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Characterizing the Effects of Two Storms on the Coastal Waters of O'ahu, Hawai'i, Using Data from the Pacific Islands Ocean Observing System

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ABSTRACT. Pathogens (and other contaminants) associated with urban storm water runoff plumes have long been recognized as adversely affecting the water quality of the coastal ocean. An understanding of the temporal and spatial characteristics of stormwater plumes is a critical first step in protecting the health of people who recreate in coastal waters. Until recently, characterization of stormwater plumes was limited to expensive vessel-based sampling and satellites, which cannot always provide imagery of the nearshore areas, particularly during storms. With the advent of coastal ocean observing systems with their fixed sensor platforms and autonomous underwater vehicles, we have begun to better understand the temporal and spatial characteristics of stormwater plumes in the coastal ocean. The Pacific Islands Ocean Observing System (PacIOOS) provides continuous environmental monitoring of island coastal waters throughout the Pacific Ocean. This network of new ocean-based monitoring stations enabled the authors to study the effects of two storms on coastal water quality. We find that storm runoff from even a relatively small, partially urbanized watershed can profoundly affect the surface waters of the coastal ocean for days to weeks, both inshore and up to hundreds of meters offshore. Even in these coastal waters exposed to the open ocean, the lower salinities and higher turbidity values indicative of stormwater plumes lingered for nearly two days along the southern coast of O'ahu, Hawai'i.

INTRODUCTION

Stormwater runoff has long been recognized as an important factor affecting the water quality of the coastal ocean. Nearly 20 years ago, the National Research Council (1993) reported:

> *Urban runoff and combined sewer overflows (CSOs) are major contributors to water quality problems in coastal urban areas.... The way in which urban runoff and CSOs affect receiving waters is much different from continuous, point source loadings. First, rainfall induced loads are not constant, but intermittent, pulsed loads. Pollutant concentrations in these flows vary dramatically during the course of a runoff event, and the total pollution load from any storm is dependent upon the intensity and spatial*

variability of the rainfall, and the time elapsed since the last rainstorm. In general, the greatest concentration of pollutants is contained in the first flush of stormwater, with concentrations decreasing dramatically for most pollutants as a storm continues. In addition, precipitation in many areas is seasonal so that urban runoff and CSOs may affect coastal waters more during some seasons than others.

The National Research Council (1993) divided runoff contaminants of major concern to human health into two major classes, specifically, hazardous chemicals and infectious agents. The former include "metals and organic chemicals that may pose varying risks depending on the method of disposal and ultimate environmental fate (i.e., disposal in the ocean, land disposal, or incineration)," and the latter include "bacteria (e.g., campylobacter, salmonellae, *V[ibrio] cholerae*), viruses (e.g., poliovirus, coxsackie, echovirus, adenovirus, and hepatitis A), and parasites (e.g., cryptosporidium, giardia, and entamoeba)."

Not to diminish the importance of hazardous chemicals, but more often than not, beaches are closed because unacceptable levels of pathogens are present. In fact, Ocean.US (2002) stated that "the presence of pathogens, derived from wastewater discharge and stormwater runoff, was considered the most probable risk for swimming activities." According to the US Environmental Protection Agency (2006), "People who swim and recreate in water contaminated with fecal pollution are at an increased risk of becoming ill because of pathogens from the fecal matter."

The Clean Water Act and Beaches Environmental Assessment and Coastal Health (BEACH) Act require coastal states to monitor recreational waters for fecal indicator bacteria (FIB) to assess water quality; according to Boehm (2007), "exposure to FIB from municipal wastewater and urban runoff in marine waters correlates to adverse health outcomes in swimmers according to formal epidemiology studies." The US Environmental Protection Agency (2008) reported in *National Coastal Condition Report III* that "some of the major causes of public notifications for beach advisories and closures were stormwater runoff, wildlife, sewer line problems, and in many cases, unknown sources."

In light of the fact that aquatic pathogens can adversely affect the health of people recreating in coastal waters and the fact that urban runoff is an important source of these pathogens and other contaminants, it stands to reason that a better understanding of the effects of runoff to the coastal ocean is important. Significant questions to address in this regard include: What is the spatial and temporal extent of a stormwater plume? How does the plume behave? What characteristics, if any, of the plume can be tracked in real time? Weisberg et al. (2000) observed: "Runoff events that can add substantial amounts of sediment, nutrients and contaminant[s], as well as change nearshore salinity patterns, occur on scales of days and kilometers. Programs that measure processes on these different scales have historically been separate and the challenge for GOOS [Global Ocean Observing System] will be in finding commonalties that link them…. While linking measurements at different scales may be difficult, it is a worthwhile challenge because effective coastal management can only be accomplished if multiple spatial scales are assessed."

To date, some of the most comprehensive studies of stormwater plumes in the coastal ocean have focused on southern California (Jiang et al., 2001; Bay et al., 2003; Washburn et al., 2003; Nezlin and DiGiacomo, 2005; Nezlin et al., 2005, 2007; Warrick et al., 2007; Reifel et al., 2009; and Corcoran et al., 2010). Nezlin et al. (2005) stated that "Knowledge of freshwater runoff plume dynamics in southern California is important for management of coastal water quality, because river discharge associated with episodic winter rainstorms can be a major source of pollutants and pathogens to coastal waters." Most of the southern California studies have concentrated on the characteristics and spatial extent of stormwater plumes in the coastal ocean and the problems associated with trying to characterize these plumes using shipboard observations, satellite remote sensing, and, to a lesser degree, fixed platforms and buoys. Nezlin et al.

(2007) examined the availability of data from shipboard sampling and satellite imagery in the 10 days following storm events. They found that ships were available for sampling about 70% of the time, and high-quality satellite imagery was available only about 23% of the time. Shipboard sampling, however, is expensive. Time-series data collected by buoys were limited to wind and wave data, not water-quality data. Warrick et al. (2007) also relied on shipboard sampling, satellite imagery, and buoys (for meteorological data only), in addition to high-frequency radar and drifters for surface and near-surface currents. They did suggest that "autonomous underwater vehicles (AUVs) would fill important information gaps on the movement and mixing of water properties when ships are not able to sail and cloud-cover prevents satellite observations."

In this paper, we characterize the effects of two storms, relying primarily on fixed water quality and physical oceanographic sensors deployed nearshore, offshore, and on the seafloor. These time-series data were augmented with event-driven deployments of an AUV, as well as manual sampling, enabling us to characterize the spatial and temporal extent of the stormwater plumes and their effects on water quality in the coastal ocean. With the exception of the manual sampling, these data were all obtained from the Pacific Islands Ocean Observing System (PacIOOS), which is the most recent of the 11 regional ocean observing systems to be brought online as part of the national Integrated Ocean Observing System (IOOS). PacIOOS is operated as a joint project among researchers within the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawaiʻi at Mānoa (UHM) and a diverse group of partners throughout the State of Hawaiʻi and US territories in the Pacific. Detailed descriptions of the PacIOOS components and data products are available on the Web (http://www.pacioos.org).

The two storms we chose to study occurred during Hawaiʻi's rainy season, which typically lasts from October through April (Giambelluca and Sanderson, 1993). During the rainy season, migratory weather systems often move through the Hawaiian Islands, resulting in less-persistent northeasterly trade winds. Southerly to southwesterly winds associated with low-pressure systems (referred to as Kona winds) that come in from the sea can bring heavy rains to the entire island. Under these conditions, rainfall can be heavy across southern Oʻahu. In contrast, rainfall from orographic storms (storms enhanced by mountain effects) under trade wind conditions tend to be lighter and concentrated inland at higher elevations. We focus on effects of these Kona storms on the coastal ocean near highly populated Waikīkī (Figure 1). This area includes the lower portion of the Ala Wai Canal watershed, the Ala Wai Canal and Harbor, Waikīkī, portions of metropolitan Honolulu, and the nearshore waters of central Māmala Bay (Figure 2).

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Description of the Study Area

The Ala Wai Canal watershed extends from the crest of the Koʻolau Range (elevation: 960 m) to Māmala Bay. It consists of the Ala Wai, Mānoa-Pālolo, and Makiki subwatersheds with a total area of 42.5 km^2, of which 46% comprises conservation lands typically at the higher elevations. About 53% of the land area is designated as urban (US Environmental Protection Agency and Hawaiʻi Department of Health, 2002). The Ala Wai Canal forms the northern and western boundaries of Waikīkī. Constructed in 1919 as part of a land-reclamation project, the canal is ~ 3,100-m long, 51–83-m wide (Fryer, 1995), and, on average, ~ 3-m deep following the 2003 dredging of the canal. Runoff from the watershed is channeled through the Ala Wai Canal into Māmala Bay.

The shoreline of Māmala Bay, an open-ocean embayment on the south shore of Oʻahu, extends ~ 31 km from Diamond Head in the east to Barbers Point in the west. Within our study area, in the central portion of Māmala Bay, the depth gradually increases to 100 m from the shoreline to approximately 1.5–2 km offshore. Beyond the 100-m isobath, the depth increases more rapidly, reaching depths of around 400 m approximately 3 km offshore. Battista et al. (2007), in their *Atlas of the Shallow-Water Benthic Habitats of the Main Hawaiian Islands*, mapped substrate and biological cover out to a depth of ~ 30 m. Based on this atlas and our observations (Pawlak et al., 2009), the substrate in our study area consists of sand, limestone pavement, and spur and groove coral reef dominated by encrusting algae and corals with sparse coverage by the lobate, reef-forming coral *Porites lobata* and the cauliflower coral *Pocillopora meandrina.* The pavement is colonized by macroalgae with coverage that ranges locally from 10 to 90% over scales of meters to tens of meters.

