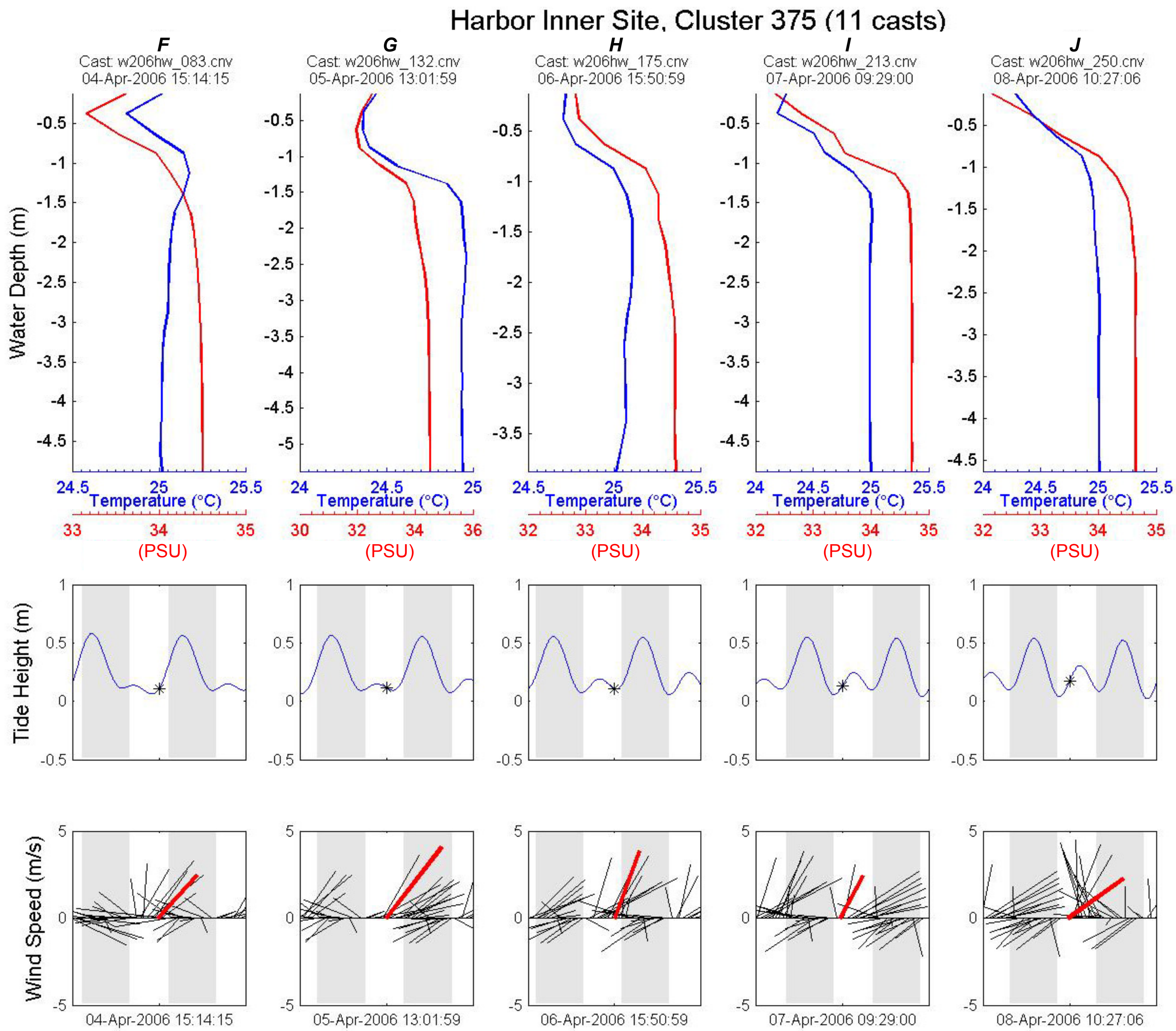


Figure 14. Temperature and salinity depth-profiles of cluster 375 located on the south study transect.



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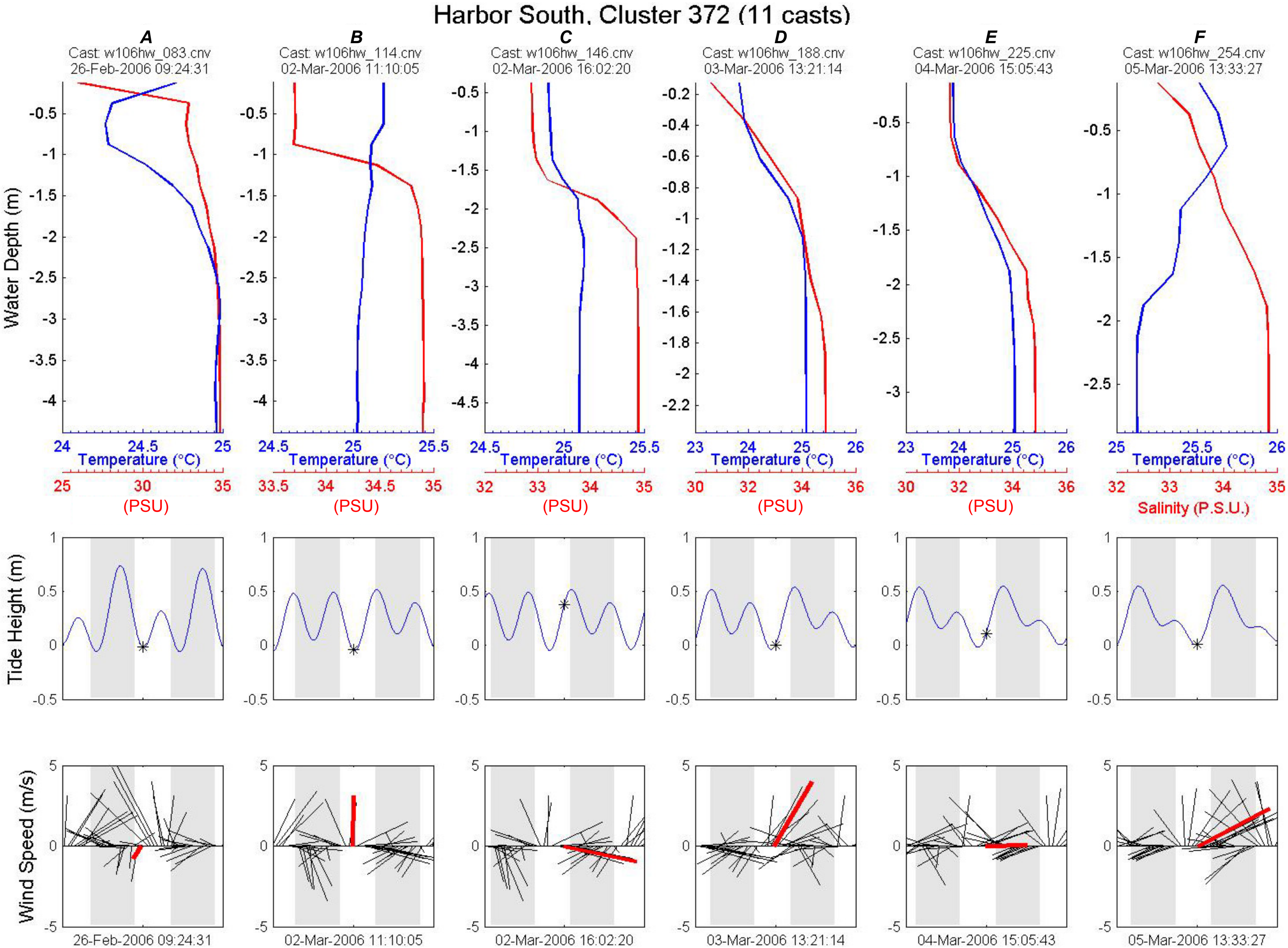
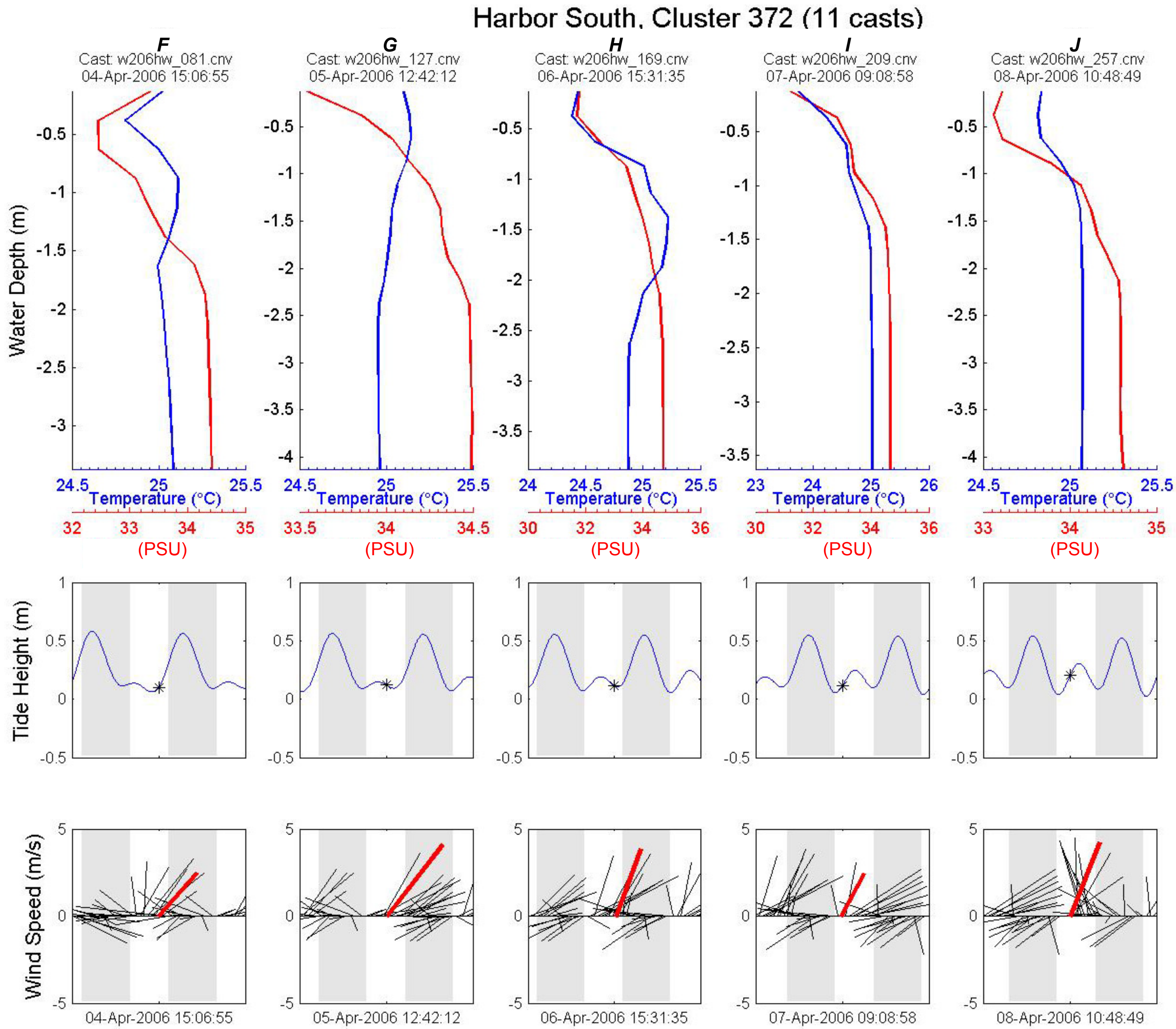


Figure 15. Temperature and salinity depth-profiles of cluster 372 located on the south study transect.



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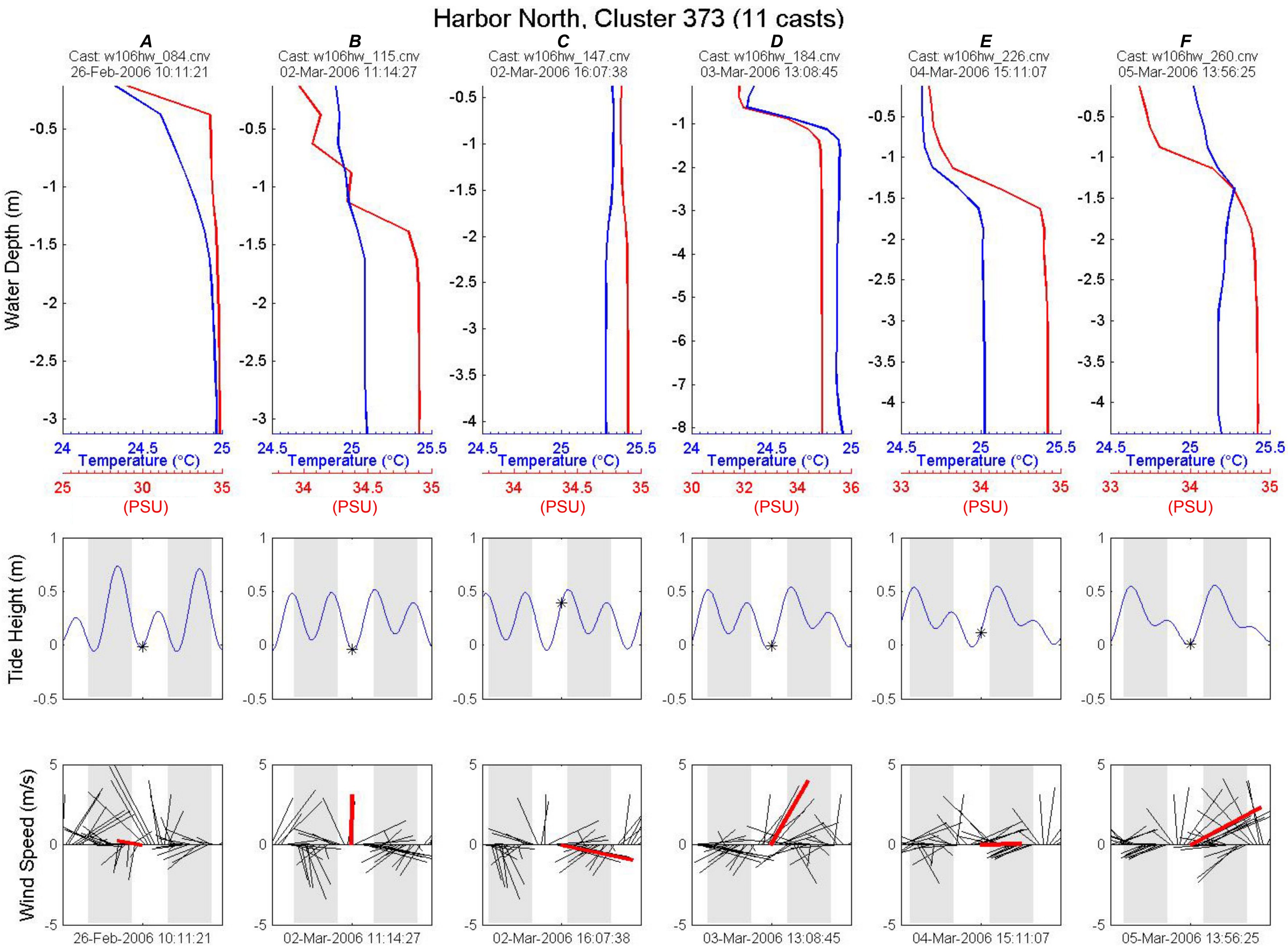
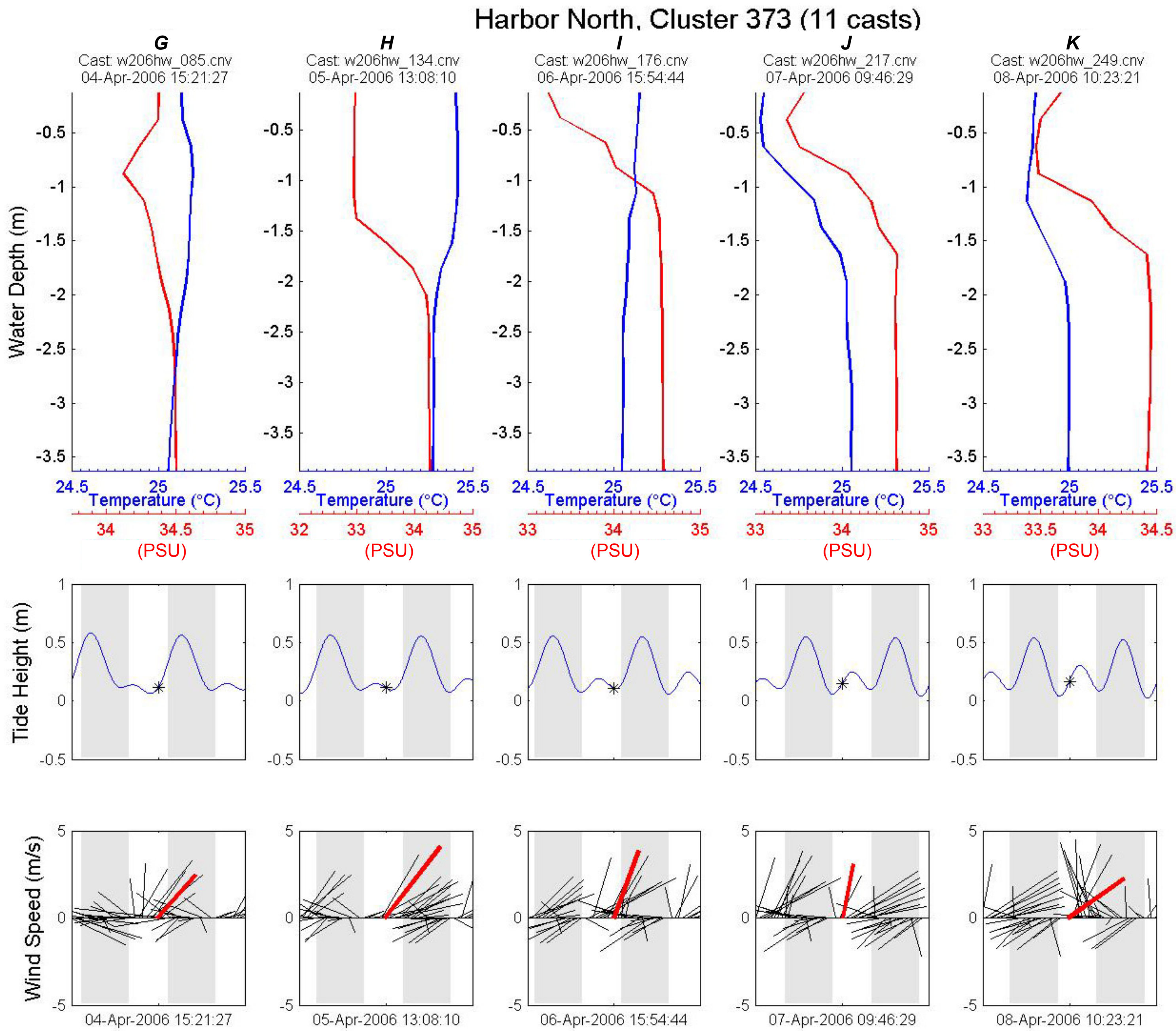


Figure 16. Temperature and salinity depth-profiles of cluster 373 located on the south study transect.



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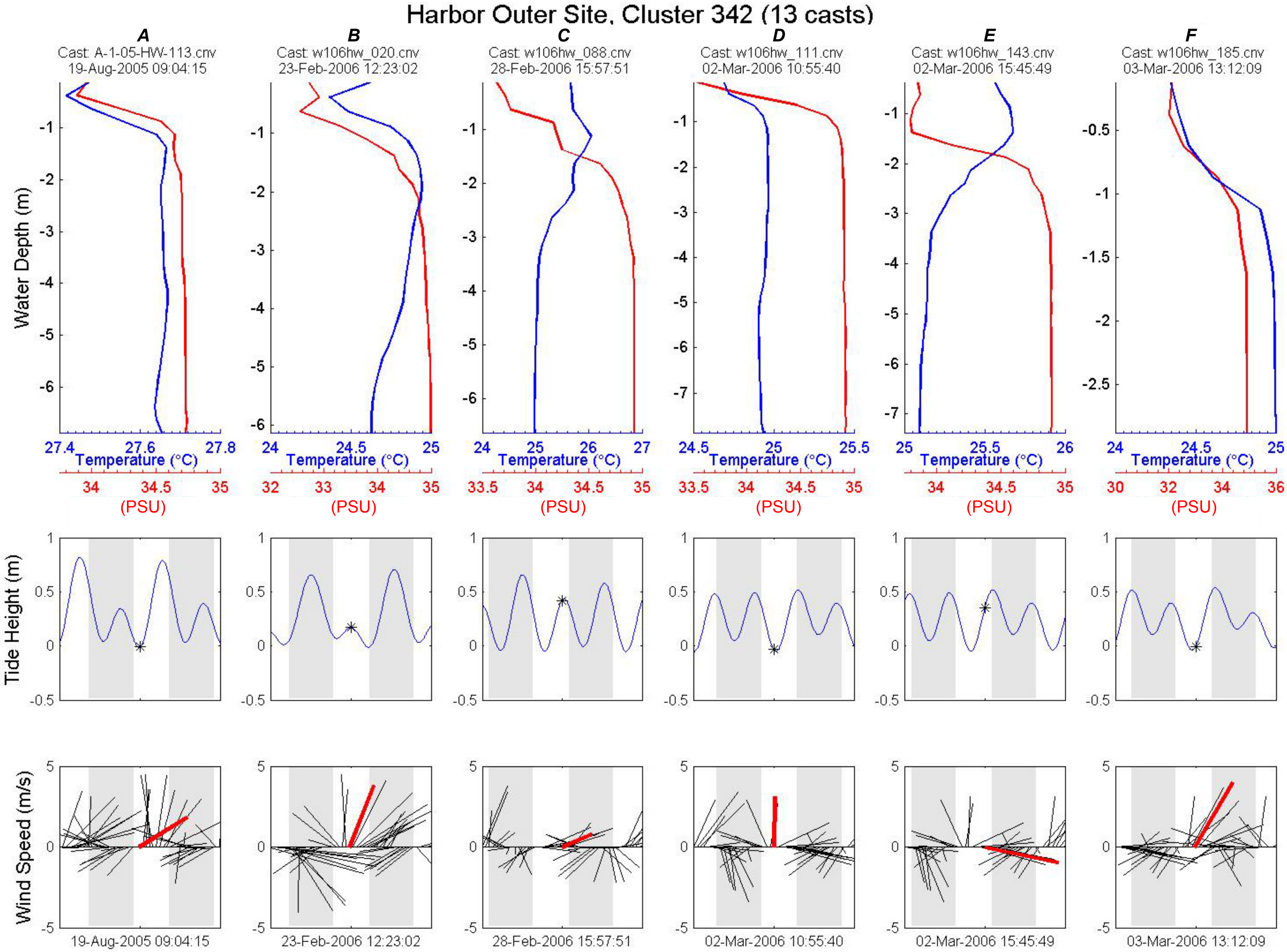


Figure 17. Temperature and salinity depth-profiles of cluster 342 located on the south study transect.

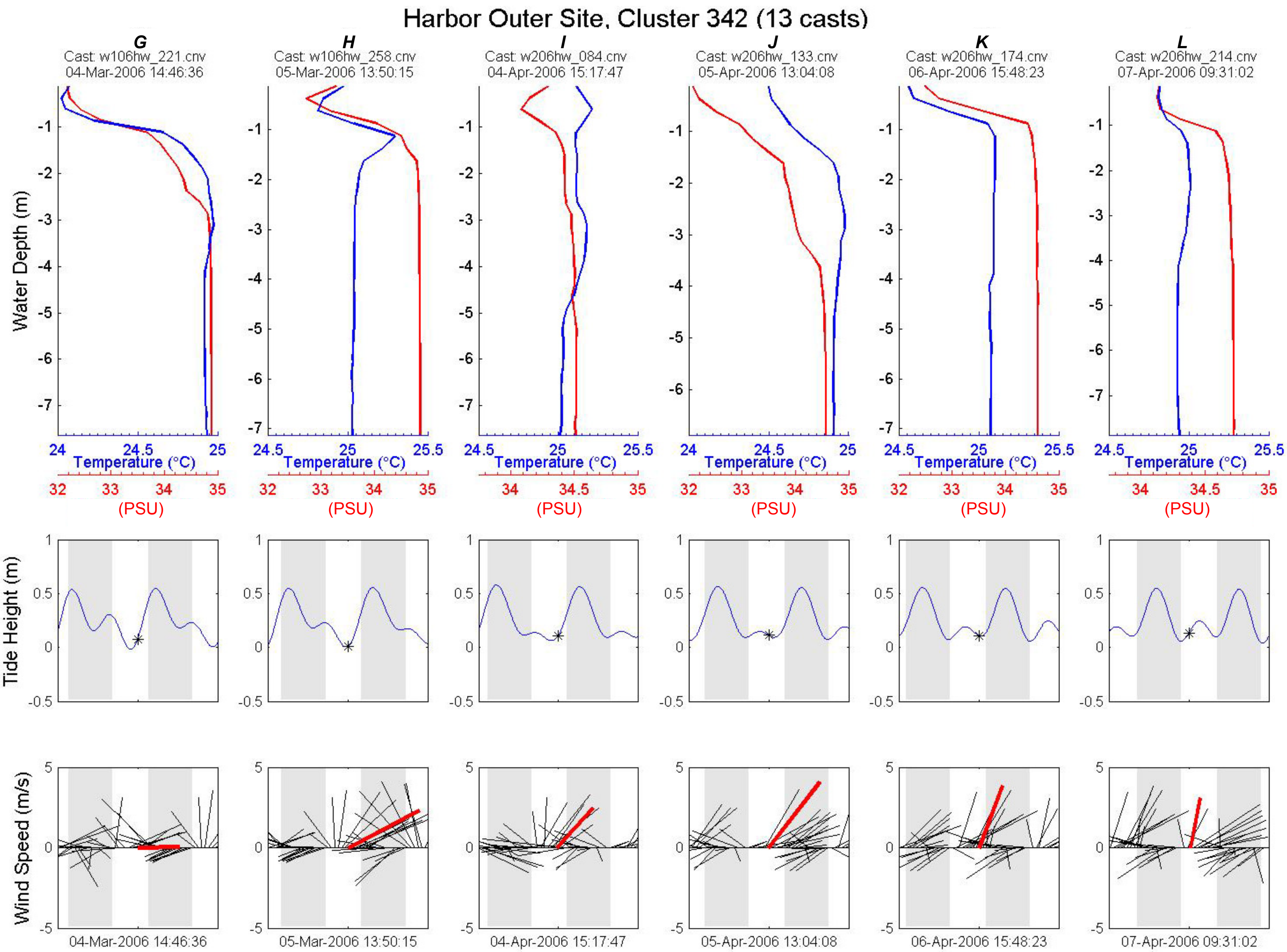
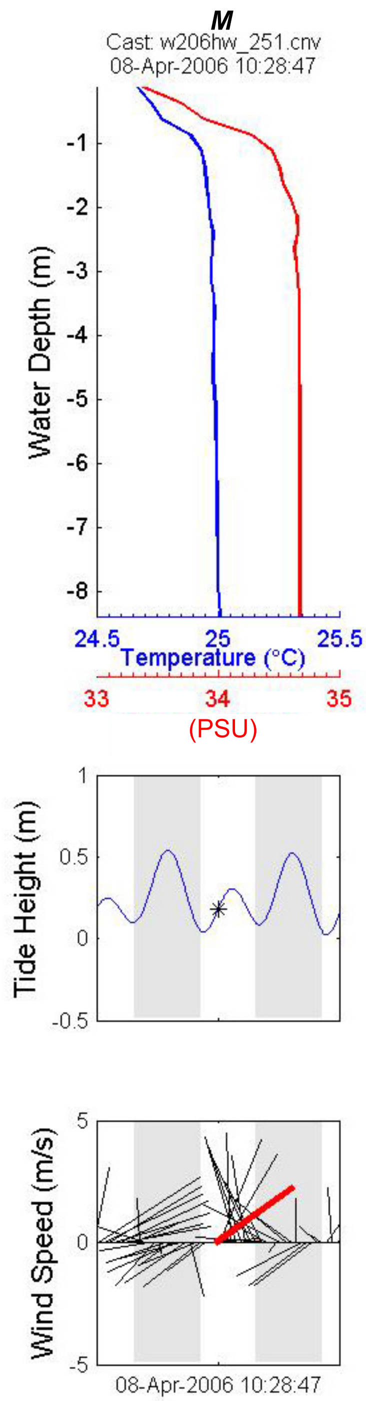


Figure 17—Continued.

offshore cluster (cluter 364, fig. 5A), a surface plume ranging from 1 to 3 m thick was observed on all surveys (fig. 18) except one, when the water column was well mixed to the bottom (fig. 18B), despite wind and wave conditions similar to other periods when plumes were present.



