# Coastal Circulation and Sediment Dynamics in Hanalei Bay, Kaua`i

## PART IV:

## Measurements of Waves, Currents, Temperature, Salinity, and Turbidity: June – September 2006

By Curt D. Storlazzi, M. Katherine Presto, Joshua B. Logan, and Michael E. Field

*QuickBird satellite image of Hanalei Bay*

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# Coastal Circulation and Sediment Dynamics in Hanalei Bay, Kaua`i

## Part IV:

## Measurements of waves, currents, temperature, salinity, and turbidity: June – September 2006

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U.S. Geological Survey, Pacific Science Center, Santa Cruz, CA 95060 USA

## Introduction

High-resolution measurements of waves, currents, water levels, temperature, salinity and turbidity were made in Hanalei Bay, northern Kaua`i, Hawai`i, during the summer of 2006 to better understand coastal circulation, sediment dynamics, and the potential impact of a river flood in a coral reef-lined embayment during quiescent summer conditions. A series of bottom-mounted instrument packages were deployed in water depths of 10 m or less to collect long-term, high-resolution measurements of waves, currents, water levels, temperature, salinity, and turbidity. These data were supplemented with a series of profiles through the water column to characterize the vertical and spatial variability in water column properties within the bay. These measurements support the ongoing process studies being conducted as part of the U.S. Geological Survey (USGS) Coastal and Marine Geology Program's Pacific Coral Reef Project; the ultimate goal is to better understand the transport mechanisms of sediment, larvae, pollutants, and other particles in coral reef settings. Information regarding the USGS study conducted in Hanalei Bay during the 2005 summer is available in Storlazzi and others (2006), Draut and others (2006) and Carr and others (2006). This report, the last part in a series, describes data acquisition, processing, and analysis for the 2006 summer data set.

### Project Objectives

The objective of this study was to understand the temporal variations in currents, waves, tides, temperature, salinity and turbidity within a coral-lined embayment that receives periodic stream discharge. Instrument packages were deployed for a three-month period during the summer of 2006 and a series of vertical profiles were collected in June 2006, and again in September 2006, to characterize water-column properties within the bay. Measurements of flow and water column properties in Hanalei Bay will provide insight into the potential fate of terrestrial sediment, nutrient, or contaminant delivery and coral larval transport within the embayment. Such information will be useful for providing baseline information for future watershed decisions and for establishing guidelines for the U.S. Coral Reef Task Force's (USCRTF) Hawaiian Local Action Strategy to address Land-Based Pollution (LAS-LBP) threats to coral reefs in the Hanalei ahupua'a (linked watershed-reef system).

### Study Area

Spatial and temporal measurements of meteorologic, hydrologic, and oceanographic data were made during the summer of 2006 in Hanalei Bay, on the north side of Kaua`i, Hawai`i, USA (fig. 1). All vessel operations, including mobilization and demobilization, were based out of

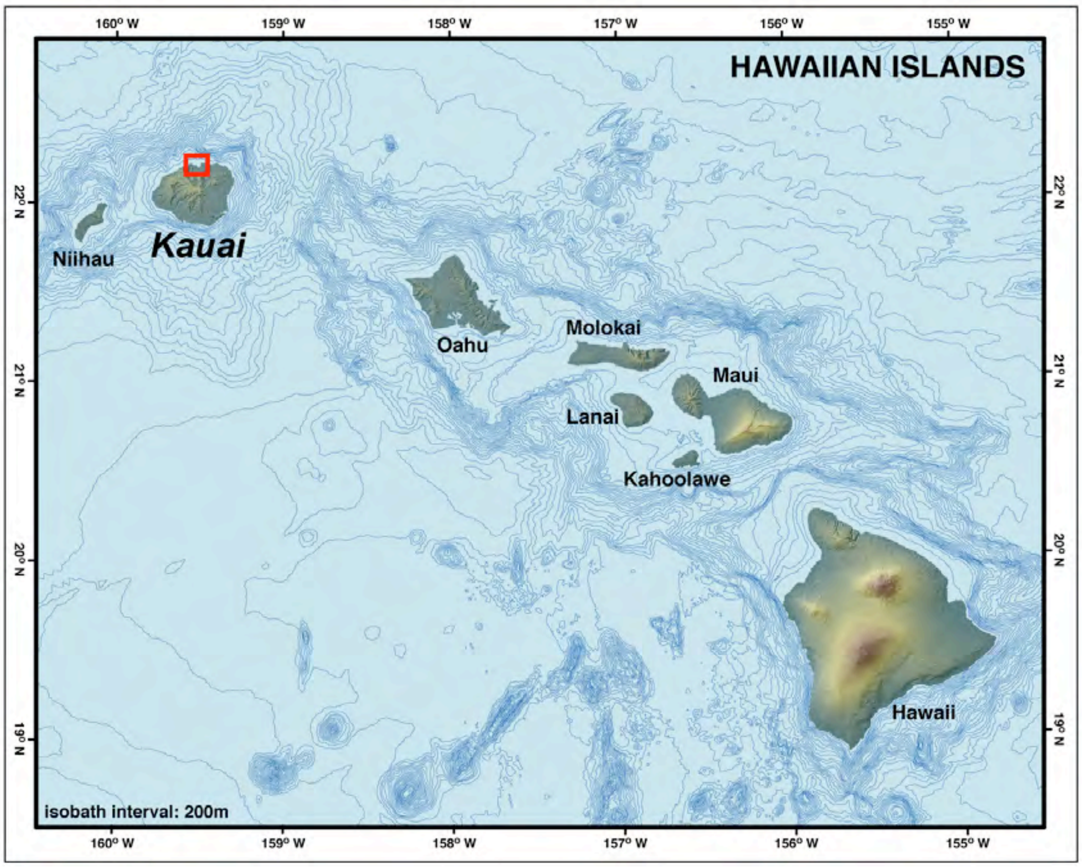


**Figure 1.** Map of the study area on the north side of Kaua`i (red square) in relation to the main Hawaiian Islands. Hanalei Bay is exposed to the large North Pacific swell during the winter but is relatively protected form the northeast trade winds during the summer.

Hanalei Bay, and all instrument packages were situated on the sandy seabed in water depths less than 10 m.

## Operations

This section provides information about the personnel, equipment, and vessel used during the deployments. See table 1 for a list of personnel involved in the experiment.

## Equipment and Data Review

Locations of deployed instrument packages (large red circles) and vertical profile casts (small white circles) are shown in figure 2. Up to four different instruments that measured waves, currents, turbidity, temperature, and salinity were deployed at each long-term sampling site. In some instances, more than one of the same instrument was used at a given site to measure the parameters at various depths.

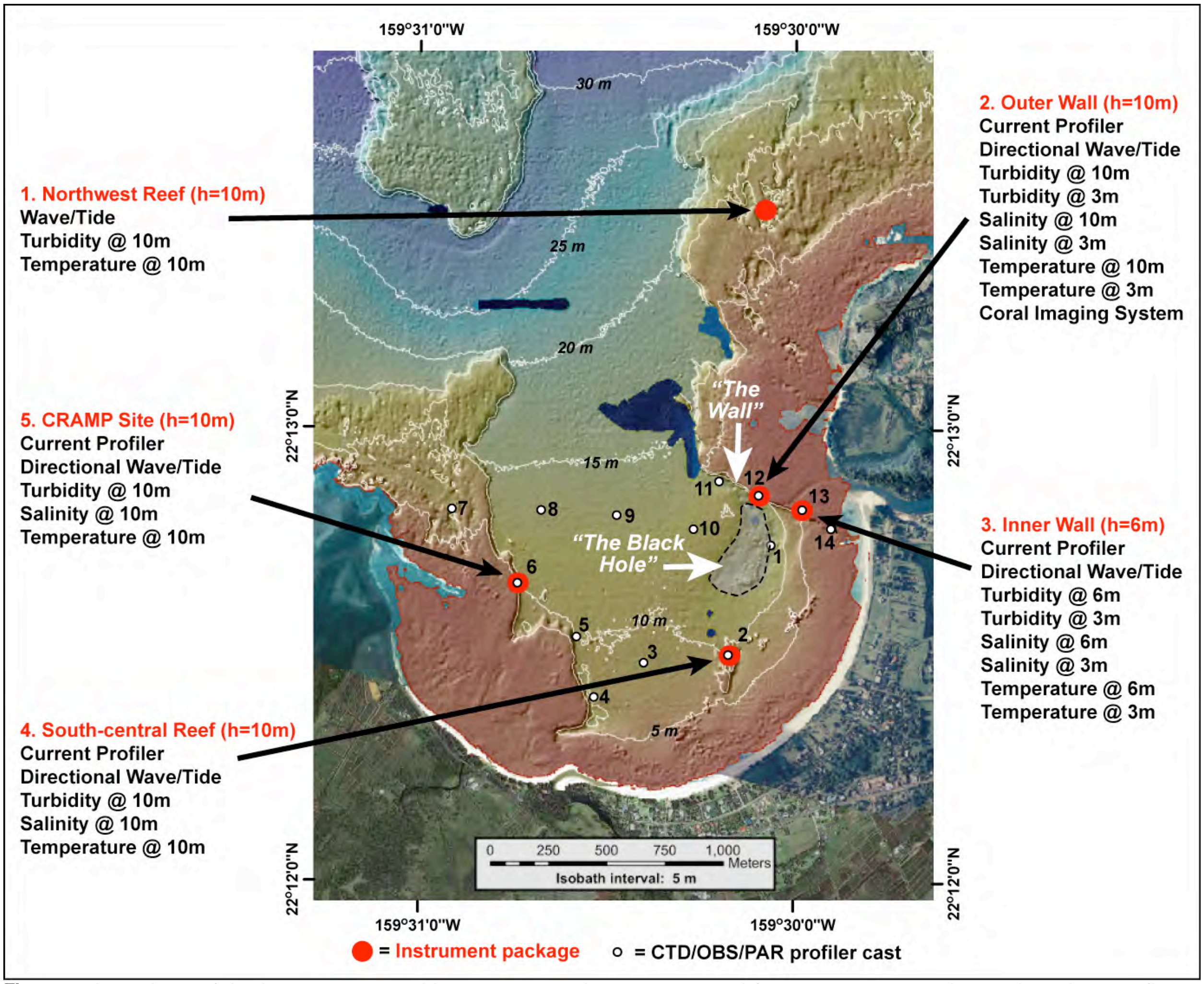


**Figure 2.** Locations of the bottom-mounted instrument packages employed for long-term sampling and vertical profile casts used in the study. The numbers following site location name refer to the water depth at the site; the number following the parameters denote the depths of the measurements below the sea surface. The CRAMP Site refers to a permanent monitoring site of the Coral Reef Assessment and Monitoring Program by the University of Hawai`i.