Persistent northeasterly trade winds, and their interaction with the Koʻolau mountain range, has led to a classification scheme that separates Oʻahu into two principal physiographic zones (i.e., windward and leeward), which relate to the exposure of these areas to the northeasterly trade winds and orographic rainfall. In general, larger drainage basins, lower rainfall, and frequent nonperennial streams characterize the leeward side, which includes Honolulu and Waikīkī, in contrast with the windward side. Median annual rainfall near the topographic crest of the Koʻolau Range exceeds 7,000 mm (Giambelluca et al., 1986) whereas, in the southern coastal areas of Oʻahu, median annual rainfall is less than 600 mm (Figure 1).

Flow in Oʻahu streams can increase dramatically in a matter of minutes because of high-intensity rainfall, small drainage-basin size (relative to the continental United States), steep basin and stream slopes, and little channel storage (Macdonald et al., 1983; Wong, 1994; Tomlinson and De Carlo, 2003; Ostrander et al., 2008). During heavy storms, 24-hour rainfall can exceed 250 mm over coastal areas and 500 mm over the mountainous interior of the

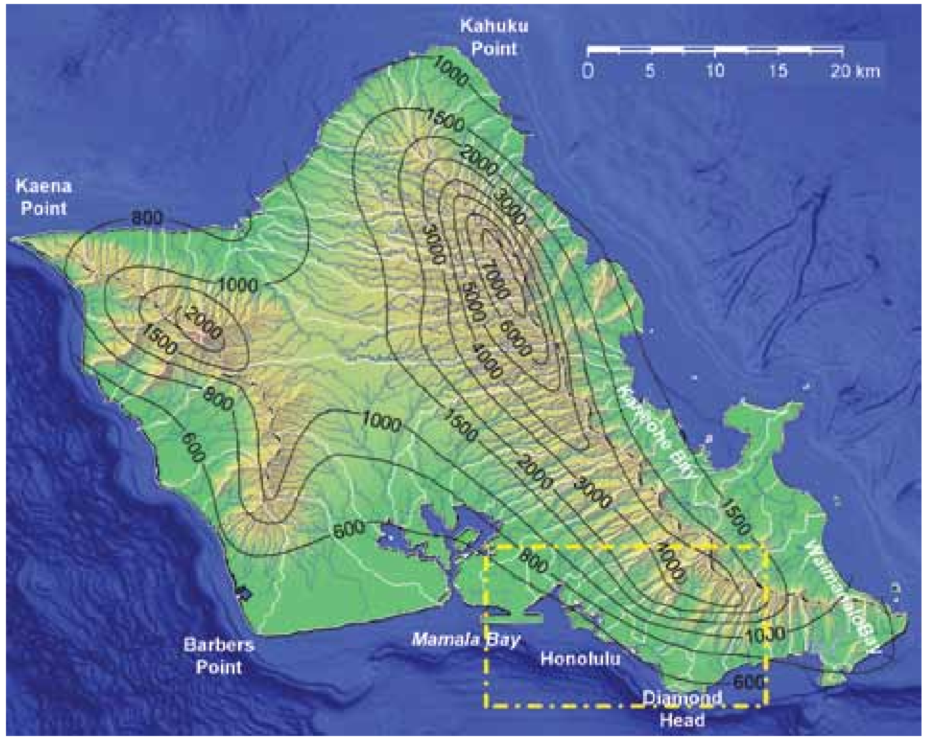

Figure 1. Map of the island of Oʻahu, Hawaiʻi, showing the study area (box) as well as physiography and bathymetry, major streams, and annual isohyets (lines of equal rainfall, in millimeters).

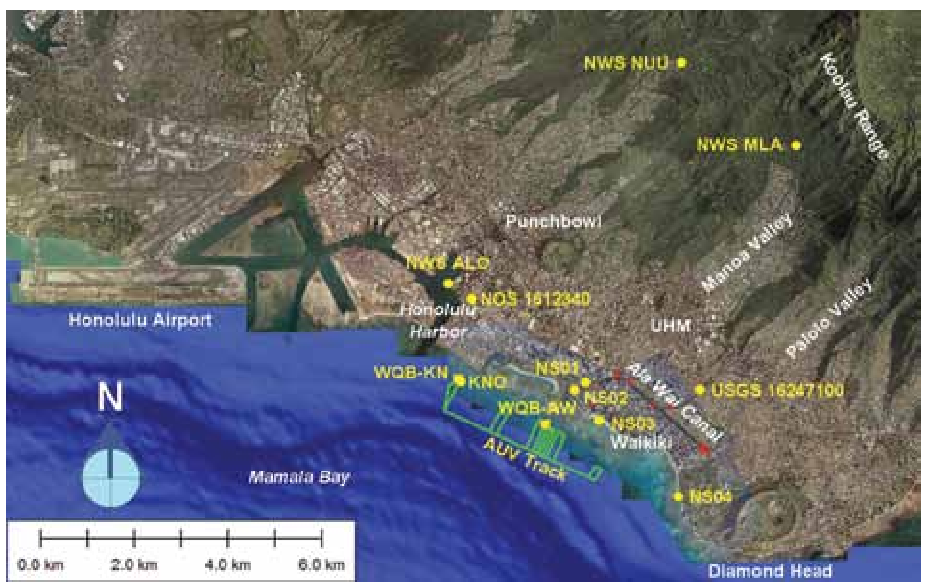

Figure 2. Locations of the Pacific Islands Ocean Observing System (PacIOOS) water-quality assets, including nearshore sensors (NS), water-quality buoys (WQB), Kilo Nalu Observatory (KNO), and the autonomous underwater vehicle (AUV) track. Non-PacIOOS assets include the National Weather Service (NWS) rain gauges, National Ocean Service (NOS) tide gauge, and US Geological Survey (USGS) stream gauge.

Koʻolau Range (Giambelluca et al., 1984). Runoff from these storms has pronounced effects on the physics, chemistry, and biology of Kāneʻohe Bay on the windward side of the island (De Carlo et al., 2007; Ostrander et al., 2008; Hoover and Mackenzie, 2009; Drupp et al., 2011). The effects of runoff in Māmala Bay on the south shore of Oʻahu appear to be less dramatic (Laws et al., 1999), in part because of the lower rainfall and greater flushing. However, the study by Laws et al. (1999) did not investigate the effects of storm events and, with only monthly sampling, did not resolve short-term effects. Considering that Oʻahu's most frequented beaches (by visitors to our state and by residents) are in the Honolulu/Waikīkī area, we were motivated to further investigate the effects of storms on the coastal waters in this region.

The tides in Māmala Bay are mixed semidiurnal, with maximum amplitudes of ~ 1 m. The currents, which are predominantly tidally driven, are about 20 cm s^{-1} and oriented alongshore (Pawlak et al., 2009). According to Hamilton et al. (1995) and Eich et al. (2004), the lunar semidiurnal (M_2) tidal component is the dominant factor in Māmala Bay currents; however, these tidal currents are highly variable. Analysis of current data at shallower depths (~ 12 m) at the Kilo Nalu Observatory west of the Ala Wai Canal shows that the M_2 and K_1 (lunisolar diurnal) tidal frequencies only account for about 30% of the total variance in the currents (Pawlak et al., 2009).

Hamilton et al. (1995) also reported that residual currents (i.e., those currents remaining after the tidal currents are filtered out) were weak and variable throughout the year, with speeds of 3–5 cm s^{-1}. Near-surface residual currents (i.e., those currents at depths < 100 m) split in the vicinity of the mouth of the Ala Wai Canal and flow eastward toward Waikīkī and Diamond Head and westward toward Barbers Point. Hamilton et al. (1995) reported that "Kona wind events had no discernible effects on the nearshore circulation." They did, however, observe that a weakening of the trade winds produced a weakening of westward flows along the shelf. Hamilton et al. (1995) also noted that residual currents near the mouth of the Ala Wai Canal were eastward "in opposition to the wind" and that "alongshore currents were interrupted at irregular intervals by 1- to 2-day, whole-column outflow events from the Ala Wai Canal," suggesting that these interruptions could be related to heavy rainfall events.

INSTRUMENTATION AND METHODS

Sensors

The PacIOOS network consists of sensors deployed nearshore on buoys, docks, and the seafloor (Figure 2). The nearshore sensor installations NS01 and NS02 consist of Sea-Bird Electronics (SBE) 16*plus* V2 SEACAT C-T Recorders, each equipped with SBE temperature and conductivity sensors and WET Labs ECO FLNTUS fluorescence (chlorophyll) and turbidity sensors. The water-quality buoys (WQB-AW and WQB-KN) are equipped with the same sensors, as well as SBE 43 DO (dissolved oxygen) sensors.

The Kilo Nalu Observatory (KNO), located approximately 2 km west of the Ala Wai Canal entrance and 1 km east of the mouth of Honolulu Harbor, includes a suite of cabled instrumentation (Pawlak et al., 2009). Among the instruments at KNO, a bottom-mounted 1200-kHz acoustic Doppler current profiler (ADCP) at a depth of 12 m provides data on waves (directional spectra, height, and period), mean current profiles, temperature, and acoustic scatter.