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North Study Transect

At the Kaloko "Cut," the landward central station of the north study transect (cluster 291, fig. 5B) located in water depths of 4 to 5 m, a prominent surface plume was observed during all surveys (fig. 19). Temperatures at the site ranged from 24.5 to 27.9ºC, and salinities ranged from 32.5 to 35.0 PSU. The surface plumes were generally from 1.0 to 3.5 m thick and consisted of water at 0.5ºC and 0.5 to 2.0 PSU lower than the bottom water. Occasionally, a lower salinity lens was observed at depth (fig. 19F, G, M). At the Kaloko landward south station (cluster 379, fig. 5B) in water depths of 4.5 to 7.0 m, a surface plume ranging from 2.0 to 4.5 m thick was observed during all surveys (fig. 20). Temperatures ranged consistently between 24.7 and 25.3ºC, and salinities ranged from 33.2 to 34.7 PSU. Generally, the surface plume varied only 0.5ºC and 0.5 PSU below the bottom water, but occasionally it was 1.0 to 1.5 PSU lower than the bottom water (fig. 20B, F). At the Kaloko landward north station (cluster 380, fig. 5B), at depths of 5.5 to 7.0 m, a lower salinity surface plume was observed during all surveys (fig. 21). The plume at cluster 380 ranged from 1.0 to 4.5 m thick. Generally, temperatures in the plume were similar to or within 0.5ºC of those at the sea floor, while salinity was, at most, 1.5 PSU lower at the surface than at the bottom. At the Kaloko central station (cluster 378, fig. 5B) in water depths of 6 to 14 m, a surface plume was present during all surveys (fig. 22). Temperatures at cluster 378 were less variable than at other stations along the transect and ranged from 24.7 to 25.1ºC. Salinities ranged from 33.5 to 34.8 PSU, with a surface plume generally 0.4 to 0.8 (maximum 1.4) PSU lower than the bottom water. At the seaward station, where the Kaloko instrument package was moored (cluster 299, fig. 5B) in water depths of 14 to 16 m, a surface plume was observed during all surveys (fig. 23). Temperatures ranged from 24.7 to 25.5ºC, and salinities ranged from 33.8 to 34.9 PSU. The plume at the surface commonly ranged from 2 to 4 m thick and once was observed to be 7 m thick (fig. 23F). Temperatures in the plume were generally about 0.2ºC lower than near the sea floor but occasionally were as much as 0.2 to 0.7ºC warmer than the bottom water (fig. 23D, I). Salinity in the plume at cluster 299 was generally 0.3 to 0.8 PSU lower than the bottom water. The most seaward cluster offshore of Kaloko Fishpond (cluster 369, fig. 5B) showed a surface plume ranging from 1 to 5 m thick; half of the observations showed the water column well mixed to the bottom (fig. 24).

Control Sites

Offshore at control site cluster 376 (fig. 3) in water depths of 10.5 to 12.5 m, a surface plume was detected in more than half of the surveys and ranged from 2.0 to 4.5 m thick (fig. 25). When a plume was present, its temperature varied by 0.5ºC (both colder and warmer than bottom water) and salinity was as much as 0.6 PSU lower than bottom

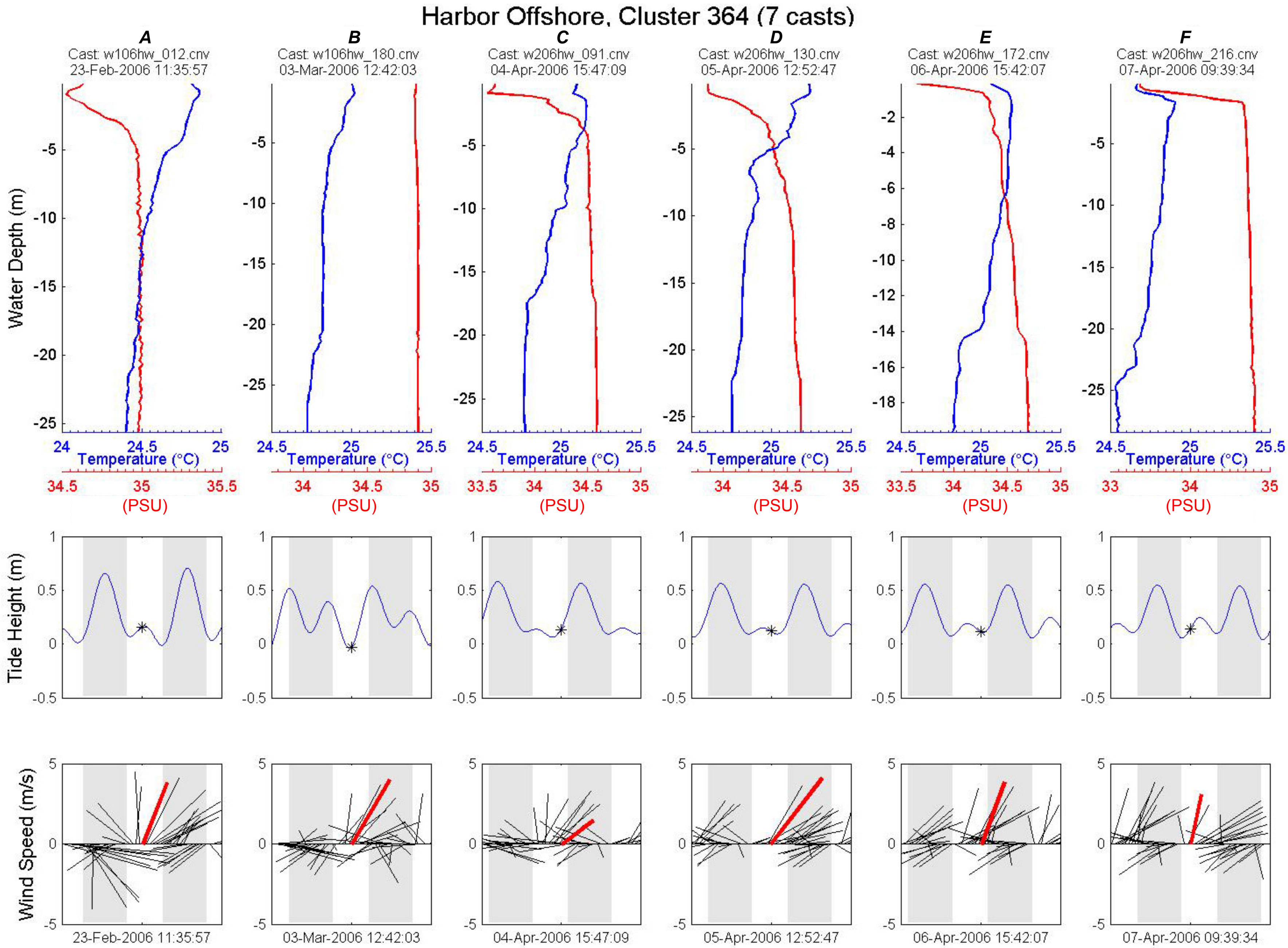
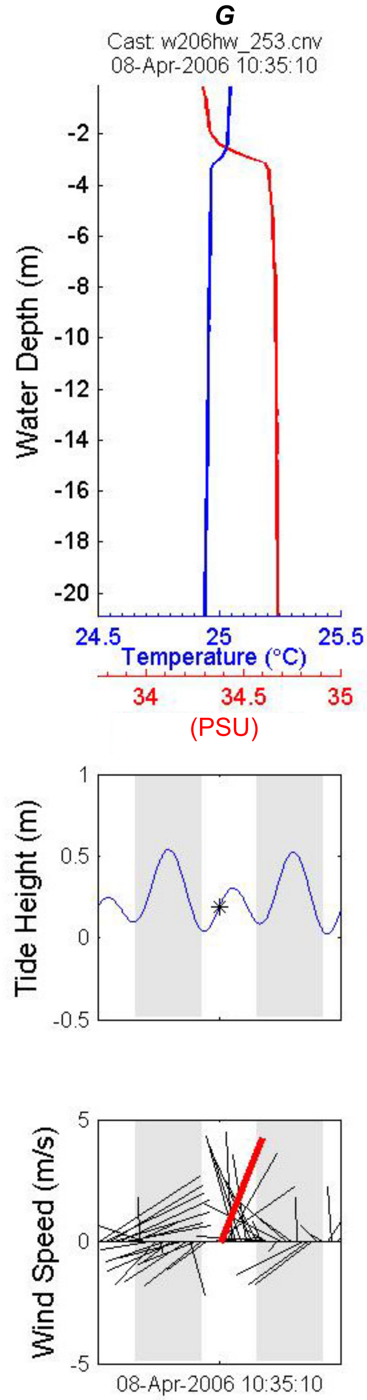


Figure 18. Temperature and salinity depth-profiles of cluster 364 located on the south study transect.



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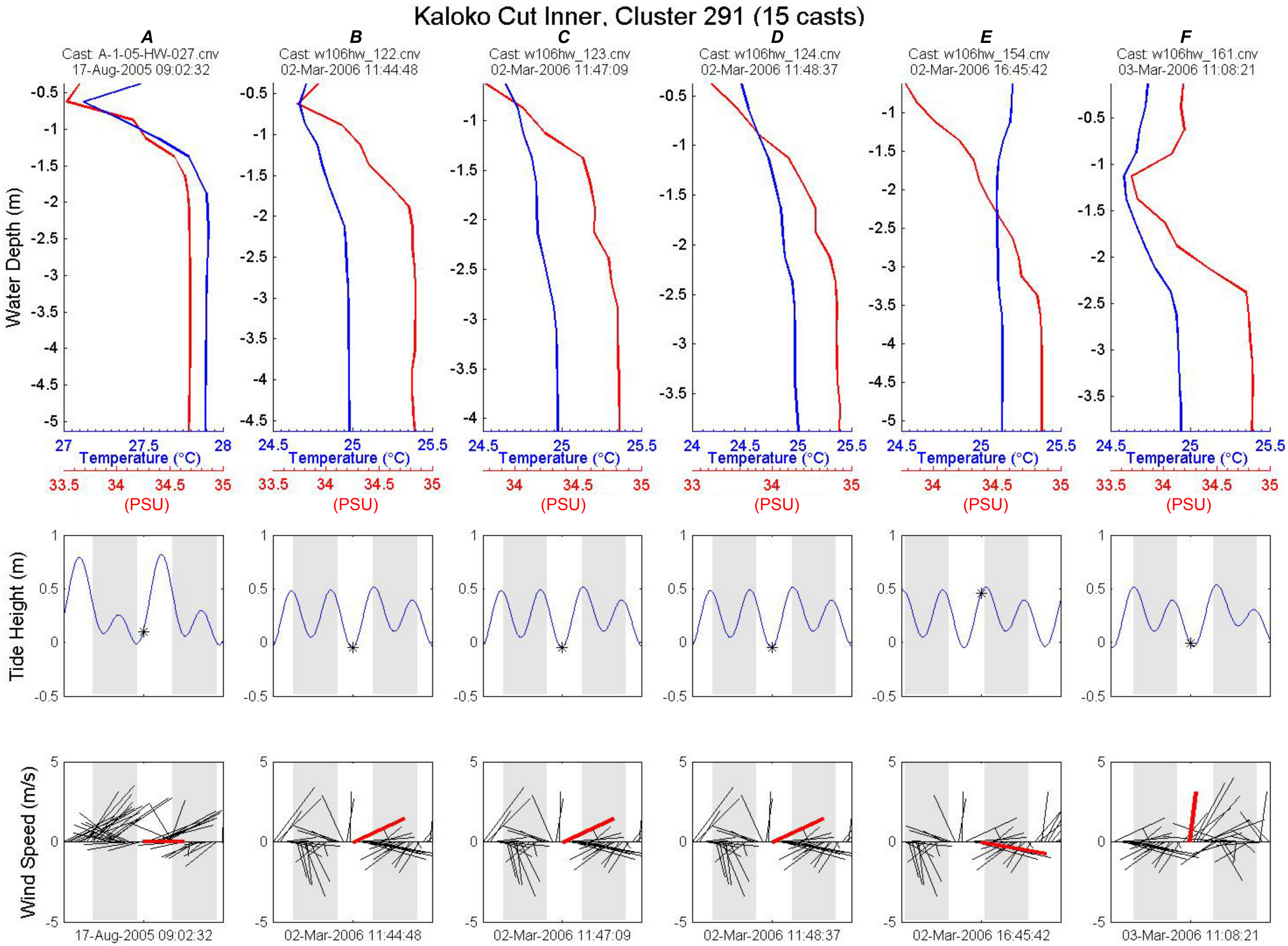
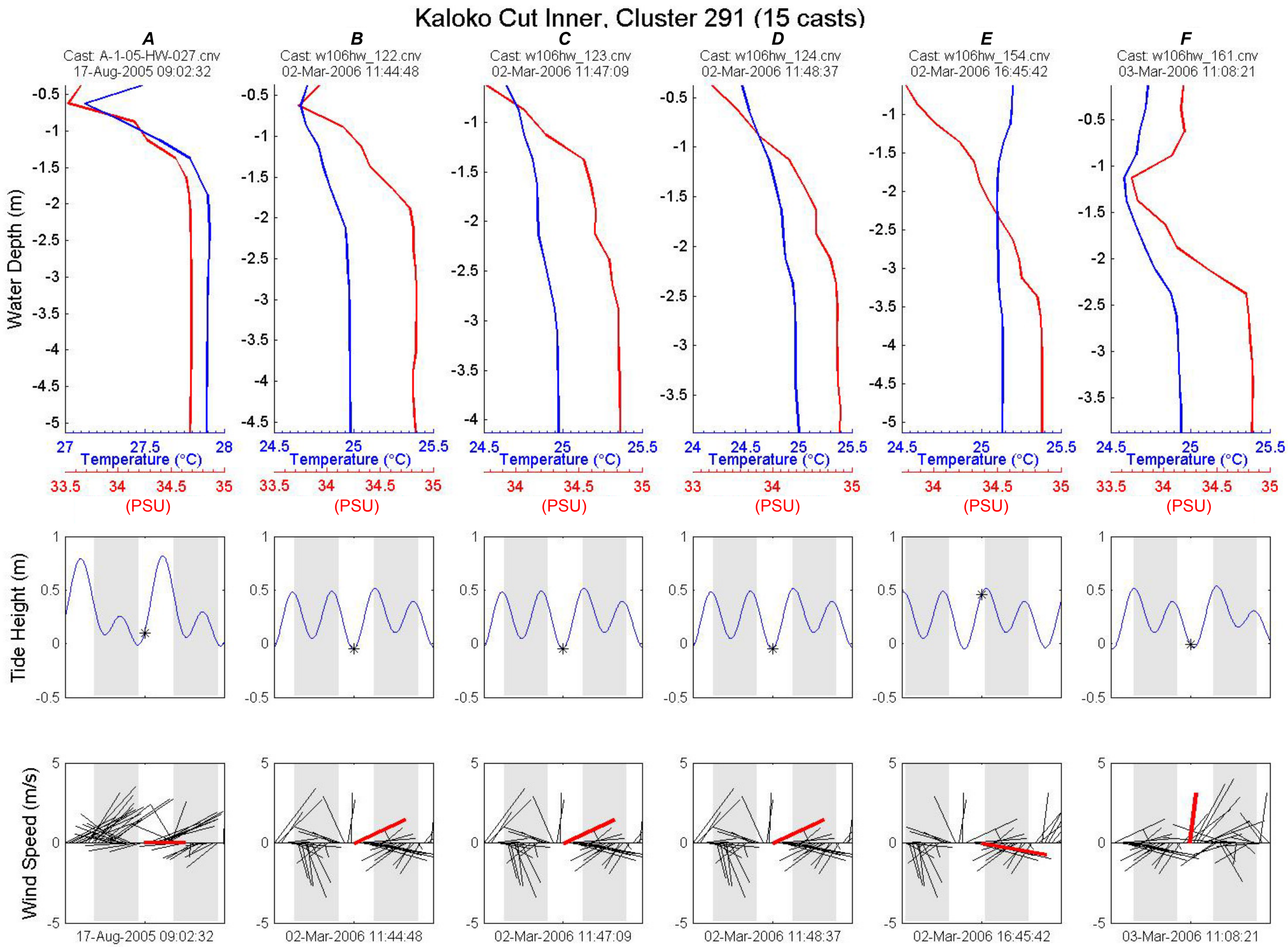


Figure 19. Temperature and salinity depth-profiles of cluster 291 located on the north study transect.



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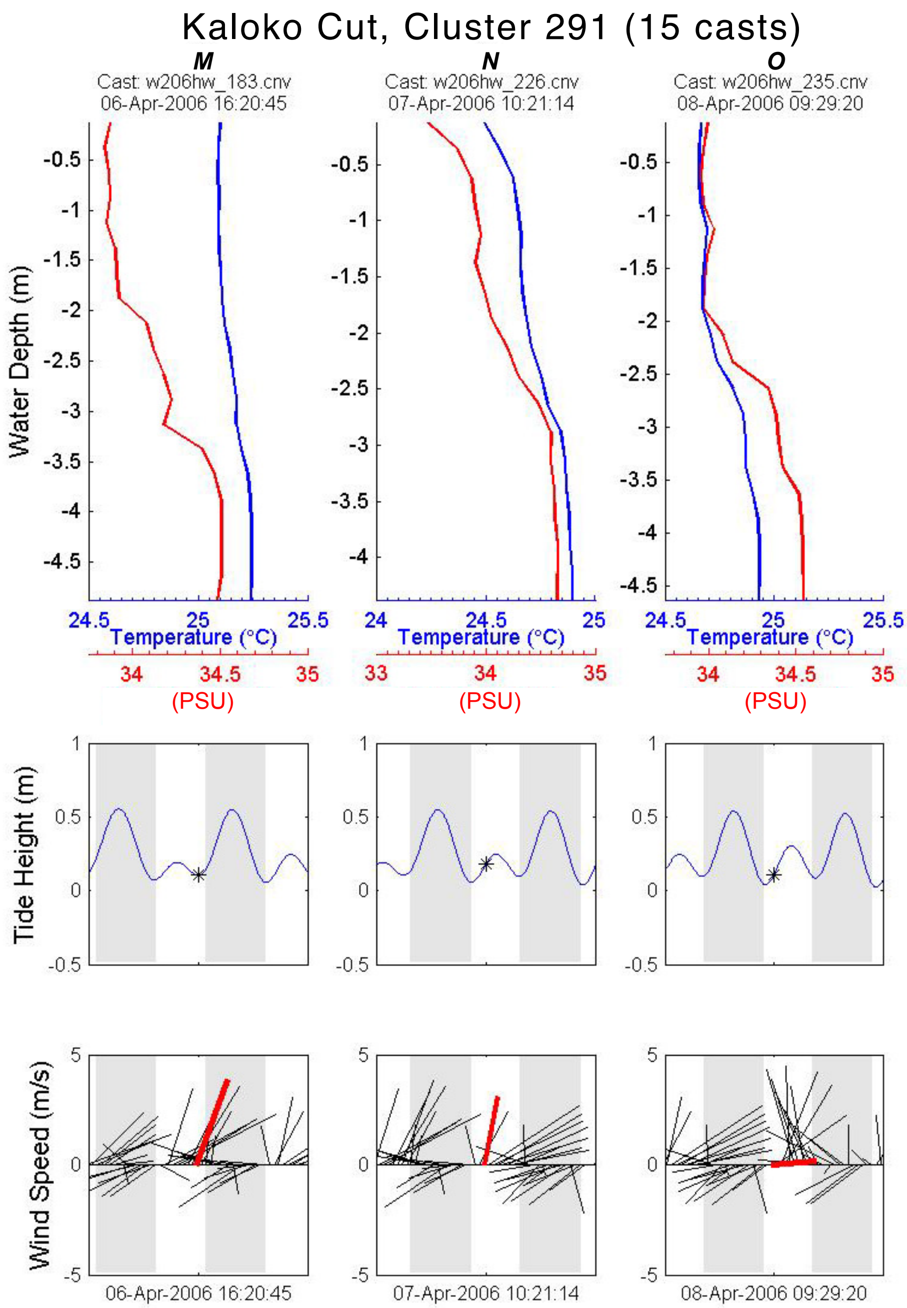

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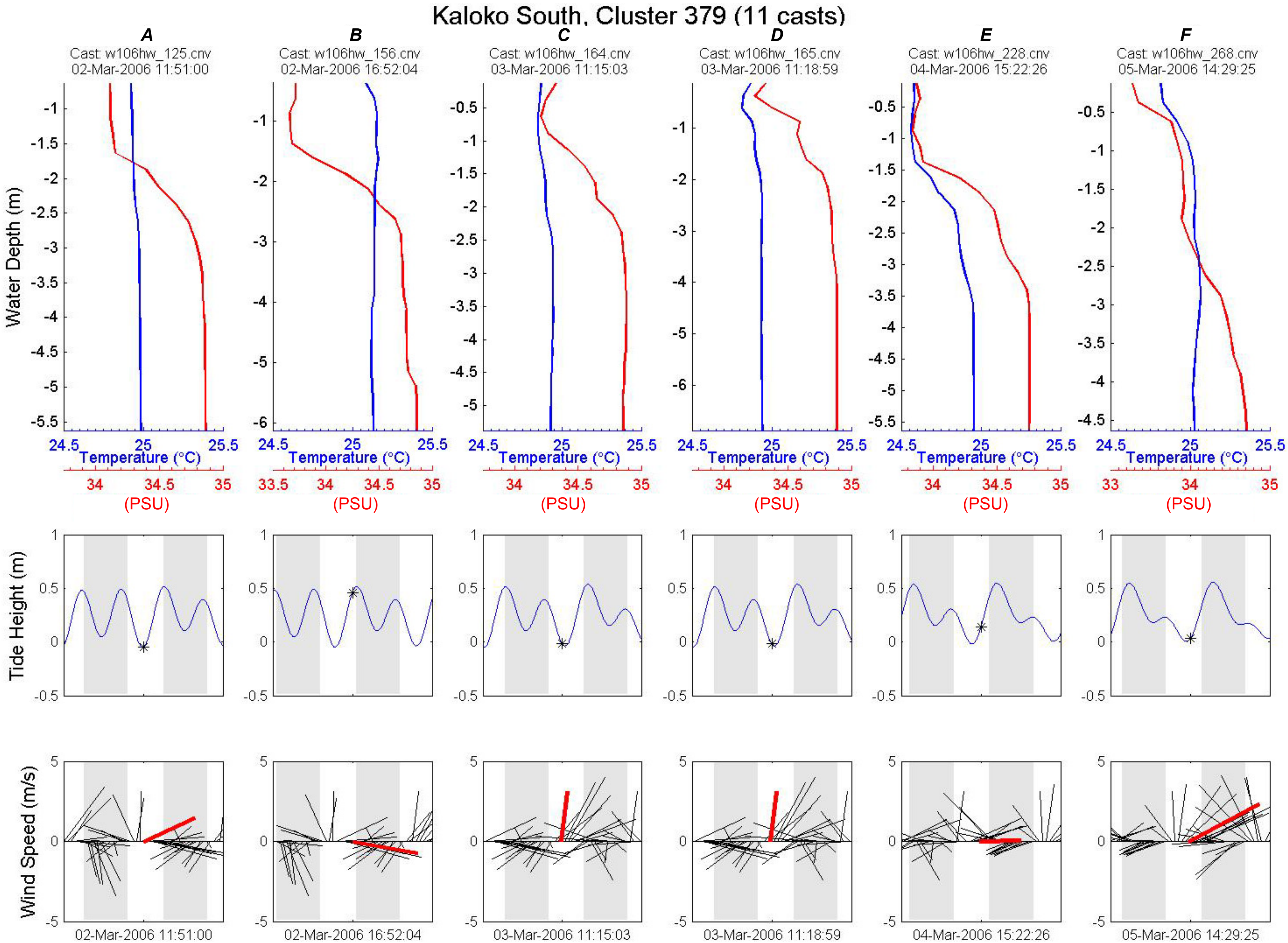
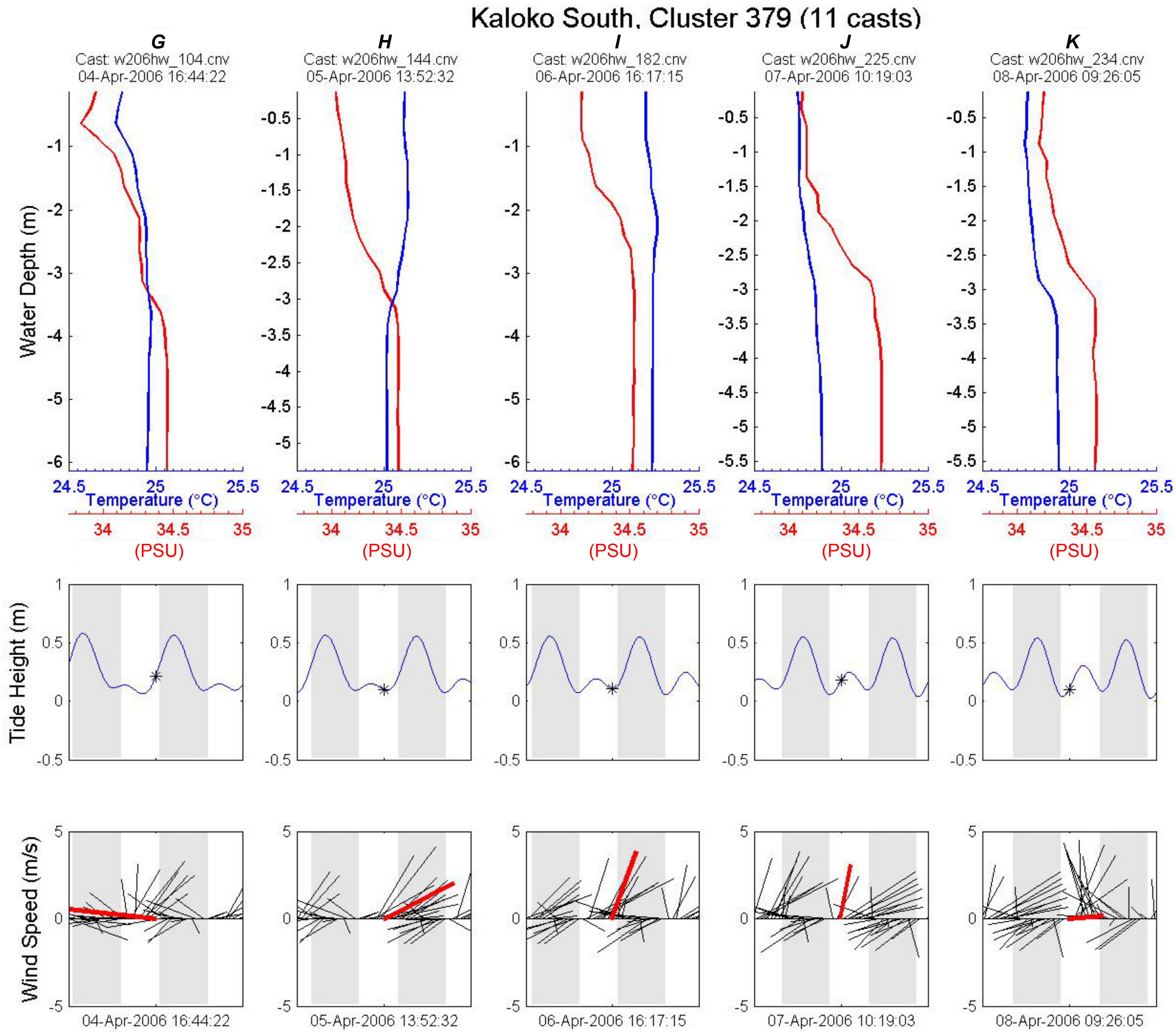


Figure 20. Temperature and salinity depth-profiles of cluster 379 located on the north study transect.