A summary of instrument packages and depths at which they were deployed is provided in table 2. The instruments included RD Instrument 600-kHz upward-looking Acoustic Doppler Current Profilers (ADCPs), Nortek 2-MHz upward-looking Acoustic Doppler Profiler (ADP), a NIWA Dobie-A wave/tide gauge, Aquatec/Seapoint 200-TY and 210-TYT self-contained optical backscatter sensors (SLOBS), and Seabird SBE-37SM Microcat conductivity-temperature

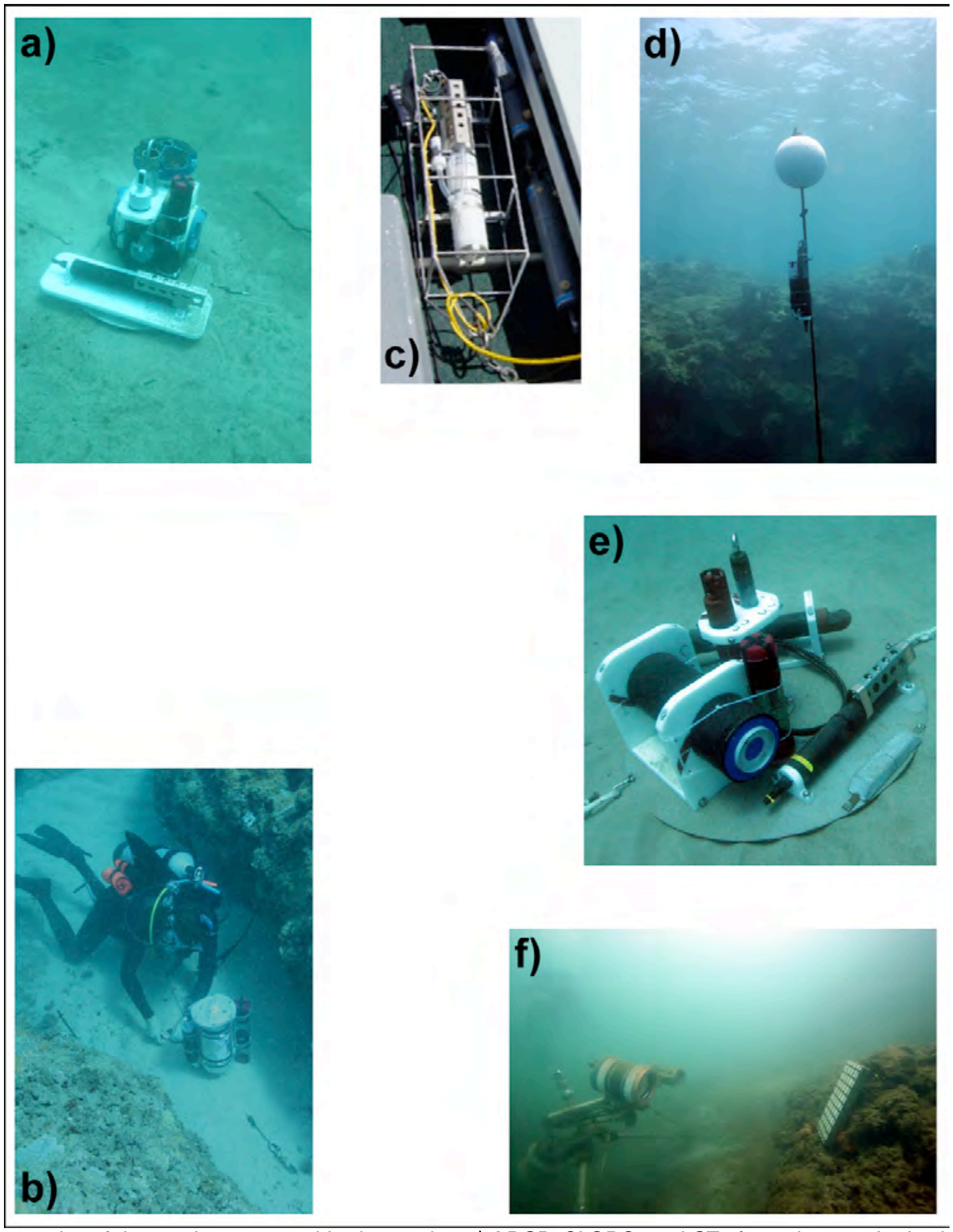


**Figure 3.** Photographs of the equipment used in the study. a) ADCP, SLOBS, and CT along the 10m isobath at the CRAMP Site. b) Dobie and SLOBS at the Northwest Reef Site. c) CTD/OBS/PAR profiler. d) Microcat and SLOBS 3m below the surface at the Outer Wall Site. e) ADP, SLOBS, and CT along the 10m isobath at the South-central Reef Site. f) CIS along the 10m isobath at the Outer Wall Site. See text for definition of acronyms. All of the instrument packages and moorings were deployed in patches of sand.

sensors (CT) as shown in figure 3. The ADCPs and ADPs collected vertical profiles of current speed and direction, which, in conjunction with the recorded pressure data, can be used to calculate wave height, wave period, and wave direction. The Dobie, SLOBSs, and CTs collected single-point measurements of waves and tides, turbidity, and temperature and salinity, respectively.

The oceanographic instruments were deployed for a 90-day period. The sensors collected measurements using three sampling schemes. The ADCP collected water depth and current information for 512 s bursts at 2 Hz every 2 hours to provide directional wave and tide information.  The Dobie collected 512 s bursts at 2 Hz every hour to provide non directional wave and tide information; the ADCPs, ADPs, SLOBSs, and CTs recorded current profiles, turbidity, temperature, and salinity data, respectively, every 5 min.  Instrument specifics and sampling schemes are listed in appendixes 1-3.

A Conductivity/Temperature/Depth (CTD) Profiler with Optical Backscatter (OBS) and Photosynthetically-Available Radiation (PAR) sensors was used to collect vertical profiles of water temperature, salinity, density, turbidity, and PAR around the bay.  The CTD/OBS/PAR data acquisition log is presented in table 3.  The instrument specifics and sampling schemes are listed appendix 4.

The USGS Coral Imaging System (CIS), consisting of a Canon D60 6.3-megapixel digital camera with a 24-mm lens, an external Canon Speedlight 550EX TTL strobe, control unit and batteries on a tetrapod (fig. 3), was used to collect a time series of sea floor images.  The CIS was deployed in a patch of sand at the Outer Wall Site, and the camera and strobe were angled to not only image adjacent reef that forms “the Wall”, but also a gridded black and white camera calibration reference block.  The CIS provided data on the natural frequency and duration of sediment deposition and resuspension on an actual coral surface.  The CIS took images every four hours throughout the deployment (00:00, 04:00, 08:00, 12:00, 16:00, and 20:00).

Far-field oceanographic and meteorologic forcing for the study period were compiled by National Oceanographic and Atmospheric Administration’s National Data Buoy Center (NDBC, 2006) Northwest Kaua`i buoy.  The Northwest Kaua`i Buoy, station identification #510001, is deployed in more than 3 km of water approximately 170 km northwest of the island.  It records measurements of wind speed (m/s), wind direction (°True), wave height (m), wave period (s), mean wave direction (°True), sea-level barometric pressure (mb), and air and sea-surface temperature (°C) every hour.  Water discharge, suspended-sediment concentration (SSC), and total sediment load of the Hanalei River were measured by the USGS Pacific Islands Water Science Center (2006) gauging station #16103000, located 9 km upstream from the river mouth.

Navigation equipment included two hand-held WAAS-equipped GPS units and a computer with positioning and mapping software.  The positioning and mapping software enabled real-time GPS position data to be combined with images of previously collected high-resolution SHOALS color-coded LiDAR, shaded-relief bathymetry, 5-m isobaths, and aerial photographs of terrestrial parts of the maps.

## Instrument Deployments and Measurements

The instrument deployments and recoveries were conducted using the *F/V Sea Cat*.  The starboard quarterdeck was adapted for instrument deployment and recovery operations, which included the use of an electric winch and an overhead davit.  The instruments were deployed by attaching a removable bridle to the instrument package with a connecting line through the davit and down to the winch.  The instruments were lowered to within a few meters of the seafloor, at which time scuba divers attached a lift bag and detached the lifting line.  The divers then moved the instrument package into position for anchoring.  After determining the instrument package’s location, it was secured with sand anchors to the seabed.  Surficial seafloor sediment samples were collected, and the heights of the sensors above the seafloor were measured and recorded. Recovery operations employed the same techniques. The CTD/OBS/PAR profiler casts were collected from the same vessel using hand casts.  The driver’s station was outfitted with an LCD display and GPS-enabled navigation system to provide the vessel captain with a graphic display of position information, speed, heading, and distance to the next cast location.

## Data Acquisition and Quality

Data were acquired for a 90-day period between June 7, 2006, and September 5, 2006. More than half a million measurements were recovered from the ADCPs, ADPs, SLOBSs, CTs, and Dobie. The raw pressure data were archived and copies of the data were post-processed to calculate water depth, tidal height, significant wave height and dominant wave period; these data, in conjunction with the ADCPs and ADPs current data, were used to calculate wave direction.

The CT data are of high quality, with little effects of biofouling noticable. The SLOBS data also are of high quality at most of the sites due to periodic cleaning of the sensors.

The CTD/OBS/PAR profile data near the bed often displayed spikes in the OBS data due to interaction of the optical beam with the seabed. The raw CTD/OBS/PAR data were archived and copies of the data were post-processed by calculating the average over 0.5 m depth bins to reduce high-frequency system noise. These 0.5 m bin-averaged data were then used for visualization and analysis. The CTD/OBS/PAR data are very high in quality, with features such as low-salinity (freshwater) surface plumes visible in the salinity data, multi-layered structures (water masses) identified by density contrasts, and turbid layers identifiable in the OBS data.

## Results

This section reviews the data collected by the instruments during the deployments and addresses the significance of the findings to better understand the local oceanographic conditions in the study area.

### Oceanographic and Atmospheric Forcing

The summer study period was relatively quiescent, with relatively consistent waves and winds (fig. 4). The waves were small (<2 m), short period (6-8 s), and typically out of the northeast, likely driven by the northeast trade winds. These trade-wind waves were intermittently overwhelmed by larger (>2 m), longer period (8-10 s) swell out of the northwest Pacific and south Pacific during the second week of June and the third and fourth weeks of July when the trade winds slackened. This generally occurs when regions of lower than average barometric pressure move through the island chain and cause the north Pacific anticyclone, which drives the trade winds, to weaken.

### River Discharge

The US Geological Survey's Pacific Islands Water Science Center (2006) maintains a water and sediment gauging station on the Hanalei River approximately 9.2 km upstream from the river mouth. This gauge provides daily mean values of water discharge ($m^3$/s), suspended sediment concentration (mg/l) and total suspended sediment load per day t/d), as shown in figure 5. Throughout the summer the discharge was relatively low except for August 6-7, 2006 (Year Days [YD] 218-219), when a 46 $m^3$/s Hanalei River flood during the time delivered 771 metric tons of sediment to the bay. This flood delivered more than twice the water and sediment as the largest flood during the 2005 summer experiment (Storlazzi and others, 2006). See Draut and others (2006) for more information regarding the time series of river discharge and sediment load.