A Remote Environmental Monitoring Units (REMUS) autonomous underwater vehicle (AUV) used by the PacIOOS program for targeted surveys is equipped to measure bathymetry, currents, salinity, temperature, optical backscatter, and chlorophyll fluorescence. The AUV was programmed to run a track planned specifically to monitor the horizontal and vertical distribution of the stormwater plume issuing from the Ala Wai Canal (Figure 2). The REMUS AUV became operational in 2009, so it was not available for the December 2008 storm. It was deployed, however, on March 16, 2009, shortly after the March 13–14 storm. This survey lasted 2 hours, 20 minutes and covered a total distance of 15.33 km.

Data from the PacIOOS sensors were complemented by data from existing, land-based sensors that include rain, stream, and tide gauges (Figure 2). The National Weather Service (NWS) rain gauges (part of the Hawaiʻi Hydronet System) measure rainfall at 15-minute intervals. Data from two stations (Figure 2) were selected for analysis: (1) Mānoa-Lyon Arboretum (MLA) at an elevation of 120 m, and (2) Aloha Tower (ALO) in downtown Honolulu near sea level. The US Geological Survey (USGS) maintains a network of stream gauges on Oʻahu. The stream gauge we selected (#16247100) provides streamflow data for Mānoa-Pālolo Drainage Canal (MPDC) at Mōʻiliʻili (the largest stream emptying into the Ala Wai Canal) ~ 600 m upstream of the Ala Wai Canal (Figure 2). According to Fryer (1995), MPDC accounts for 58% of the flow into the Ala Wai Canal. The National Ocean Service (NOS) tide gauge (#1612340) located in Honolulu Harbor (Figure 2) supplied water level, water temperature, and meteorological data (wind speed and direction, barometric pressure, and air temperature).

Data from the land-based networks and the PacIOOS network were collected at disparate sampling intervals (from 4 to 20 minutes); for this reason, the USGS software GRAN (from granularity or time interval; Cuffney and Brightbill 2008) was used to assemble a database with a uniform time interval of 30 minutes. Base flow (i.e., that part of the streamflow not attributable to direct runoff, and usually sustained by groundwater discharge) was calculated using the USGS software BFI 4.1 (Wahl and Wahl, 1995) and the nine full years of daily streamflow data available for MPDC. Descriptive statistics (median, interquartile range, maximum, and minimum) were calculated with the statistical package SPSS. The December 2008 and March 2009 storms were compared using the Mann-Whitney U test and the Kolmogorov-Smirnov Z test. The two-tailed significance value $\alpha = 0.05$ was selected for these tests.

Manual Sample Collection and Nutrient Analyses

To supplement the data from the automated networks of sensors, samples for nutrient analyses were collected in the mouths of two streams that drain into the Ala Wai Canal, at 12 sites along the shore of the canal, and at one site in Ala Wai Harbor. The samples, collected at 5–10-cm depths in acid-washed, brown, high-density polyethylene bottles, were stored in the field on ice packs in a cooler and transported to the laboratory within three hours. Subsamples from the bottles were shipped on dry ice to the Oregon State University nutrient analysis facility. A Technicon AutoAnalyzer II was used for the analysis of phosphate and ammonium, and an Alpkem RFA 300 was used for silicic acid, nitrate + nitrite, and nitrite. Detailed analytical and data processing methods are described in Gordon et al. (1994).

Microbiological Data

Data on the concentrations of sewage-indicator bacteria in the genera *Enterococcus* and *Clostridium* were obtained from the Hawai‘i Department of Health Clean Water Branch Web site (http://emdweb.doh.hawaii.gov/CleanWaterBranch/WaterQualityData). The data retrieved were for samples collected on December 15, 2008, and March 16, 2009, at two beaches to the east and three beaches to the west of the mouth of Ala Wai Harbor. The annual median values for each genus at these same sites were calculated from the data.

RESULTS

The Storms and Their Effects

The two storm events considered in this study occurred in December 2008 and March 2009. Both events were characterized by a shift in the prevailing wind conditions from northeast trade winds to southern Kona winds and rainfall

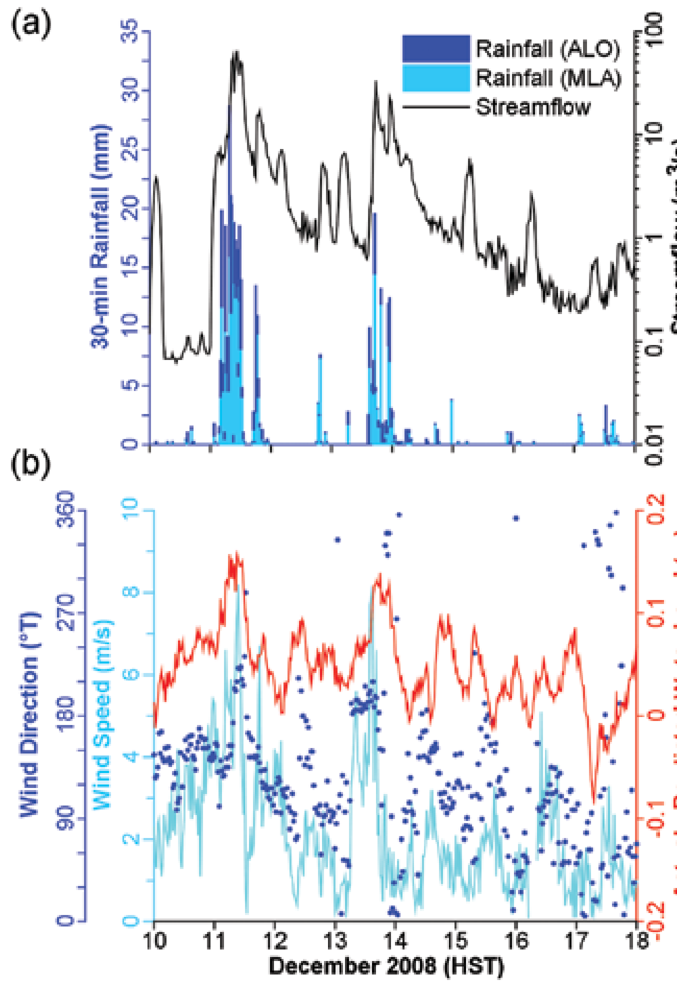

Figure 3. (a) Readings of 30-minute rainfall (mm) from National Weather Service rain gauges at Mānoa-Lyon Arboretum (MLA) and Aloha Tower (ALO), and streamflow ($m^3 s^{-1}$) for USGS stream gauge #16274100 on Mānoa-Pālolo Drainage Canal at Mōʻiliʻili. (b) Wind direction (°T) and speed ($m s^{-1}$) and actual minus predicted water level (m) measured at NOS tide gauge #1612340 in Honolulu, Hawaiʻi, from December 10 to 18, 2008.

patterns characteristic of mesoscale processes (as opposed to trade-wind-induced orographic uplifting).

December 2008

In the seven days prior to the storm (December 4–10, 2008), a total of 14 mm of rain were recorded at MLA rain gauge and ~ 1.5 mm at ALO rain gauge. In the 24-hour period beginning at ~ 0115 HST on December 11, 2008, 183 mm of rain were recorded at the MLA rain gauge and 100 mm at ALO (Figure 3a), representing the two-year, 24-hour storm. The next day (December 12), only 15 mm of rain were recorded at MLA and < 1 mm was recorded at ALO. On December 13, a total of 76 and 31 mm of rain were recorded within 24 hours at the MLA and ALO gauges, respectively, during a second rain event that occurred during the same atmospheric low that caused the first rain event. Winds during these events were from a southeasterly to southwesterly direction (Kona winds) rather than the northeasterly trade winds (Figure 3b).

Just prior to the December 11 storm, streamflow in Mānoa-Pālolo Drainage Canal (MPDC) was 0.08 $m^3 s^{-1}$, which was below the estimated mean base flow (~ 0.16 $m^3 s^{-1}$). Flow in MPDC peaked at 72 $m^3 s^{-1}$ on December 11 (Figure 3a), which was the highest flow measured at this location in 2008 and 450 times the mean base flow. Streamflow declined over the next two days, but peaked again late on December 13, in response to the second period of rainfall. Within hours of the first rainfall, salinity dropped in the surface waters of the Ala Wai Canal from 34 to ~ 2 and temperature from around 25.5 to 22.5°C for ~ 12 hours (Figure 4a). Temperature and salinity had not yet returned to pre-storm values when they dropped again during the second period of rainfall (Figure 4a). These latter declines were similar in magnitude but shorter in duration than the first. The two periods of freshening and cooling were also detected offshore at WQB-AW but to a lesser degree (35.0 to 30.5 and 25.4 to 24.5°C) and with approximately a two-hour lag in the freshening of offshore waters (Figure 4d). These signals also appeared at WQB-KN, located ~ 2,100 m from the mouth of the Ala Wai Canal, but they were smaller still. At both offshore buoys, the second period of freshening and cooling was much less pronounced than the first. Moreover, the temperature changes at both buoys were small compared to the normal diel signal caused by solar daytime warming and nighttime cooling (Figure 4d).

The decrease in temperature resulting from the storm measured by the WQBs would have increased the density of the surface water if the salinity had remained the same; however, salinity decreased during the storm, and its effect on density was greater than the temperature effect. As a result, the density of the surface water surrounding WQB-AW and WQB-KN decreased from 1.0232 gm cm^{-3} to a minimum of 1.0200 and 1.0214 gm cm^{-3}, respectively.

