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Temporal and Spatial Variability of Freshwater Plumes in a Semienclosed Estuarine–Bay System

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Abstract While the physical forcing mechanisms that govern the outflows of major rivers throughout the world are well documented in the literature, comparably less research has been done to examine the mechanisms that govern the contributions of small rivers and streams to coastal ocean systems. These rivers and streams provide a direct means for the transport of anthropogenic and terrigenous materials from watersheds to coastal oceans. This study describes the temporal and spatial variability of freshwater plumes from Kaneohe Stream, Hawaii, USA, after storm events in the Kaneohe Bay watershed. Freshwater plumes were examined using a combination of fixed moorings, synoptic shipboard surveys, and lagrangian surface drifters. Data sets were collected over the course of 19 months from August 2005 to March 2007 with particular attention paid to storms during the boreal winters. Stream discharge and duration were found to exert a primary control on plume persistence in the southern Kaneohe Bay system. Time series data show a strong coherence between wind forcing and surface currents, which, in combination with data derived from shipboard and aerial surveys, indicate that the spatial variability of freshwater plumes is primarily determined by atmospheric forcing.

Keywords River discharge · Kaneohe Bay · Freshwater · Richardson number · Plume

Introduction

The properties and physical variability of freshwater plumes from major river systems throughout the world have been well documented in the literature (Berdeal et al. 2002; Fong et al. 1997; Geyer et al. 2000; Hitchcock et al. 1997; Huret et al. 2005). However, less attention has been paid to quantifying the physical forcing mechanisms that govern the variability of plumes from small rivers and streams that discharge into coastal ocean systems. Rivers and streams provide the dominant means for storm-derived runoff to enter the coastal ocean. A large fraction of this runoff comes from small, high-relief drainage basins such as the watershed of Kaneohe Bay, Hawaii, USA (Milliman and Syvitski 1992). Drainage from these coastal environments is typically dominated by a steady baseflow constituent, sustained by groundwater discharge (Hoover 2002). However, intense and episodic rainfall events in these watersheds produce flood events of relatively large volume (10^5 m^3) and short duration (<12 h; Tomlinson and DeCarlo 2003). These flood events are of great interest to coastal residents, resource managers, and researchers as they provide a rapid and direct mechanism for the transport of anthropogenic materials into coastal and bay systems (DeCarlo et al. 2004) and collectively have a greater area of influence than larger river systems (Warrick and Fong 2004).

Land use change has dominated the Kaneohe watershed—with the population nearly doubling in the past three decades—driving the annual river discharge to increase by a factor of nearly five (Smith et al. 1981; US Census Bureau 2006). Kaneohe Stream is the largest source of freshwater to the bay and drains an area of highly developed and populated land—leading to the possibility of heavy nutrient and pollutant loads at the outfall site of the stream (Hoover 2002). The insurgence of people into the area, the develop-

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ment of the Kaneohe Bay watershed, and the associated possibility of heavy pollutant and nutrient shedding from the land have necessitated a careful examination of the impacts of human expansion on the Kaneohe Bay ecosystem.

Stream inputs to Kaneohe Bay have been examined in detail in recent years from both biological and geochemical standpoints (DeCarlo et al. 2007; Fagan and Mackenzie 2007; Hoover et al. 2006; Ringuet and Mackenzie 2005; Scheinberg 2004)—however, there has been no focused and consistent sampling to provide a physical oceanographic description of the freshwater outflows. The work presented herein aims not only to quantify the point source inputs of freshwater to the Kaneohe Bay ecosystem, but to describe how the stream inputs interact with the ambient bay water. Specifically, we aim to elucidate the physical mechanisms that drive the spatial and temporal evolution of freshwater plumes from Kaneohe Stream after intense rainfall events in the Kaneohe watershed.