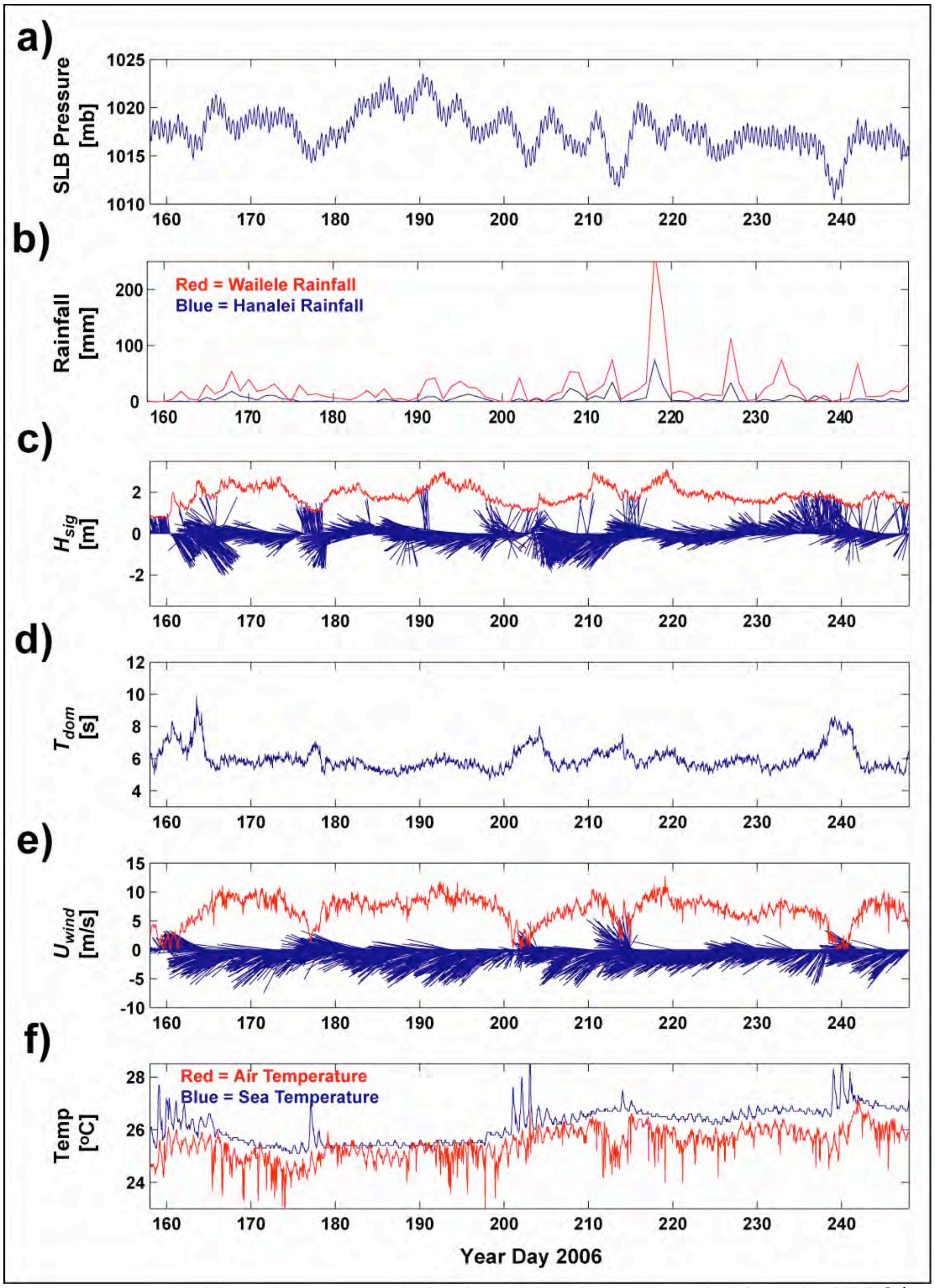


**Figure 4.** Deep-water oceanographic and meteorologic forcing during the study period from the NDBC (2006) buoy. a) Sea-level barometric pressure. b) Rainfall. c) Significant wave height. d) Dominant wave period. e) Wind speed (red) and velocity and direction (blue). f) Air (red) and sea surface (blue) temperature. The waves were predominantly due to the northeast trade winds throughout most of the experiment except for two periods of larger-than-normal waves in early June (YD 161-165) and late July (YD 202-205).

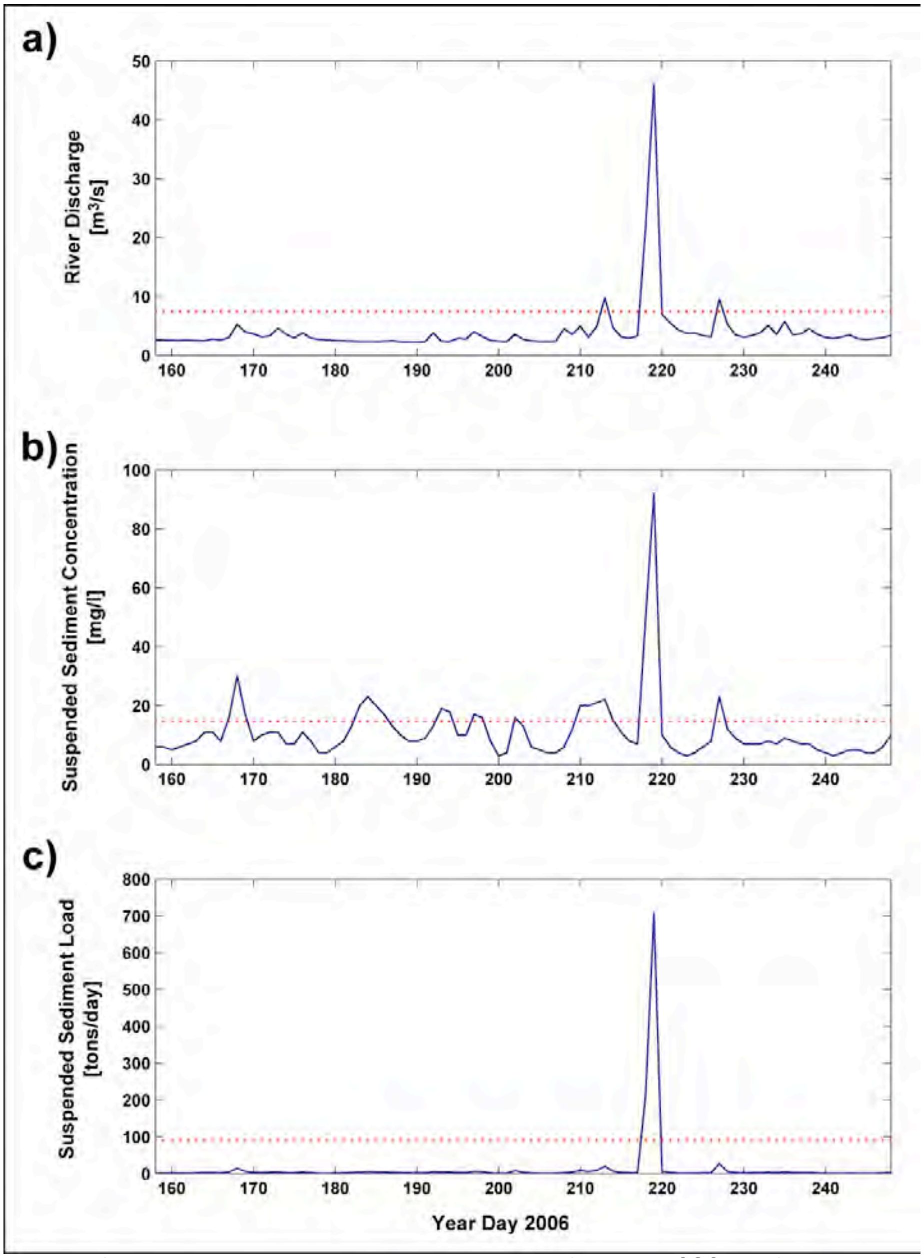


**Figure 5.** Discharge data for the Hanalei River during the study period from the USGS Pacific Islands Water Science Center (2006). a) Discharge. b) Suspended sediment concentration. c) Suspended sediment load. The daily mean data are in blue; the mean values for the 2005-2006 water year are shown in red. The August 6-7 (YD 218-219) flood delivered more than twice the water and sediment as the largest flood during the 2005 summer when a similar experiment was conducted (Storlazzi and others, 2006).

## Tides

The study period encompassed more than six complete spring-neap tidal cycles. The tides in Hanalei Bay are mixed, semi-diurnal with two uneven high tides and two uneven low tides per day; thus the tides change just over every 6 hours (fig. 6). The mean daily tidal range is roughly 0.6 m, while the minimum and maximum daily tidal ranges are 0.4 m and 0.9 m, respectively.

## Waves

The waves that impacted Hanalei Bay during the experiment are shown in figure 6 and, while substantially smaller and shorter period than those observed further offshore (fig. 4),

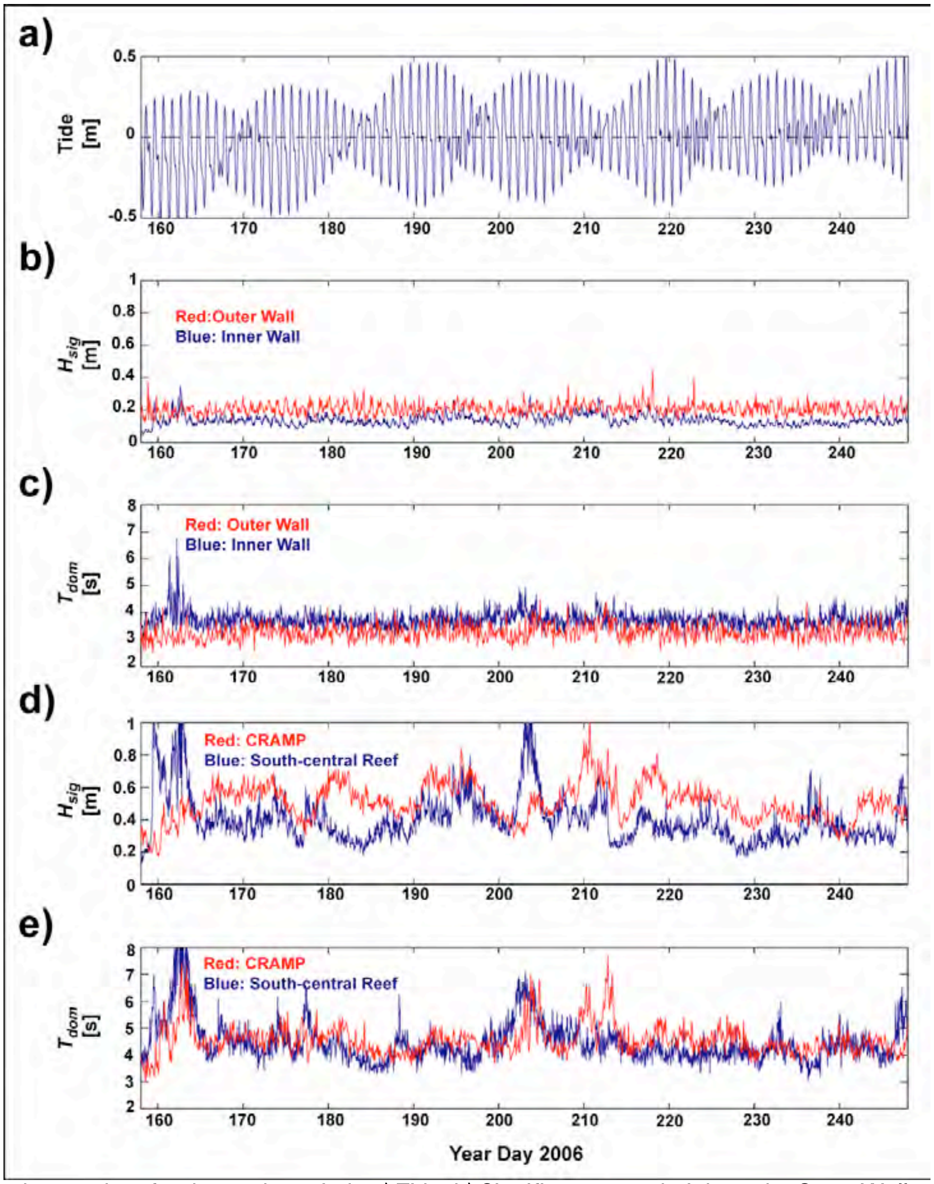


**Figure 6.** Tide and wave data for the study period. a) Tide. b) Significant wave height at the Outer Wall and Inner Wall Sites. c) Dominant wave period at the Outer Wall and Inner Wall Sites. d) Significant wave height at the CRAMP and South-central Reef Sites. e) Dominant wave period at the CRAMP and South-central Reef Sites. The wave heights and periods were smaller relative to offshore (fig. 4) due to shoaling, refraction, diffraction, and breaking.

their temporal variations are in general agreement with the deep-water NDBC data. The variability of wave height, period, and direction was a direct response to the location of the instrument in Hanalei Bay and potential sheltering from offshore wave conditions. In the eastern side of the bay at the Outer Wall Site, significant wave heights ($H_{sig}$) ranged from 0.13 m to 0.45 m, with a mean significant height ± one standard deviation of 0.21±0.04 m. Dominant wave periods ($T_{dom}$) varied from 2.5 s to 4.5 s, with a mean dominant period ± one standard deviation of 3.3±0.31 s. Mean wave direction ± one standard deviation was 254.9°±68.3°. Just inland of the Outer Wall Site at the Inner Wall Site, $H_{sig}$ ranged from 0.05 m to 0.35 m, with a mean significant height ± one standard deviation of 0.13±0.03 m. $T_{dom}$ varied from 2.9 sec to 6.8 s, with a mean dominant period ± one standard deviation of 3.7±0.30 s. Mean wave direction ± one standard deviation was 144.4°±119.3°. The small wave heights and short periods for these two sites may be a result of sheltering by the reef flat from the northeast trade-wind waves.