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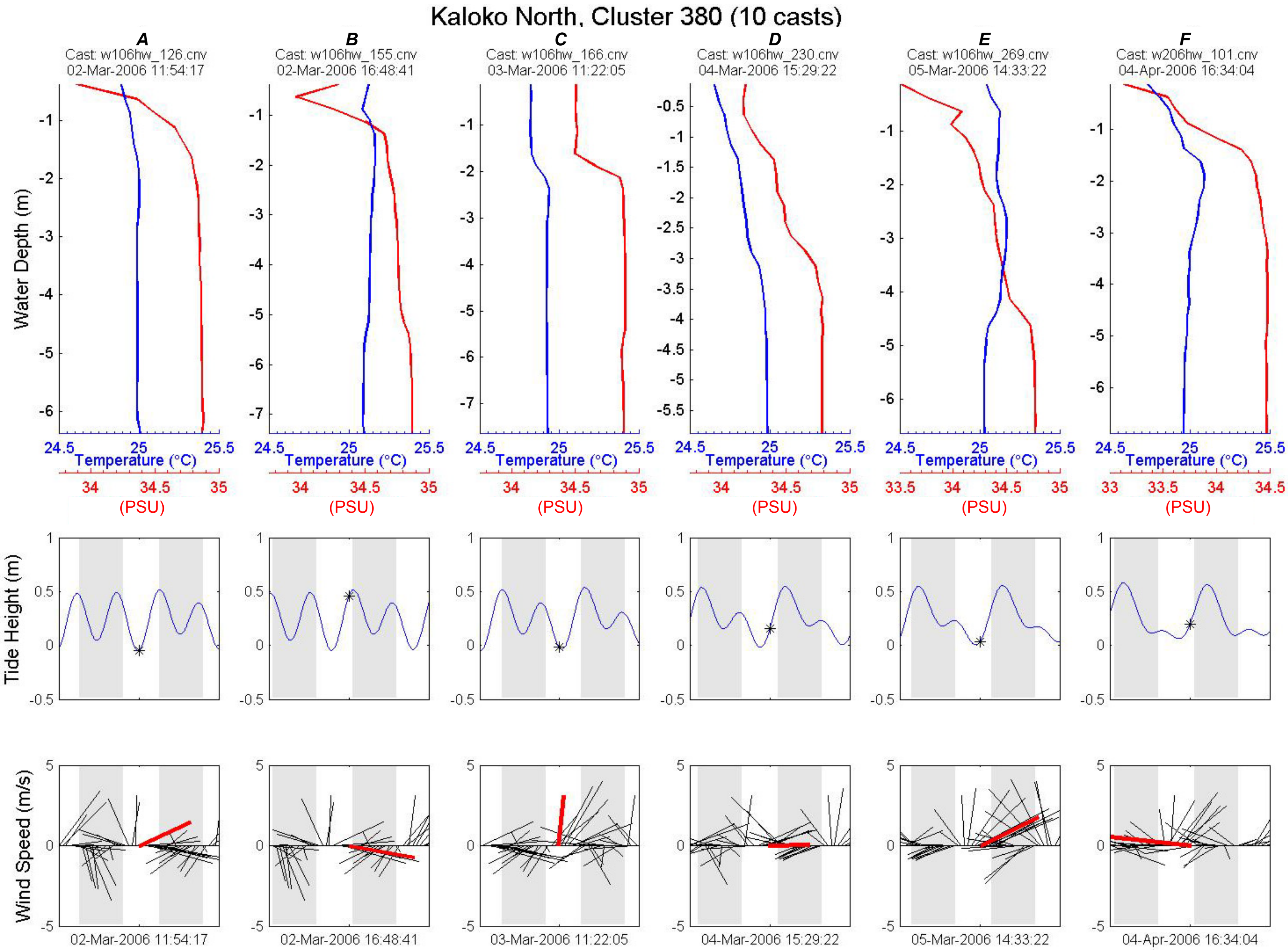
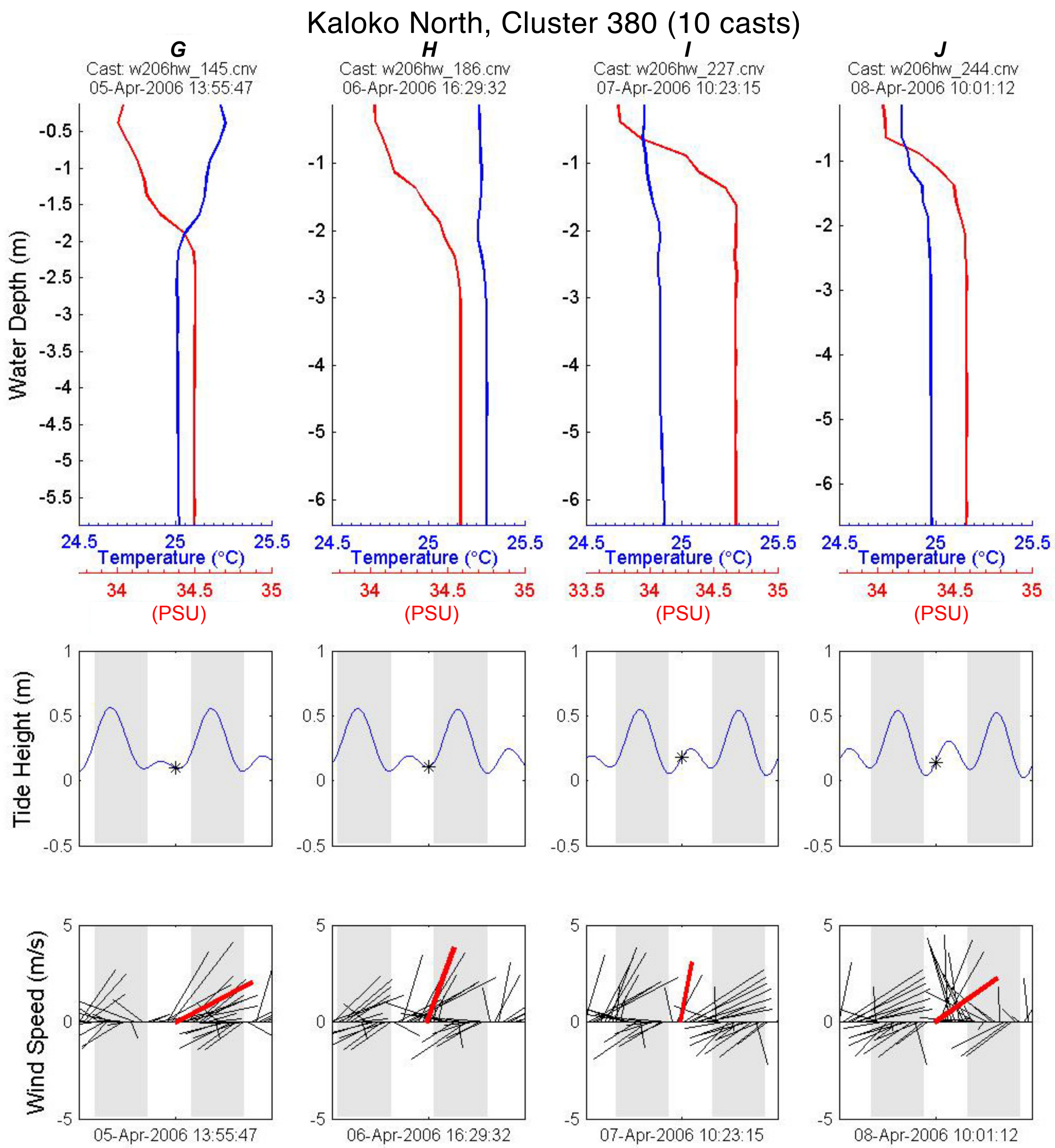


Figure 21. Temperature and salinity depth-profiles of cluster 380 located on the north study transect.



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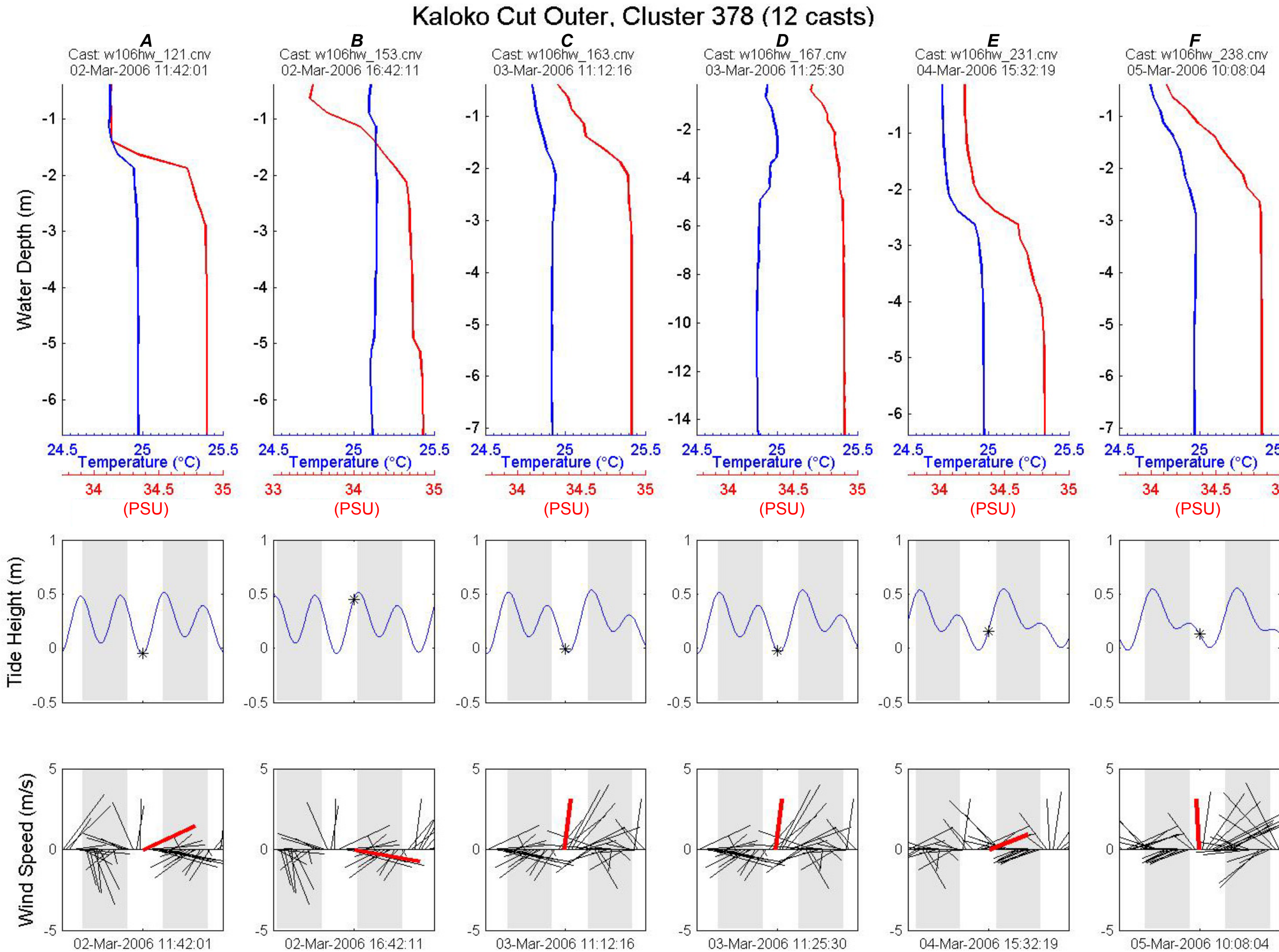
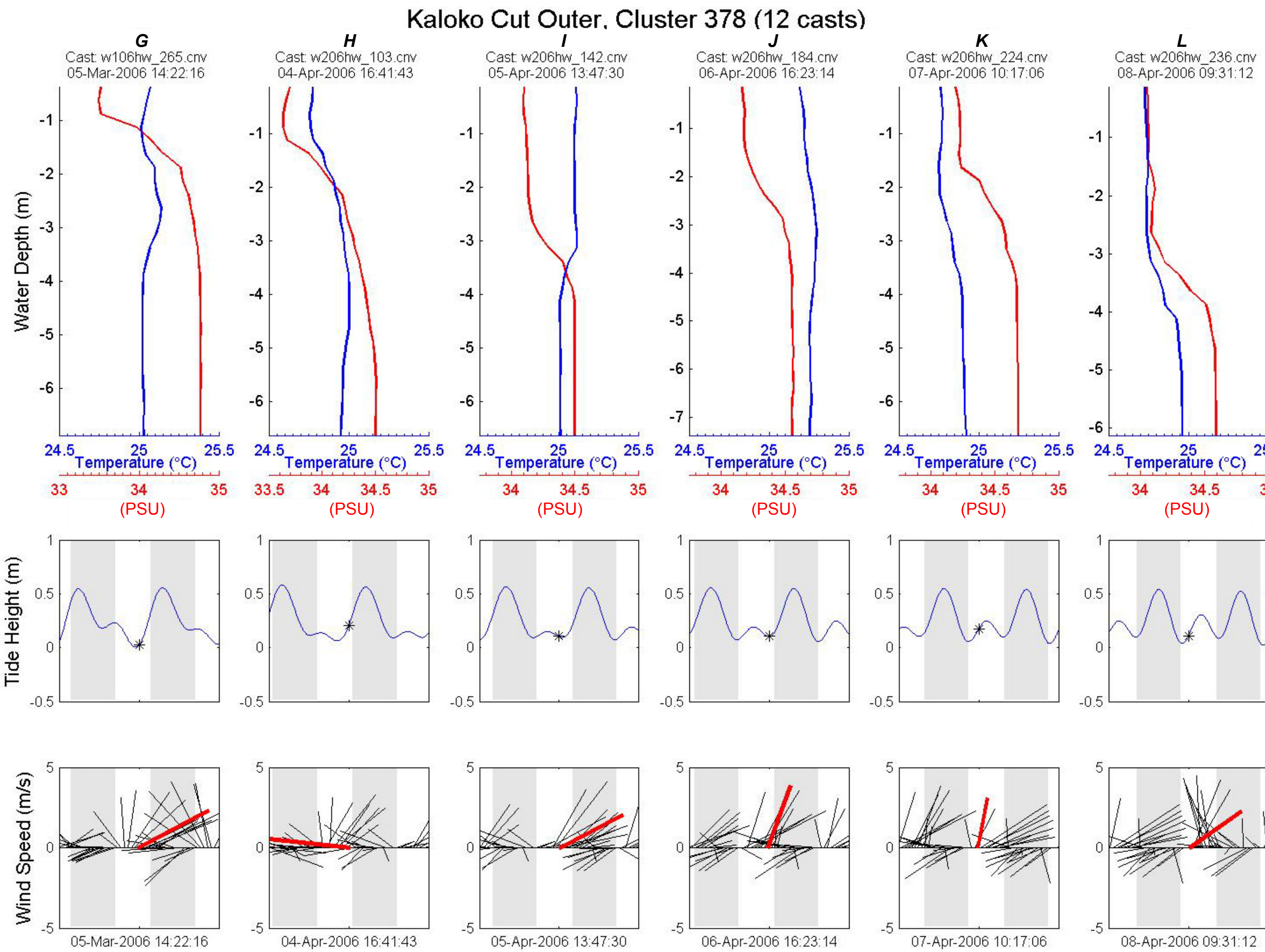


Figure 22. Temperature and salinity depth-profiles of cluster 378 located on the north study transect.



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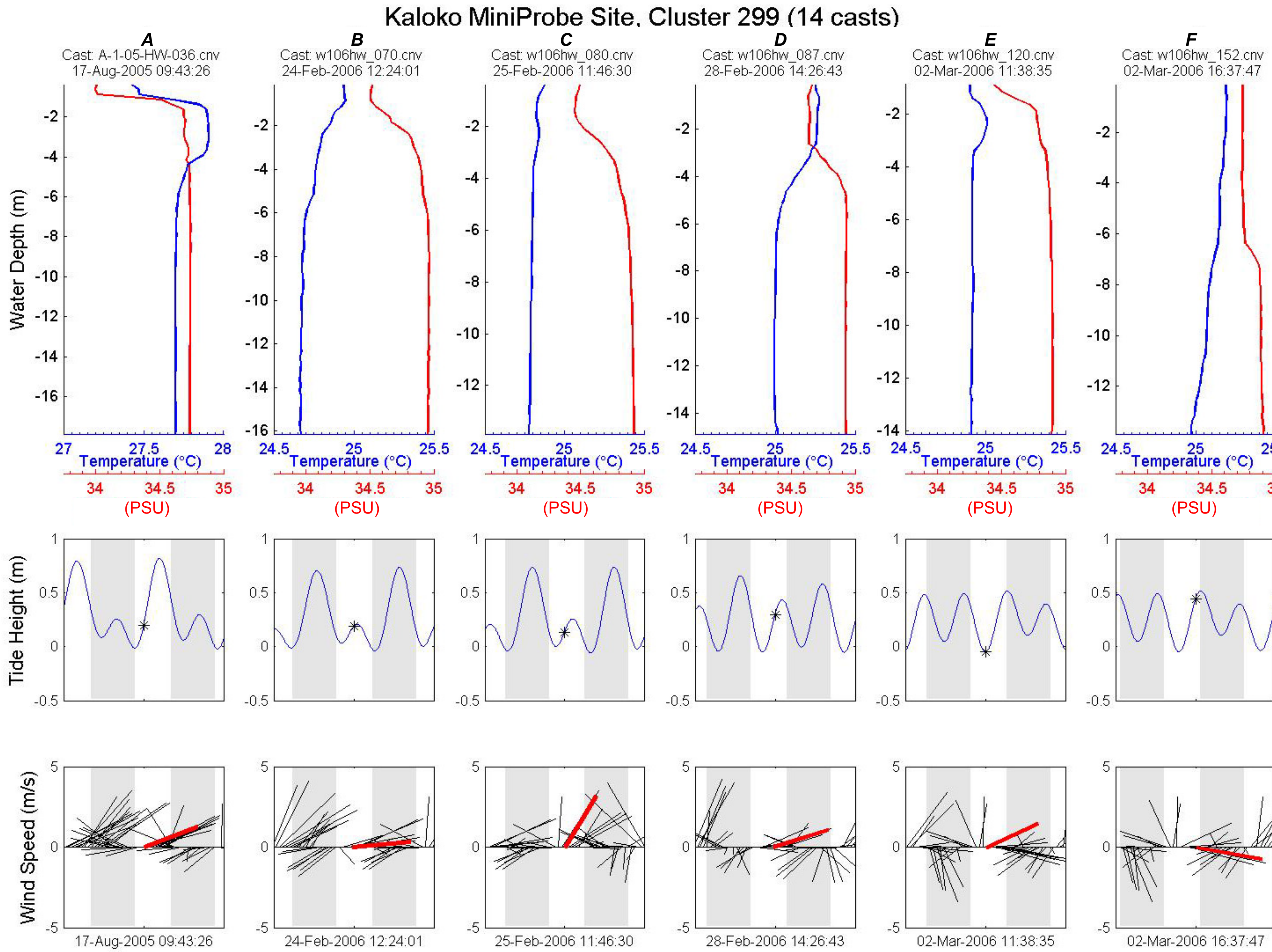
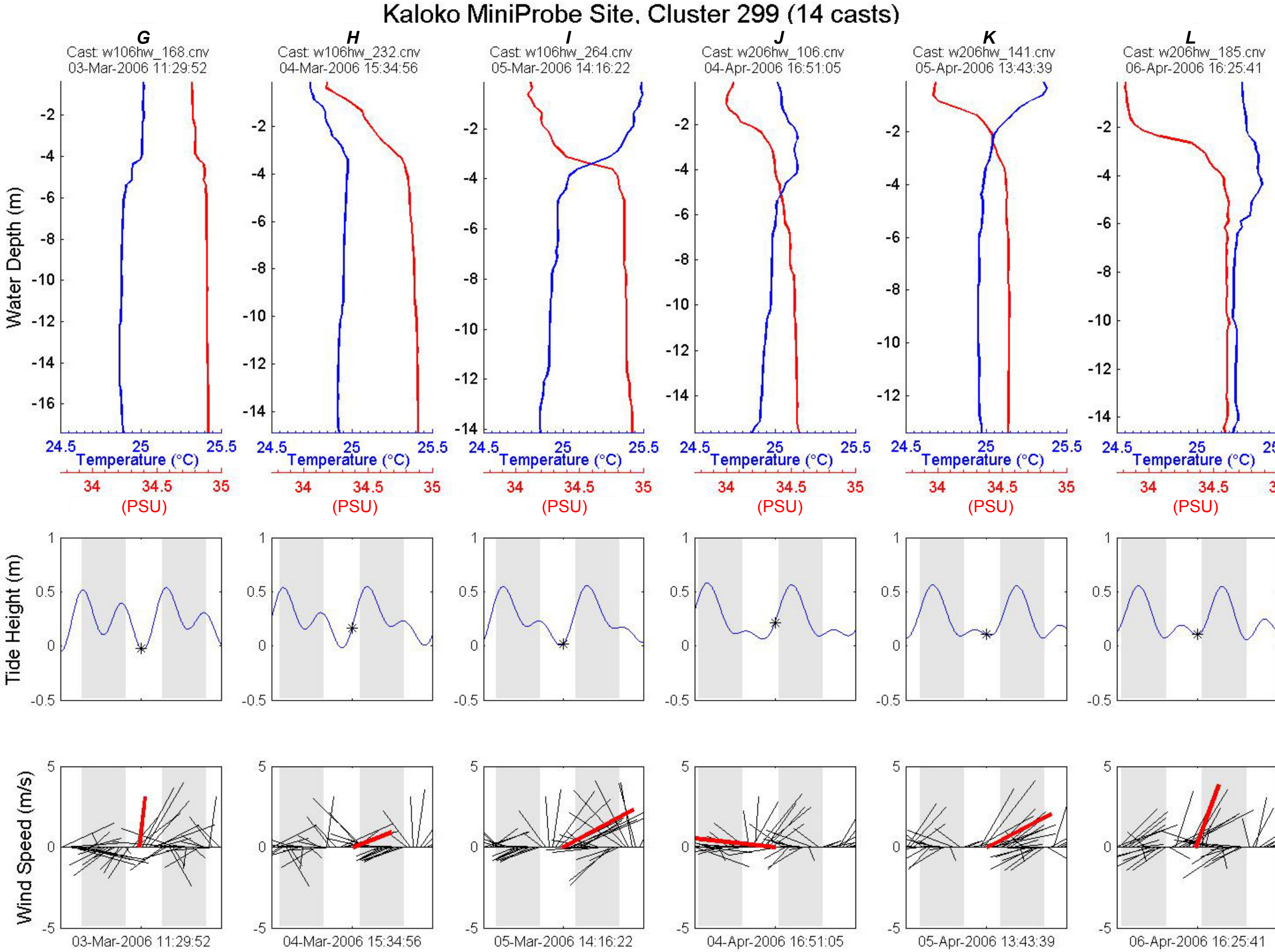


Figure 23. Temperature and salinity depth-profiles of cluster 299 located on the north study transect.



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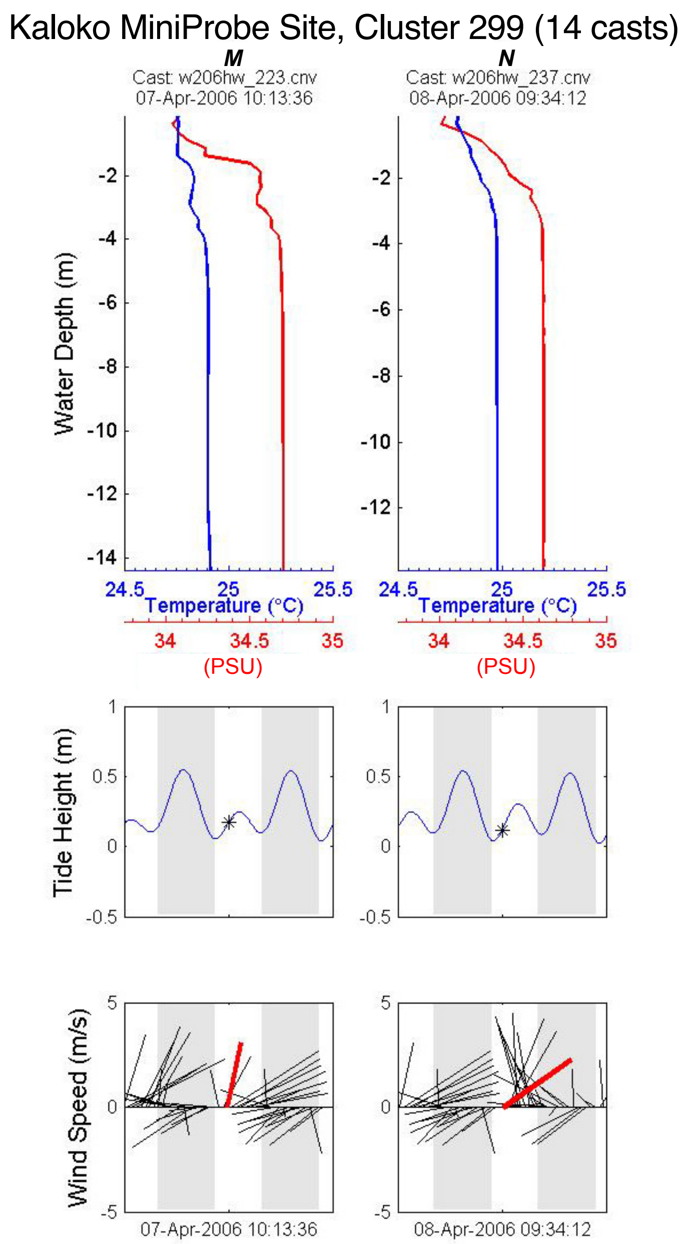

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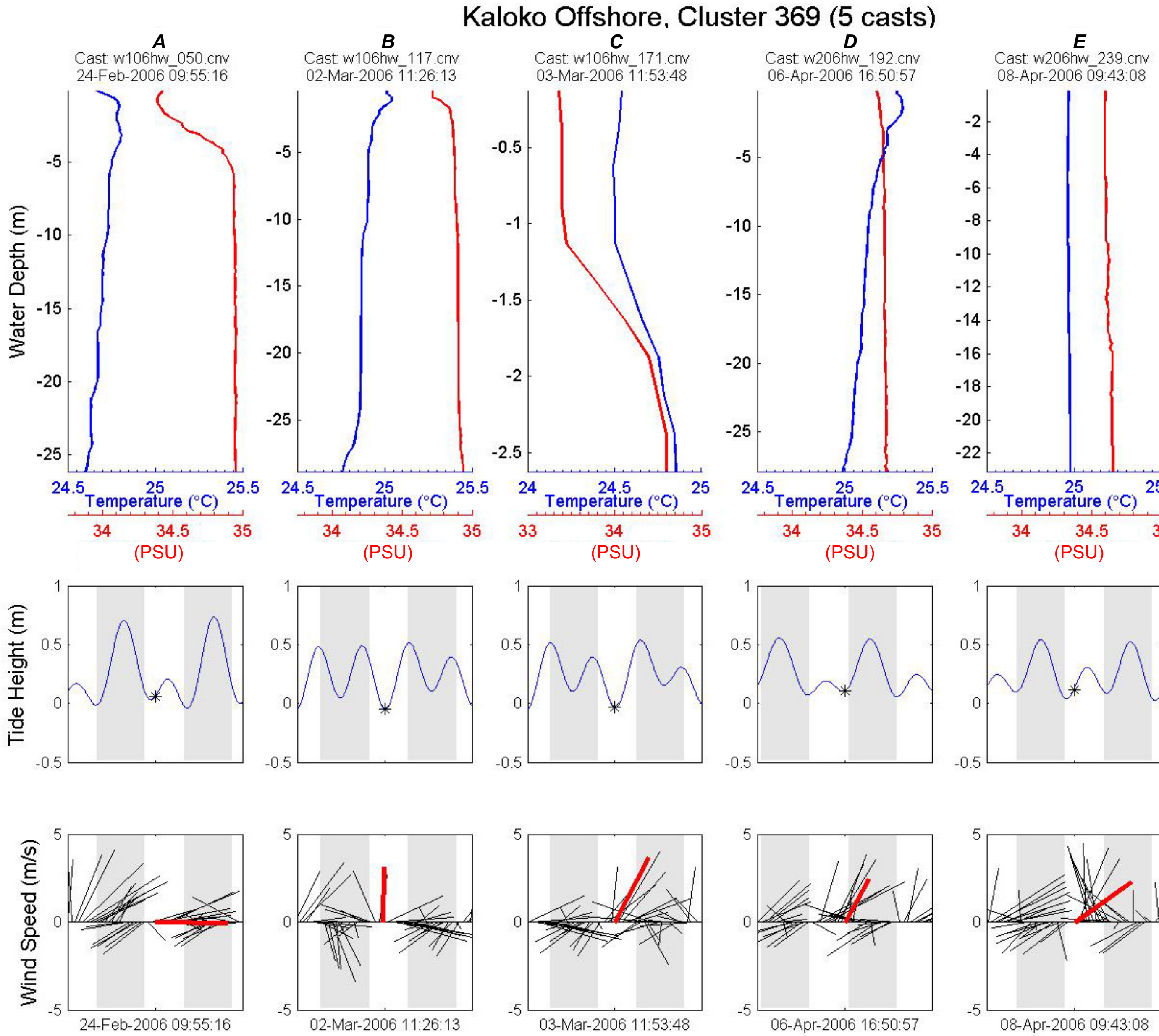

Figure 24. Temperature and salinity depth-profiles of cluster 369 located on the north study transect.