Location and Setting

Kaneohe Bay is a semienclosed estuarine–bay system located on the northeast coast of Oahu (Fig. 1) and is the largest sheltered body of water in the Hawaiian Islands. The southern portion of the bay, the area considered for this study, has a surface area of 8.37 km^2 and a mean depth of ~10 m (Bathen 1968; Smith et al. 1981). Past studies have estimated the residence time of the basin in the range of 5–13 days (Bathen 1968; Smith et al. 1981; Steinhilper 1970). The annual precipitation in the Kaneohe Bay watershed ranges from less than 100 cm to as high as 350 cm, with a long-term mean of nearly 200 cm (Giambelluca et al. 1986). Nearly three fourths of the total runoff entering the southern basin enters through Kaneohe Stream. The mean discharge (~0.20 m^3 s^{-1}) of Kaneohe Stream peaks (>0.45 m^3 s^{-1}) during periods of high precipitation in boreal winter/spring. The drainage basin of Kaneohe Stream covers a surface of 9.9 km^2 and enters the bay through a narrow manmade channel (<15 m width; Hoover 2002). Tides are mixed with semidiurnal dominance and microtidal (<2 m). Tides enter the south bay as a bore, and tidal currents in the narrow channels can be greater than 30 cm s^{-1} over brief periods of time (<1 h). Wind forcing on the system is produced mainly by northeast trade winds generated by a semipermanent high-pressure system located north of the Hawaiian Islands. While the trade wind locus of generation is 45°, from the northeast, predominant local winds in Kaneohe can range from 0 to 135° because of the topographic steering of the rugged island terrain (Kimmerer et al. 1982) and interaction with the diurnal sea breeze (Presto et al. 2006). The seasonal passage of large low-pressure winter storms to the north of the islands (Kona Lows) during boreal winter can shut down the predominant trade winds and cause periodic shifts in the wind to southerly (Giambelluca et al. 1986).

General Circulation Patterns

Bathen (1968) showed that the bathymetry of the Kaneohe Bay system has a controlling effect on its general circulation patterns. The existence of large reef areas restricts the flow from the open ocean and serves to further isolate the southern portion of the system—leading to a higher residence time than the rest of the bay. Changes in tidal height force currents along the major axes of the two channels that allow for exchange with the outer bay and open ocean. The strength and direction of these currents was found to generally be dependent upon the tidal cycle and direction of wind forcing. Recent work by Lowe et al. (2006) has shown that flow in the main Kaneohe Bay basin is also affected by incoming wave set up over the numerous reef areas. The southern basin of Kaneohe Bay is effectively isolated from the influence of incoming waves and oceanic swell and is likely not directly affected by this forcing mechanism (Lowe et al. 2006). The system is subject to persistent wind forcing—modeling and observation studies have shown surface currents respond to this wind forcing throughout the basin (Hearn 1999; Kimmerer et al. 1982; Smith et al. 1981).

Data

This study examines the temporal and spatial variability of the motion of freshwater plumes derived from Kaneohe Stream using fixed moorings, synoptic shipboard surveys, and lagrangian drifters. Data were collected over a period of ~19 months between August 2005 and March 2007 with particular attention paid to storm events during the boreal winters.

Time Series Data

One upward-looking RD Instruments 600 kHz Acoustic Doppler Current Profiler (ADCP) was deployed over two 4-month periods at the locations marked in Fig. 1. Measurements of current velocity in three dimensions and acoustic backscatter intensity were made at 1-m intervals from 2 m above the bed to the surface. The ADCP averaged 50 pings every 10 min and provided observations of current magnitude and direction as well as backscatter at 13–15 different elevations above the substrate (Table 1).

Three Onset Computer temperature/pressure sensors (HOBO, U20) were deployed at locations marked in Fig. 1 during the 2006–2007 boreal winter to examine the effects of wind and tidal forcing on the height of the water