In the southern side of the bay at the South-central Reef Site, $H_{sig}$ ranged from 0.12 m to 1.36 m, with a mean significant height ± one standard deviation of 0.40±0.15 m. $T_{dom}$ varied from between 3.0 s and 10.1 s, with a mean dominant period ± one standard deviation of 4.5±0.8 s. Mean wave direction ± one standard deviation was 174.8°±90.9°. $H_{sig}$ at the CRAMP Site ranged from 0.17 m to 1.06 m, with a mean significant height ± one standard deviation of 0.51±0.11 m. $T_{dom}$ varied from between 3.0 s and 7.7 s, with a mean dominant period ± one standard deviation of 4.5±0.5 s. Mean wave direction ± one standard deviation was 38.26°±19.1°. The waves were primarily out of the north-northeast and appear to be due to the trade winds.

The wave heights are greater and their directions are more consistent at the CRAMP and South-central Reef Sites than the Inner and Outer Wall Sites, as the CRAMP Site is directly exposed to the northeast Trade wind waves and the South-central Reef Site is more exposed to Northwest Pacific swell, while the Inner and Outer Wall Sites are shadowed by the reef, as discussed above.

## Currents

Mean current speeds ± one standard deviation at the Outer Wall Site were 0.03±0.02 m/s close to the surface and 0.01±0.01 m/s close to the sea floor (fig. 7). Mean current speeds ± one standard deviation at the Inner Wall Site were 0.05±0.05 m/s close to the surface and 0.02±0.02 m/s close to the sea floor. At the CRAMP Site, mean current speeds ± one standard deviation were more than 50% higher both close to the surface (0.06±0.04 m/s) and close to the sea floor (0.01±0.01 m/s) than along the Outer Wall Site. The fastest currents were measured at the South-central Reef Site, where the mean current speeds ± one standard deviation were 0.12±0.09 m/s close to the surface and mean current speeds ± one standard deviation were 0.02±0.01 m/s close to the bottom.

Most of the daily variability in current speed and direction at the study sites is due to the tides. The principal axes of tidal flow during the experiment were oriented roughly parallel to the local isobaths and showed no asymmetry; the orientation of tidal flow ellipses were more variable close to the surface and in the relatively flat southern portion of the bay (fig. 8). Similar to the tidal currents, the principal axes of low-frequency wave- and wind-driven currents near the surface were oriented relatively parallel to the local isobaths; these currents, however, showed strong net anti-cyclonic flow. The orientation of low-frequency current ellipses near the bed were oriented relatively parallel to the local isobaths and smaller than near the surface; unlike the near-surface low-frequency flows, the net low-frequency flows were all oriented approximately shoreward into the bay, similar in orientation to the mean wave directions discussed above.

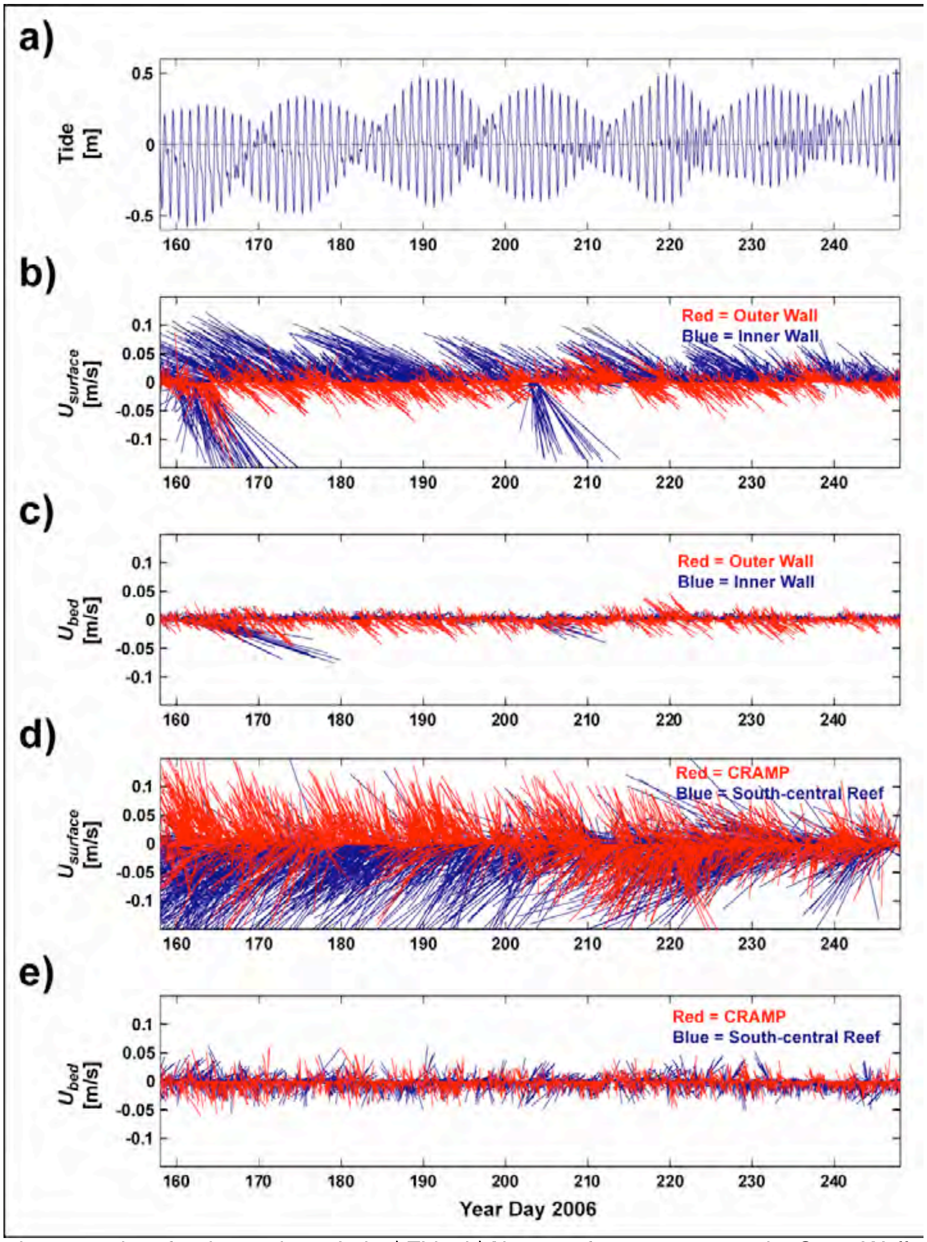


**Figure 7.** Tide and current data for the study period. a) Tide. b) Near-surface currents at the Outer Wall and Inner Wall Sites. c) Near-bed currents at the Outer Wall and Inner Wall Sites. d) Near-surface currents at the CRAMP and South-central Reef Sites. e) Near-bed currents at the CRAMP and South-central Reef Sites. The vectors denote the speed and direction of the currents at the different depths. In general the currents were stronger near the surface and in the western and southern parts of the bay, likely due to its greater exposure to the open ocean.

## Shear Stresses

The total shear stresses imparted on the seabed, computed from the wave and mean current data using the methodology presented by Ogston and others (2004), was dominated by wave-orbital motions (not shown). This resulted in a pattern of near-bed shear stress on the seabed during the experiment similar to the distribution of waves, with the largest total shear stresses in the more exposed western portion of the bay at the CRAMP Site (0.13±0.07 N/m$^2$) and smaller in the eastern portion of the bay at the Outer Wall Site (0.01±0.02 N/m$^2$). Even though the waves were smaller, the total shear stress was slightly higher and much more variable at the Inner Wall Site (0.03±0.10 N/m$^2$) than the Outer Wall Site because it is shallower (6 m versus 10 m).

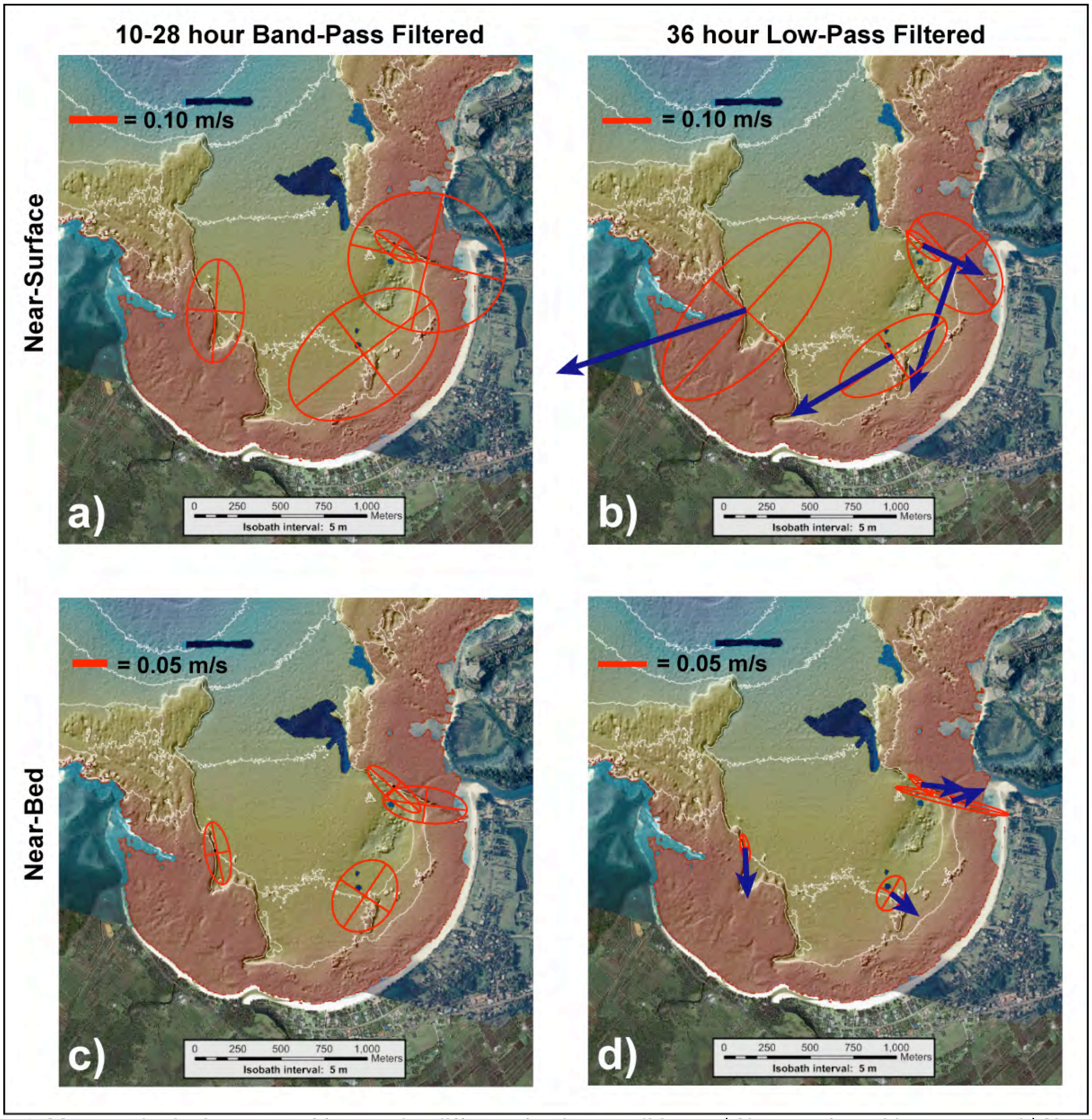


**Figure 8.** Mean and principal axes of flow under different forcing conditions. a) Near-surface tidal currents. b) Near-surface wind- and wave-driven currents. c) Near-bed tidal currents. d) Near-surface wind- and wave-driven currents. Blue vectors show the orientation and magnitude of net flow; red ellipses show the variability of flow. The tidal currents (left) are primarily shore-parallel and show no net mean flow. The sub-tidal wind- and wave-driven currents (right) show anti-cyclonic net near-surface flow and net onshore flow near the seabed.