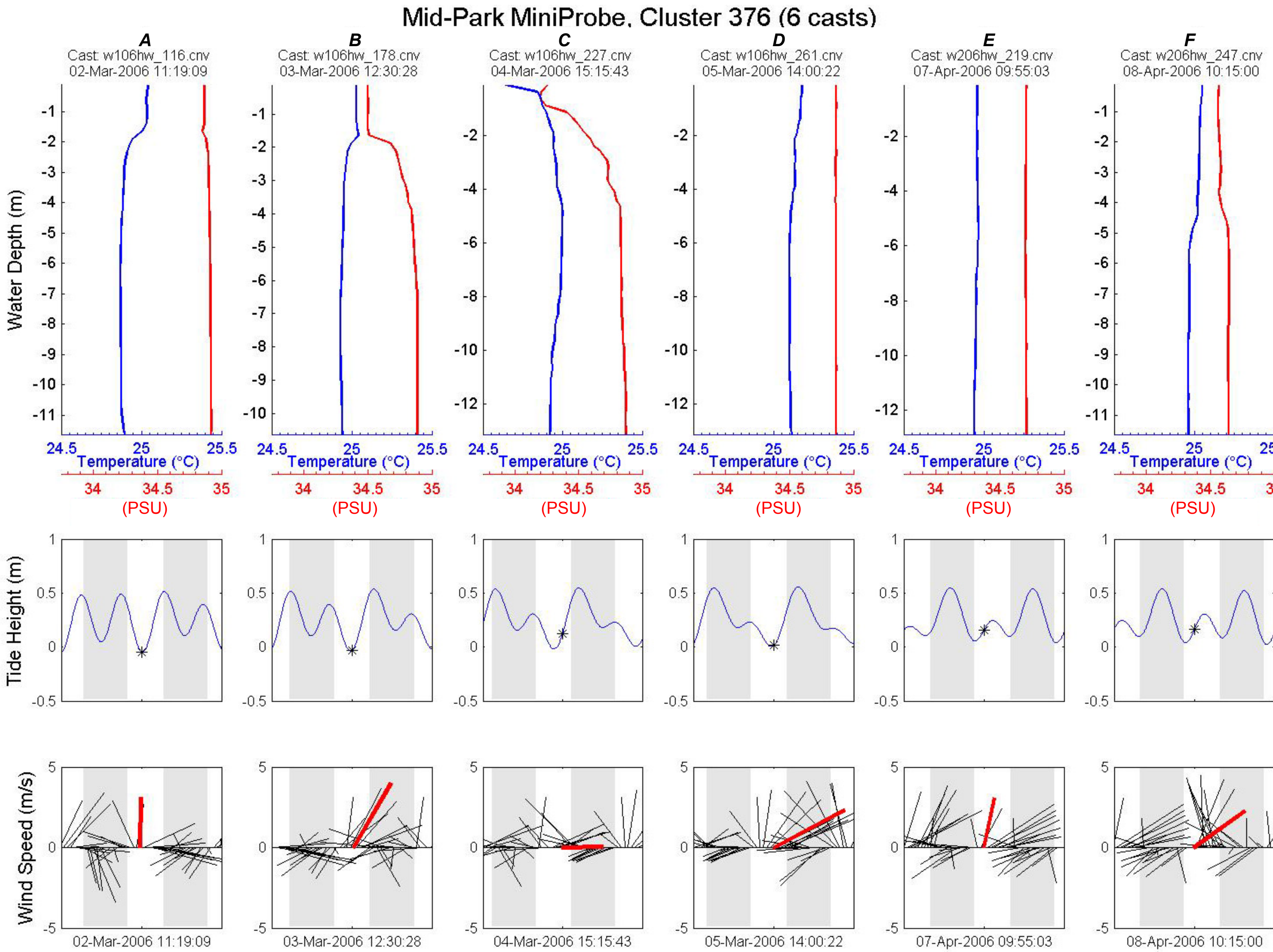

Figure 25. Temperature and salinity depth-profiles of cluster 376 located at the mid-park control site.

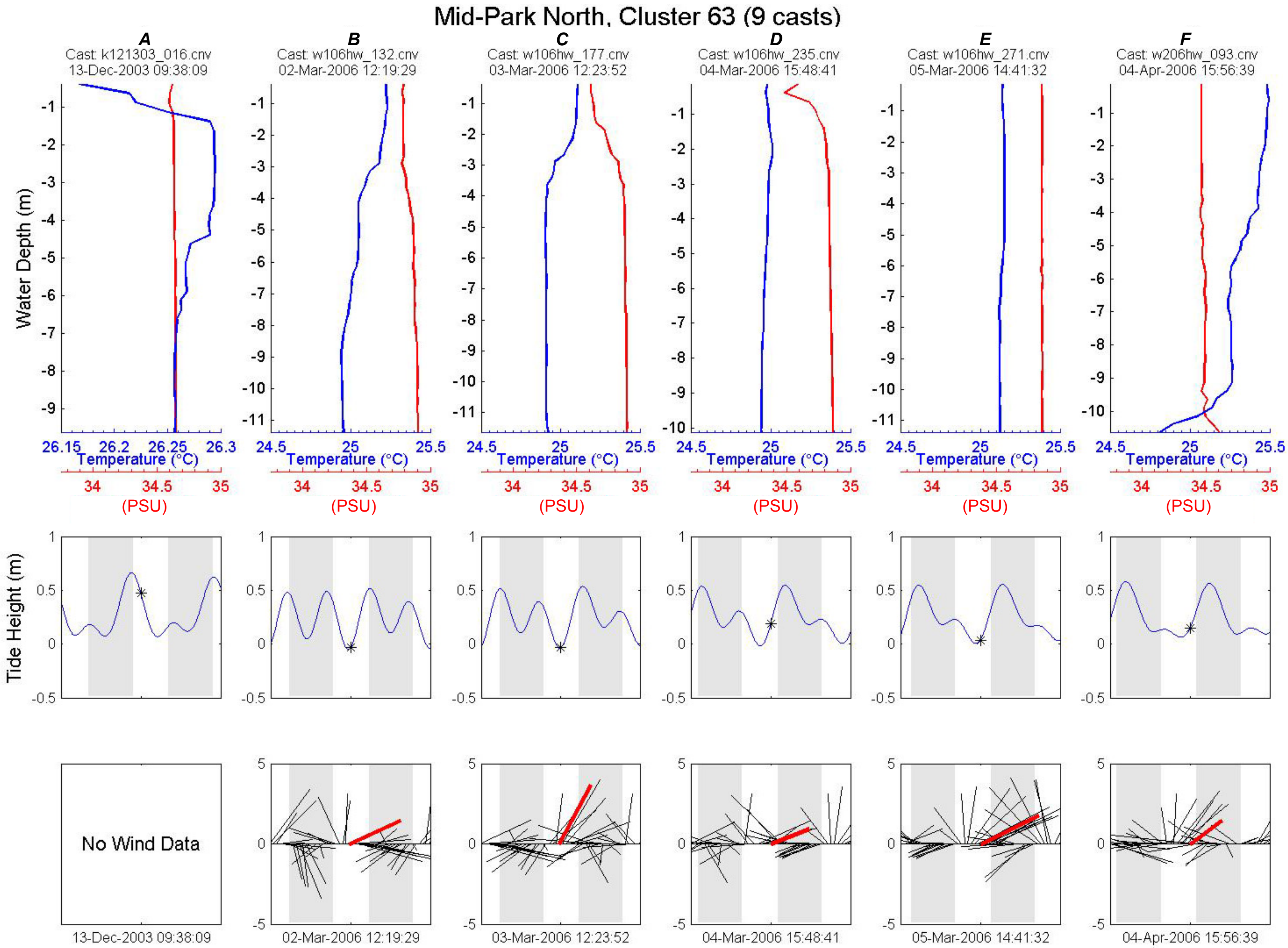

Figure 26. Temperature and salinity depth-profiles of cluster 63 located on the northern control site.

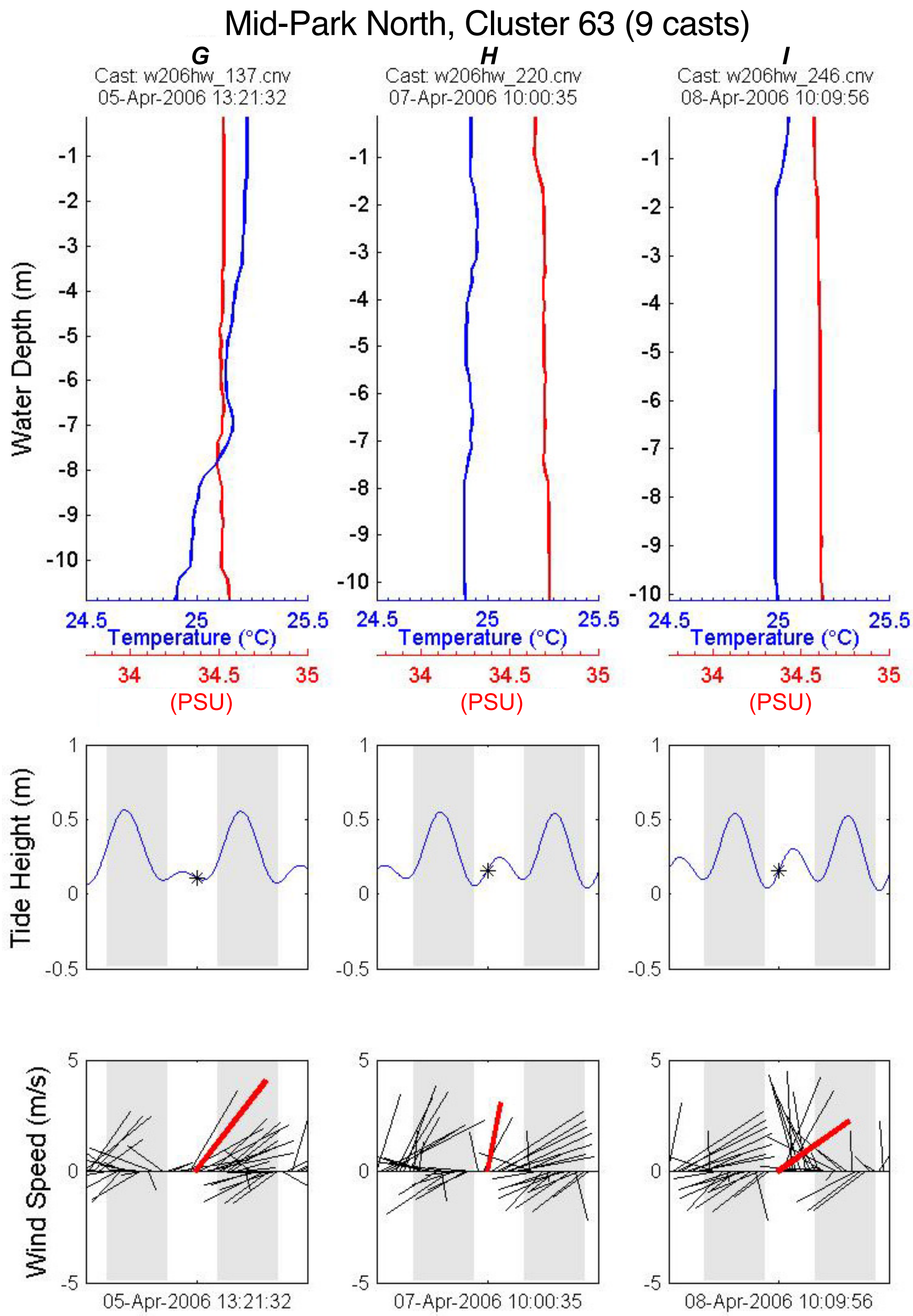

Figure 26—Continued.

water. Commonly, the water at this station was well mixed to the bottom (fig. 25D, E, F). At control site cluster 63 (fig. 3), a surface lower salinity plume was observed on only two out of nine surveys (fig. 26C,D). When present, the plume was 1 to 3 m thick and coincided with low southerly to moderately high southwesterly winds in February–March 2006. An interesting lower temperature surface layer was observed overlying a warmer layer between –1.5 and –5.0 m, despite no salinity variation in December 2003 (fig. 26A). The warm layer at depth may have resulted from advection of water from the shallower, inner reef platform where it had warmed in the sun before mixing at cluster site

Seasonal Statistics and Variability of Nearshore Water Properties

The seasonal patterns in surface temperature across the nearshore are summarized in figure 27, which shows statistics of minimum (A), maximum (B), mean (C), and variations (D) in temperature at 1-m depth intervals for each survey period. Minimum temperatures ranged from 19.0 to 27.5ºC (fig. 27A). These data show the clear variability between periods of study, with surveys in August 2004 and 2005 exhibiting minimum temperatures from 1 to 2ºC higher throughout the water column relative to surveys in December 2003, April 2004, and November 2005. Minimum temperatures in the August surveys were generally 2 to 4ºC higher than in February and April 2006. The lowest minimum temperatures were almost always observed at the surface and near the shoreline, except for April 2004, when lower minimum temperatures were observed at a depth of 3 m. The reason for this anomaly is unclear but may be related to the moderate winds from the west that piled warm water close to shore to create a stratification with a warmer surface layer.

Maximum temperatures recorded across all survey activities ranged between 25 and 30ºC (fig. 27B). Although peak temperatures during summer surveys (August 2004 and 2005) were on average 2ºC higher throughout the water column than other seasons, December 2003 exhibited, on average, peak temperatures 1ºC warmer for all depths than other surveys in winter and spring (April 2004, November 2005, February–March 2006, April 2006). Maximum temperatures in the upper 3 m of the water column were 1 to 2ºC higher in the August 2004 and 2005 surveys than in the December 2003 and April 2004 surveys and generally between 4.5 and 5.0ºC higher than in the April 2004, November 2005, February–March 2006, and April 2006 surveys.

Mean temperatures ranged from 22.5 to 28.0ºC across all seasons and for all depths (fig. 27C). August 2004 and 2005 had mean temperatures greater than 26.5ºC throughout the entire water column. December 2003 and April 2004 were slightly (1 to 2ºC) cooler, while February and April 2006 were 2.0 to 2.5ºC cooler. The variability in temperature (fig. 27D) was largely restricted to the upper 5 m of the water column, where most of the seasons surveyed showed between 1.8 and 3.0ºC differences. Exceptions to this pattern include December 2003 and April 2004, which displayed very little variability in the upper 5 m (less than 0.5ºC), and August 2004, which exhibited variability greater than 0.5ºC to depths of 15 to 18 m.

The seasonal variations in salinity across the nearshore are summarized in figure 28, which shows statistics of minimum (A), maximum (B), mean (C), and variations (D) in salinity at 1-m depth intervals of each survey period. Minimum salinity within each 1-m depth bin across the entire study domain ranged between 5.0 and 34.7 PSU, with April 2004 showing slightly lower salinity than the other seasons throughout the entire water column (fig. 28A). April 2006 also showed lower salinity down to 15-m depth. Minimum salinities within 5 to 10 m of the surface generally ranged between 20 and 30 PSU, and within 3 m of the surface they ranged between 20 and 25 PSU. An exception was observed in April 2004, when minimum salinities of 5 PSU were measured in depths of 1 to 2 m in the surface waters.

Maximum salinities within each depth bin ranged between 30 and 35 PSU, and they generally were quite uniform throughout the entire water column during all surveys (fig. 28B). April 2004 was slightly different, with surface water 1-2 PSU fresher than at depth. December 2003, November 2005, and February–March 2006 were more saline through the entire water column than August 2004, August 2005, and April 2006. Each of these surveys showed slightly more saline waters through the water column than April 2004.

Mean salinities found within each depth interval ranged from 28.5 to 35.0 PSU and were relatively uniform below about 5 to 8 m depth in each season surveyed (fig. 28C). Above 5 to 8 m depth, mean salinities ranged from 28.5 to 35.0 PSU, with the lowest mean salinities (29 PSU) in the surface waters (1-4 m depths) observed in November 2005. In December 2003, April 2004, and April 2006, mean salinities in the uppermost 4 m ranged from 31 to 32 PSU, while in Augest 2004 and 2005 and February 2006, they ranged from 32 to 33 PSU.

The variability in salinity with depth reveals that the majority of variability in salinity occured in the upper 3 m of all surveys except August 2004, where high variability was observed down to a depth of 6 m (fig. 28D). In the upper 3 m of the water column variability ranged between 2 and 12 PSU, with the greatest variability (12 PSU) observed in April 2006. The upper 3 m of the water column in August 2004, August 2005, and February–March 2006 exhibited variability of 8 to 10 PSU, while April 2004 and November 2005 showed variability between 5 and 7 PSU. December 2003 showed the lowest variability in salinity in the upper 3 m of the water column. A greater percentage of the water column experienced variability in salinity in August 2004, when variation of 1-2 PSU occurred down to depths of 5 to 6 m.

These statistics reflect the general seasonal patterns in the magnitude, range, and variability in nearshore temperature and salinity across the range of depths studied. The differences in temperature and salinity between surveys likely

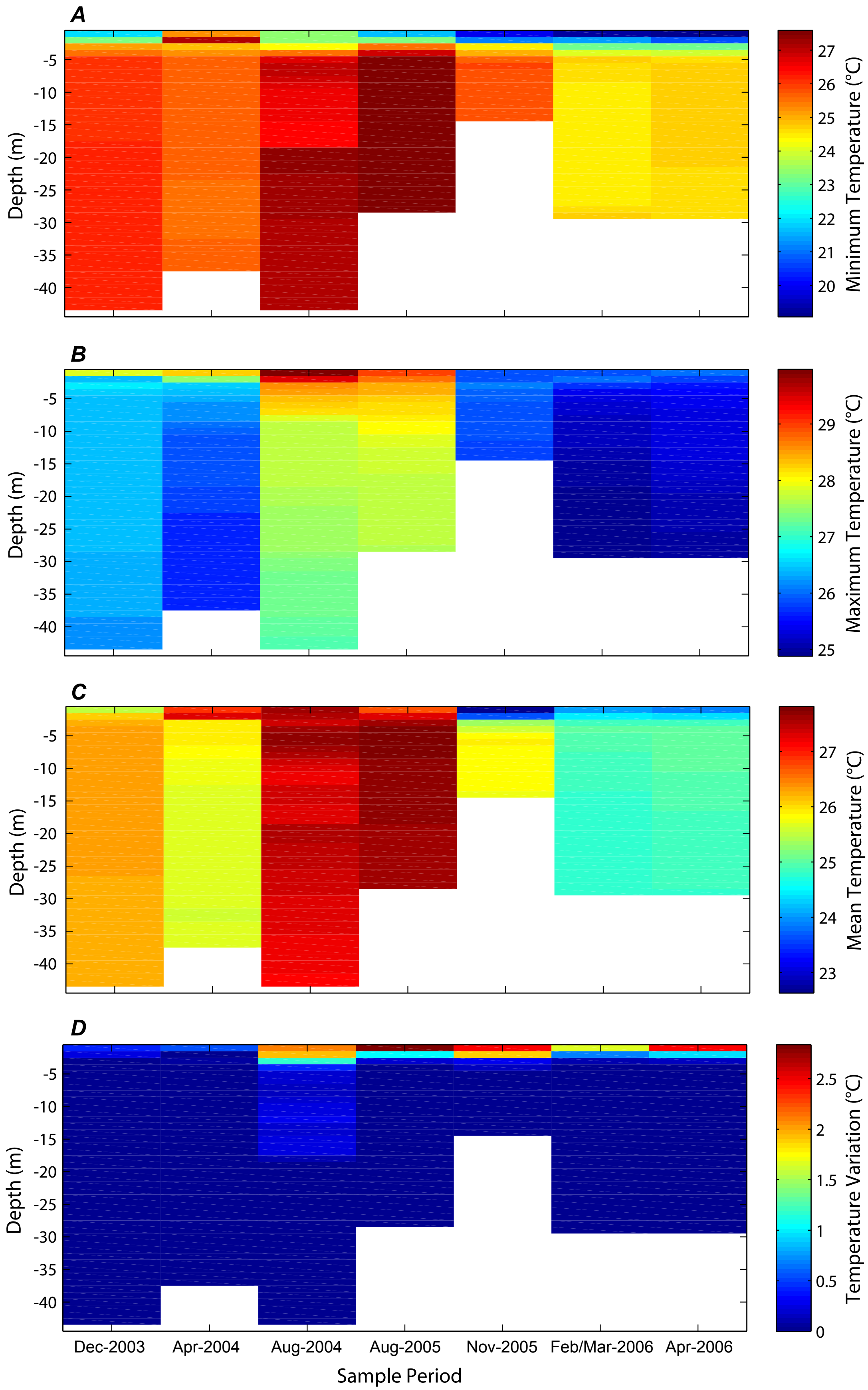

Figure 27. Seasonal statistics of temperature at 1-m depth intervals for all survey periods.

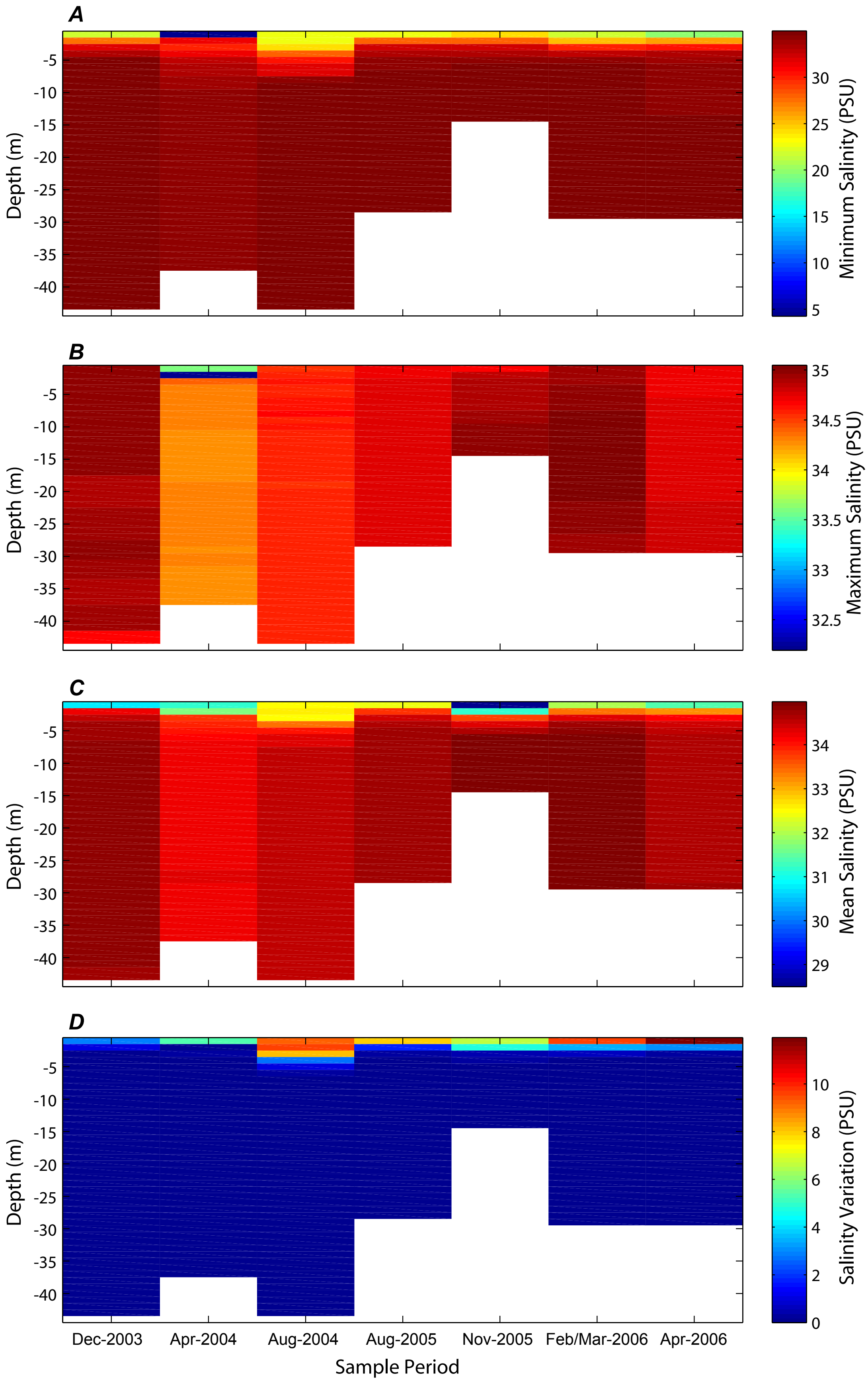

Figure 28. Seasonal statistics of salinity at 1-m depth intervals for all survey periods.

reflect seasonal and interannual differences in heating, cooling, and links between precipitation, groundwater recharge, and SGD that affect regional patterns. The differences in the amount of variability within each survey and between surveys likely reflects varying degrees of mixing that affect patterns locally. In the nearshore waters of Kaloko-Honokōhau, high variability in salinity occurs within the upper 5 to 6 m of the water column, while variability in water temperature extends to depths of 18 m. Below 20 m little variability in temperature and salinity was observed; however, mean temperature varied as much as 5ºC and salinity varied as much as 1 PSU between different seasons. The following section examines the spatial patterns showing the variability in these water quality parameters with regard to season and the meteorologic (diurnal warming, cooling, winds, and precipitation) and oceanographic (waves and tidal) processes that influence the buoyant, less saline, and colder surface waters fed by SGD.

Spatial Patterns in Nearshore Water Properties

To examine the areas of the National Park waters that are influenced by the buoyant SGD plumes, gridded surface temperature and salinity maps and cross sections were generated for specific depth and time intervals in ArcGIS 9.2. Temperature and salinity from surface (upper 0.5 and/or 1 m) or bottom (deepest 0.5-m interval) waters or from entire casts along select transects of stations made within an approximate 2-hour window and reflecting unique tide, diurnal, wind, and wave-driven variations were extracted for individual grids. These subsets of the data were gridded using the natural neighbor algorithm in ArcGIS, which interpolates heights using the closest subset of input samples and applying weights to them based on proportionate areas to produce a surface that passes through the input samples. These grids were constructed at 5-m spacing, and an analysis mask was used to restrict the extrapolation to the area constrained by the data. This section reviews representative seasonal surface maps of temperature and salinity to examine patterns in SGD and its influence on different areas of the Park.

The mean surface water temperature in the upper 0.5 to 1.0 m across the Park in December 2003 ranged from 23.3 to 27.0°C, with the coldest water masses observed near the shoreline and extending out 250 m immediately south of ‘Aimakapā Fishpond and throughout the Honokōhau Small Boat Harbor (fig. 29). A narrow band of lower temperature water was observed reaching west across the central inner reef, then out across more than 1 km of the outer reef in a northwest orientation. Mean surface salinity ranged from 24.4 to 34.9 PSU, with the lowest salinity found along the shore between ‘Aimakapā Fishpond and the harbor and immediately offshore of Kaloko Fishpond. A tongue of low salinity extended out across the inner reef 250-400 m in the southern area of the Park offshore of ‘Aimakapā, coinciding with lower temperature. This period of time (December 2003) was characterized generally by spring tides, moderately low air tempertures ranging from 22 to 28ºC, and low to intermediate winds (<5 m/s) (fig. 6).