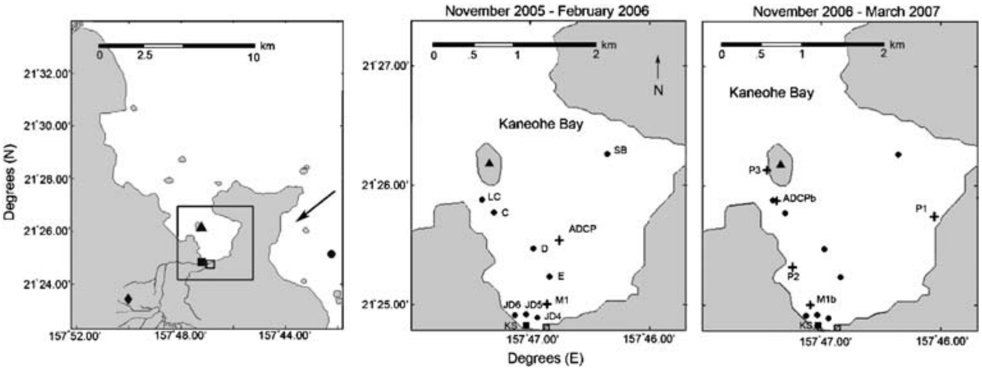


Fig. 1 The *left panel* shows Kaneohe Bay and surrounding area including: watershed rain gage location at Luluku (*filled diamond*), Kaneohe Stream (*filled square*) and Kawa Stream (*empty square*) outflows, Coconut Island wind station (*filled triangle*), and Coastal Information Data Program wave buoy location (*filled circle*). The Southern Kaneohe Bay study area is outlined in *black*. Synoptic sampling and mooring locations in Southern Kaneohe Bay for November 2005–February 2006 and November 2006–March 2007 are shown in *center* and *right panels*. Bimonthly survey locations were constant throughout the study and are indicated by *filled circles*. *Crosses* represent mooring locations. Nortek and SBE-37SM locations are denoted by the prefix *M* and temperature/pressure sensors by the prefix *P*. The National Oceanic and Atmospheric Administration CO_2 buoy is located at station C

column. The sensors were calibrated by the manufacturer before deployment and were programmed to sample at 10-min intervals (Table 1).

One Nortek AS current meter (Aquadopp 3D with Aquafin) was deployed over two 4-month periods inline with a thermistor chain. In addition to current measurements of undisturbed flow, the Aquadopp measured temperature, pressure, tilt, and heading at a depth of 2 m and had a sampling interval of 10 min (Table 1).

Meteorological measurements including local precipitation, air temperature, water temperature, wind direction, and wind speed were recorded hourly at the Hawaii Institute of Marine Biology located on Coconut Island (Fig. 1). Precipitation measurements in the watershed were obtained at 15-min intervals from the Luluku station of the US Geological Survey (USGS). Hourly tidal data were obtained from the National Oceanic and Atmospheric Administration (NOAA) station at Coconut Island (ID no. 1612480).

One Onset Computer temperature/pressure sensors (HOBO, U20) were deployed at the mouth of Kawa Stream from August 2006 to March 2007. Two additional temperature/pressure sensors were deployed at established USGS measurement locations in Kapunahala and Kamooalii Stream. These two streams are the constituent members that join to form Kaneohe Stream. The sensors measured pressure and temperature at 10-min intervals (Table 1). Pressure data were used in conjunction with established USGS rating curves to calculate baseflow and storm discharge rates. An additional pressure sensor was deployed at an elevation of 4 m at Coconut Island to obtain a record of barometric pressure for correction of the data from the stream sensors.

Time series of salinity and temperature were obtained from sensors on the University of Hawaii/Pacific Marine Environmental Laboratory's (NOAA/PMEL) CRIMP/CO_2 Buoy (SBE, Model 37SM). The buoy was placed in service in December 2005 and was deployed throughout the duration of the study. Temperature and salinity were measured at 1 m depth every 3 h. An additional SBE 37-SM was deployed near the Kaneohe Stream mouth at location M1b (Fig. 1) during a 4-month period spanning November 2006 to March 2007 and measured the water column at 0.1 m depth every 10 min.

Table 1 Names, instrument types, depths (below surface), and sampling periods for moorings deployed from November 2005 to February 2006 and November 2006 to March 2007

Mooring name	Instrument type(s)	Depth(s) (m)	Sample period (min)
November 2005–February 2006			
M1	Current Meter (Nortek)	2	10
ADCP	Current Meter (ADCP)	13	10
November 2006–March 2007			
M1b	Current Meter (Nortek)	2	10
	Salinity/temperature	0.1	10
P1	Pressure/temperature	10	10
P2	Pressure/temperature	7	10
P3	Pressure/temperature	2	10
ADCPb	Current Meter (ADCP)	17	10

Significant wave height, dominant period, direction, and surface ocean temperature outside the mouth of the bay were obtained from the Scripps Institution of Oceanography Coastal Data Information Program buoy located 6.5 km southeast of Mokapu Point (Fig. 1).