Turbidity (a surrogate for total suspended particulate concentration) in the Ala Wai Canal was elevated during the storms and remained elevated for ~ 20 hours after each of the storm-related peaks in streamflow (Figure 4b). Turbidity values exceeded the maximum range of the sensors at NS01 and NS02 (25 NTU) for nearly 18 hours after the December 11 peak streamflow; turbidity did not return to pre-storm levels for ~ 6 days. Increases in turbidity were detected at both WQB-AW and WQB-KN (Figure 4e), but, as observed with temperature and salinity, the signal was about two-thirds weaker for the second event at both locations, and the peaks were smaller at WQB-KN, which is farther from the mouth of the canal.

The higher average wind speeds associated with the December 11 and 13 rain events (Figure 3b), peaking at ~ 8 $m s^{-1}$ (with gusts up to 16.8 $m s^{-1}$), were associated with higher significant wave heights of up to 3 m on December 11 and 2 m on December 13 (Figure 4c), as measured at KNO. Higher acoustic scatter counts (Figure 4c) were commensurate with these higher significant wave heights. Cross-correlation analysis of the 30-minute interval time-series data revealed that acoustic backscatter was significantly correlated ($\alpha = 0.05$) with precipitation measured at Aloha Tower at zero lag (CCF [cross correlation function] = 0.18), with streamflow in MPDC using a 2–2.5-hour lag (CCF = 0.15), and with significant wave height measured at KNO using a 30-minute lag (CCF = 0.20).

A statistically significant CCF of 0.20 between acoustic scatter counts (surrogate for suspended particulates) and significant wave height is not altogether surprising. The estimated wavelength (λ) for the 6–8-s waves is ~ 46–70 m using the method described by Fenton and McKee (1990). Given that a wave begins to *feel* bottom at ½ λ and the water depth at KNO is 12 m, it is probable that sediment could be resuspended as a result of wave action. Although not included in the time-series plots, the highest near-bottom current speeds (maximum = 0.64 $m s^{-1}$) could resuspend sand-sized sediment. Therefore, it is quite likely that there were two sources of suspended matter in the water column: (1) turbid

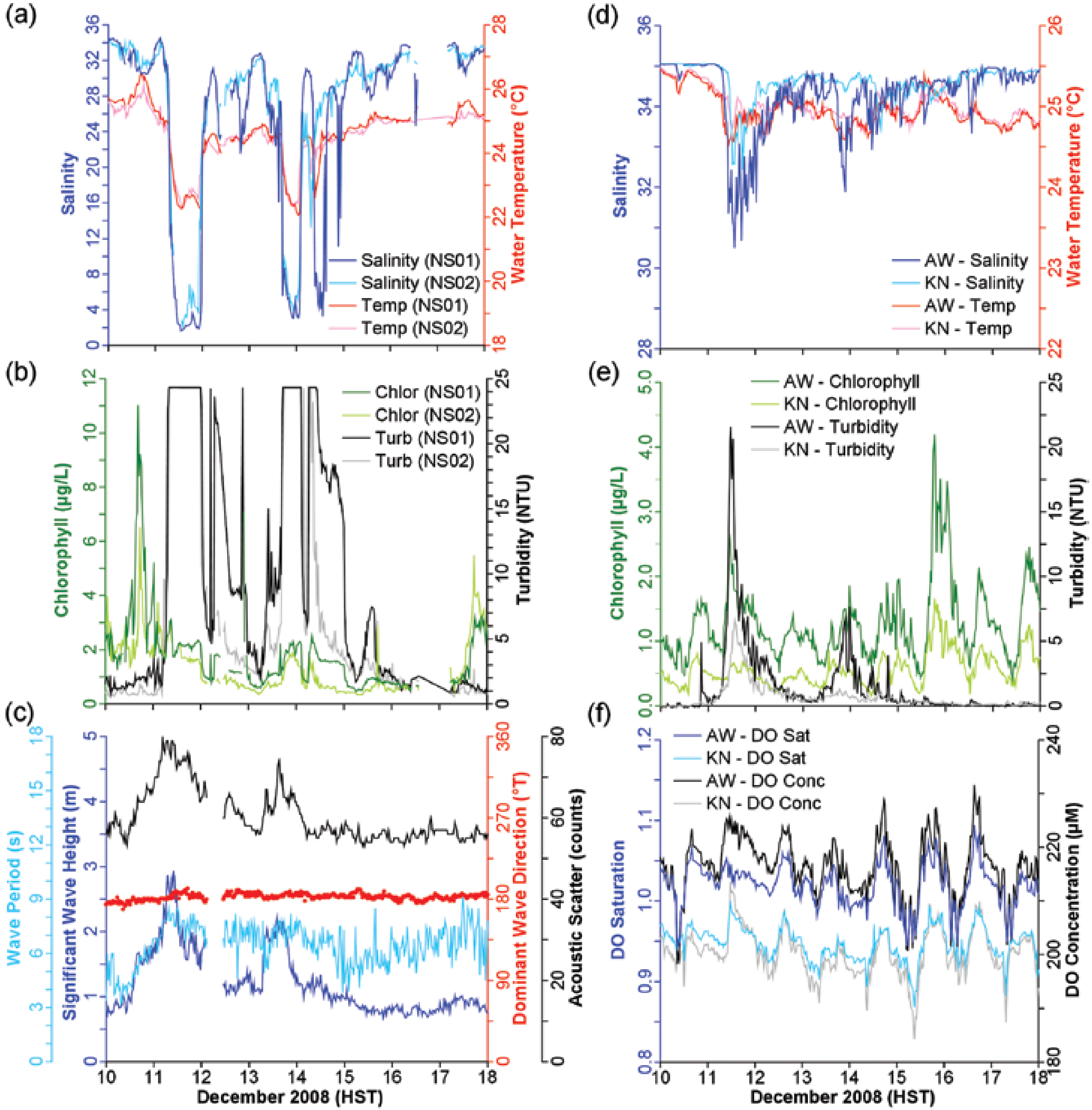

Figure 4. Time-series plots of data from PacIOOS nearshore sensors NS01 and NS02 for (a) salinity and temperature and (b) chlorophyll and turbidity. (c) Kilo Nalu Observatory (KNO) wave and acoustic scatter data. Data from water quality buoys WQB-AW and WQB-KN for (d) salinity and temperature, (e) chlorophyll and turbidity, and (f) dissolved oxygen (DO) from December 10 to 18, 2008. Note the effects of the December 11 and 13 rain events on water-quality variables, particularly salinity, temperature, turbidity, and chlorophyll.

stormwater runoff, and (2) resuspended bottom sediments.

Both water-quality buoys revealed diel fluctuations in chlorophyll and dissolved oxygen saturation (Figure 4e and 4f, respectively), but values for each of these variables were consistently higher at WQB-AW. During the December 11 and 13 storms, the diel fluctuation in dissolved oxygen saturation appeared somewhat dampened. The daily maximum values of chlorophyll fluorescence at both sites approximately doubled between December 15 and 16.

In the Ala Wai Canal, with the exception of Station 8, nitrite + nitrate ($NO_2^- + NO_3^-$) concentrations were higher on December 11 (sampled during the storm) than at any of the other monthly samplings over the course of a year (Figure 5). At Station 8, which had higher concentrations of $NO_2^- + NO_3^-$ than any other station during the rest of the year, the sample collected during the storm was lower than usual (10 μM), but still comparable to or higher than values at the other stations during nonstorm conditions. The introduction of elevated concentrations of $NO_2^- + NO_3^-$ could account for the chlorophyll peak that occurred on December 16, presumably after the turbidity decreased sufficiently to favor photosynthesis.

Four of the five beach sites adjoining our study area sampled by the Department of Health on December 15, 2008, had concentrations of *Enterococcus* spp. nine to 62 times higher than the annual median for 2008. *Clostridium perfringens* counts were elevated at three of the five sites by a factor of three to six relative to the 2008 annual median. At the remaining two locations, the values were identical to the annual median.

March 2009

In the seven days prior to the March 13–14 storm, a total of 163 and 16 mm of rain fell at MLA and ALO rain gauges, respectively. The storm commenced with the first