In April of 2004, mean surface temperature in the upper 0.5 m of the water column ranged from approximately 25.5 to 26.5°C, although the commonly coldest area within the harbor was not surveyed (fig 30). Surface water temperature was lowest near the mouth of the harbor, in the central reef offshore of ‘Ai‘ōpio Fishtrap, and north of Kaloko Fishpond. High temperatures above 27ºC were observed within ‘Ai‘ōpio Fishtrap throughout all hours of the day and appear to be related to the low wind and high insolation typical for April. Mean surface salinity ranged from 22.1 to 34.3 PSU, with the lowest salinities occurring at the harbor mouth, along the shore between ‘Ai‘ōpio Fishtrap and ‘Aimakapā Fishpond, and offshore of Kaloko Fishpond. The results in the southern area are based on only one measurement, but the general patterns are consistent with other surveys (December 2003). The patterns observed in the northern region were consistent over at least two measurements. April 2004 was characterized by tides immediately following spring conditions, air temperatures ranging from 22 to 29ºC, and relatively low winds (<5 m/s), as shown in figure 7. April 2004 was anomalous relative to the other surveys in that colder waters offshore of the north and in the harbor in the south were more saline than other times, perhaps related to upwelling. Also, low salinity waters off of ‘Aimakapā were warmer than the surrounding water, possibly owing to warming on the wide reef platform.

Beginning in August 2005, surveys focused on the regions offshore of the harbor and Kaloko Fishpond to examine variability in the two principal SGD plumes influencing the park. Control sites were monitored along the 10-m isobath between the two plumes. Mean surface water temperature in August 2005 ranged from 21.9 to 28.0°C (fig. 31). The coldest water was restricted to within the harbor in the southern area and offshore of Kaloko Fishpond in the northern area, where it extended 400 to 500 m offshore. Salinity ranged from 23.9 to 34.7 PSU, with the lowest salinity observed within and immediately outside of the harbor and near the Kaloko Fishpond entrance. A tongue of water with salinity ranging from 33.0 to 33.5 PSU extended offshore 400 to 500 m in the central portion of the northern study area. Environmental conditions in August 2005 were characterized by spring tides, air temperatures ranging from 23 to 32ºC, and moderate southwest winds during the afternoon (fig. 9).

In February–March 2006, mean surface water temperature ranged from 24.7 to 25.2°C, with the coldest surface waters occurring within the harbor and offshore of Kaloko Fishpond, where a cold plume was observed extending out 500 m from shore (fig. 32). Mean surface salinity ranged from 23.9 to 34.9 PSU, with the lowest salinities occurring in and immediately outside of the harbor and offshore of Kaloko Fishpond. Offshore of Kaloko Fishpond, the colder surface water extended 50 to 100 m offshore and concentrated south of the fishpond. The environmental conditions during this survey period were characterized by spring tides, air temperatures ranging 19 to 28ºC, and more variable winds during daylight hours blowing from the south, west, and northwest at moderate speeds (fig. 11).

In April of 2006, mean surface water temperature ranged from 20.1 to 25.4°C (fig. 33), with the coldest water found inside and immediately outside of the harbor and offshore of Kaloko Fishpond, where the cold plume extended 200 to 300 m offshore. A tongue of cold water was also observed farther south along the shore to the southern edge of Kaloko Bay. Mean surface salinity in April 2006 ranged from 22.7 to 34.6 PSU. The lowest salinities were observed within and around the entrance to the harbor and were associated with the coldest water offshore of Kaloko Fishpond. Salinities of 33.5 to 34.0 PSU extended across much of Kaloko Fishpond. Environmental conditions during the April 2006 survey were characterized by moderate spring tides, air temperatures of 19 to 28ºC, and moderate winds generally from the south during daytime survey hours (fig. 12).

The mean seasonal surface temperature and salinity maps presented here show that a prominent nearshore surface plume of lower salinity and colder temperature was observed in each season examined. The plumes were associated with groundwater discharge points observed in remote sensing surveys conducted during 12 flights spanning 10 days in November and December of 1992 (Wilkins, 1992) and again in August of 2005 (Johnson and others, 2008), revealing the persistent nature of the submarine groundwater discharge points and plumes occurring across the nearshore. These results also show that temperature and salinity are generally correlated

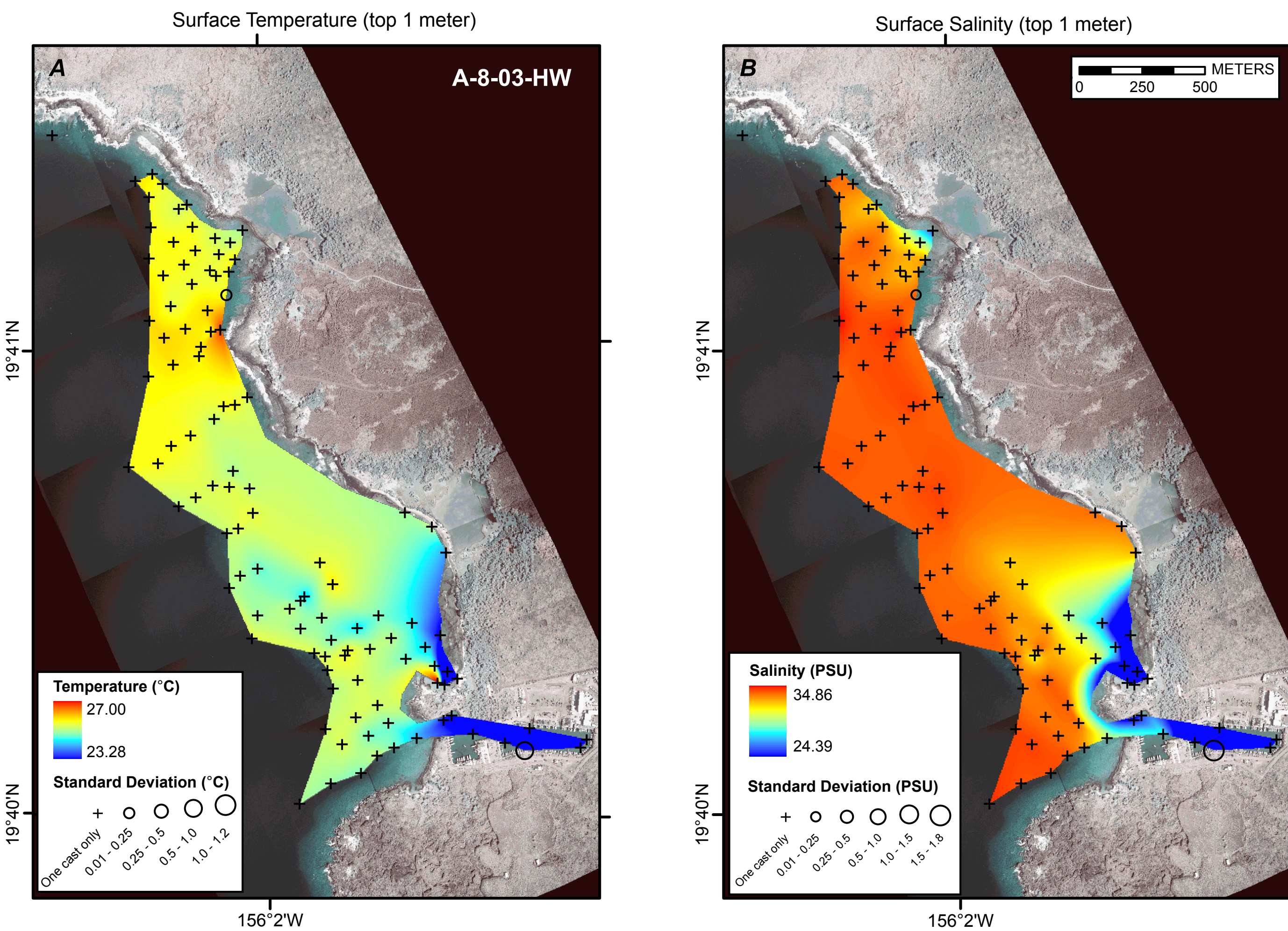

Figure 29. Maps of mean surface temperature (*A*) and salinity (*B*) during December 2003 surveys.

laterally within at least the upper 0.5 to 1.0 m of the surface waters (the next section provides more details on depth of influence) and that much of Kaloko Bay and the habor are influenced daily and seasonally by SGD-derived plumes.

Tidal, Wind, and Diurnal Variations in Nearshore Water Properties

The seasonal and spatial patterns of nearshore temperature and salinity described in the previous sections are influenced by forces operating on daily and event time scales, including solar heating, night time cooling, tides, winds, waves, and precipitation. This section describes the variability due to these forcings, with representative examples in map view, vertical cross sections, and individual cast comparisons.

Tidal and Diurnal Forcing on Nearshore Water Properties

Cross sections of temperature and salinity data in March 2006 show the extent to which the fresh to brackish groundwater and tides influence salinity and temperature at depth through the Honokōhau Small Boat Harbor and outside into Honokōhau Bay. Twelve CTD casts from the morning of March 2, 2006, at low tide show the fresh-to-brackish groundwater plume emanating from the inner harbor depressing seawater salinities out at least 900 m and outside of the harbor entrance (fig. 34). The plume within the harbor generally ranged from 2 to 3 m thick; however, salinity was depressed below normal seawater (~35 PSU) down to the sea floor (5-m depth) and across the first 300 m of distance from shore. Salinities in the plume ranged from 26.5 to 34.5 PSU, and an area of lower salinity at 600 m

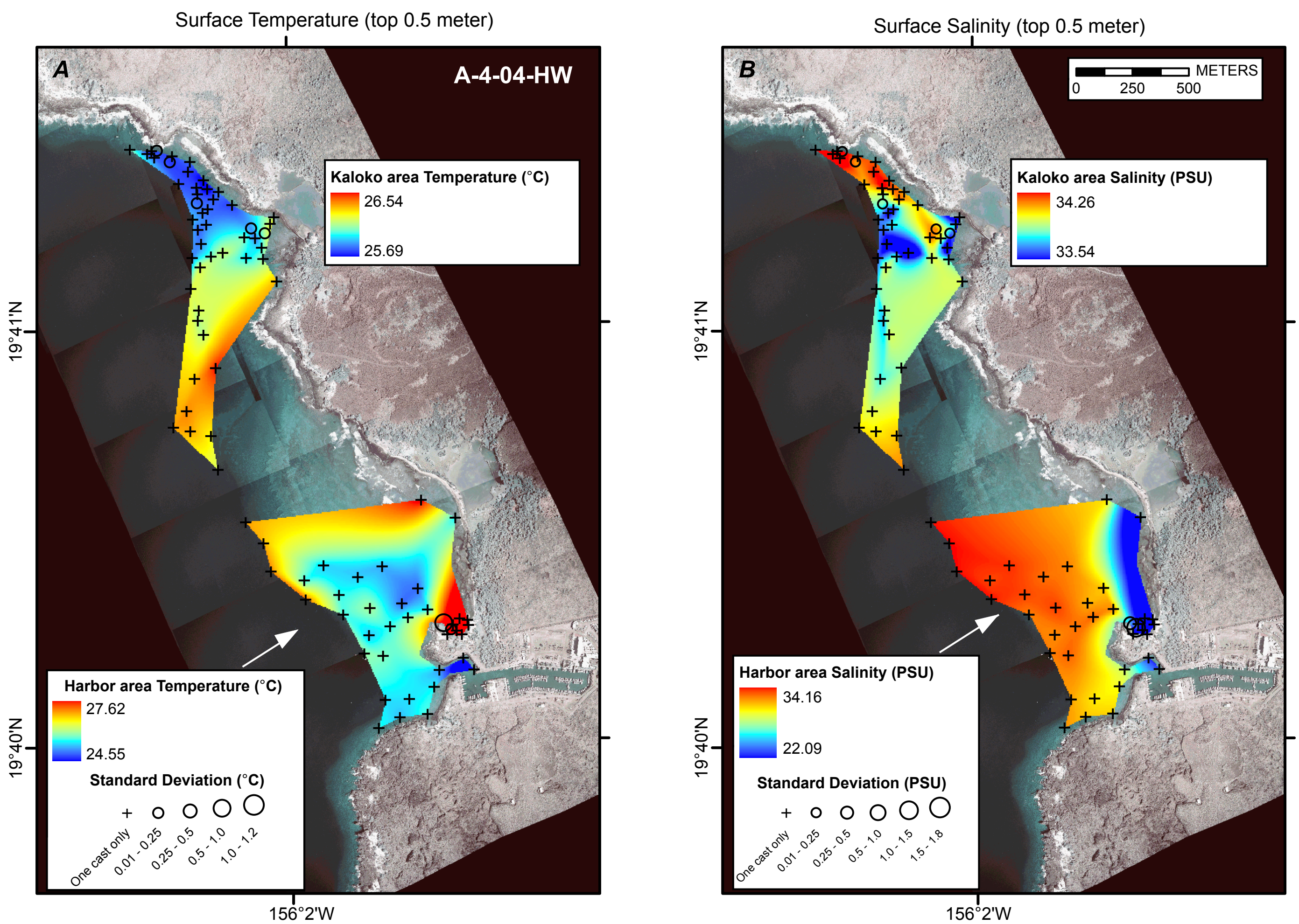

Figure 30. Maps of mean surface temperature (*A*) and salinity (*B*) during April 2004 surveys.

from shore is likely correlated with a second groundwater input within the harbor. Temperatures ranged from 21 to 25ºC. This pattern is commonly observed in the CTD data of all seasons, and in several cases the plume was observed to extend out 1,000 to 1,500 m into Honokōhau Bay (fig. 15A, B, C).

Cross sections of nine CTD casts from the afternoon of March 2, 2006, collected as the tide rose to a modest high tide, show the extent that the incoming tide pushes the fresh-to-brackish surface plume landward and reduces its spatial and vertical influence (fig. 35). The tidal change of 0.4 m on March 2, 2006, represents about 50 percent of the entire spring tide range and was associated with an approximate 100- to 200-m landward retraction of the seaward edge of the plume. Interestingly, the absolute salinity values in the landward portion of the plume were lower at the incoming tide than at low tide, presumeably a result of reduced mixing, reduced upwelling, or a temporary increase in SGD flux. Variations in surface salinity may also be influenced by boat traffic, as observed in the 1992 remote-sensing imagery (Wilkens, 1992) where warm (more saline) water appears as streaks amidst cooler (fresher) water behind boat wakes. Boat waves and propellers may be important in mixing the fresh-brackish plume along the Harbor corridor, especially during peak transit times of regular fishing and tour boat operations. Temperatures in the afternoon plume were 1 to 2ºC warmer than in the morning, likely a result of solar insolation and/or mixing with warmer seawater, and perhaps influenced by boat traffic.

Eight CTD casts from the morning of March 2, 2006, at low tide show the fresh-to-brackish groundwater plume

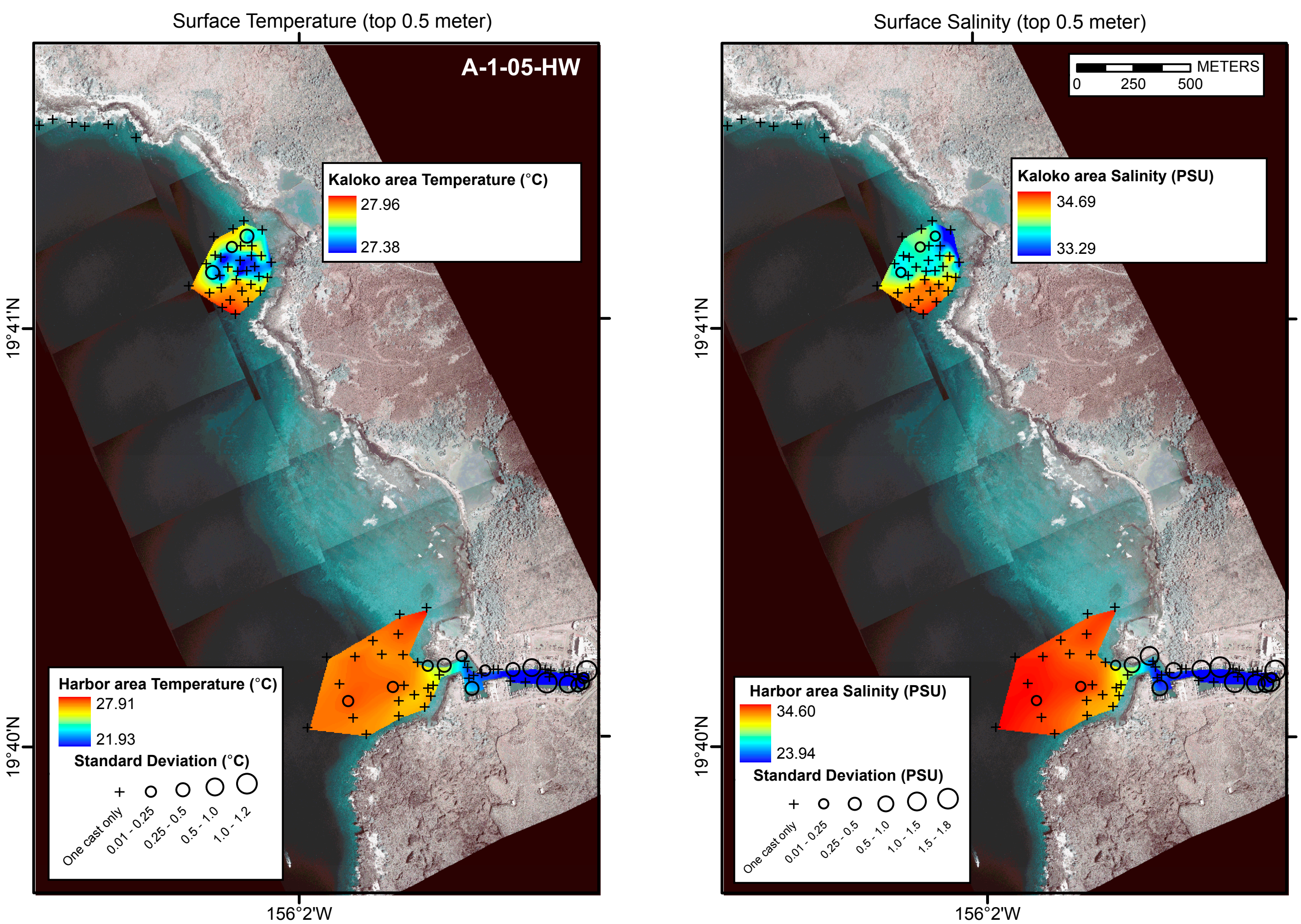

Figure 31. Maps of mean surface temperature (*A*) and salinity (*B*) during August 2005 surveys.

emanating from the Kaloko Fishpond and The Cut area and its influence on depressing seawater salinities out across at least 450 m of the nearshore (fig. 36). The landward portion of the plume reached 2 m thick with salinity of 33.5 PSU and temperature of 24.5ºC, 1 PSU and 1ºC lower than the marine water offshore. The smaller and thinner extent of the SGD plumes off of Kaloko Fishpond and “Cut” relative to the Honokōhau Small Boat Harbor were likely a result of that coast’s greater exposure to wave energy, which actively mixes waters more thoroughly and rapidly. Our observations through the various seasons showed that the SGD plumes off of Kaloko Fishpond were comparable to that of March 2, 2006, and in several cases reached 3 to 5 m in thickness and extended across the entire 400- to 500-m area from shore (figs. 19, 20, 21, 22, 23).

Data from six CTD casts from the afternoon of March 2, 2006, at near high tide show that the incoming tide pushed the fresh-to-brackish groundwater plume emanating from the Kaloko Fishpond and “Cut” area 50 to 150 m landward (fig. 37). Salinities and temperatures similarly increased across the area by about 1 PSU and 1ºC, respectively, as a result of the incoming tide and daily warming.

The variability in the response of the SGD plume extent, thickness, salinity, and temperature structure to tide fluctuations described here reveals general patterns of SGD across the nearshore with changing water levels and diurnal changes in solar heating and cooling. Most of the data collected for this study show that the spatial extent and thickness of the SGD plumes expanded by approximately 30 percent during

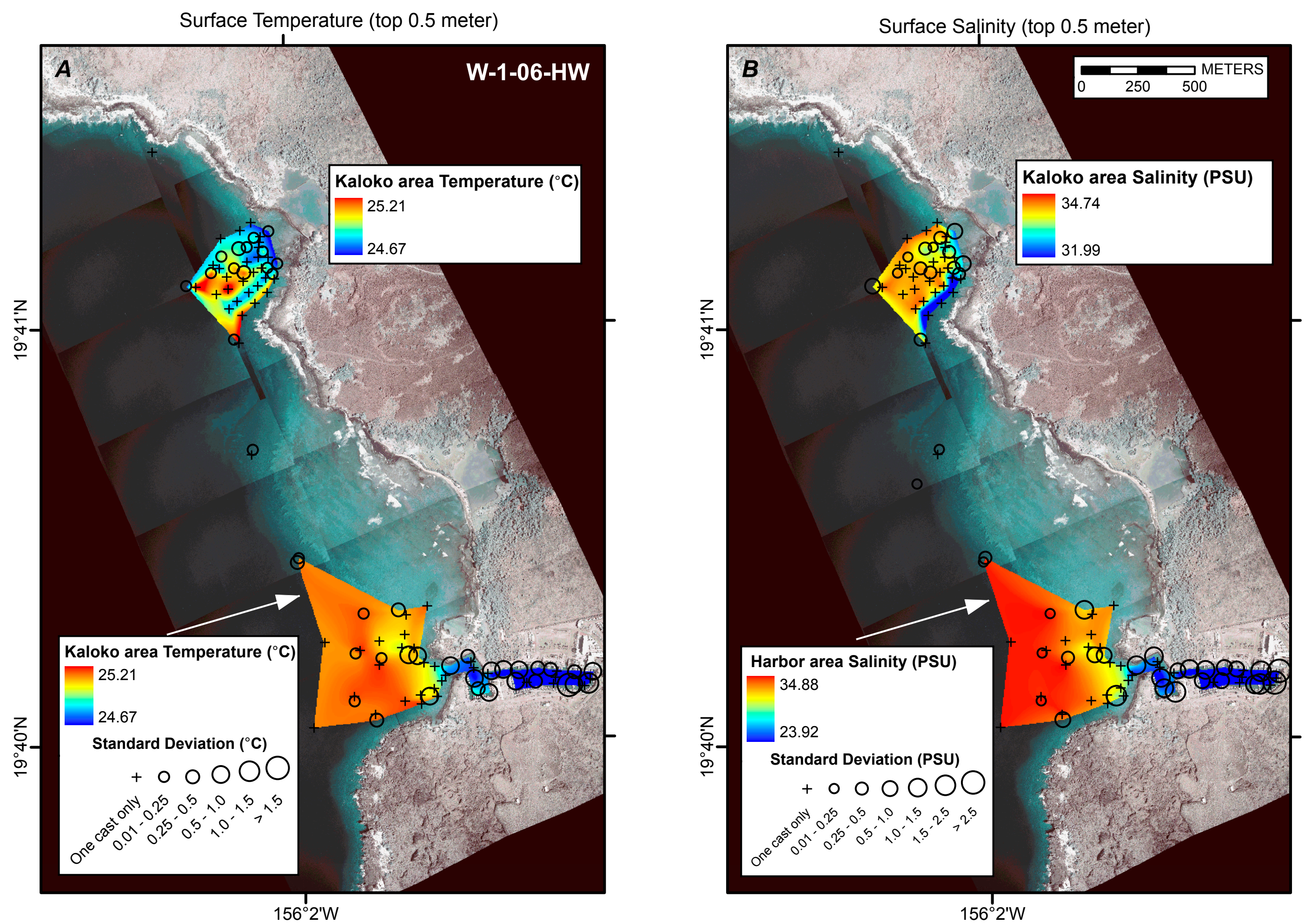

Figure 32. Maps of mean surface temperature (*A*) and salinity (*B*) during February/March 2006 surveys.

low tides. The spatially discrete patterns that occur with the SGD plumes are described in more detail below.

Wind Forcing on Nearshore Water Properties

Although the SGD-fed plumes are most extensive at low tides, winds quickly and thoroughly mix the plumes with the surrounding seawater. CTD casts in March 2006 show the abrupt and effective manner by which the SGD plumes were mixed through the water column and influenced salinity down to depths of 13 m and greater. For example, at cluster 376 (fig. 3), on March 4, 2006, near low tide and during a low (<2 m/s) west wind, a prominent SGD plume existed at the surface, depressing seawater salinities to a depth of 4 to 5 m (fig. 25C). The next day, March 5, wind velocity increased twofold to 5 m/s (fig 25D). During this time and a similar low tide, the surface SGD plume disappeared as the entire 13-m water column was mixed uniformly to the sea floor. Associated with the mixing was a decrease in salinity through the entire water column. Similar responses to wind-driven mixing were observed throughout the seven study periods, generally when winds exceeded 4-5 m/s and originated from the south, west, or northwest.

Spatial Extent and Volume of SGD in Nearshore Waters

Using the salinity inflection points from multiple CTD casts collected within specific 2-hour periods as shown in the cross-section plots of the previous section, volumes of the

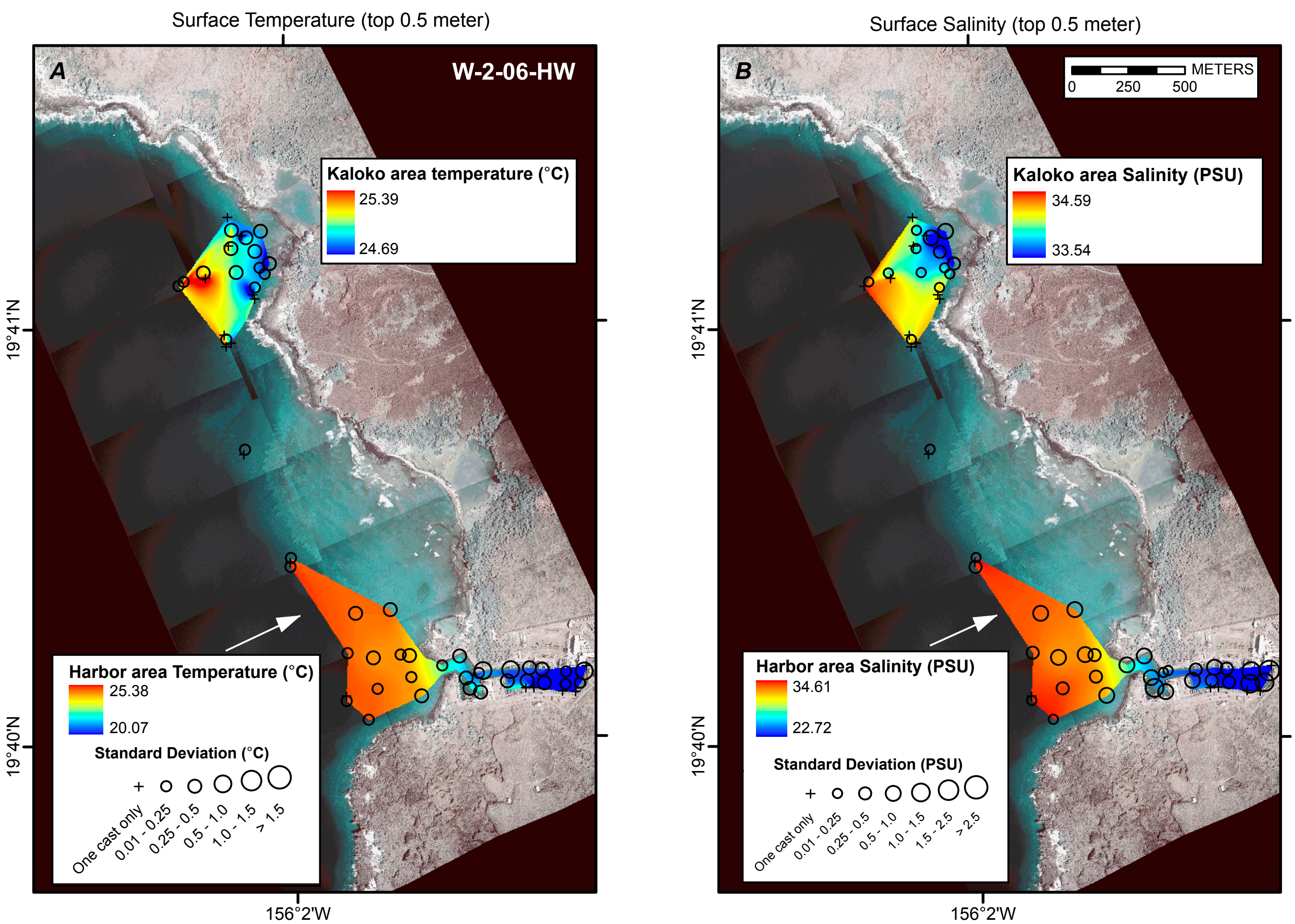

Figure 33. Maps of mean surface temperature (*A*) and salinity (*B*) during April 2006 surveys.