Shipboard Survey Data

Shipboard surveys were conducted under two different regimes: (1) *Nonstorm*—to verify the reported current patterns and establish the mean water properties during nonstorm conditions and (2) *Storm*—to describe the physical effects of freshwater discharge on the circulation patterns of the southern Bay system, as well as quantify the physical processes controlling plume motion and persistence.

Nonstorm

Nonstorm surveys of water column properties were conducted using a Yellow Springs Instruments multiparameter sonde (YSI, Model 6600). Vertical profiles of temperature and salinity were taken synoptically at the stations in Fig. 1 bimonthly over the course of 19 months. The sonde was fitted with external buoyancy control to ensure its separation from shipboard movement (after McManus et al. 2003). The sonde had a decent rate of ~0.10 cm s^{-1} and a sampling interval of 2 s providing 0.02-m resolution in the vertical. Salinity was calibrated before each deployment using standards prepared according to protocols provided by the manufacturer. The calibration of the sonde was verified postdeployment using the predeployment standards. Temperature and salinity were also verified against the measurements of the moored SBE 37-SM at the CRIMP/CO_2 buoy.

Storm

Storm surveys were conducted after significant rainfall in the Kaneohe watershed. After the convention established by previous studies in the bay, the rainfall threshold was set at 5.1 cm of precipitation at Luluku station in the preceding 24-h period (Fagan and Mackenzie 2007, Ringuet and Mackenzie 2005). Vertical profiles were taken with the sonde at the same stations occupied during nonstorm surveys on days 1, 2, and 3 after the initial rainfall event. Additional profiles were taken along the boundaries of the low-salinity plume to increase spatial resolution in the area of strongest salinity gradients.

The shipboard determination of the spatial extent of plumes was complemented with aerial reconnaissance in a Robinson R22 light helicopter. Overflights were used to identify and verify the location of plumes and to provide a platform from which high-resolution photographs were taken.

Lagrangian Drifter Surveys

Five CODE/Davis-style surface drifters manufactured by Brightwaters Instrument (Model 110) were used to examine the temperature and motion of the surface water in Kaneohe Bay. The drifters recorded their global positioning system (GPS) location and measured water temperature every minute. Drifter GPS measurements were verified against shipboard measurements and locations transmitted by Service Argos.

A total of 45 separate deployments over a range of flood, ebb, spring, and neap tidal cycles as well as trade (northeasterly) and Kona (southerly) wind conditions were conducted in the south and central portions of Kaneohe Bay to analyze both storm and nonstorm motion of surface water. Drifter and wind headings were averaged into 1-h bins, and the data from each deployment in the southern portion of the Bay were used to examine the relationship between wind forcing and water response.

Materials and Methods

Influence of Coriolis Acceleration on the System

The influence of rotation on the motion of freshwater plumes in the system was examined by calculating the Rossby deformation radius (R) for each plume examined. R is responsive to the depth of the plume, and twice the order of R provides a length scale at which the consideration of rotational effects becomes as important as buoyant forces on the system (Hill 1998). For a two-layer system in which a stream of uniform density discharges into a receiving body of uniform density, R is given by:

$$R = \frac{\left(\left(\frac{g\,\Delta\rho}{\rho}\right)h\right)^{\frac{1}{2}}}{f} \tag{1}$$

where ρ is the density of the receiving waters, $\Delta\rho$ is the density difference in the two-layer system, h is the depth of the plume, and f is the Coriolis parameter (Wiseman and Garvine 1995).