## Water Column Properties

The water column properties that were measured by the bottom-mounted CTs and SLOBS included variations in temperature (ºC), salinity (PSU) and optical backscatter (NTU). The water column properties that were measured by the CTD/OBS/PAR profiler included variations in temperature (ºC), salinity (PSU), optical backscatter (NTU) and change in PAR (mE) with depth.

## *Spatial and Temporal Variability in Temperature*

Water temperatures ranged between 23.72 °C and 28.53 °C, with a mean temperature ± one standard deviation of 25.9±0.08 °C (table 4). The water typically warmed 0.1°C during the day, likely due to insolation, and cooled again at night; water temperatures also decreased a fraction of a degree during rising tides as cooler oceanic water moved onshore into the bay. A seasonal warming trend of more than 2 °C was also observed from early June to early September (fig. 9).

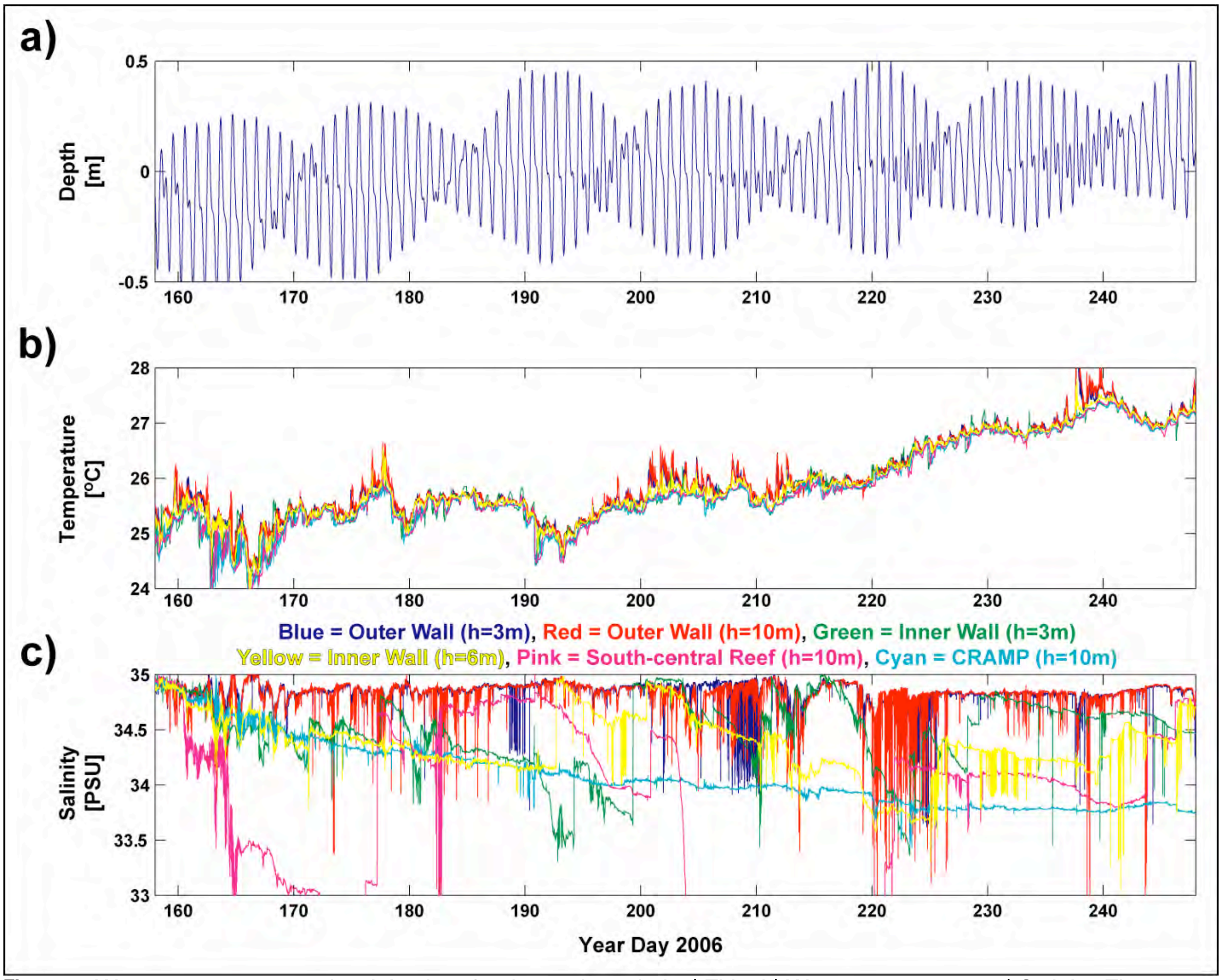


**Figure 9.** Water temperature and salinity data for the study period. a) Tide. b) Water temperature. c) Salinity. The higher variability and lower salinities at the Inner Wall and CRAMP Sites is likely due to the greater proximity to terrestrial freshwater discharge. The low frequency variations in salinity mirror those in water temperature, suggesting some large-scale variations in water mass composition in the bay. The data from the South-central Reef Site appears to have been contaminated from sediment clogging the sensor, resulting in lower than normal salinities.

## *Spatial and Temporal Variability in Salinity*

Salinity in the bay ranged between 31.76 PSU and 35.23 PSU, with a mean salinity ± one standard deviation of 34.52±0.31 PSU (table 4). The salinities generally varied on the order of 0.01 PSU (fig. 9) and usually decreased slightly during flood tides and increased slightly during

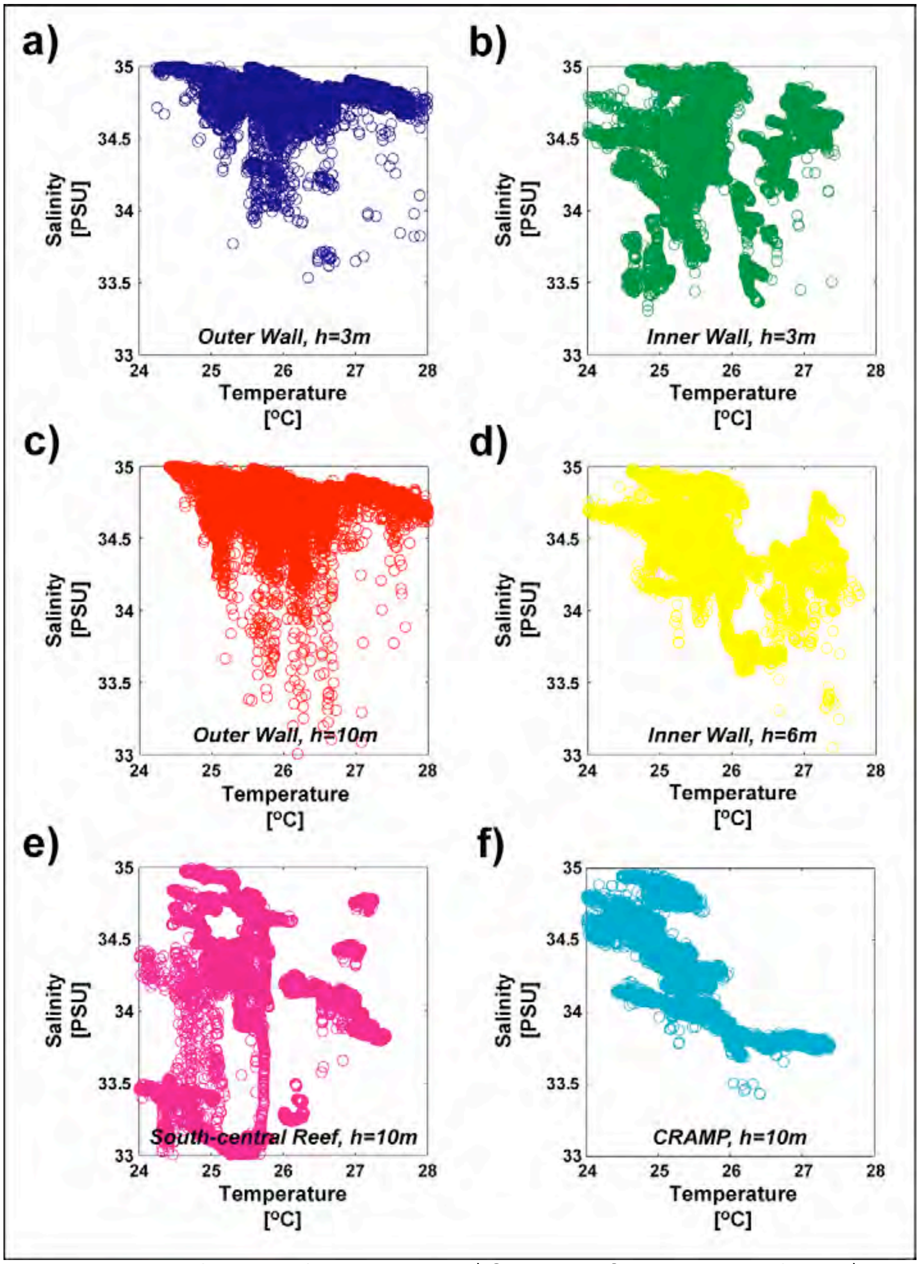


**Figure 10.** Variation in salinity as a function of temperature. a) Outer Wall Site at a depth of 3 m. b) Inner Wall Site at a depth of 3 m. c) Outer Wall Site at a depth of 10 m. d) Inner Wall Site at a depth of 10 m. e) South-central Reef Site at a depth of 10 m. f) CRAMP Site at a depth of 10 m. The general trend of increasing salinity with decreasing temperature is indicative of oceanic waters. This inverse temperature-salinity relationship seen throughout most of the bay is overprinted by a decrease in temperature with a decrease in salinity that indicates freshwater being transported into the area, likely from the adjacent river and streams and possibly through submarine groundwater discharge.

ebb tides. In general, salinities at the Outer Wall Site were higher and less variable than at the Inner Wall Site and at the CRAMP Site. The lowest and highest salinities were observed at the Inner Wall Site 3 m below the sea surface. The greater variability at this sight is likely due to the proximity to freshwater being discharged by the Hanalei River as well as the increase in evaporation at this shallow site.