SGD plumes were estimated. This section describes the estimated spatial extent and volume of the plumes and, where data are available, how these compare to calculated fluxes of SGD derived from direct measurements using radium isotope and conservative tracer methods (Knee and others, 2008). In some cases, only cross-section plots are shown for ease of visualization; however, actual volumes were derived by integrating the depth to the salinity inflection point over the observed plume areas associated with cross sections discussed.

On December 12, 2003, salinities measured during a falling spring tide within the middle of the harbor ranged from 30 to 31 PSU, whereas 1,300 m offshore of the harbor, values were close to those of marine waters (35 PSU) (fig. 38). Temperature was closely correlated with salinity inside the plume, ranging from 24.0 to 25.5ºC. The groundwater plume extended 750 to 800 m offshore, just outside the harbor entrance, and reached 3 m thick. The plume generally spanned the entire surface area of the harbor, and the minimum salinity

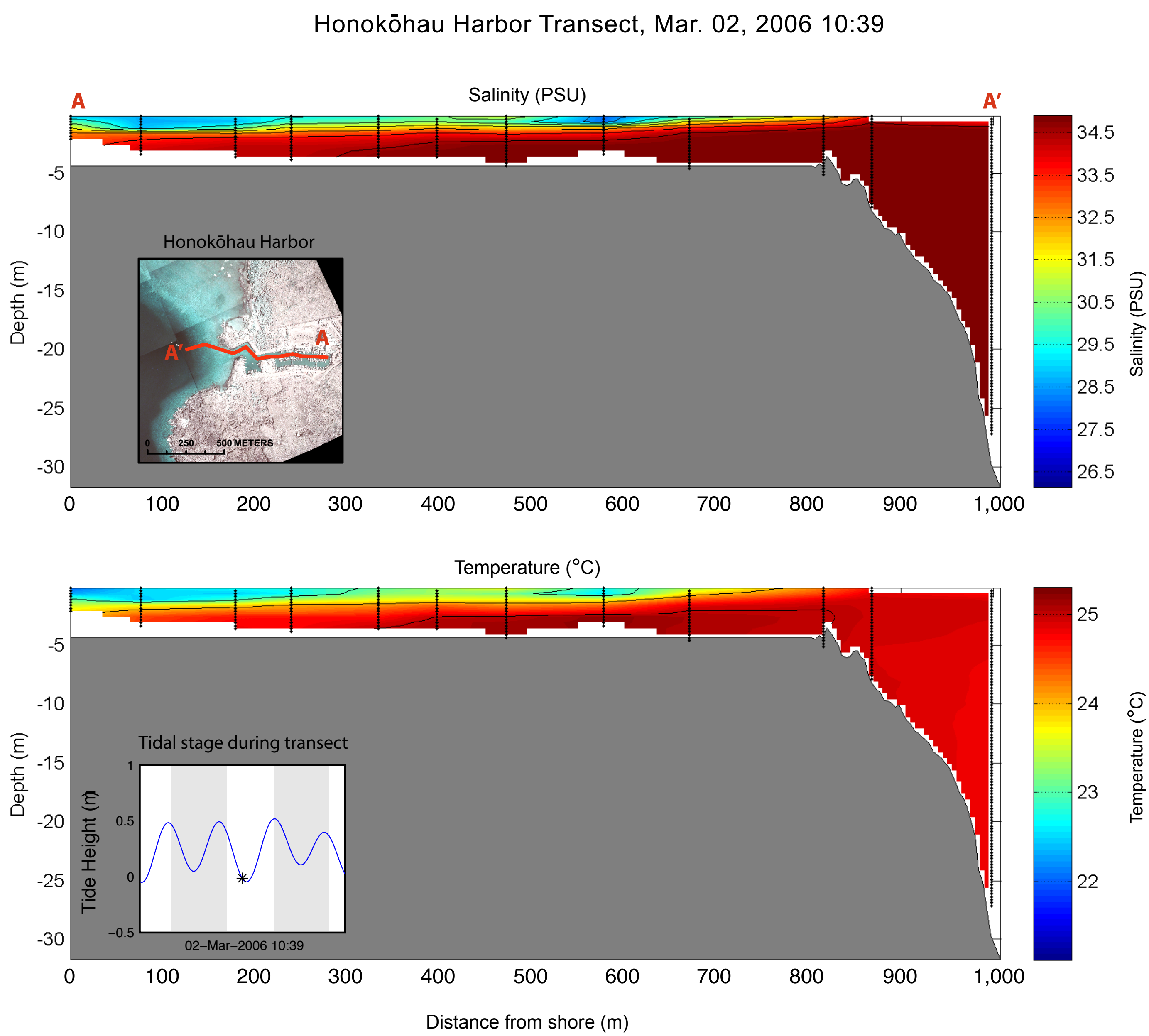

Figure 34. Cross-section of salinity (top) and temperature (bottom) of nearshore waters through Honokōhau Small Boat Harbor and Honokōhau Bay during low tide on the morning of March 2, 2006.

value measured at the landward edge of the harbor during the December 2003 survey was 24 PSU, significantly lower than the marine end-member (fig. 28). By applying a mean 3-m thickness across the harbor, we calculate that the plume had a volume of 241,350 cubic meters (63.7 MGal). This volume represents nearly 30× the flux calculated for the December 2003 survey derived from Ra isotope methods (Knee and others, 2008). The difference may reflect additional SGD sources contributing to the plume, longer plume residence time, or measurement or calculation errors with either method. On April 21, 2004, a cross section of salinity measured just after low tide during a spring tide cycle shows the plume in the harbor characterized by salinities ranging from 30 to 31 PSU that influenced waters at least 1,000 to 1,100 m

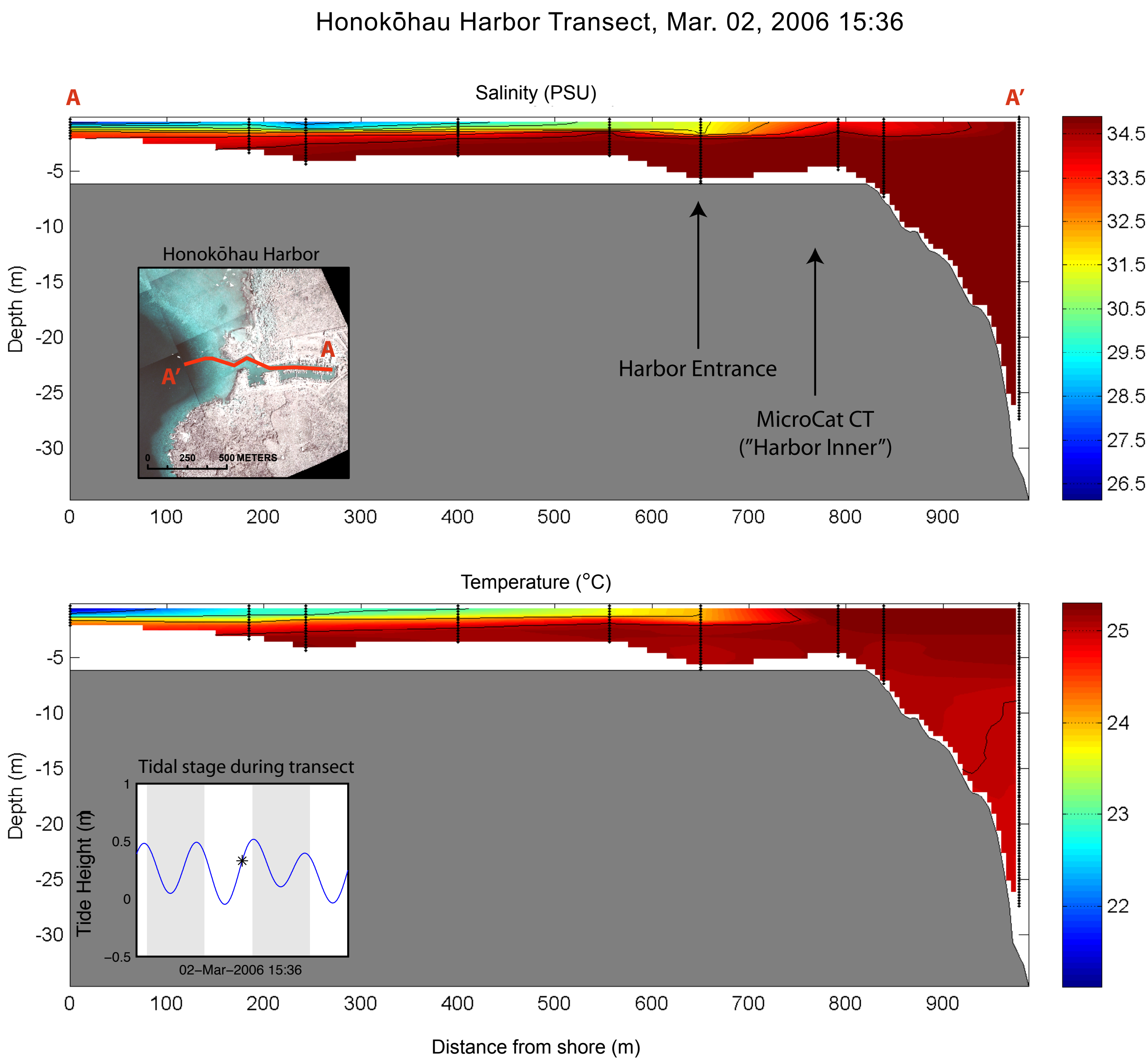

Figure 35. Cross-section of salinity (top) and temperature (bottom) of nearshore waters through Honokōhau Small Boat Harbor and Honokōhau Bay during low tide on the afternoon of March 2, 2006.

offshore (marine values of ~35 PSU were not yet observed). The groundwater plume reached the harbor sea floor at 4-m depth, and discharge was high enough to produce near-vertical salinity contours at the harbor entrance (fig. 39) The plume extended 300 m outside the harbor entrance and, on the basis of surface maps of the plume (fig. 29), likely influenced an area 300 m alongshore. By applying a 2-m mean thickness of the plume to account for its thinning over this distance offshore, we calculated that the combined volume of the plume inside and outside of the harbor was 501,800 cubic meters (132.5 MGal). SGD flux measurements from this study period are not available for comparison, but the overall lower salinity observed across the Park in April 2004 may reflect higher SGD occurring during this time frame. The temperature within

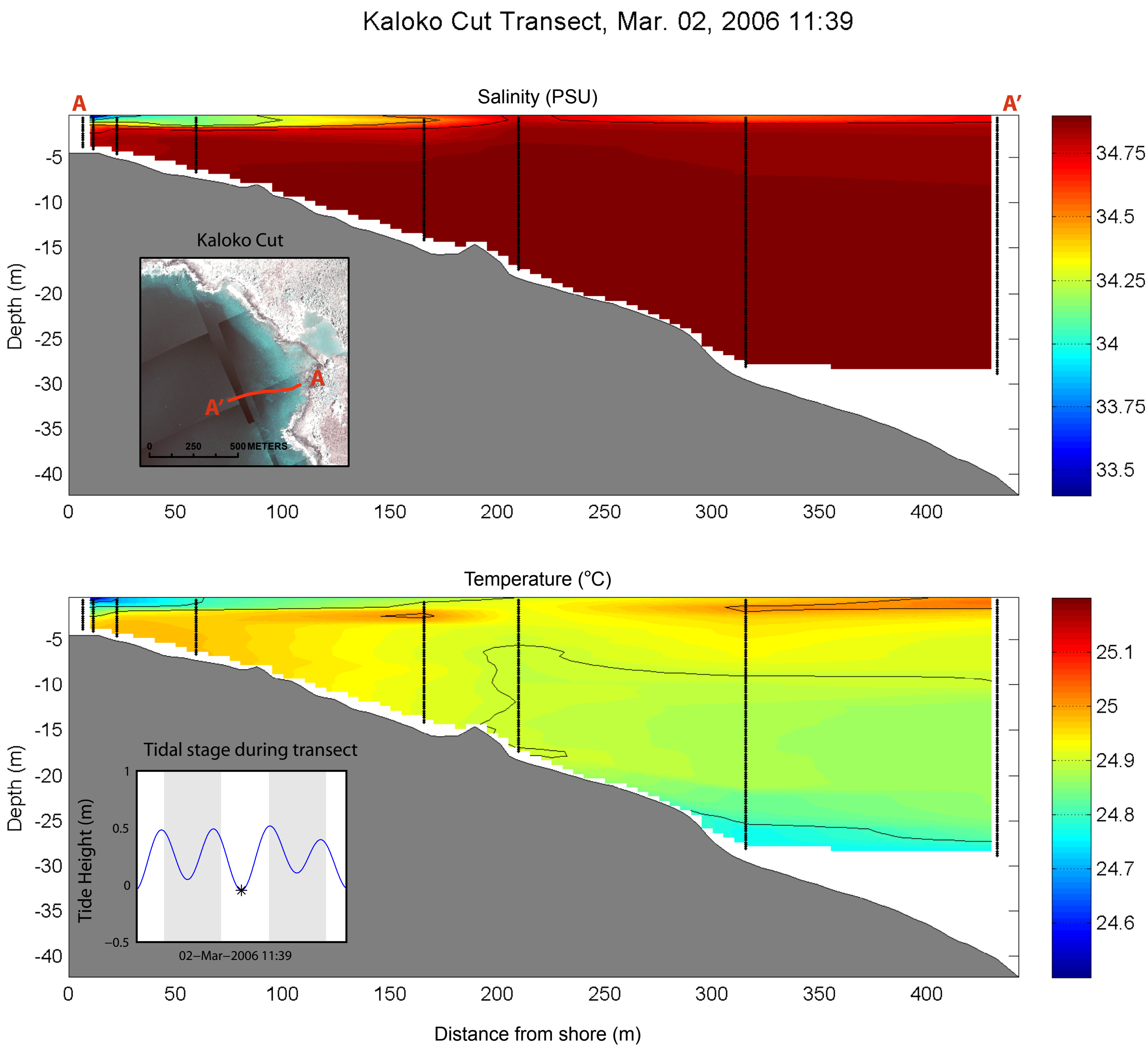

Figure 36. Cross-section of salinity (top) and temperature (bottom) of nearshore waters in Kaloko Bay offshore of Kaloko Fishpond and the “Cut” during low tide on the morning of March 2, 2006.

the plume was closely correlated with salinity, ranging from 24.5 to 25.5ºC.

On August 19, 2005, a cross section of salinity measured during the beginning of a flood tide within a spring tide cycle shows the plume in the harbor was characterized by salinities ranging from 24 to 32 PSU and influenced waters 700 to 750 m offshore to the harbor entrance (fig. 40). The groundwater plume averaged 2 m thick and had a volume of 161,000 cubic meters (42.5 MGal). Temperatures within the plume ranged from 21.7 to 26.0ºC and were closely correlated with salinity. On the previous day (August 18), the harbor plume extent and volume were very similar, despite a slightly higher tide.

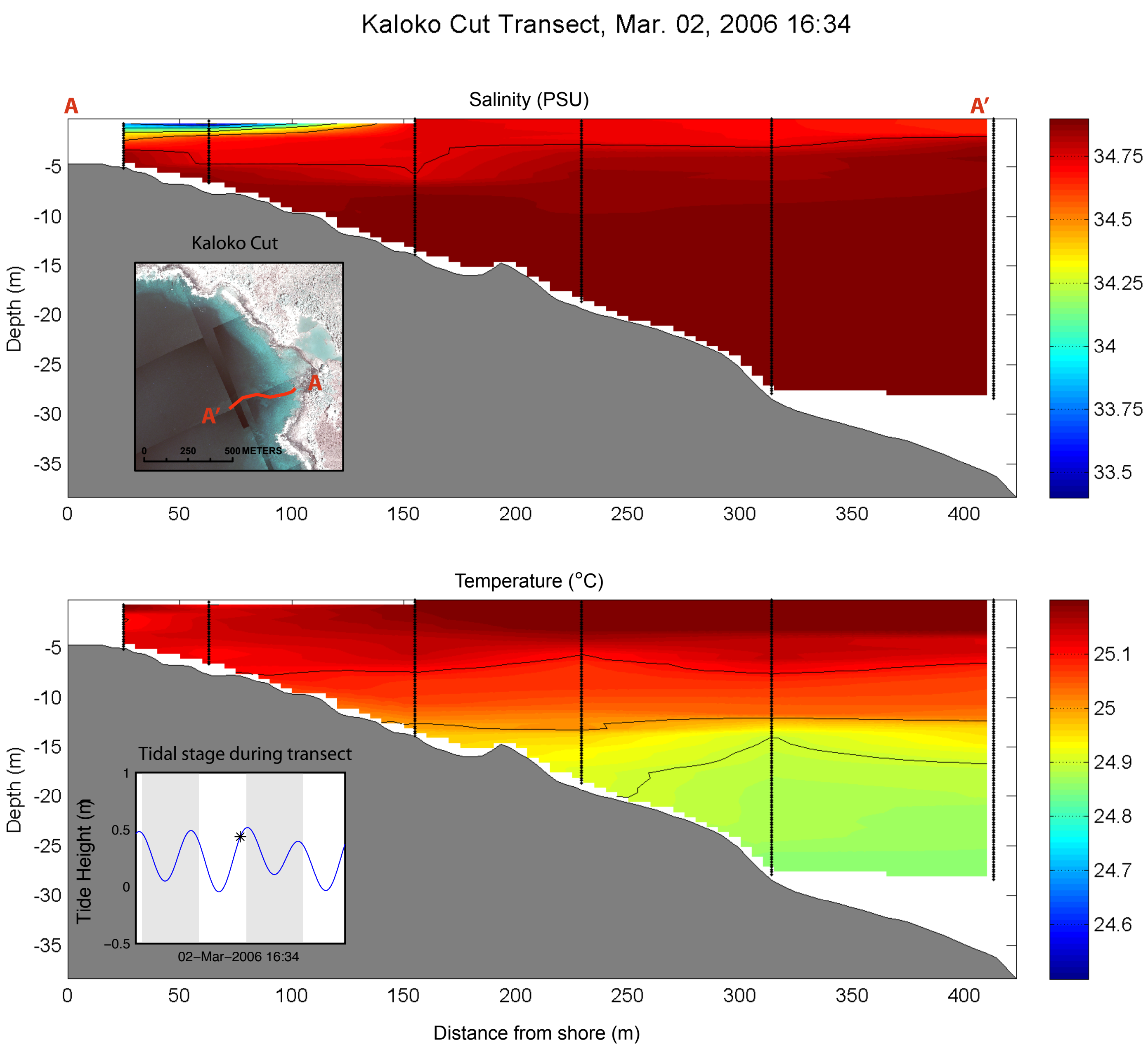

Figure 37. Cross-section of salinity (top) and temperature (bottom) of nearshore waters in Kaloko Bay offshore of Kaloko Fishpond and the "Cut" during low tide on the afternoon of March 2, 2006.

On April 4, 2006, a cross section of salinity measured at low tide shows that the plume offshore of Kaloko Fishpond and the “Cut” was characterized by salinities ranging from 33 to 35 PSU and influenced waters out to 400 m offshore (fig. 41). Alongshore, this plume extended nearly 350 m across Kaloko Bay and ranged from 2 to 3 m thick, with a slightly fresher signal in the northern portion of the bay (fig. 42). The corresponding volume of this plume for the dimensions observed ranged from 280,000 to 420,000 cubic meters (74 to 100 MGal). Temperatures within the plume, ranging from 21.7 to 26.0ºC, were closely correlated with salinity. A similar volume was observed offshore of Kaloko Fishpond and the “Cut”

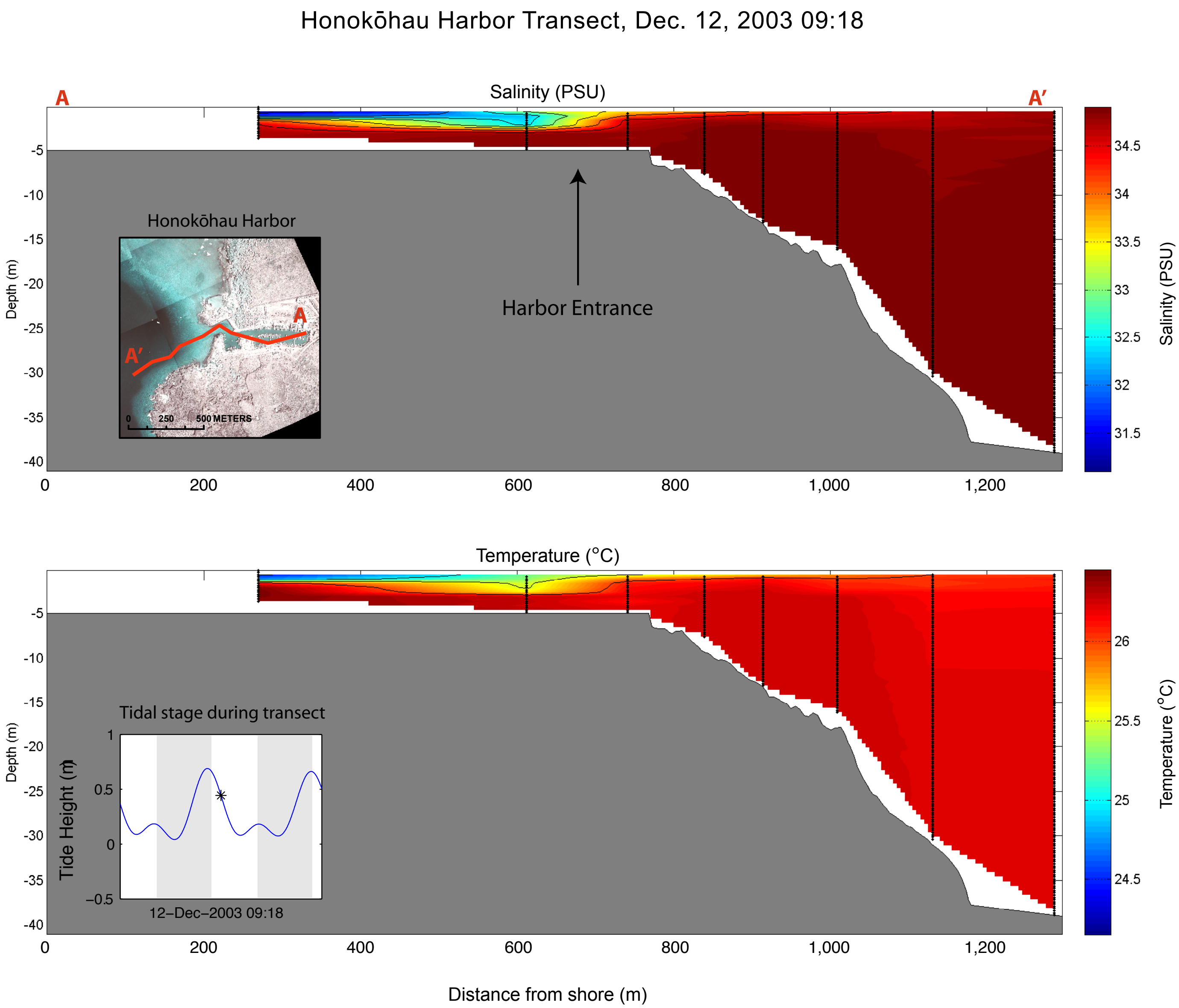

Figure 38. Cross-section of salinity (top) and temperature (bottom) of nearshore waters through the Honokōhau Small Boat Harbor and Honokōhau Bay on December 12, 2003.

on March 2, 2006, where a cross section of salinity measured at low tide showed the plume extended nearly 350 m offshore.

Correlations between Salinity and Temperature with Depth

Salinity was generally postively correlated with temperature throughout the different study periods and across the Park's nearshore waters; however, important relationships exist at different depths and areas within the Park that likely affect coral reef and coastal ecosystems. For example, in December 2003 surface salinity generally increased with increasing temperature at depths between 0 and 3 m (fig. 43); however, the highest correlation ($R^2 = 0.84$) was found at 1.75-m depth (fig. 43B) and not at the surface ($R^2 = 0.17$). Buoyant fresher SGD plumes are generally expected at the surface, but a significantly higher correlation of these data at a depth of 1.75 m

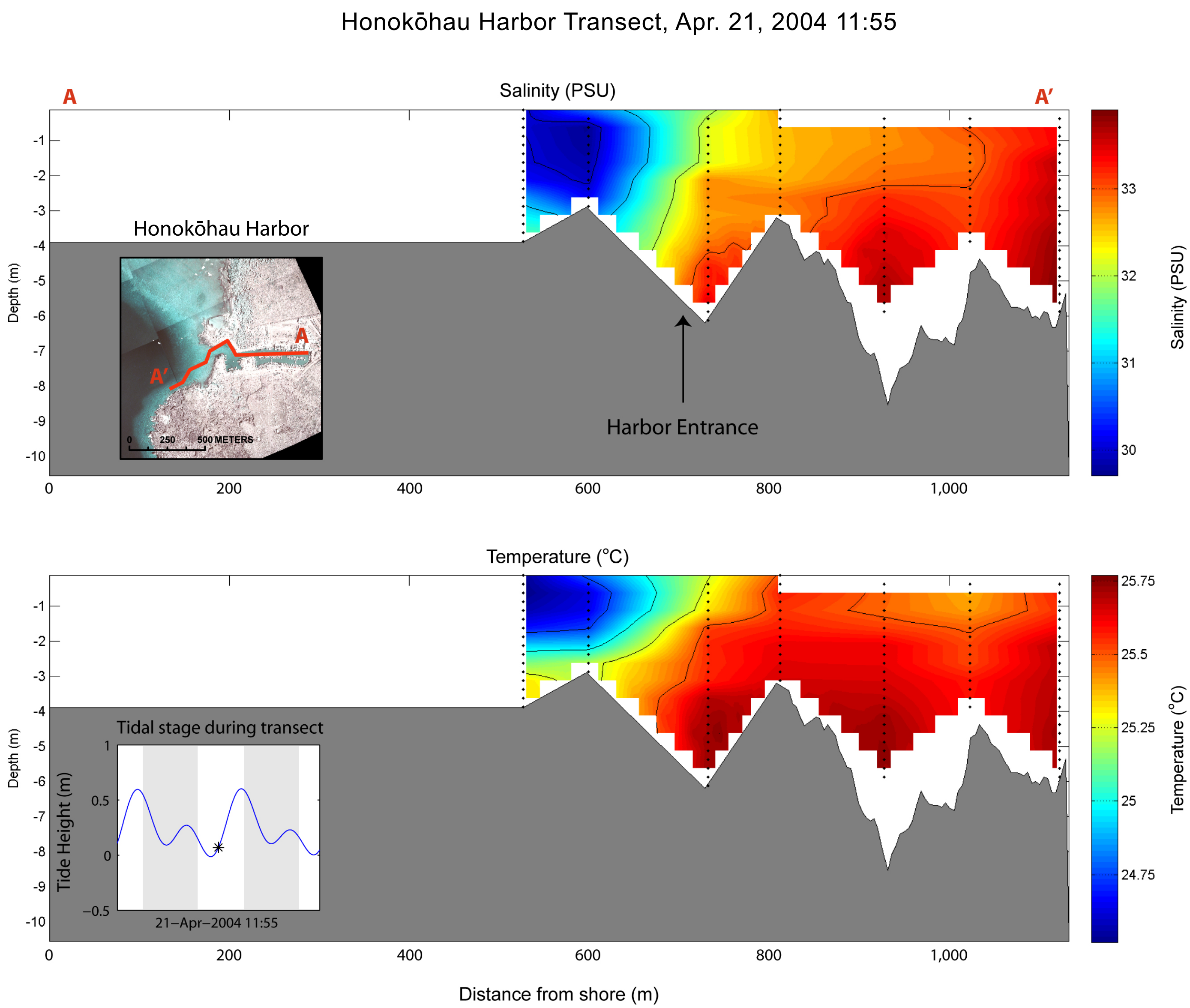

Figure 39. Cross-section of salinity (top) and temperature (bottom) of nearshore waters through the Honokōhau Small Boat Harbor and Honokōhau Bay on April 21, 2004.

indicates either a stronger source of groundwater at depth and/or less disturbance of water masses at this depth from either mixing of different layers of water, warmer freshwater from the surface, or upwelling of colder saline water from depth. If such patterns are common, with strong correlation between colder, less saline water at depth, they likely influence coral reef and coastal biota through controls on temperature, salinity, and water quality (for example, associated nutrients and contaminants; Knee and others, 2008).