Potential and Kinetic Energy Contributions to the System

The contribution of potential energy to the system (E_{m}) by the buoyant stream outflow was calculated using:

$$E_{\mathrm{m}} = \frac{h}{2}\,\Delta\rho \mathrm{Q}_{\mathrm{f}} Tg \tag{2}$$

where h is the tidal average stream depth, $\Delta\rho$ is the density difference between outflow and receiving waters, Q_{f} is the river discharge, T is the tidal period, and g is the gravitational acceleration (Savenije 2005). The kinetic energy imparted to the system by tidal currents (E_t):

$$E_{\mathrm{t}} = \frac{1}{2}\rho A_0 E_0 v_0^2 \tag{3}$$

where ρ is the average density of the system, A_0 is the cross-section area of the estuary mouth, E_0 is the tidal excursion, and v_0 is the amplitude of the tidal flow at the estuary mouth (Savenije 2005).

The ratio between the two contributions of energy was examined using the Estuarine Richardson (N_{r}) as adapted from Fischer et al. (1979) and Savenije (2005).

The Estuarine Richardson number is a useful tool in examining temporally intermittent stratified systems—a large N_{r} (>0.8) signals a strongly stratified system, while a small N_{r} (<0.08) is characteristic of well-mixed systems. N_{r} is defined as:

$$N_{\mathrm{r}} = \frac{E_{\mathrm{m}}}{E_{\mathrm{t}}} = \frac{\Delta\rho}{\rho} \times \frac{gh}{v^2} \times \frac{\mathrm{Q_f}t}{P_t} \tag{4}$$

where t is time period and P_t is the flood volume per unit time.

Data Processing

All raw data were downloaded and initially processed using the product-specific software provided by each manufacturer. Additional processing was done using codes from the USGS SEA-MAT toolbox. Principal tidal constituents were calculated using harmonic analysis as described in Pawlowicz et al. (2002). Data were divided into two 56-day subwindows with a 50% overlap, detrended using a linear fit to each subwindow, and multiplied by a Hanning window to compute coherence and phase spectra. Statistical significance in coherence was calculated with the Goodman formula using the same methods as Drake et al. (2005), Harris (1978), and Thompson (1979). Coastline data for figures were obtained from the NOAA National Geophysical Data Center. All data analyses and plotting were done using Matlab v7.0.4.

Plume Identification

Both salinity and temperature were examined as markers for freshwater plumes; however, salinity proved to be the best indicator of water masses because of the high contrast in ocean (~35.0) and stream water (0.0) and the large diurnal and seasonal variations in stream water temperature. The boundaries of plume events were determined from vertical sonde casts, aerial overfights, and high-spatial-resolution discrete samples of surface water salinity.

Results and Discussion

Numerous theoretical, observational, and modeling studies have examined the forcing mechanisms that dictate the temporal and spatial variability of freshwater plumes in the coastal ocean (Fong and Geyer 2001; Garvine 1987; Piñones et al. 2005; Washburn et al. 2003; Yankovsky and Chapman 1997). These studies have shown that plumes are responsive to: (1) the flow rate and duration of the discharge, (2) acceleration because of Coriolis forcing, (3) tidal forcing, and (4) wind magnitude and direction. Coriolis acceleration does not limit the progression of plumes in southern Kaneohe Bay, as the width of the basin is less than twice the calculated Rossby deformation radius (R; see Eq. 1) for all plumes surveyed. As such, rotational effects are not considered for this study. It is necessary, however, to examine the response of freshwater signals in the basin to the local physical forcing contributed by the stream flow rate and duration, tidal forcing, and wind magnitude and direction to determine which local forcing mechanisms drive temporal and spatial variability of freshwater plumes.

The interdependence of these physical forcing parameters was examined using a suite of moorings deployed from November 2006 to March 2007. A representative time series of the measured parameters is shown in Fig. 2.