The variability in salinity as a function of temperature is shown in figure 10. The near-surface and near-bed measurements at the Outer Wall Site in general show similar variations with decreasing salinity with increasing temperature, as well as the overprint of a freshwater

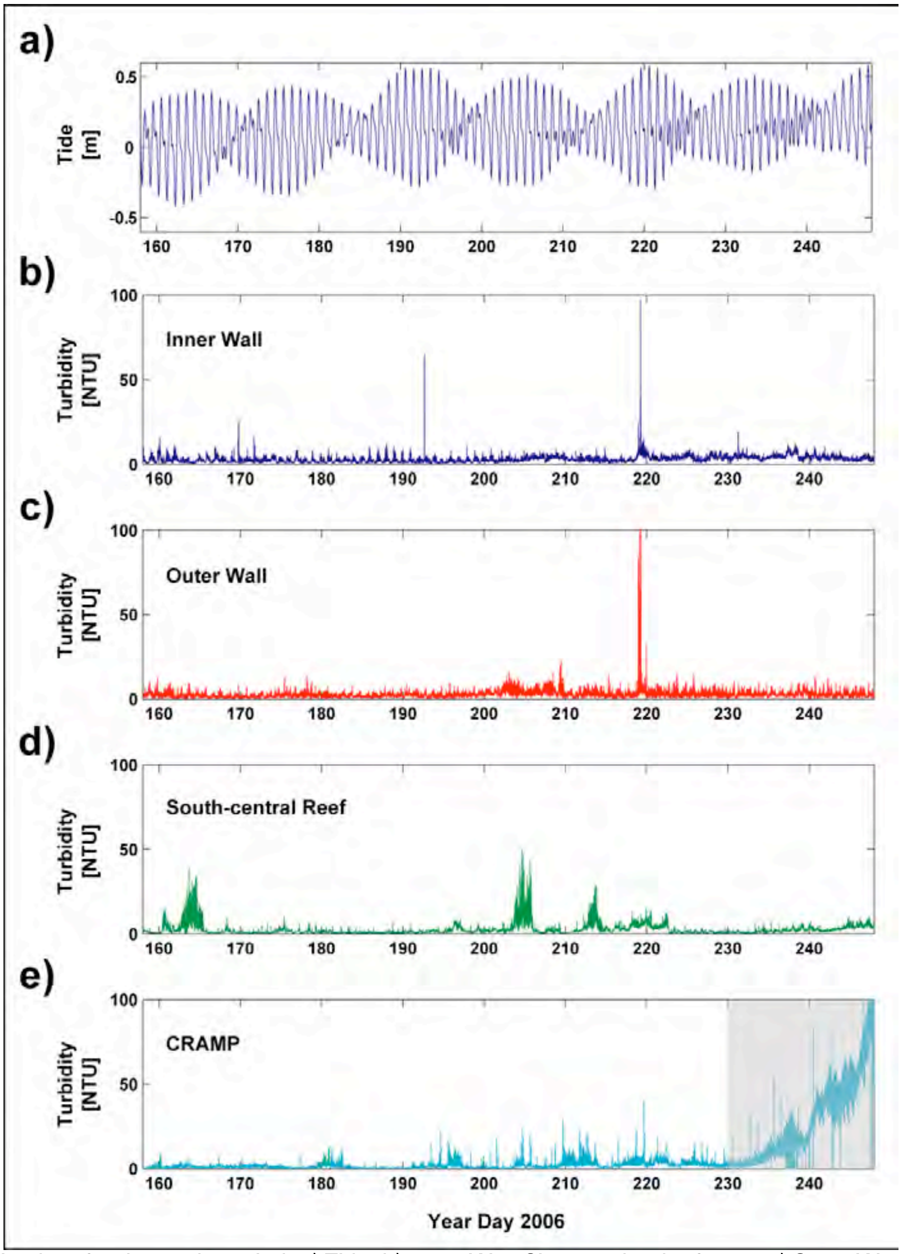


**Figure 11.** Turbidity data for the study period. a) Tide. b) Inner Wall Site at a depth of 10 m. c) Outer Wall Site at a depth of 10 m. d) South-central Reef Site at a depth of 10 m. e) CRAMP Site at a depth of 10 m. The highest turbidity levels were measured close to the bed at the Inner and Outer Wall Sites during the Hanalei River flood on August 6-7 (YD 218-219). The turbidity was also high in the southern part of the bay at the South-central Reef Site, likely caused by resuspension of sediment due to high shear stresses during times of large waves.

signal. This freshwater is identifiable in these plots as a vertical trend in the temperature-salinity of a variation in more than 0.5 PSU in salinity at a constant temperature. Data from the Inner Wall Site show a pattern similar to the Outer Wall Site; in addition, the near-surface measurements at the Inner Wall Site show less influence from oceanic water and more influence from fresh water being discharged from the Hanalei River. The pattern at the CRAMP Site shows an expected temperature-salinity relationship seen along the wall overprinted by a decrease in temperature with an increase in salinity that indicates oceanic water being transported into this area. The data from the South-central Reef Site appears to have been contaminated from sediment clogging the sensor, resulting in lower than normal salinities being recorded during the deployment.

### Spatial and Temporal Variability in Turbidity

Concurrent, reliable data were recorded for 72 days (June 7-August 18) for the majority of turbidity instruments. During that time period, the turbidity in the study area ranged between 0.0 NTU and 171.87 NTU, with a mean turbidity ± one standard deviation of 2.2±0.78 NTU (TABLE 5). Mean near-bed suspended sediment concentrations (SSCs) measured by the OBSs were smallest and least variable (0.93±0.68 mg/l) at the Inner Wall Site and highest (3.08±6.22 NTU) at the South-central Reef Site (fig. 11). In general, the mean SSCs closer to the seafloor throughout the bay (2.61 NTU) were twice the value of those close to the surface (1.31 NTU) at the Outer and Inner Wall Sites.

Water on the eastern and southern sides of the bay, especially close to shore and close to the seafloor, were typically more turbid than those on the western side. The highest turbidity levels (>90 NTU) were measured close to the bed at the Inner and Outer Wall Sites during the Hanalei River flood on August 6-7 (YD 218-219). The turbidity was also high in the southern part of the bay at the South-central Reef Site, likely due to resuspension of sediment by wave stresses from large waves.

All of the mean turbidity values recorded during this dry summer period exceed the State of Hawai`i Department of Health's Administrative Rules, Title 11, Chapter 54, Water Quality Standards for "open ocean out to 600 foot depth" as defined on page 54-30 of that report (Department of Health, 2004). The maximum allowable wet season mean turbidity level (which are roughly twice those of dry season levels) is 0.50 NTU; the mean turbidity near the seafloor at the Inner Wall Site exceeds the maximum acceptable mean level by more than half an order of magnitude (table 5).

### Variability in Temperature, Salinity, and Turbidity with Depth

The overall trends for the variation in water column properties with depth during the 2006 surveys display a very thin buoyant freshwater surface plume overlying a stable water column (figs. 12,13). In general, temperature decreased with depth while salinity and turbidity increased with depth. The higher turbidity but lower salinity at the surface is indicative of the turbid, buoyant lower-salinity surface plume, likely due to runoff from Hanalei River and the streams that drain into Hanalei Bay. The temperature typically rose to its maximum just below the surface, below which it decreased slowly towards the bed. The higher turbidity close to the bed was likely due to resuspension of the fine sediment and organics that covered the sea floor following the August 6-7 (YD 218-219) Hanalei River flood that delivered 771 metric tons of sediment to the bay. Spatially, the water in Hanalei Bay is generally more saline and cooler farther offshore and with increasing depth.

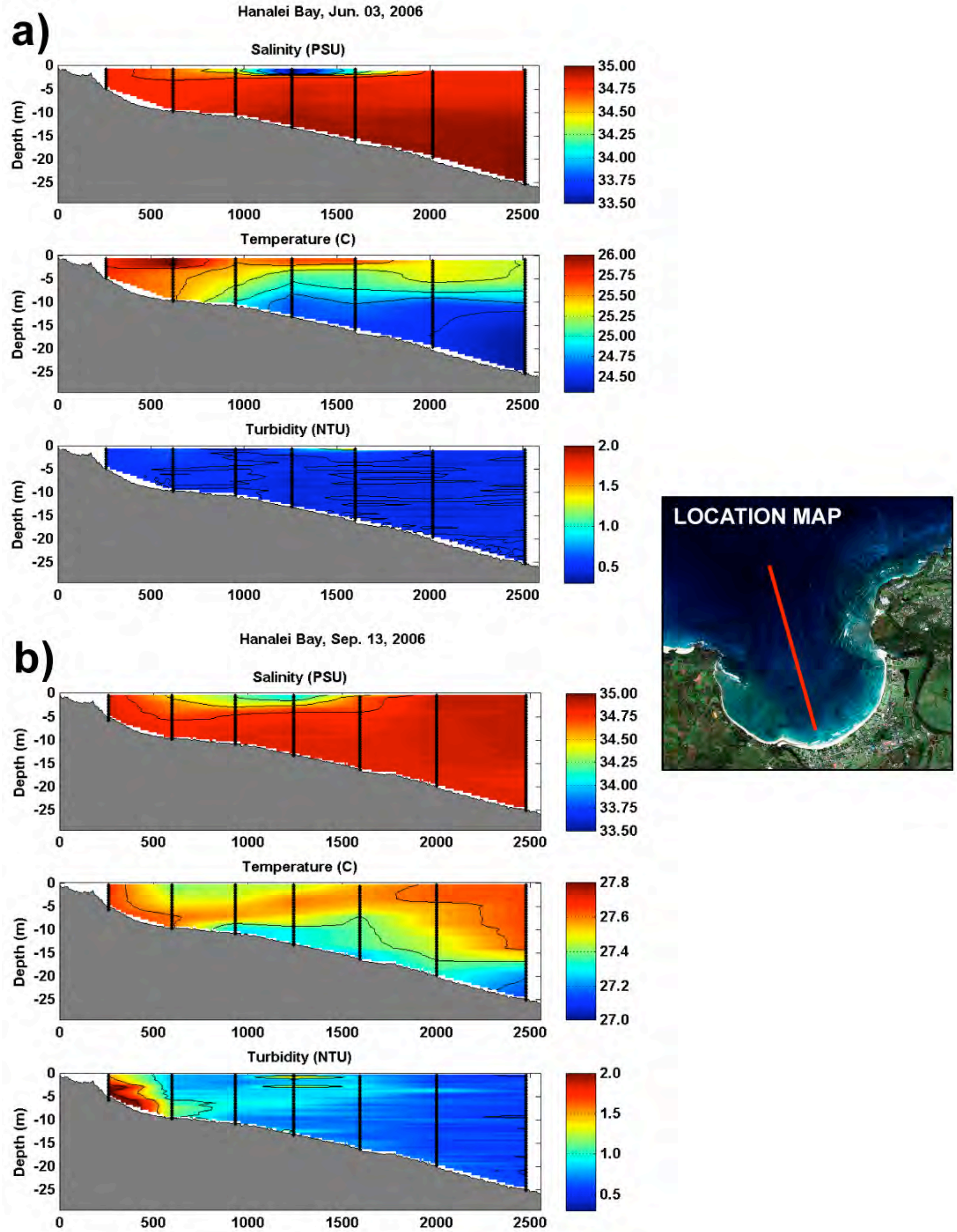


Figure 12. Spatial variability in water column properties along a north-northwest-trending survey transect in Hanalei Bay. a) Data from June, 2006. b) Data from September, 2006. INSET: Location of the survey transect. Note the different color bar scales. Overall, the water was warmer later in the summer. Close to shore, turbidity was much greater (values > 20 NTU) in September, likely due to the August 6-7 (YD 218-219) flood that delivered 771 metric tons of sediment to the bay.