Examining this relation for all study periods through an analysis of the correlation between salinity and temperature of all measurements made within individual 0.25-m depth intervals across the study area reveals that the depth at which the strongest relationship between salinity and temperature occurs varied between 0.25 m and 2.5 m between study periods (fig. 44). In August 2005, November 2005, and February–March 2006, the strongest positive correlation between salinity and temperature occurred in the uppermost 0.5 m. The correlation

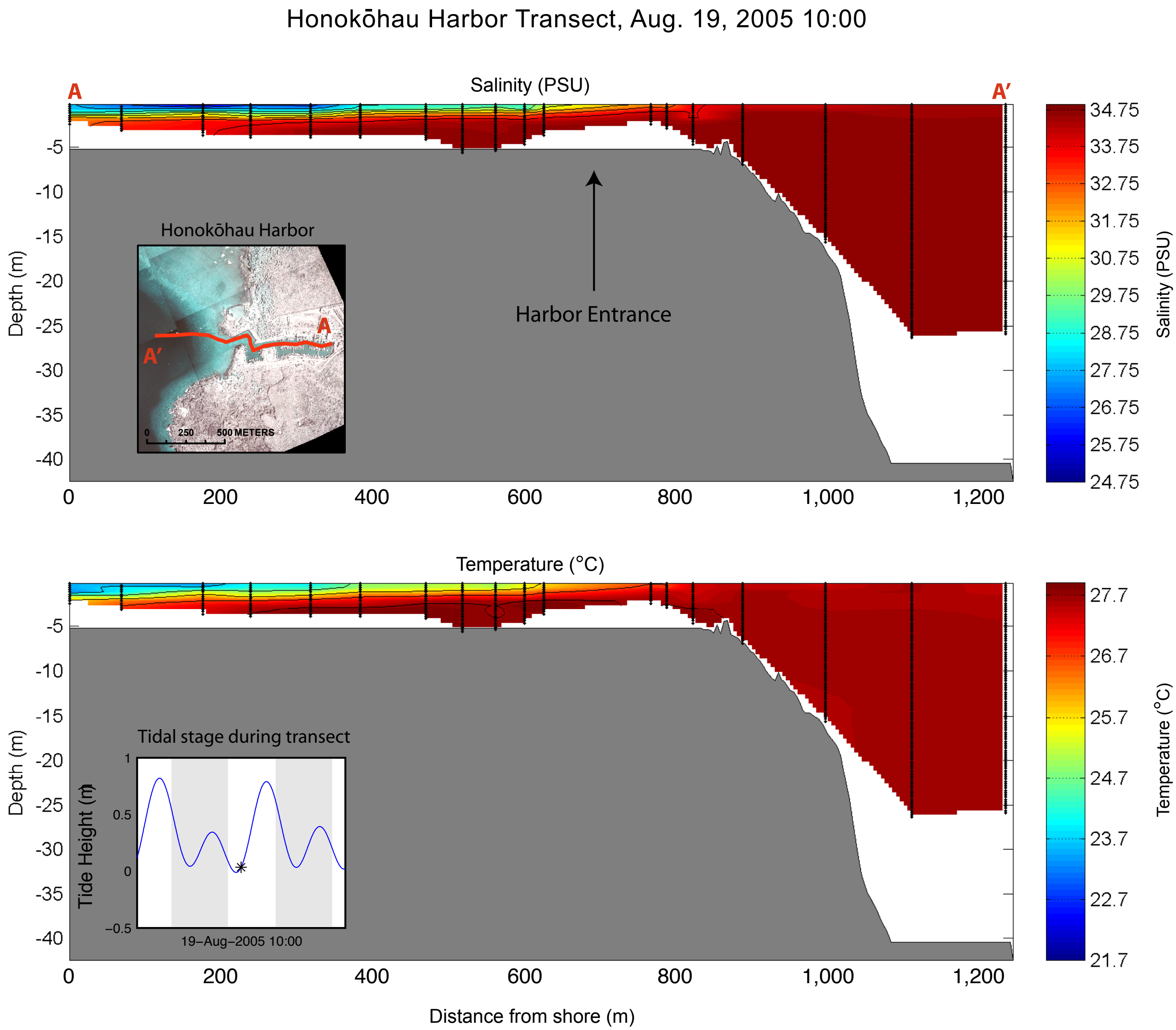

Figure 40. Cross-section of salinity (top) and temperature (bottom) of nearshore waters through the Honokōhau Small Boat Harbor and Honokōhau Bay on August 19, 2005.

slowly decreased with depth. In December 2003 and August 2004, a different relation existed, with a much stronger correlation between salinity and temperature occurring between 1 and 2 m, and between 2 and 3 m, respectively. In April of 2004, salinity was negatively correlated with temperature in the uppermost 0.5 m and then became positively correlated between 0.5 and 3.0 m, with the highest positive correlation found at 2.5-m depth. The reason for the April 2004 difference is unclear but perhaps related to moderate west winds that piled saline marine water onto the shelf, where it warmed relative to deeper colder and fresher waters.

These results indicate that, although salinity is generally positively correlated with temperature, variations in this relation occur and the strongest correlations may exist at

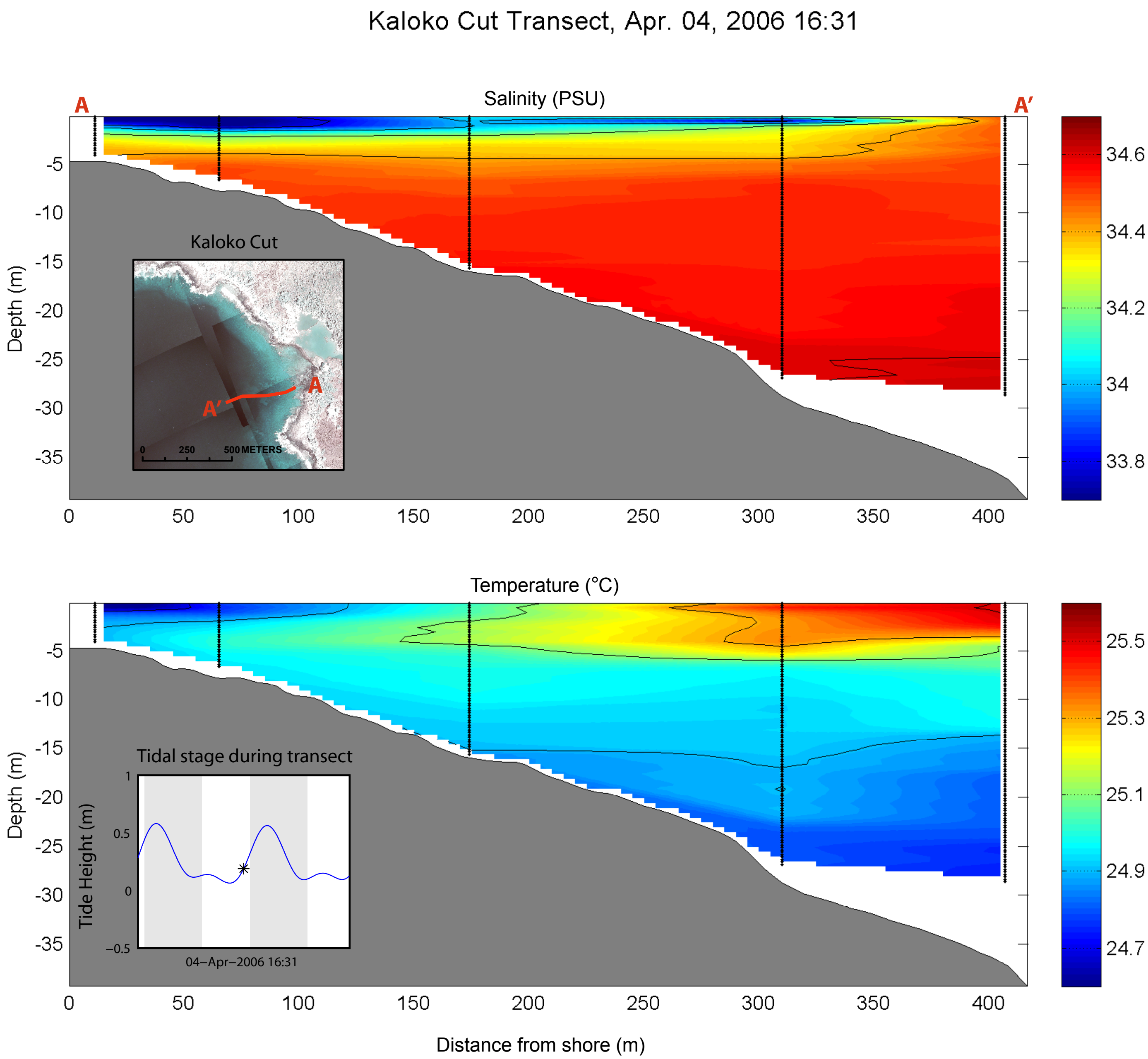

Figure 41. Cross-section of salinity (top) and temperature (bottom) of nearshore waters in Kaloko Bay offshore of Kaloko Fishpond and the "Cut" on April 4, 2004.

depth. This correlation pattern has important implications for understanding the magnitude and depth that SGD influences benthic habitats. Subsurface circulation (currents, internal waves) transports and mixes the SGD plumes observed in this study and places these colder, fresher water masses into contact with reef biota. Very little is known about the importance of groundwater to overall coral reef growth, reef organisms, or the ecosystem services that groundwater provides to nearshore habitats and their resilience. Some work indicates fresh-to-brackish estuarine waters are important to numerous fishes, including the striped mullet (Major, 1978), which is culturally significant in Hawai‘i. It is important to improve understanding of the extent to which these groundwater plumes influence reef biota, including quantifying the duration of the time that

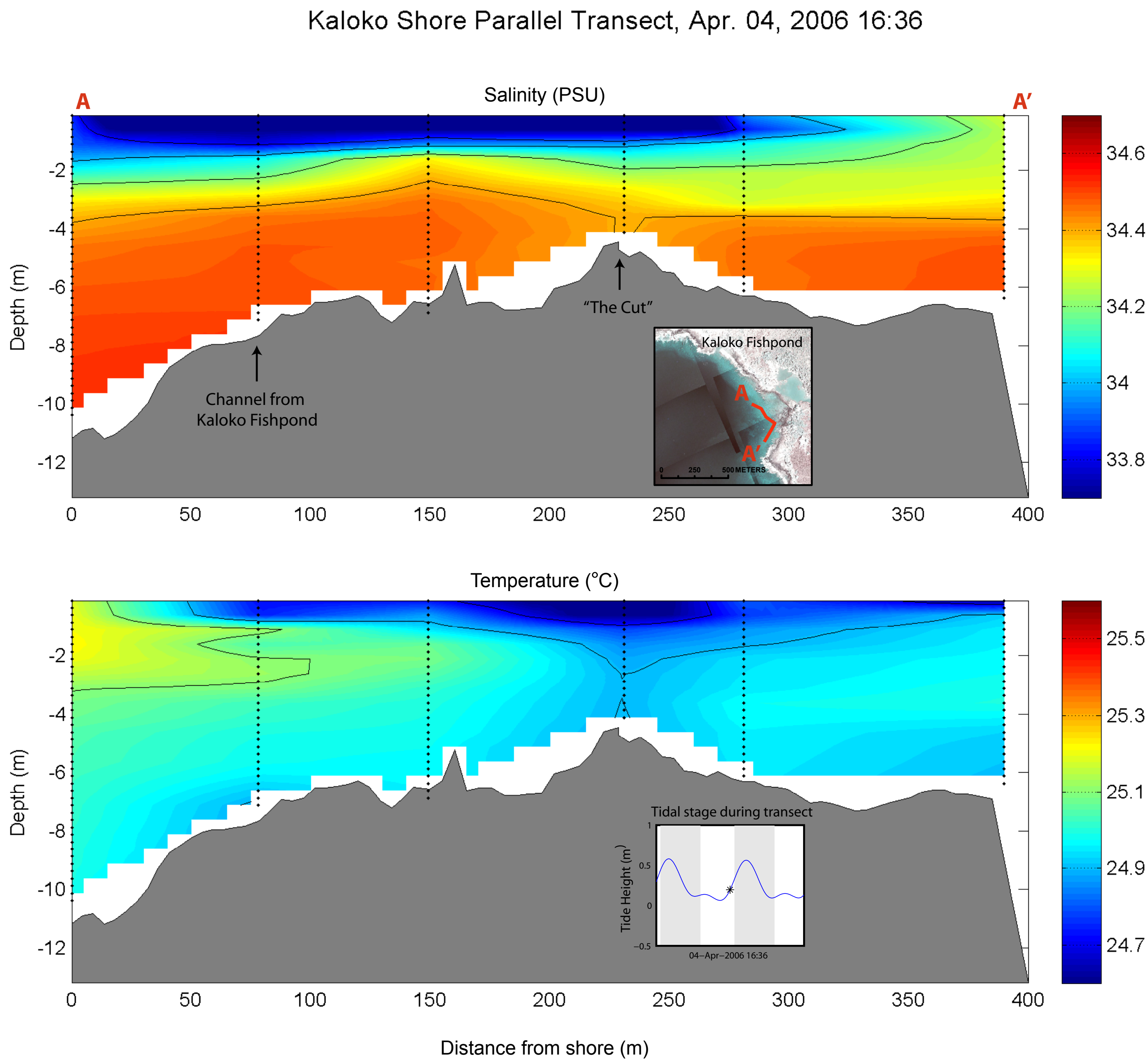

Figure 42. Cross-section of salinity (top) and temperature (bottom) of nearshore waters alongshore in Kaloko Bay offshore of Kaloko Fishpond and the “Cut” (looking landward) on April 4, 2004.

reef biota experience groundwater and how they respond to temperature, salinity, and associated nutrients and contaminants in groundwater. This will become increasingly important as plans are developed for greater groundwater use and as groundwater quantity and quality are altered by land use and climate change.

The correlation results shown in figure 44 also place important constraints on other methods of characterizing SGD. For example, thermal infrared imaging techniques that only capture thermal contrasts of the upper 1–10 mm of the surface ocean and that generally rely on a positive correlation model between salinity and temperature may not characterize the most significant contributions of SGD that occur at depth. Similarly, geochemical methods based on conservative tracers may better quantify SGD and fluxes if paired with physical measurements like those presented in this study. This combination will allow researchers to target and directly sample the fresh-to-brackish waters of interest that may occur at depth and play the most significant role to benthic biota.

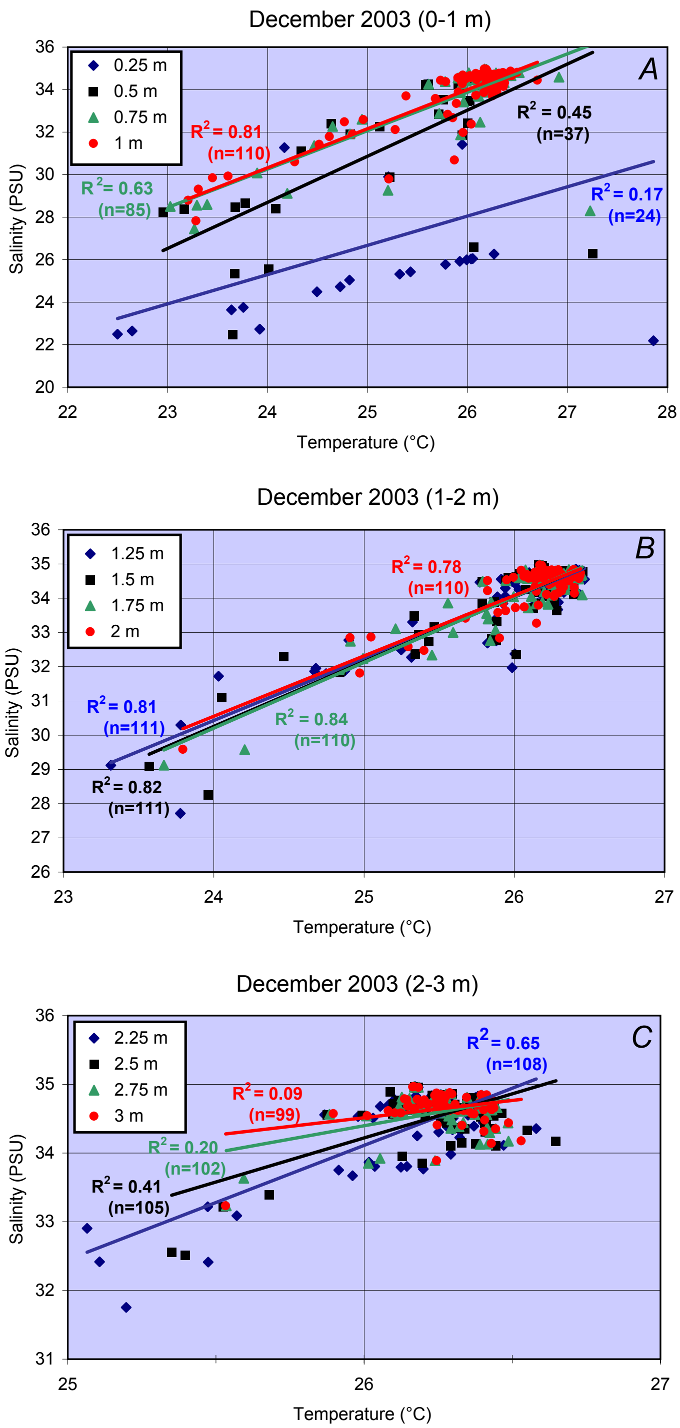

Figure 43. Plots showing correlation between salinity and temperature within individual 0.25-m depth intervals for 0 to 1 m (*A*), 1 to 2 m (*B*), and 2 to 3 m (*C*) during December 2003.

Exposure to Submarine Groundwater Discharge

The results of this study show that brackish surface plumes derived from SGD are persistent and influence most of the areas of Kaloko-Honokōhau National Historical Park within 5-m depth (fig. 45). Despite the relatively energetic wave climate and circulation along the coast, the influence of high SGD and nearshore circulation generally maintained buoyant brackish surface plumes across the 0- to 5-m depth region during all of the sampling periods studied here. The 0- to 5-m depth region is particularly important for pioneer

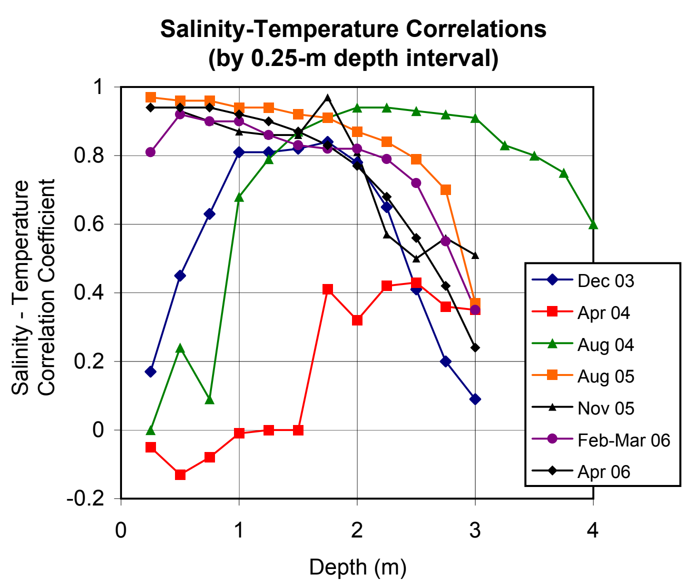

Figure 44. Plot showing correlation between salinity and temperature within individual 0-25 m depth intervals for each survey period.

(Pocillopora meandrina), hearty (Porites lobata, Montipora capitata, M. patula), and soft (Sarcothelia edmondsi) coral species that exist within the Park, especially in the southern end immediately adjacent to the Kaloko-Honokōhau Small Boat Harbor entrance and offshore of Kaloko Fishpond. Some of these species may be particularly adapted to or reliant on the influence of groundwater and its composition. Observations throughout this study indicate that the soft coral Sarcothelia edmondsi is clearly the most abundant and often exclusive species in and around the groundwater seeps and persistent plumes identified. It may be ecologically tied to groundwater, filling a specific niche where other corals and algae are unable to compete. It is also important to note that periodic high waves and winds mix these SGD plumes to depths of 15 m, placing the nutrients and contaminants entrained in the groundwater into contact with deep habitats across the region. These results are important for beginning to quantify the significance and role of SGD to the coral and algal community structure along the Hawaiian coast and other coral reef settings so that future responses of coral-reef and coastal ecosystem, including coral-reef resilience, can be predicted as a result of changes in the quantity and quality of SGD.

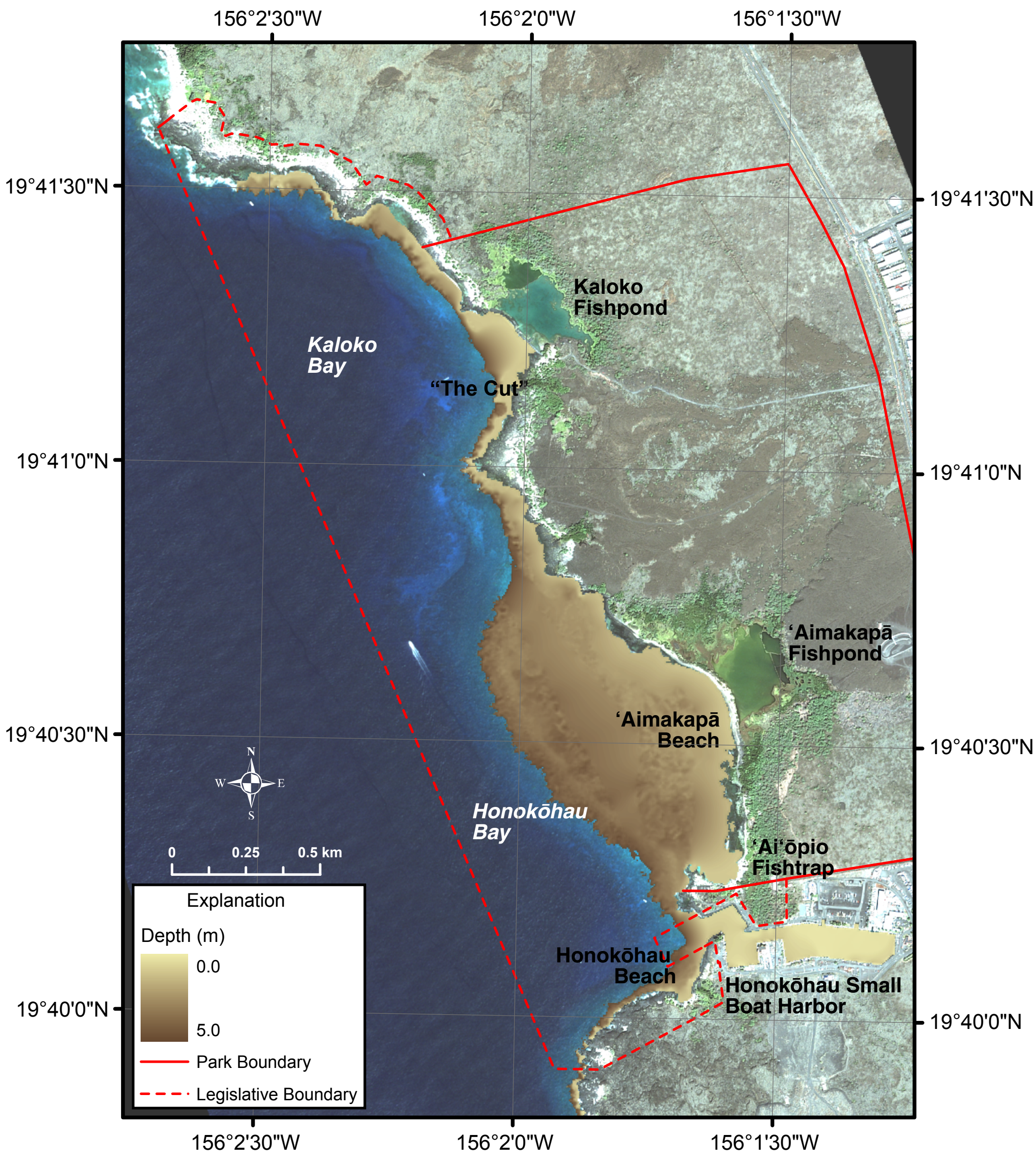

Figure 45. Map showing the area of Kaloko-Honokōhau National Historical Park that is within 5-m depth and persistently influenced by submarine groundwater discharge as observed in this study.

Conclusions and Recommendations

Individual profiles, surface maps, and cross sections of temperature and salinity from 1,045 CTD casts collected across the Kaloko-Honokōhau National Historical Park over seven different seasonal surveys show the persistence of brackish plumes fed by submarine groundwater discharge (SGD in the Park's nearshore marine area and coral reef. These plumes generally ranged from 1 to 3 m thick, with a maximum of 5 m, and extended 400 m offshore of Kaloko Fishpond in the north and between 700 and 1,000 m through the Honokōhau Small Boat Harbor and across the nearhore in the south. Temperature and salinity of the nearshore water varied greatly in the upper 5 m, and that water could be classified as generally estuarine, transitioning to marine water by 1,000 m offshore. The nearshore waters out to 1,000 m were clearly and persistently stratified, with a buoyant, fresher and colder SGD plume overlying marine water when winds and waves were low. An exception occurred in April 2004, when lower salinities were associated with slightly warmer waters in the upper 1 to 2 m, perhaps a result of the mild onshore wind pattern. Winds blowing onshore and exceeding 4 to 5 m/s typically mixed the plumes completely down through the entire water column. Tides shifted the seaward boundary of the SGD plumes by 100 to 300 m near the entrance of the Kaloko-Honokōhau Small Boat Harbor and by 50 to 100 m offshore of Kaloko Fishpond. Salinity was generally positively correlated with temperature in the surface waters, but this correlation was not always highest at the surface. Commonly the highest correlation occurred at depths of 0.5 to 2 m. These SGD plumes influence a large portion of the National Park's marine resources because of the narrow and relatively shallow reef complex at Kaloko-Honokōhau National Historical Park.

These results represent the first comprehensive examination of the influence of submarine groundwater discharge on the nearshore water properties of coastal Kaloko-Honokōhau National Historical Park. They provide important, quantitative baseline information on water quality with which to identify present and potential areas of impairment and to detect and quantify future changes. Understanding the patterns and processes that influence the fate of SGD mixing with nearshore waters is important for more effective management of coastal resources. While these results show the spatial and temporal pattern of the estuarine influence in the Park relating to the processes studied (seasons, diurnal cycles, tides, winds), the full range of depths and subhabitats that are affected by the submarine groundwater remains uncertain. It is recommended that strategic sampling of the principal SGD plumes be conducted to trace their influence spatially and temporally under the full range of climatic, oceanographic, annual to interannual, and seasonal conditions important to Park planning. For example, recent climate observations and predictions of drier conditions in the coming decades may place pressures on nearshore ecosystem processes reliant on specific quantities of SGD, as well as on the temperature, salinity structure, and composition of SGD.