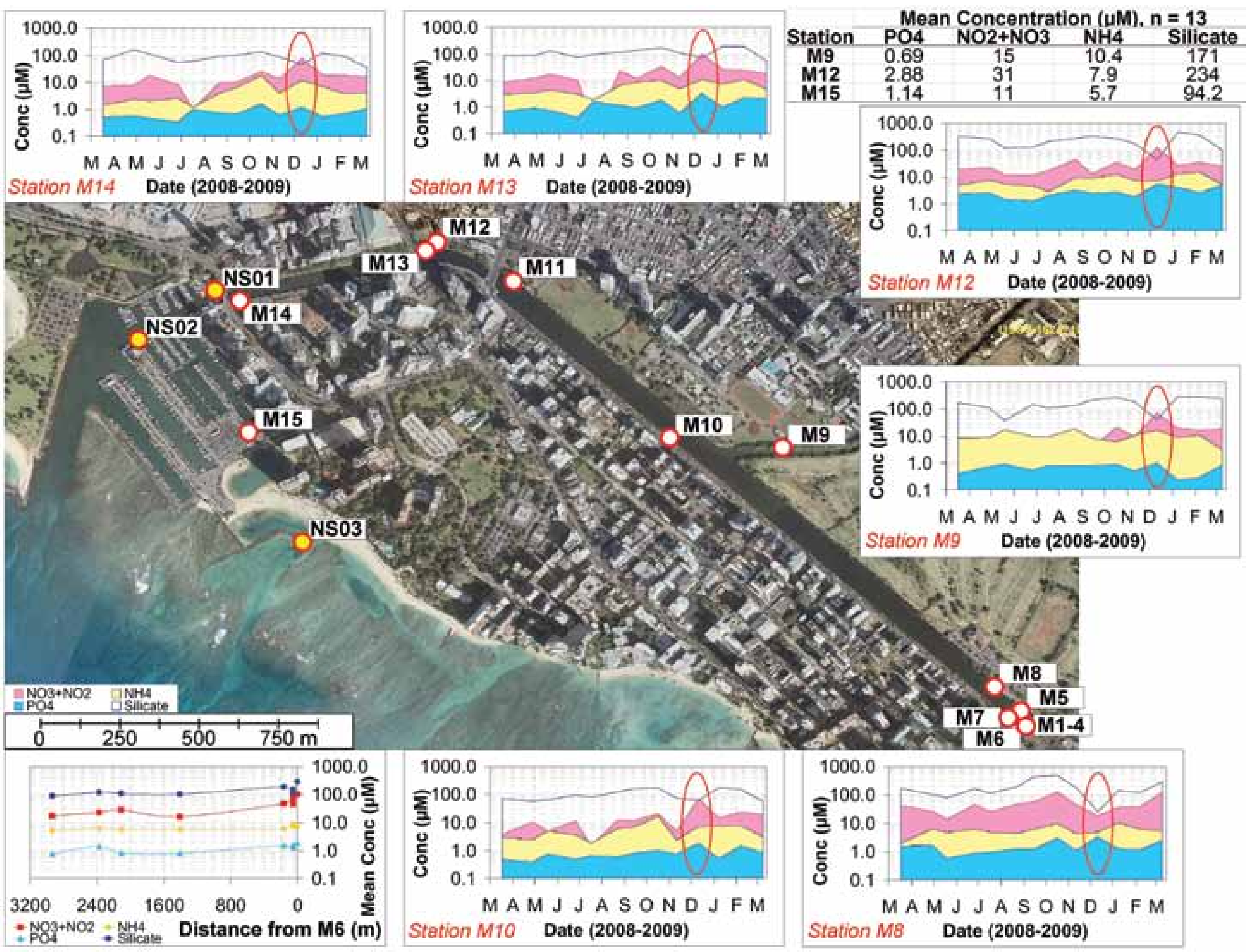

Figure 5. Results from event-driven nutrient sampling stations (M1 through M15) in the Ala Wai Canal and Harbor; the nearshore sensor (NS) installations are included for reference. The elevated concentrations of nitrate + nitrite ($NO_3^- + NO_2^-$) observed at all stations (except Station M8) during the December 11, 2008, storm are readily apparent (ellipses).

rainfall at about 2130 HST on March 13 (Figure 6a). Rainfall peaked within eight hours of the first rainfall, and by the end of 24 hours, a total of 94 and 58 mm had fallen at the MLA and ALO rain gauges, respectively. Prior to the onset of the rains, wind speed increased to ~ 8 m s^{-1} from the west-southwest (Figure 6b). The streamflow in the MPDC increased from < 0.5 m^3 s^{-1} just prior to the storm to a peak of 84 m^3 s^{-1}, which occurred just after the peak rainfall. Streamflow had declined to < 1 m^3 s^{-1} by approximately two days after the first rainfall and remained below this level for the following week, except for occasional spikes (Figure 6a).

Water temperature in the canal, which had been at ~ 23°C, declined by nearly 4°C and did not return to pre-storm levels for about two to three days (Figure 7a). Salinity in the Ala Wai Canal during this storm dropped from ~ 32 down to 2, with the freshening and recovery coincident with the changes in temperature (Figure 7a). The sensors at NS01, but not NS02, recorded two additional decreases in temperature and salinity within 24 hours of the first event, but these were of lesser magnitude and duration than the initial response. At the offshore Ala Wai water-quality buoy (WQB-AW), temperature dropped by little more than 1°C, and salinity dropped from 35 to ~ 28 (again with a commensurate drop in surface water density from 1.0234 to 1.0187 gm cm^{-3}), but this minimum was short-lived (Figure 7d). Salinity at the new nearshore sensor installation (NS03, dotted line in Figure 7a), located on a dock off Waikīkī, recorded a relatively small decrease in salinity (dropping by ~ 3); however, this area did not return to oceanic values for nearly 45 days (Figure 8). AUV surveys in March better illustrate the spatial distribution of salinity shortly after the storm (Figure 9). It is apparent from this plot that salinity two days after the March 13–14 storm remained about 0.3 to 0.5 lower than pre-storm salinity over a rather large area of the coastal ocean fronting Honolulu.

Increases in turbidity were recorded by the nearshore sensors and offshore sensors mounted on the two water-quality buoys (Figure 7b,e). The turbidity signal at NS02 had dropped substantially within 24 hours from ≥ 20 NTU to ~ 5 NTU, but turbidity at NS01 was still elevated at this time (≥ 20 NTU). Peak turbidity measured at WQB-AW (~ 15 NTU) was lower than in the canal and recovered more quickly (Figure 7e). A second, smaller spike in turbidity at WQB-AW (~ 1 NTU) coincided with small decreases in temperature and salinity at the same location and with similar, but larger-magnitude, signals at NS01. Although an increase in turbidity was detectable at WQB-KN, the signal was small (~ 1 NTU) and, like salinity at this location, was delayed by ~ 8 hrs relative to the other sensors.

Unlike December 2008, it is less certain that wave- and bottom-current-induced sediment resuspension contributed as much to the turbidity or acoustic scatter. Figure 7c shows the significant wave height was only about 1.5 m and the wave period, which was around 13 s

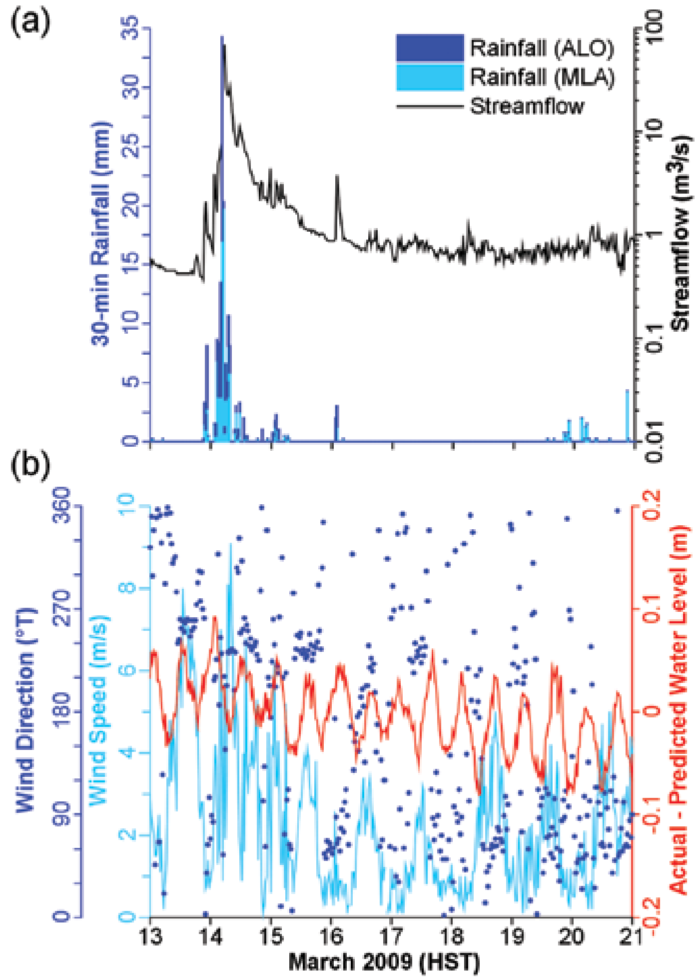

Figure 6. (a) Measurements of 30-minute rainfall (mm) from NWS rain gauges at Mānoa-Lyon Arboretum (MLA) and Aloha Tower (ALO) and streamflow (m^3 s^{-1}) for USGS stream gauge #16274100 on Mānoa-Pālolo Drainage Canal at Mōʻiliʻili. (b) Wind direction (°T) and speed (m s^{-1}) and actual minus predicted water level (m) measured at NOS tide gauge #1612340 in Honolulu, Hawaiʻi, from March 13 to 21, 2009.