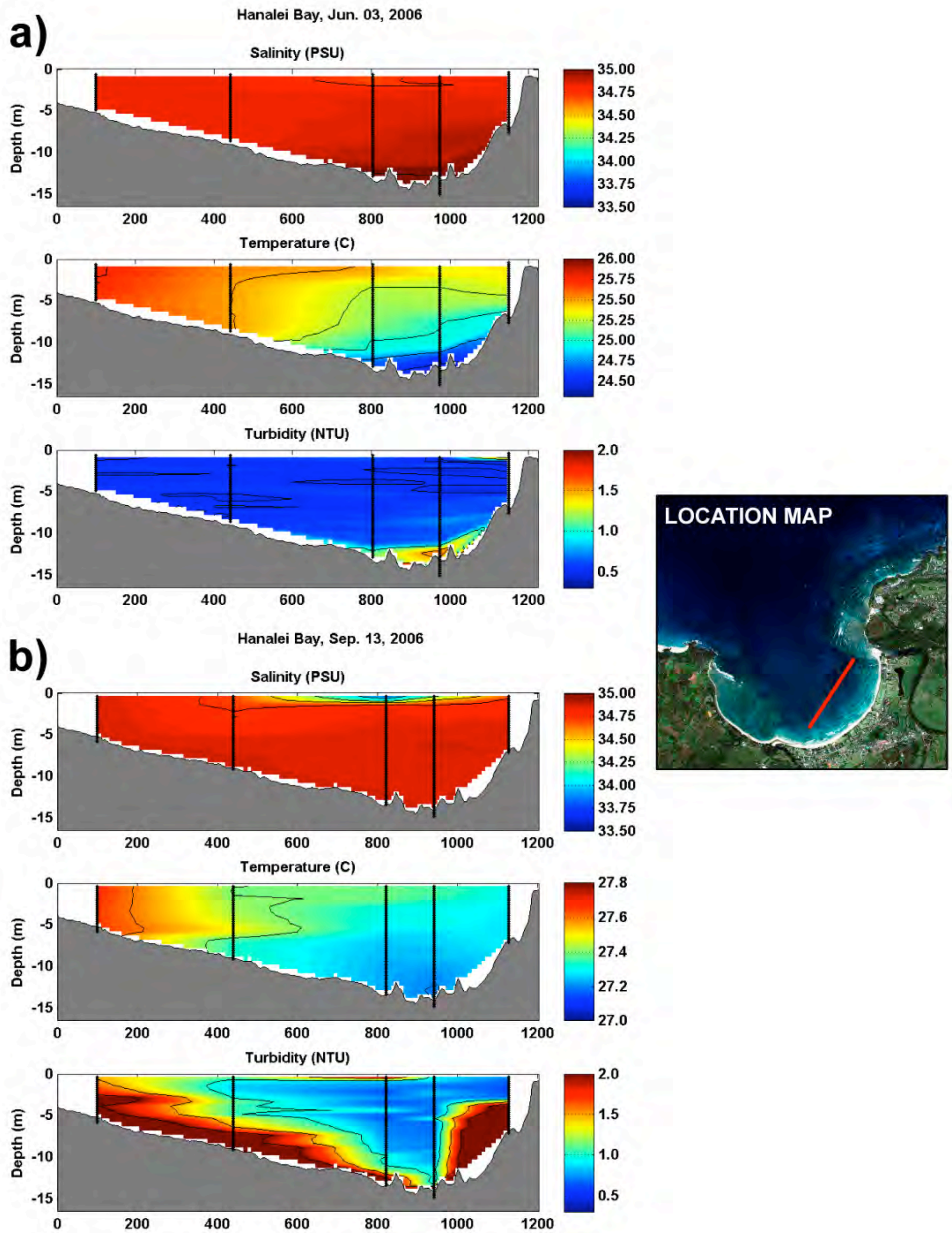


Figure 13. Spatial variability in water column properties along a northeast-trending survey transect in Hanalei Bay. a) Data from June, 2006. b) Data from September, 2006. INSET: Location of the survey transect. Note the different color bar scales. Overall, the water was warmer later in the summer. Turbidity, especially in the shallow areas and along the Wall, was much greater (values > 20 NTU) in September, likely due to the August 6-7 (YD 218-219) flood that delivered 771 metric tons of sediment to the bay.

## Short-term Sediment Deposition and Resuspension

The Coral Imaging System (CIS) was placed roughly 5 m west-northwest of the Outer Wall Site to provide visual documentation of sedimentation on coral surfaces along the Wall to be correlated with measurements of waves, currents, rainfall, turbidity, and stream discharge (fig.

14). The CIS's images show whether the particles actually settled on the reef or were transported through the field of view. The gridded concrete block was used as a proxy for an


**Figure 14.** Images of the reef along the Outer Wall Site at different times from the Coral Imaging System (CIS). a) Relatively clear water and some fine-grained sediment on the fore reef at the beginning of the study period. b) Higher turbidity during the first large wave event out of the northwest in early June (YD 161-165). c) The 46 $m^3/s$ Hanalei River flood that delivered 771 metric tons of sediment to the bay on August 6-7 (YD 218-219) resulted in 24 hours of complete "brown-out" at the Outer Wall Site. Also note the more reddish color of terrigenous material compared to the wave event in figure 4b. d) Following the flood, all of the potential coral recruitment sites remained buried for the rest of the study.

irregular coral surface so that estimates of sediment accumulation - and erosion - could be correlated with other measurements and improve the understanding of conditions that affect sedimentation on corals. Imagery from the CIS at the Outer Wall Site documented relatively clear water and some fine-grained sediment on the fore reef at the beginning of the study period. During the first large wave event out of the northwest in early June (YD 161-165), higher turbidity was imaged by the CIS. The August 6-7 (YD 218-219) Hanalei River flood resulted in 24 hours of complete "brown-out" at the Outer Wall Site, followed by three days of elevated turbidity. The blue and green bands in the CIS imagery during this time were depressed relative to the entire red-green-blue color spectrum, which was not observed during the previous wave events, further supporting the influx of fine-grained, reddish terrestrial sediment. While the individual coral colonies appeared to survive the flood's sediment load, as evidenced by their relatively fast sloughing off the mud, all of the potential recruitment sites for new coral larvae remained buried for the rest of the study period.

## Conclusions

In all, more than half a million measurements of currents, waves, tides, temperature, salinity, turbidity, and PAR were made in Hanalei Bay, Kaua`i, Hawai`i, during the three-month period between June 7, 2006, and September 5, 2006. Key findings from these measurements and analyses include:

1) The waves were generally small during the deployments and primarily driven by the northeast trade winds. Circulation was generally sluggish, except during periods of larger-than-normal waves and strong winds. The tidal currents were primarily oriented parallel to shore and showed no net mean flow. The subtidal wind- and wave-driven currents showed anti-cyclonic net near-surface flow and net onshore flow near the seabed. Both waves and currents were more energetic in the western part of the bay that was more directly exposed to the trade winds.

2) Lower salinities and higher turbidities were observed closer to shore, especially near the mouths of the Hanalei River and smaller streams discharging into the south and eastern parts of the bay.

3) The water in Hanalei Bay was generally more saline and cooler farther offshore and with increasing depth. This general trends is evident in some of the data, but many times masked by an opposite trend brought about by the presence of freshwater either discharged from the river and streams that drain into the bay or submarine groundwater discharge.

4) The highest turbidity levels were measured close to the bed at the Inner and Outer Wall Sites during the Hanalei River flood on August 6-7 (YD 218-219). The turbidity was also high in the southern part of the bay at the South-central Reef Site, likely due to resuspension of sediment from wave stresses during times of high waves.

5) Imagery from the CIS at the Outer Wall Site documented relatively clear water and some fine-grained sediment on the fore reef at the beginning of the study period. The first large wave event in early June (YD 161-165) caused elevated turbidity at the site. The August 6-7 (YD 218-219) Hanalei River flood resulted in 24 hours of complete “brown-out” at the site, followed by three days of elevated turbidity. While the individual coral colonies appeared to survive the flood’s sedimentary load, as evidenced by their relatively fast sloughing off the mud, all of the potential recruitment sites remained buried for the rest of the study period.

These data provide information on the nature and controls on flow and water column properties in Hanalei Bay during the summer months. A number of interesting phenomena were observed that indicate the complexity of coastal circulation and sediment dynamics in Hanalei Bay and may help to better understand the implications of the processes on coral reef health.

## Acknowledgments

This work was carried out as part of the USGS Pacific Coral Reef Project as part of an effort in the U.S. Pacific waters to better understand the effect of geologic processes on coral reef systems. Carl Berg (formerly of the Hanalei Watershed Hui) overextended himself by helping us with every aspect of the fieldwork and coordinating our efforts with the numerous other institutions working in the Hanalei watershed-reef system. The U.S. Fish and Wildlife Service kindly provided storage space at the Hanalei National Wildlife Refuge's maintenance area for the USGS equipment during the course of the two and a half years of field operations in Hanalei Bay. This work was supported by the USGS's Coastal and Marine Geology Program, the USGS Western Region's Ridge-to-Reef Project, and a grant from the Fish and Wildlife Foundation to C. Berg and M. Field. We would like to thank Hanalei residents Charlie Bass and Garret Santos of the *F/V Sea Cat*, who graciously donated their time, effort and aloha during our numerous instrument deployment and recovery operations. We would like to make a special acknowledgement to Matt Rosener (formerly of the Hanalei Watershed Hui) for frequently diving in murky conditions to clean the optics of the SLOBS and CIS. We would also like to thank Nancy Prouty (USGS) and Susan Cochran (USGS), who contributed numerous excellent suggestions and a timely review of our work.

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Storlazzi, C.D., Presto, M.K., Logan, J.B., and Field, M.E., 2006, Coastal circulation and sediment dynamics in Hanalei Bay, Kaua`i, Part I, measurements of waves, currents, temperature, salinity and turbidity, June - August, 2005: U.S. Geological Survey Open-File Report 2006-1085, 35 p. http://pubs.usgs.gov/of/2006/1085/

## Additional Information

For additional information on the instrument deployments, please see:
http://walrus.wr.usgs.gov/infobank/s/s106ka/html/s-1-06-ka.meta.html
http://walrus.wr.usgs.gov/infobank/s/s206ka/html/s-2-06-ka.meta.html

For an online PDF version of this report, please see:
http:// pubs.usgs.gov/of/2008/1295/

For more information on the U.S. Geological Survey Western Region's Coastal and Marine Geology Team, please see:
http://walrus.wr.usgs.gov/

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

## Direct Contact Information

General Project Information:
Dr. Michael E. Field (Project Chief) mfield@usgs.gov

Regarding this Report:
Dr. Curt D. Storlazzi (Lead Oceanographer) cstorlazzi@usgs.gov

## Table 1. Experiment personnel

| Person | Affiliation | Responsibilities |
|---|---|---|
| Mike Field | USGS | Chief scientist, diver |
| Curt Storlazzi | USGS | Co-chief scientist, diver |
| Joshua Logan | USGS | Information specialist, diver |
| Kathy Presto | USGS | Oceanographer, Instrument specialist |
| Amy Draut | USGS | Geologist, diver |
| Tom Reiss | USGS | Dive safety officer |
| Susan Cochran | USGS | Logistics, geologist |
| Dave Gonzales | USGS | Instrument specialist |
| Hank Chezar | USGS | Instrument specialist |
| Carl Berg | HWH | Hanalei Watershed Hui science coordinator |
| Charlie Bass | *F/V Sea Cat* | Vessel captain |
| Garret Santos | *F/V Sea Cat* | First mate |

## Table 2. Oceanographic instrument package sensors

| Site Name | Depth [m] | Sensors |
|---|---|---|
| Northwest Reef [1] | 10 | NIWA Dobie-A wave/tide gauge |
| | 10 | Aquatec/Seapoint 200-TY optical backscatter sensor |
| Outer Wall [2] | 10 | RD Instruments 600 kHz Workhorse Monitor acoustic Doppler current profiler |
| | 10 | Aquatec/Seapoint 200-TY optical backscatter sensor |
| | 10 | Seabird SBE-37SI Microcat conductivity-temperature sensor |
| | 10 | Coral Imaging System time-series camera |
| | 10 | Rotary Sediment Time Series Trap |
| | 3 | Seabird SBE-37SI Microcat conductivity-temperature sensor |
| | 3 | Aquatec/Seapoint 200-TYT optical backscatter sensor with temperature sensor |
| Inner Wall [3] | 6 | Nortek 2 MHz Aquadopp acoustic Doppler current profiler |
| | 6 | Aquatec/Seapoint 200-TYT optical backscatter sensor with temperature sensor |
| | 6 | Seabird SBE-37SI Microcat conductivity-temperature sensor |
| | 3 | Aquatec/Seapoint 200-TYT optical backscatter sensor with temperature sensor |
| | 3 | Seabird SBE-37SI Microcat conductivity-temperature sensor |
| South-central Reef [4] | 10 | Nortek 2 MHz Aquadopp acoustic Doppler current profiler |
| | 10 | Aquatec/Seapoint 200-TYT optical backscatter sensor with temperature sensor |
| | 10 | Seabird SBE-37SI Microcat conductivity-temperature sensor |
| | 10 | Rotary Sediment Time Series Trap |
| CRAMP [5] | 10 | RD Instruments 600 kHz Workhorse Monitor acoustic Doppler current profiler |
| | 10 | Aquatec/Seapoint 200-TY optical backscatter sensor |
| | 10 | Seabird SBE-37SI Microcat conductivity-temperature sensor |

Numbers in brackets refer to locations on figure 2.