Developing a monitoring strategy that can detect the change to those ecosystem processes may help in forecasting future impacts to habitats and biota. And although it is conceptually known that estuarine waters provide important ecosystem functions and services to Hawai‘i's coastal system, including Hawai‘i's rare and unique anchialine pools, less is understood of the role of SGD in shaping and maintaining coral reefs. It is recommended that studies of SGD be integrated with focused examination of the biotic responses of ecologically, culturally, and economically important habitats and biota. For example, the influence of SGD as observed in this study likely controls temperature, salinity, and nutrient concentrations to depths of 3 to 5 m across the Kaloko-Honokōhau National Historical Park, and changes in the mean (or threshold) occurrences of SGD may influence coral species diversity or cover in ways we cannot fully predict. The cold groundwater may buffer the thermal stress in corals expected with increasing global temperatures, so identifying what temperature thresholds exist and what rates of change can be sustained by the coral communities of the Park may be important for planning as climate impacts in the Park are being exacerbated by land use, including increasing groundwater use.

Acknowledgements

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Appendix 1. Maps showing individual surveys and sampling sites in Kaloko-Honokōhau National Historical Park

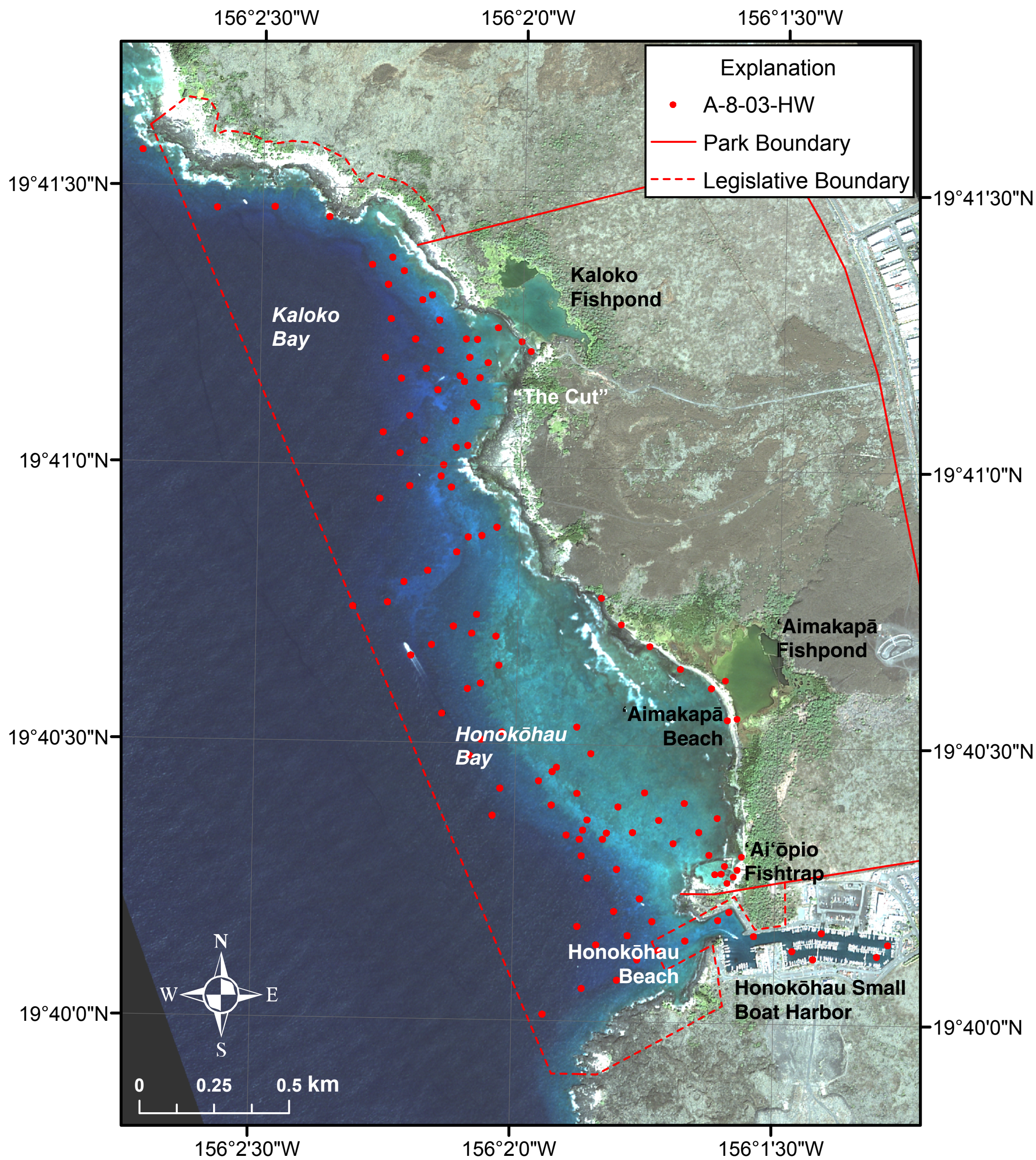

Figure A1.1. Map of sample locations for survey A-8-03-HW in December 2003.

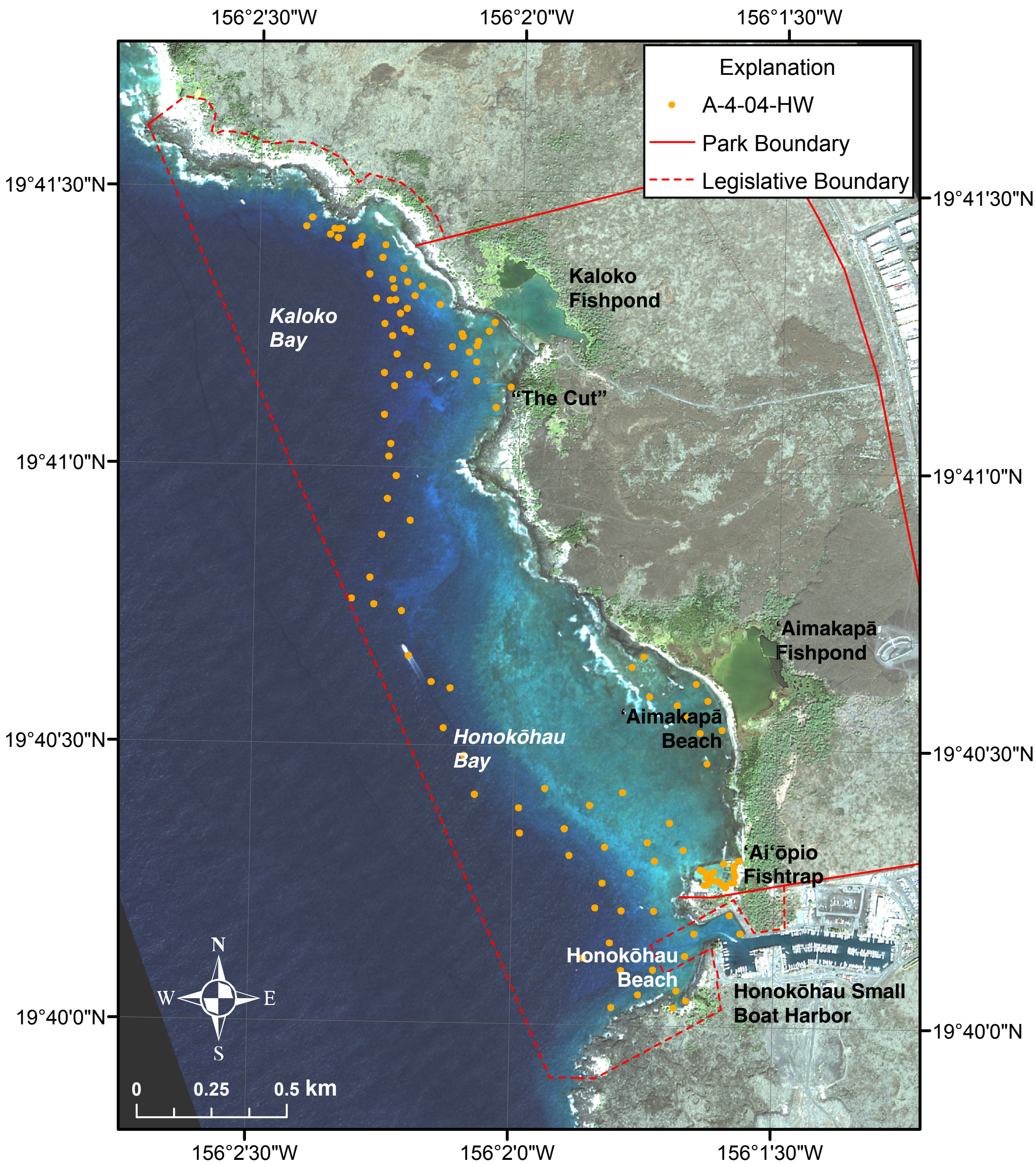

Figure A1.2. Map of sample locations for survey A-4-04-HW in April 2004.

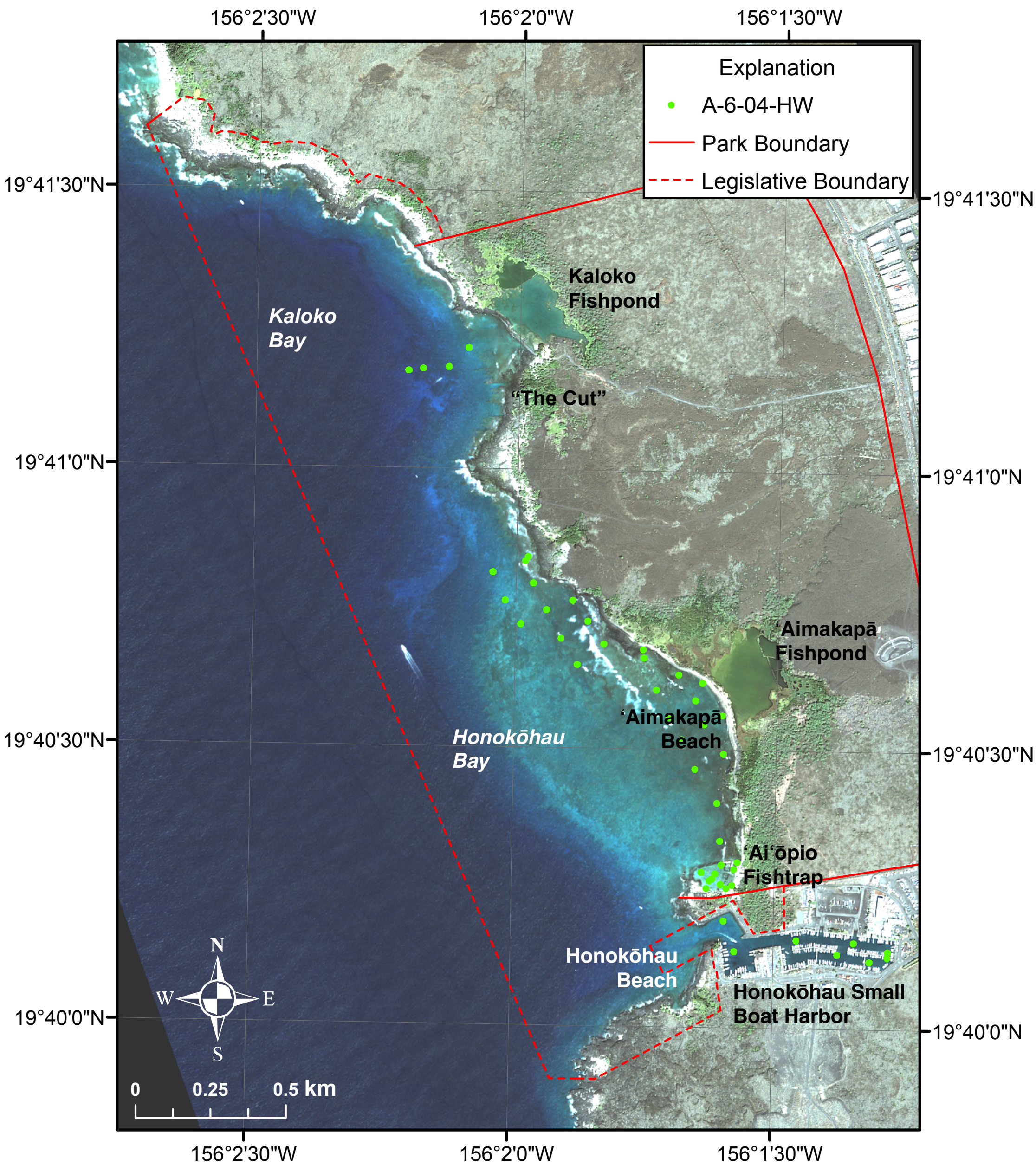

Figure A1.3. Map of sample locations for survey A-6-04-HW in August 2004.

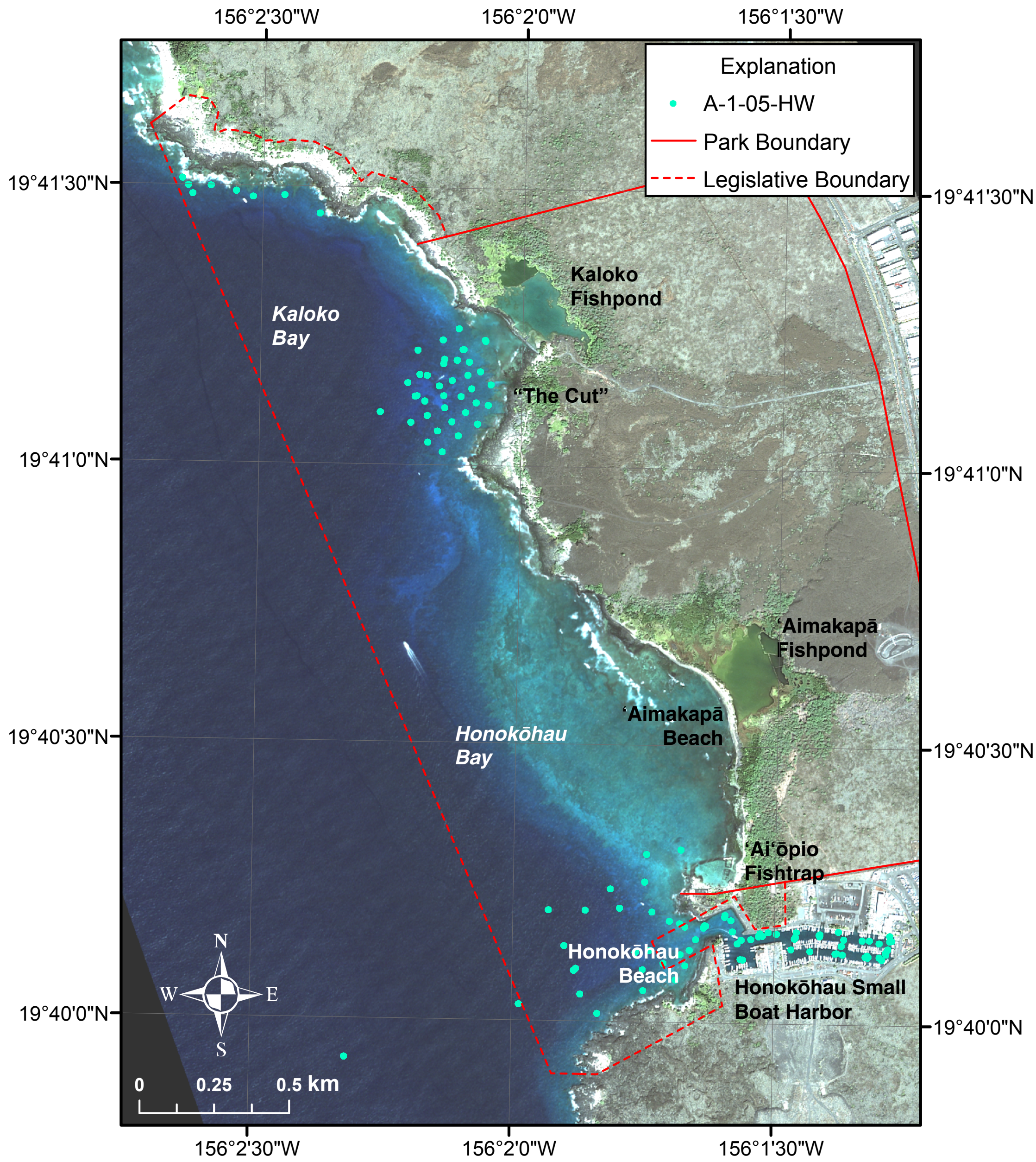

Figure A1.4. Map of sample locations for survey A-1-05-HW in August 2005.

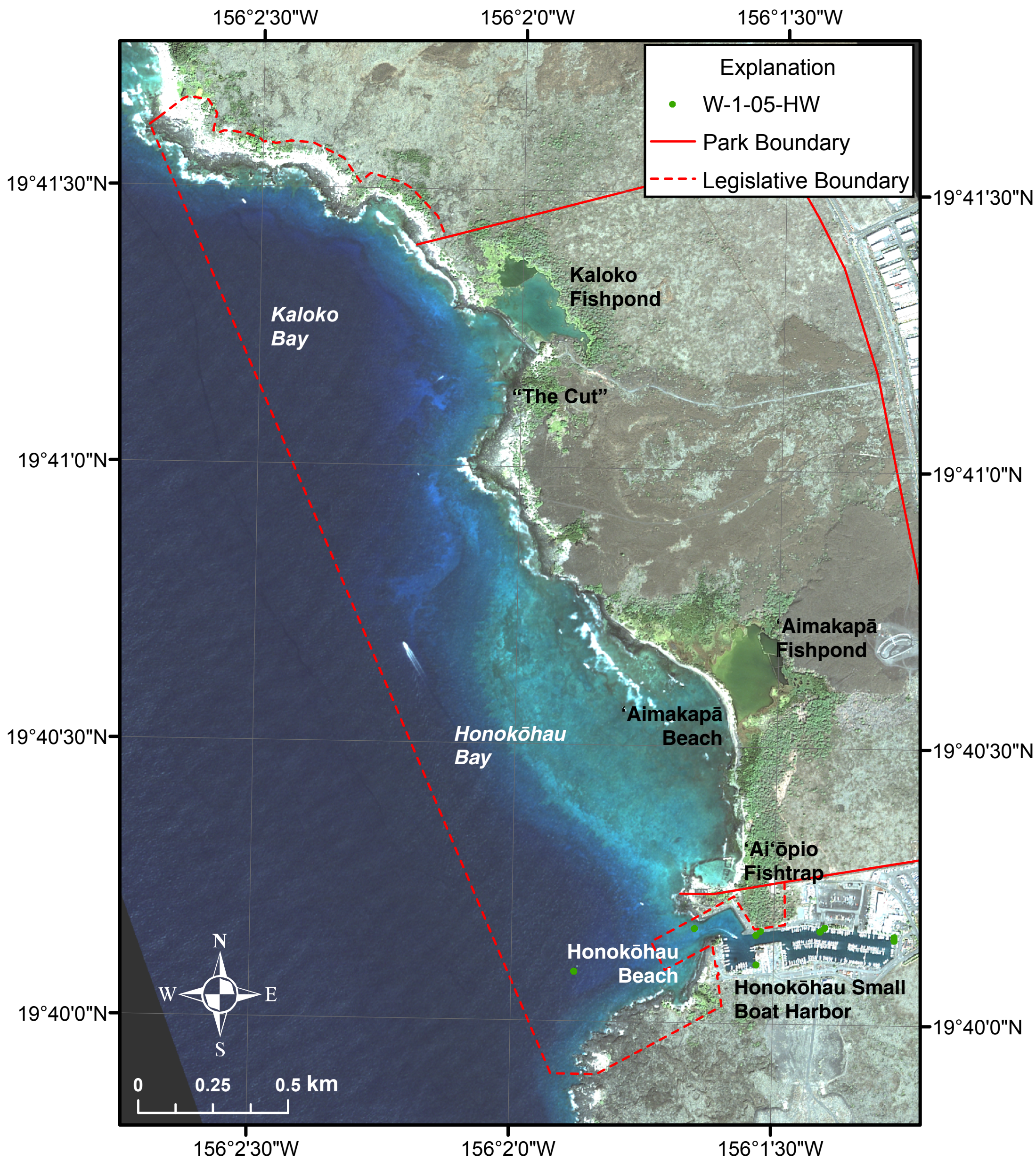

Figure A1.5. Map of sample locations for survey W-1-05-HW in November 2005.

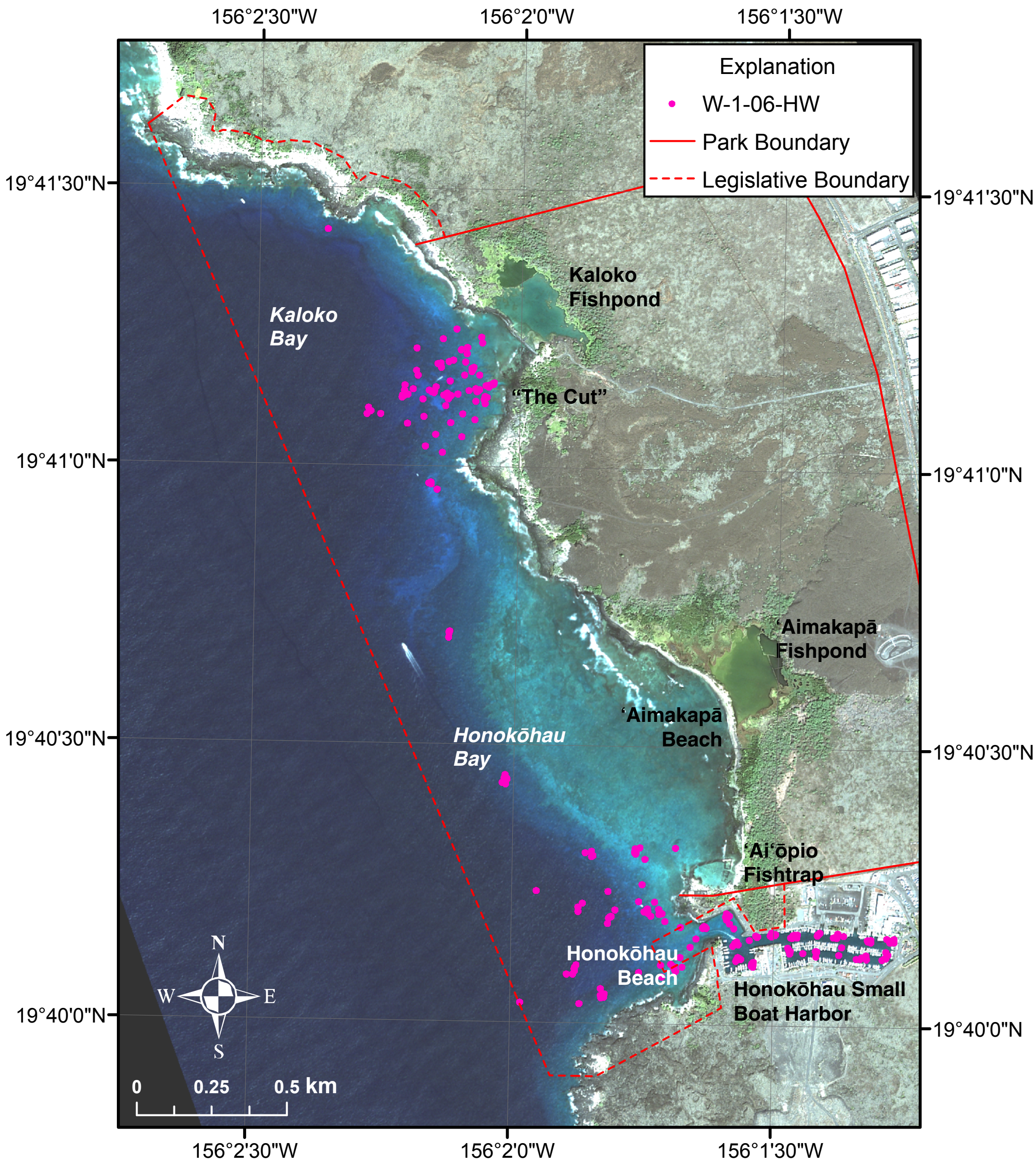

Figure A1.6. Map of sample locations for survey W-1-06-HW in February 2006.

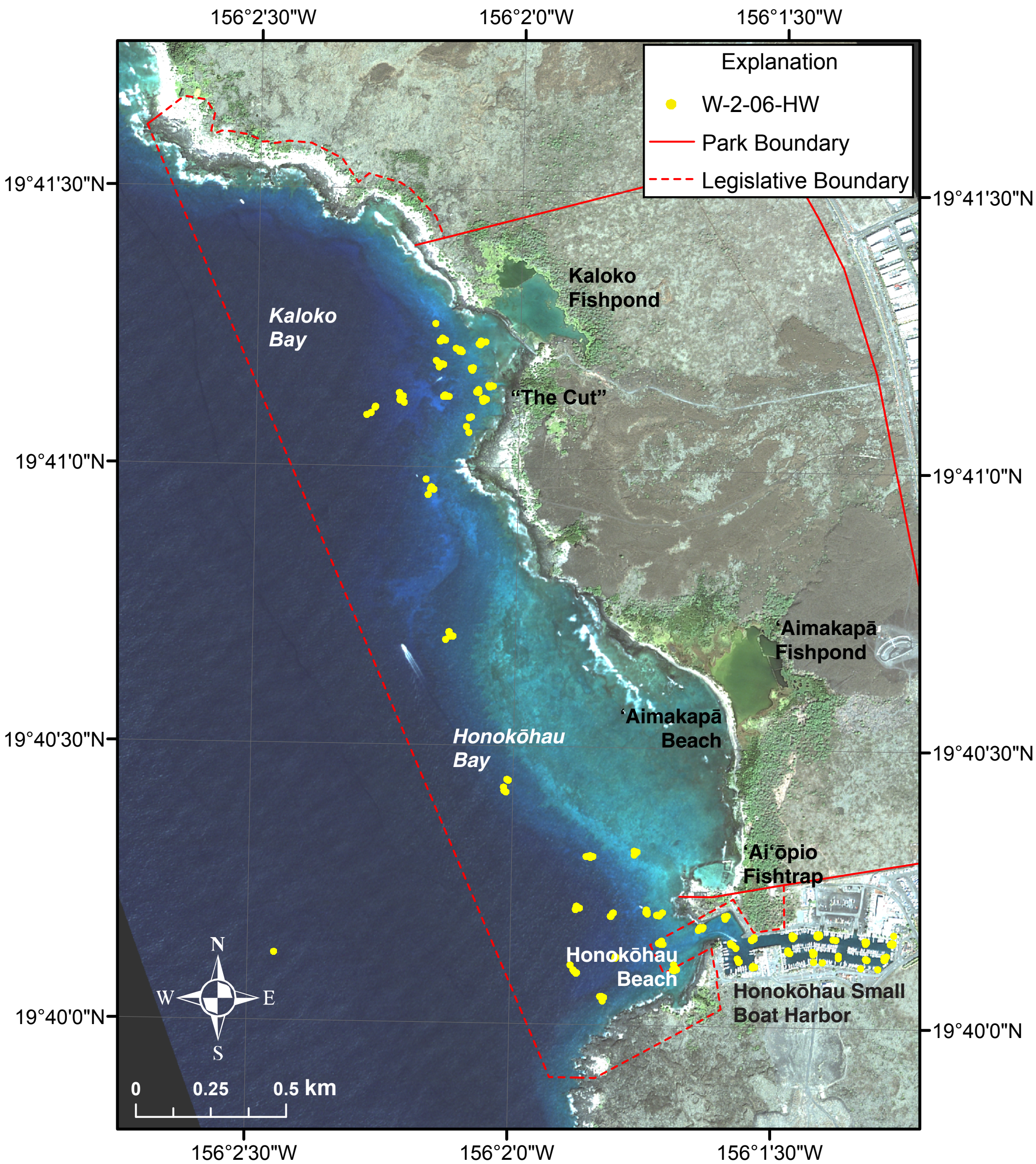

Figure A1.7. Map of sample locations for survey W-2-06-HW in April 2006.

Appendix 2. Seabird 19-Plus Profiler and Sensor Specifications

Specifications for Conductivity/Temperature/Depth (CTD) Profiler with Optical Backscatter (OBS) and Photosynthetically-Available Radiation (PAR) Sensor Information

Instruments

Seabird 19-Plus CTD; s/n: 4299
D&A Instruments OBS-3; s/n: 1983
Li-Cor SPQA-3562; s/n: 825

Sampling Frequency

4 Hz

Position Information

Garmin GPSMAP-76 GPS

Data Processing

The data were averaged into 0.25 m vertical bins and spurious data marked by a flag in the raw data were removed for visualization and analysis.

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