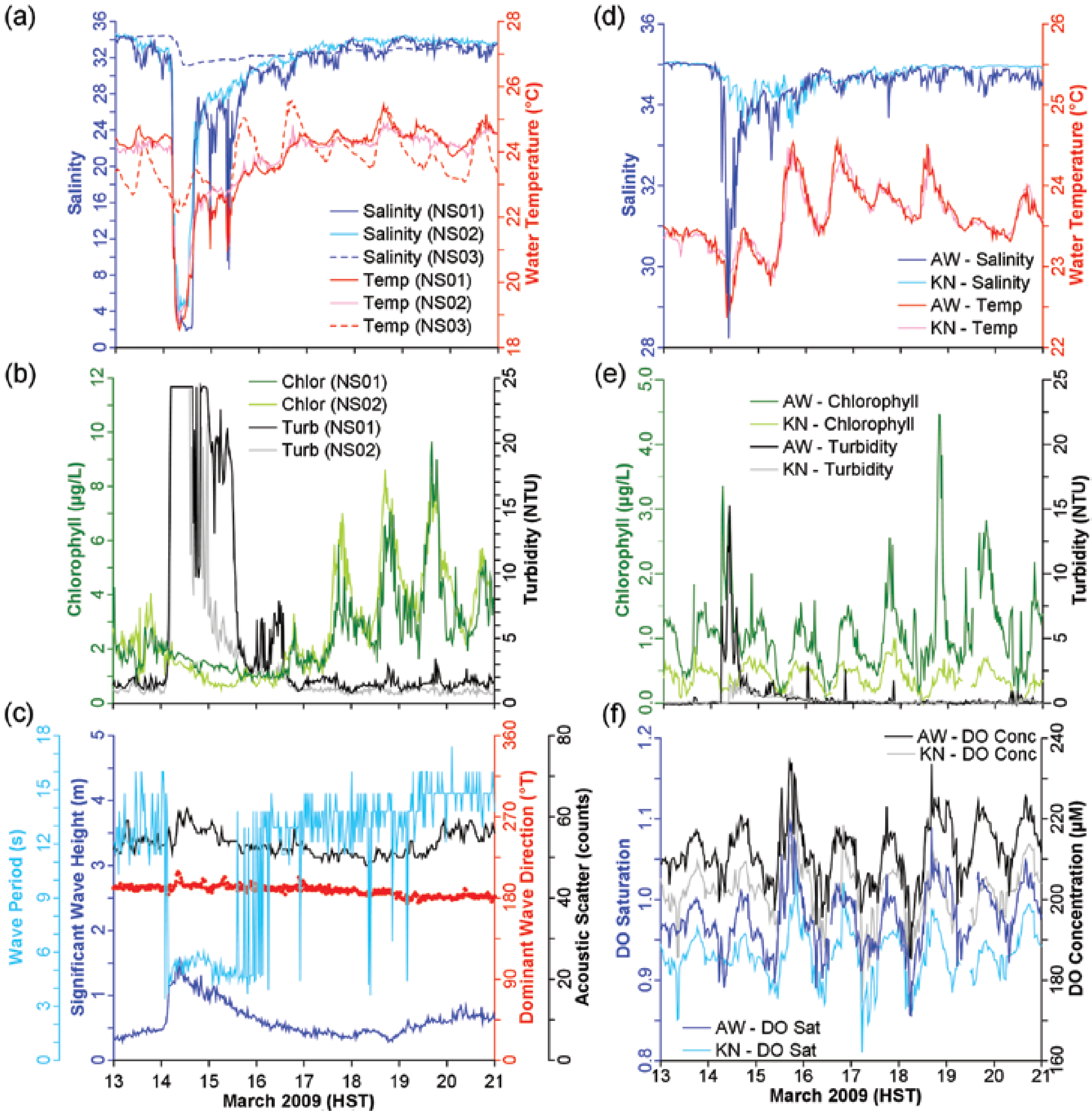

Figure 7. Time-series plots of data from PacIOOS nearshore sensors NS01 and NS02 for (a) salinity and temperature and (b) chlorophyll and turbidity. (c) Kilo Nalu Observatory (KNO) wave and acoustic scatter data. Data from water-quality buoys WQB-AW and WQB-KN for (d) salinity and temperature, (e) chlorophyll and turbidity, and (f) dissolved oxygen (DO) from March 13 to 21, 2009. Note the effect of the March 13 rain event on water-quality variables, particularly salinity, temperature, turbidity, and chlorophyll.

before the storm, decreased to about 5 s for 1.5 days before returning to longer periods of about 15 s. A 5-s wave would have a wavelength λ of ~ 34 m, technically enough to affect the bottom but with less impact than longer-period waves. Moreover, the maximum bottom-current speed during this storm was only about 0.27 m s^{-1}, which might have resuspended sediment, but to a lesser degree than in December 2008. This supposition is supported by the acoustic

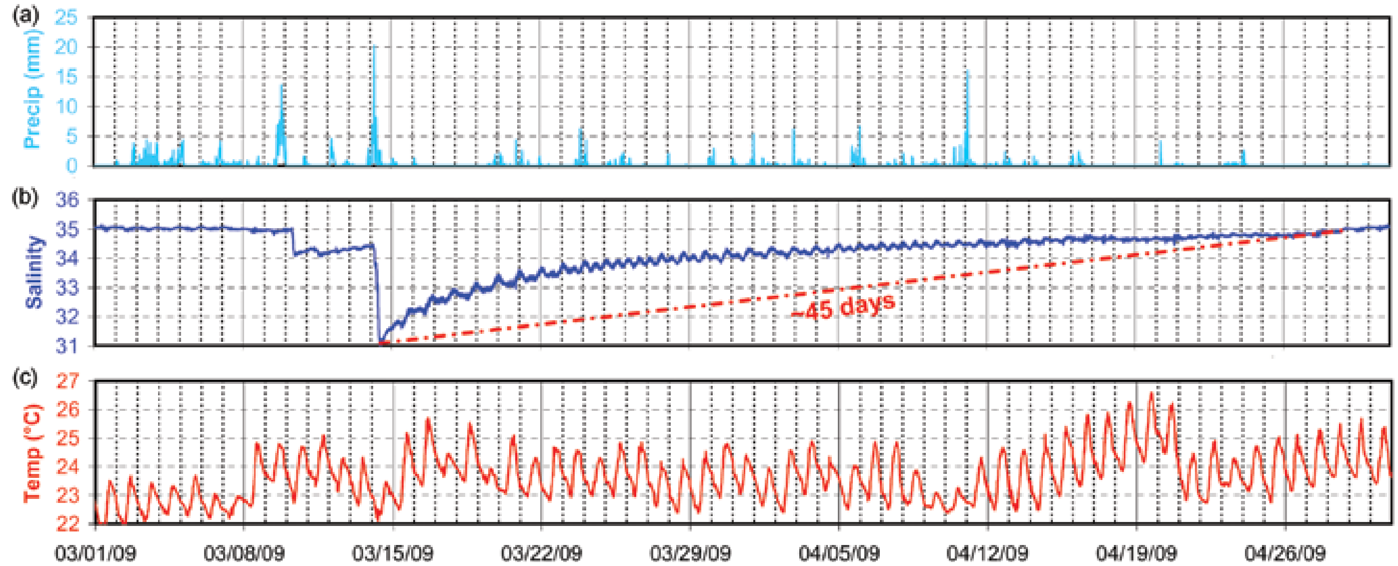

Figure 8. Time-series plots of (a) rainfall measured at the NWS MLA rain gauge, and (b) salinity and (c) temperature measured at nearshore sensor NS03 located in Māmala Bay prior to and following the March 13, 2009, storm. Note that near-surface (~ 1 m) salinity did not return to oceanic values for nearly 45 days following the storm.

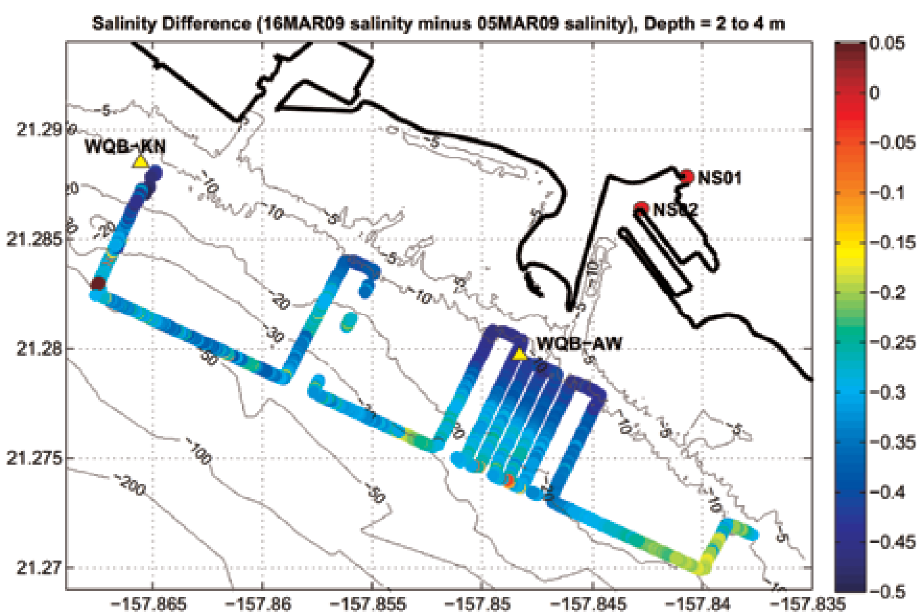

Figure 9. Results of autonomous underwater vehicle (AUV) survey of coastal waters conducted on March 16, 2009, (about two days after the March 13 storm) commencing about 2130 HST. The data, collected at depths between 2 and 4 m, compare salinity measured following the storm with salinity measured during an identical survey conducted on March 5, 2009, prior to the storm. Note that fresher water (blue) is still present in the coastal waters as a result of the storm.

scatter data (Figure 7c), which did not change appreciably during the storm, unlike the December 2008 storm.

As we observed in December 2008, chlorophyll and dissolved oxygen saturation showed diel variations during March 2009 (Figure 7b,e,f), and the diel fluctuation in dissolved oxygen saturation measured at both water-quality buoys appeared dampened at the height of the storm. Chlorophyll fluorescence measurements increased at all sensors for approximately three days after the storm and remained elevated for at least three days at all locations except WQB-KN where the effect lasted only one day.