## Table 3. CTD/OBS/PAR profiler log

| Cast Number/Site | Date | Time [HST] | Latitude [decimal degrees] | Longitude [decimal degrees] |
|---|---|---|---|---|
| 1 | 6/3/2006 | 13:29 | 22.22603 | -159.50144 |
| 2 | 6/3/2006 | 13:37 | 22.22920 | -159.51078 |
| 3 | 6/3/2006 | 13:43 | 22.22473 | -159.50962 |
| 4 | 6/3/2006 | 13:49 | 22.22031 | -159.50886 |
| 5 | 6/3/2006 | 13:55 | 22.21672 | -159.50765 |
| 6 | 6/3/2006 | 14:00 | 22.21108 | -159.50653 |
| 7 | 6/3/2006 | 14:04 | 22.20809 | -159.50722 |
| 8 | 6/3/2006 | 14:09 | 22.20792 | -159.50378 |
| 9 | 6/3/2006 | 14:12 | 22.20528 | -159.50550 |
| 10 | 6/3/2006 | 14:17 | 22.20710 | -159.50903 |
| 11 | 6/3/2006 | 14:20 | 22.20896 | -159.51010 |
| 12 | 6/3/2006 | 14:23 | 22.21122 | -159.51168 |
| 13 | 6/3/2006 | 14:27 | 22.21435 | -159.51372 |
| 14 | 6/3/2006 | 14:31 | 22.21403 | -159.51024 |
| 15 | 6/3/2006 | 14:35 | 22.21366 | -159.50754 |
| 16 | 6/3/2006 | 15:27 | 22.21505 | -159.50325 |
| 17 | 6/3/2006 | 15:33 | 22.21505 | -159.50325 |
| 18 | 6/3/2006 | 15:35 | 22.21393 | -159.50165 |
| 19 | 6/3/2006 | 15:55 | 22.21289 | -159.50459 |
| 20 | 6/3/2006 | 16:01 | 22.21072 | -159.50197 |
| 21 | 6/3/2006 | 16:05 | 22.21220 | -159.50152 |
| 22 | 6/3/2006 | 16:09 | 22.21272 | -159.49933 |
| 23 | 6/3/2006 | 16:13 | 22.21341 | -159.50043 |
| 1 | 9/13/2006 | 15:57 | 22.22908 | -159.51072 |
| 2 | 9/13/2006 | 16:04 | 22.22468 | -159.50975 |
| 3 | 9/13/2006 | 16:10 | 22.22047 | -159.50868 |
| 4 | 9/13/2006 | 16:15 | 22.21692 | -159.50769 |
| 5 | 9/13/2006 | 16:19 | 22.21378 | -159.50721 |
| 6 | 9/13/2006 | 16:23 | 22.21102 | -159.50664 |
| 7 | 9/13/2006 | 16:26 | 22.20802 | -159.50716 |
| 8 | 9/13/2006 | 16:31 | 22.20806 | -159.50383 |
| 9 | 9/13/2006 | 16:36 | 22.20542 | -159.50551 |
| 10 | 9/13/2006 | 16:39 | 22.20670 | -159.50885 |
| 11 | 9/13/2006 | 16:44 | 22.21089 | -159.50170 |
| 12 | 9/13/2006 | 16:49 | 22.21192 | -159.50132 |
| 13 | 9/13/2006 | 16:52 | 22.21299 | -159.50437 |
| 14 | 9/13/2006 | 16:56 | 22.21513 | -159.50330 |
| 15 | 9/13/2006 | 17:00 | 22.21399 | -159.50172 |
| 16 | 9/13/2006 | 17:04 | 22.21325 | -159.50022 |
| 17 | 9/13/2006 | 17:07 | 22.21265 | -159.49923 |
| 18 | 9/13/2006 | 17:14 | 22.21436 | -159.49674 |

Cast numbers refer to locations on figure 2.

## Table 4. Salinity and temperature statistics

| Site Name | Depth [m] | Salinity [PSU] | Temperature [ºC] |
|---|---|---|---|
| Outer Wall [2]-mooring | 3 | 34.84±0.11 | 25.99±0.73 |
| Outer Wall [2]-MP | 10 | 34.09±0.30 | 25.80±0.78 |
| Inner Wall [3]-mooring | 3 | 34.81±0.15 | 26.01±0.73 |
| Inner Wall [3]-MP | 6 | 34.37±0.28 | 25.93±0.73 |
| South-central Reef [4]* | 10 | 33.16±1.97 | 25.82±0.77 |
| CRAMP [5] | 10 | 34.48±0.33 | 25.86±0.75 |

All values are mean ± one standard deviation for days June 7 – September 5.
Numbers in brackets refer to locations on figure 2.
* The salinity sensor may have been clogged by sediment resulting in lower salinities

## Table 5. Turbidity statistics

| Site Name | Depth [m] | Turbidity [NTU] | 10% Exceedance | 2% Exceedance |
|---|---|---|---|---|
| Northwest Reef [1]* | 10 | 2.67±2.82 | 5.87 | 9.53 |
| Outer Wall [2]-mooring | 3 | 1.68±1.44 | 3.15 | 5.11 |
| Outer Wall [2]-MP | 10 | 2.81±2.66 | 4.84 | 7.46 |
| Inner Wall [3]-mooring** | 3 | 0.93±0.68 | 1.8 | 2.5 |
| Inner Wall [3]-MP | 6 | 2.77±2.34 | 4.82 | 7.20 |
| South-central Reef [4] | 10 | 3.08±6.22 | 6.35 | 18.22 |
| CRAMP [5] | 10 | 1.79±1.84 | 3.98 | 6.78 |

All values are mean ± one standard deviation.
Numbers in brackets refer to locations on figure 2.
These data are from the time period from June 7-August 18 when concurrent, reliable data were recorded.
* Biofouling during much of this period, so statistics are only from June 7–June 24.
** The turbidity sensor at the Inner Wall shallow location may have been exposed to UV light, possibly resulting in false measurements; the statistics, therefore, are for the period from June 7-June 14.

# Appendix 1

ADCP Information

RD Instruments 600 kHz Workhorse Monitor; s/n: 2074 and 2432

| | |
|---|---|
| Transmitting Frequency: | 614 kHz |
| Depth of Transducer: | 10 m |
| Blanking Distance: | 0.25 m |
| Height of First Bin above Bed: 1.11 m | |
| Bin Size: | 0.5 m |
| Number of Bins: | 28 |
| Operating Mode: | High-resolution, broad bandwidth |
| Sampling Frequency: | 2 Hz |
| Beam Angle: | 20 deg |
| Time per Ping: | 00:03.00 |
| Pings per Ensemble: | 100 |
| Profile Ensemble Interval: | 0:05:00.00 |
| Wave Ensemble Interval: | 2:00:00.00 |
| Sound Speed Calculation: | Set salinity, updating temperature via sensor |

Data Processing:

The data were averaged over 28-bin (1 hour) ensembles, all of the spurious data above the water surface were removed and all of the data in bins where the beam correlation dropped below 60 percent were removed for visualization and analysis.

Position Information:

Garmin GPS-76 GPS; s/n: 80207465; USGS/CRP unit#1
RDI internal compass/gyroscope, set to –10 degrees magnetic offset

# Appendix 2

Dobie, CT, and SLOBS Sensor Information

NIWA Dobie-A Wave/tide Gauge; s/n: 2000-20

| | |
|---|---|
| Depth of Transducer: | 10 m |
| Operating Mode: | Water level time series |
| Sampling Frequency: | 2 Hz |
| Measurements per Burst: | 1024 |
| Time Between Bursts: | 01:00:00.00 |

Seabird Microcat SBE-37SM CT; s/n: 1161, 3372, 3800, 3801, 4368, 4369

| | |
|---|---|
| Sampling Frequency: | 2 Hz |
| Measurements per Burst: | 8 |
| Time Between Bursts: | 00:05:00.00 |

Aquatec/Seapoint 200-TY SLOBS; s/n: 371-013, 371-026
Aquatec/Seapoint 210-TYT SLOBS; s/n: 024-002, 024-005, 024-006, 024-007 and 024-018

| | |
|---|---|
| Sampling Frequency: | 2 Hz |
| Measurements per Burst: | 30 |
| Time Between Bursts: | 00:05:00.00 |

Data Processing:

The Dobie water level data were averaged over the entire 20 min burst to compute tidal height while hourly significant wave height and dominant wave period data. The SLOBS and CT data were post-processed for visualization and analysis by removing all instantaneous (only one data point in time) data spikes that exceeded the deployment mean + three standard deviations.

Position Information:

Garmin GPS-76 GPS; s/n: 80207465; USGS/CRP unit#1

# Appendix 3

ADP Information

Nortek Instruments 2 MHz upward-looking Aquadopp; s/n: 1861 and 1862

| | |
|---|---|
| Depth of Transducer: | 6 m / 10m |
| Blanking Distance: | 0.25 m |
| Height of First Bin above Bed: | 0.75m |
| Bin Size: | 0.50m |
| Number of Bins: | 14 |
| Average interval: | 480 s |
| Profile interval: | 1200 s |
| Wave interval: | 3600 s |
| Wave cell size: | 2 m |
| Operating Mode: | High-resolution |
| Vertical Velocity Precision: | 0.1 cm/s |
| Horizontal Velocity Precision: | 0.4 cm/s |
| Sound Speed Calculation: | Set salinity, updating temperature via sensor |

Data Processing:

The data were averaged over 14-bin (20 min) ensembles, all of the spurious data above the water surface were removed and all of the data in bins where the beam correlation dropped below 60 percent were removed for visualization and analysis.

Position Information:

Garmin GPS-76 GPS; s/n: 80207465; USGS/CRP unit#1

# Appendix 4

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

Instruments:

| | |
|---|---|
| Seabird 19plus 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 GPS-76 GPS; s/n: 80207465; USGS/CRP unit#1

Data Processing:

The data were averaged into 0.5 m vertical bins and all of the spurious data marked by a flag in the raw data were removed for visualization and analysis. Stratification were measured as the difference between the mean of the top three bins (0.5-1.5 m below the surface) and the bottom three bins (0.5-1.5 m above the bed).