Clostridium perfringens concentrations on March 16, 2009, were not elevated compared to the annual median at any of the five stations sampled by the Department of Health, lending credence to the concept of first-flush effects. It is possible that antecedent rains flushed *Clostridium perfringens* from the land surface. The counts of *Enterococcus*, which are present and actively growing in soils in tropical and subtropical environments (Byappanahali and Fujioka, 2004; Hardina and Fujioka, 1991) and not subject to first-flush effects, were identical to the annual median values at two stations but were 5–6½ times higher than the annual median at the remaining three stations.

Comparison of the December 2008 and March 2009 Storms

To more clearly illustrate the differences in timing of the two storms and their subsequent effects on the coastal ocean, we overlaid the time-series data from each storm for a 36-hour window beginning at six hours before each storm (Figure 10). Time zero was set at 0115 HST on December 11, 2008, and 2130 HST on March 13, 2009, when rainfall was first detected at the MLA and ALO rain gauges (Figure 10a and 10k, respectively). In December, streamflow in MPDC showed an immediate but small increase at time zero (Figure 10b). Flow did not increase again substantially until six hours later when rainfall doubled. Four subsequent peaks in the streamflow followed spikes in rainfall with lag times of just under an hour. The peak rainfall at MLA in both December and March occurred seven hours after time zero, and a peak in streamflow in each case occurred approximately 45 minutes later at the stream gauge in MPDC. In contrast to the December storm, the distribution of rainfall and streamflow in March was essentially unimodal (Figure 10k and 10b). In March, 16.8% of the 24-hour rain fell within a 1.5-hour window around the peak, whereas in December this number was only 15.2%. Consequently, the peak streamflow in March was slightly higher than in December, although total rainfall and total integrated flow over 24 hours was lower.

Minor declines in the salinity in the Ala Wai Canal measured at NS01 and NS02 were first detected ~ 2 hours after the rain started in December (Figure 10c). After four hours in December 2008 and seven hours in March 2009, salinity started to decrease precipitously. The maximum rate of decline occurred at six hours and seven hours after time zero with salinity dropping ~ 15 units in 15 minutes. By 12 hours elapsed time, salinity reached a minimum of 2 at NS01 and NS02 for both storms (Figure 10c). In the ocean, salinity measured at WQB-AW began to decrease five hours after the rain started during both storms (Figure 10d), whereas there was no discernible decrease observed at WQB-KN until nearly eight hours after the rain started during both storms. Salinity at WQB-AW showed oscillations with a period of ~ 30 minutes during both storms that were not apparent at WQB-KN. The amplitude of these oscillations was greater during the March storm with maximum excursions of ~ 3 occurring between 10 and 12 hours after time zero.

Temperature started to decrease at both the nearshore sensors and water-quality buoys ~ 5 hours after the rains started in December 2008 and after ~ 6 hours in March 2009 (Figure 10e,f). The magnitude of the temperature change was greater for the Ala Wai Canal (NS01 and NS02) than for the offshore waters. The temperature decrease during December 2008 was ~ 3°C; during March, the decrease was ~ 5°C. The change in temperature offshore (WQB-AW and WQB-KN) during both storms was only ~ 0.8°C.

Turbidity during December 2008 and March 2009 began to increase in the Ala Wai Canal (Stations NS01 and NS02 in Figure 10g) ~ 3 hours after the rain started. It increased to greater than 25 NTU in ~ 7 hours, and remained above 25 NTU for another 12–15 hours. An increase in turbidity in the ocean (WQB-AW and WQB-KN, Figure 10h) became apparent ~ 6 hours after the rain started during both storms. The turbidity increased more quickly at WQB-AW than at WQB-KN and with a greater magnitude, peaking at ~ 22 NTU at 10.5 hours during December 2008 and ~ 15 NTU at 11 hours during March 2009. Turbidity at WQB-KN did not peak until 12.5 hours after the rain started and then only to 7 NTU during December 2008; there was no pronounced turbidity peak measured at WQB-KN during the March 2009 storm. The turbidity remained elevated in the Ala Wai Canal and coastal ocean for 12–36 hours after the rains ceased. As stated previously, significant wave height and wave period were less during the March 2009 storm compared with December 2008 (Figures 4c and 7c). Moreover, maximum near-bottom current speeds were lower during March 2009 (0.27 m s^{-1}) compared with December 2008 (0.64 m s^{-1}). The acoustic scatter record from KNO reflects the small, shorter-period waves and slower near-bottom current speeds of March 2009.

In the 36-hour window, estimated chlorophyll was highest (3–6 μg L^{-1}) just prior to the rains at NS01 in December (Figure 10i). At NS02 in December and at both NS01 and NS02 in March (Figure 10i), chlorophyll was 2–3 μg L^{-1}. In all cases the chlorophyll declined to 2 μg L^{-1} and the signals became smoother within two hours of the first rainfall. Although high-frequency variability declined, there were occasional large spikes in the chlorophyll fluorescence signal in December, but not in March. In contrast to the declines at NS01 and NS02, there was an increase in the magnitude and variability of chlorophyll fluorescence at WQB-AW

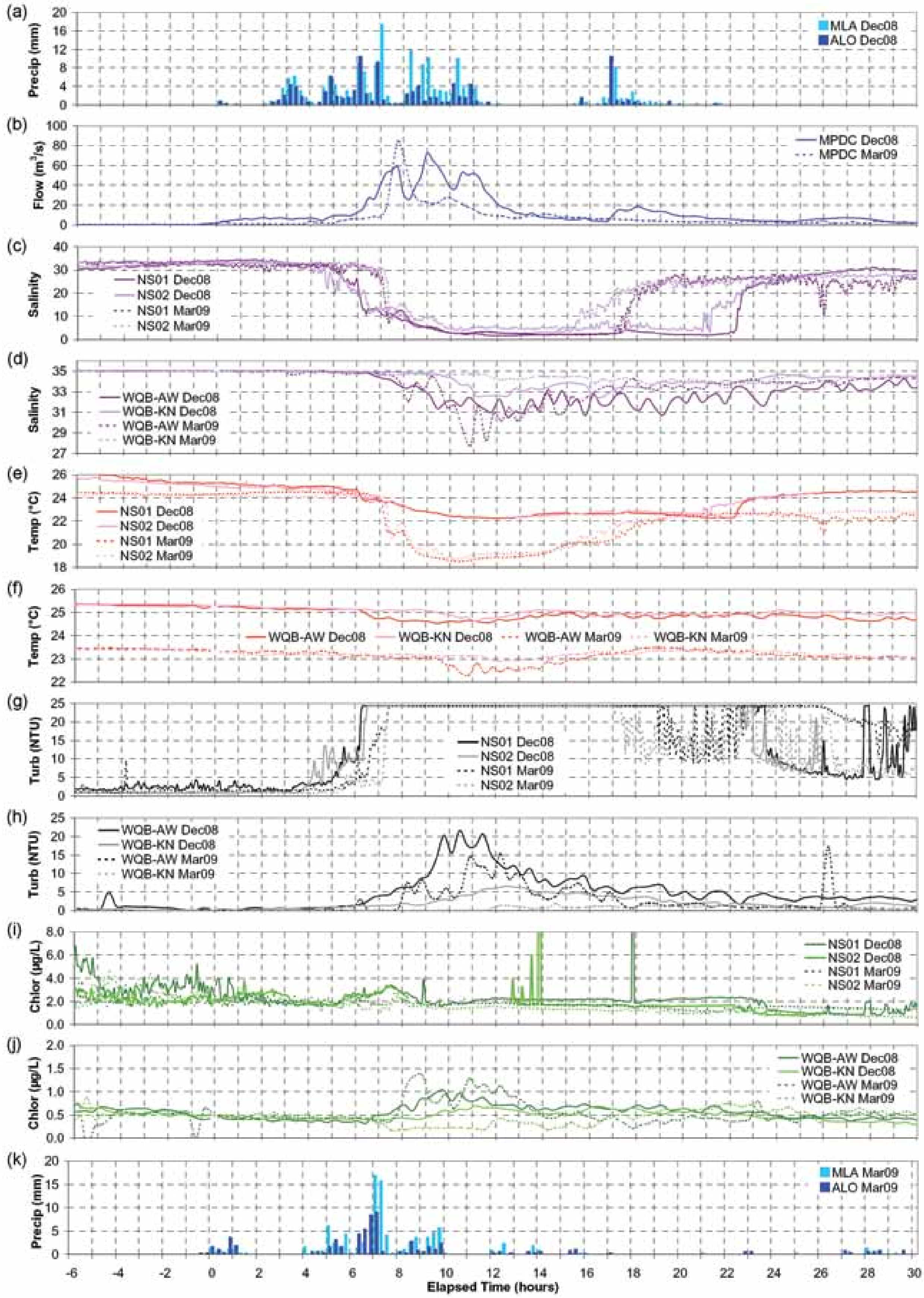

Figure 10. A comparison of the December 2008 and March 2009 storms for selected variables including rainfall (a and k), streamflow (b), salinity (c and d), water temperature (e and f), turbidity (g and h), and chlorophyll (i and j) from six hours before onset of the rain until 24 hours after the onset of the rain.

at ~ 8 hours after time zero (Figure 10j). At WQB-KN, chlorophyll varied little in response to the storm in December, but declined slightly (from 0.5 to 0.25 μg L^{-1}) between 8 and 17 hours after the first rainfall in March (Figure 10j).

In order to test for significant differences between the responses to the two storms (two-tailed significance level of $\alpha = 0.05$), we used nonparametric statistics to compare selected variables. We compared not only the eight days (192 hours) of data, but also a 24-hour subset of these data extending from the onset of the rain to 24 hours after the onset of the rain. While the eight-day rainfall was significantly different between December and March, the 24-hour rainfall was not different. For the most part, streamflow at MPDC was significantly different between the storms for both the eight-day and 24-hour time periods. We estimated the total flow during the eight days for the December 2008 and March 2009 storms to be 2.8×10^6 and 1.3×10^6 m^3, respectively. Although magnitude of decline in salinity in the Ala Wai Canal was the same for both storms (dropping by 32 in each case), there were significant differences in salinity for the eight days around each storm. Generally, the salinities recorded offshore by the buoys WQB-AW and WQB-KN also were significantly different as were all other variables measured offshore by the buoys. In addition, the variables measured at KNO (12-m water temperature, significant wave height, peak wave period, dominant wave direction, and 12-m current speed) were all significantly different between the December and March data sets. The reader is referred to online Supplement Table S1 for the detailed results of our statistical analyses of these data.

DISCUSSION

Using the PacIOOS infrastructure, we have been able to monitor changes in coastal water quality in an urban estuary and its surrounding waters at much higher temporal resolution than was previously practical. Moreover, deployment of the AUV during the March 2009 storm enabled us to better understand the spatial distribution of the runoff plume without the high cost of sampling with a vessel or the inability of satellite imagery to penetrate the cloud cover during critical storm periods. In this report, we focused on the effects of two large Kona storms on coastal water quality. We observed many similarities in the response of the coastal waters to the storms, but also some differences that we attribute to differences in the total amount and the temporal patterns of precipitation. To provide perspective on the relative size of these storms, we note that, according to the *Rainfall-Frequency Atlas of the Hawaiian Islands* (US Department of Commerce Weather Bureau, 1962), 24-hour storms having magnitudes equivalent to those we studied in December 2008 and March 2009 have return periods of two years and one year, respectively.

Despite the relatively small size of the urban watershed feeding our study area (42.5 km^2), freshwater input can be substantial. Using the streamflow data for the Mānoa-Pālolo Drainage Canal, and its estimated contribution to total freshwater flow into the Ala Wai Canal (Fryer, 1995), we calculated that the total surface runoff volume into the Ala Wai Canal during the December 2008 and March 2009 storms would have been around 4.8×10^6 and 2.2×10^6 m^3. In addition, there would be nonpoint source runoff and groundwater from seepage.

Although the 24-hour rainfall, and consequent runoff, from the March storm was lower than that in December (by a factor of two), it was sufficient to reduce salinity at the nearshore sensors in the mouth of the Ala Wai Canal by an equivalent amount. The reduced salinity persisted for a shorter time in March than December (11 vs. 16 hours), most likely a consequence of both lower total rainfall and rainfall over a shorter time period. The wetter antecedent conditions and temporal distribution of rainfall in March resulted in a 16% higher peak streamflow and may explain why a larger, but short-lived, drop in salinity was detected offshore at WQB-AW during the March storm. This larger offshore drop in salinity was not reflected in a corresponding higher turbidity signal, suggesting that the suspended load carried by the streams was not proportional to the streamflow. According to the gauge data, rainfall at MLA and ALO in the week prior to the December storm was 10 times lower than in the week prior to the March storm. It is therefore possible that the drier conditions prior to the December storm resulted in a "first-flush" effect that was absent or reduced for the March storm.

The NS03 sensor, located outside and to the east of the Ala Wai canal, was more exposed to the open ocean than NS01 or NS02, but unlike the water-quality buoys, it is inside the reef. Because of its location, we expected the salinity drop to be smaller at NS03 than at NS01 and NS02, but were surprised that the return to pre-storm values was relatively slower. Salinity was, for example, often below the values at NS01 and NS02 four to six days after the storm. We speculate that groundwater seepage stimulated by rainfall from the

March storm could have contributed to the low salinity signal at this location. Submarine groundwater discharges into the coastal ocean can be significant in Hawaiʻi (Peterson et al. 2009), but we do not know the magnitude of this process in our study area.

Short, but variable, period (≤ 30 min) oscillations in the salinity and turbidity signals were seen at WQB-AW, but were greatly attenuated at WQB-KN. This observation suggests that the meandering of a low-salinity plume originating from the Ala Wai Canal primarily generated the signals at WQB-AW. The attenuated response at WQB-KN may be a result of dilution of this plume, or it may reflect the influence of nonpoint source runoff. Temperature excursions and oscillations were attenuated compared to salinity, especially offshore, presumably as a consequence of the hundredfold greater diffusivity of heat relative to salts.

Rain and associated runoff were key factors affecting the Ala Wai Canal and nearshore ocean waters, but other storm-related factors, namely wind and waves, also affected the coastal ocean. Although the turbidity signals at the water-quality buoys appear to be best explained by suspended particulates in runoff, acoustic scattering measured at Kilo Nalu is better correlated with wave height, suggesting that it was driven by resuspension of bottom material or by bubble injection at the surface. Although winds could contribute to resuspension and bubble injection, the correlation with wind is poor, suggesting that forcing by waves, rather than wind, was primarily responsible.

PacIOOS does not have instrumentation to directly test for pathogens or indicator microorganisms, so we have relied on publicly available data from the State Department of Health monitoring program to provide some insight into the effects of storms on beach water quality. The concentration of *Enterococcus* spp. is an accepted indicator of sewage contamination by the US Environmental Protection Agency (USEPA). It has been shown however, that these bacteria are present and actively growing in soils in tropical and subtropical environments (Byappanahali and Fujioka, 2004; Hardina and Fujioka, 1991). Concentrations of enterococci in streams and coastal waters therefore may be elevated after rainfall even in the absence of sewage contamination. *Clostridium perfringens*, although not yet officially accepted as an indicator of fecal contamination by the USEPA, appears to be a more reliable indicator of fecal contamination in Hawaiʻian waters (Fujioka and Shizumura 1985). Although *C. perfringens* does not grow in the environment, spores of this bacterium can persist for long time periods in previously contaminated soils and sediments (Davies et al., 1995; Desmarais et al., 2002), meaning that concentrations of *C. perfringens* in the water column could increase as a result of resuspended sediments in stormwater runoff. The elevated counts of *C. perfringens* and enterococci following the December, but not the March, storm might, therefore, be caused by the "first flush" effect, as we speculated occurred for turbidity. Nevertheless, we cannot rule out that there was a real difference in sewage contamination during these two storms. The rainfall in December was twice that in March, which could have placed a greater burden on Honolulu's aging and leaky sewer system.

In addition to directly influencing chemical and microbiological water quality, storms can have an indirect influence on the biology of the coastal environment. Most notably, the introduction of nutrients in runoff can stimulate intense plankton blooms in relatively enclosed waters such as Kāneʻohe Bay (Hoover et al. 2006). Despite the openness of Māmala Bay, which leads to high dilution rates of terrestrial runoff (Laws et al. 1999), the very large fluxes of freshwater into the coastal waters from these storms resulted in elevated chlorophyll concentrations within several days after each storm. The total nutrient influx from the December storm was presumably larger than in March because of the larger volume of runoff and a first flush effect. Nevertheless, the chlorophyll response in December appears to be much less dramatic than in March within the first week. This outcome is presumably due to prolonged rainfall, which resulted in persistently high streamflows and a short residence time for nutrients in the canal. We note that the increase in chlorophyll in March began two days after the streamflow had dropped to $< 1\ m^3\ s^{-1}$. Streamflow in December was highly variable after the storm began and was still spiking above $1\ m^3\ s^{-1}$ four to five days after the onset of the storm.

CONCLUSIONS AND FUTURE PROSPECTS

Using PacIOOS infrastructure, we were able to characterize stormwater plumes both temporally and spatially without the high cost of sampling from a vessel or the limitations associated with satellite imagery. We show that even a relatively small, urbanized watershed can have profound effects on the coastal ocean and surrounding beaches and that these effects can last for several days after a storm ends. We also show that chlorophyll concentrations can increase, probably caused by the introduction of nutrient-rich runoff combined with decreasing turbidity as the waters clear after the storm. Although we have not yet had the opportunity to compare an orographic storm with a Kona storm of similar magnitude using the PacIOOS network, previous work (De Carlo et al., 2004, 2007; Ostrander, 2007) indicates that there are significant differences between the two types of storms as reflected in event timing, physical stream and nearshore response, and stream geochemistry.

Since this writing, two new PacIOOS components have come online off south Oʻahu: (1) a high-frequency radar for measuring surface currents along the entire south shore of Oʻahu, and (2) ISUS nitrate sensors on the AW and KN water-quality buoys. With both of these components now fully operational we expect to gain a better understanding of the extent and behavior of the Ala Wai Canal stormwater plume, how it varies in response to different types of storms, and its effects on the nearshore waters and beaches of south Oʻahu. This understanding, combined with our understanding of response times, will go a long way toward establishing a reliable early-warning system for water-quality and health-related problems potentially impacting the beaches of southern Oʻahu, the Hawaiian Islands, and ultimately the US Territories in the Pacific as the PacIOOS network is expanded.

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