Effects of Stream Flow and Tidal Forcing

The Estuarine Richardson number is a measure of the ratio of buoyant to shear forces in the system and is an indicator of conditions that are favorable for the formation of stratification in the water column. Surface measurements of salinity can also be used to infer periods of stratification, as depressed salinity values near the stream mouth indicate the presence of a freshwater plume. As such, a strong correlation between the persistence of surface salinity in the moored record, and the calculated N_{r} would indicate that plumes coincide with periods of theoretical stratification. Furthermore, a strong correlation would indicate that the system responds to both stream flow and tidal forcing—the two constituents that comprise the N_{r} calculation—under the range of represented physical conditions. The lack of such a relationship indicates that occurrence of freshwater plumes in the southern basin of Kaneohe Bay is temporally independent of ideally stratified conditions. This implies that one of the constituent physical forcing mechanisms comprising the Estuarine Richardson number—tidal or stream flow—may not be strongly affecting variability in the persistence of freshwater signals in the near-shore surface waters.

Cross-correlation between the calculated value of N_{r} and salinity for the 4-month deployment period spanning

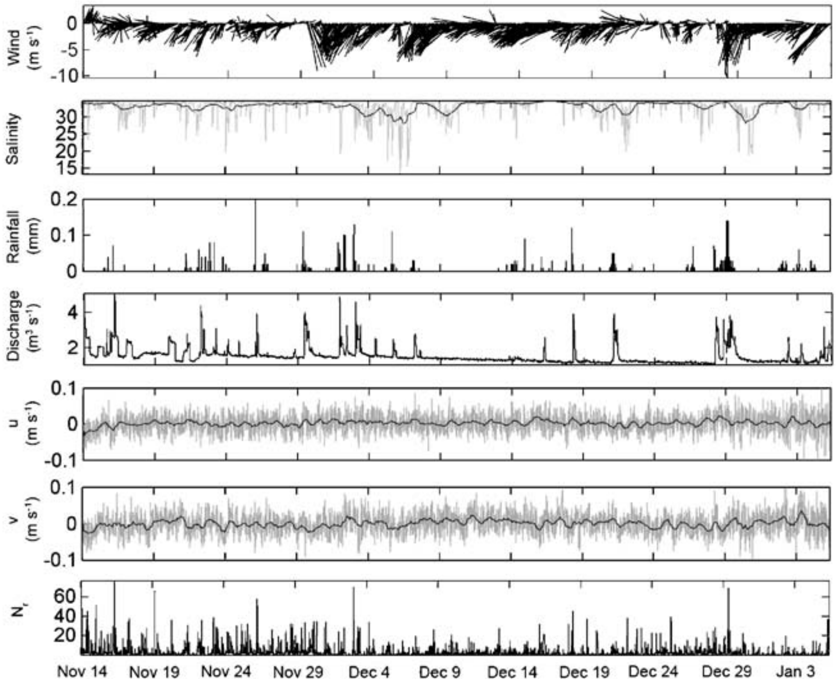


Fig. 2 Time series from 14 November 2006–5 January 2007 of 1-h wind averages at Coconut Island; measured surface salinity (*light*) and smoothed salinity (*dark*); rainfall measured in 15-min increments at Luluku station; combined stream discharge of Kaneohe and Kawa streams; measured (*light*) and low-pass filtered (*dark*) meridional currents below salinity sensor at location M1b; measured (*light*) and low-pass filtered (*dark*) zonal currents measured at same location; Estuarine Richardson number calculated from data at 10-min intervals. Salinity data was filtered using a forward- and backward-moving average filter with a 1-h window—current data was filtered using the same method with a 12-h window

November 2006 to March 2007 showed a significant, although very weak, correlation at a 4-h time lag (Fig. 3). This weak relationship between N_r and surface salinity indicates that the presence of freshwater plumes may occur independently of periods where conditions are best suited for the establishment of stratification—necessitating a more careful examination of the deterministic roles stream discharge and tidal forcing play in plume dynamics.

Effects of Stream Flow on Salinity

Cross-correlations between the measured stream flow at both Kaneohe and Kawa streams and the measured surface salinity over the length of the deployment showed a strong negative correlation at 24 h for Kaneohe Stream and 26 h for Kawa Stream (Fig. 3). This indicates that approximately 1 day after a peak in stream flow, the strongest low-salinity signal was detected at station M1b (Fig. 1).

Tidal Effects on Salinity and Currents

The stage of the tide had no detectable effect on the salinity signal in the study region. Calculated coherence and phase spectra between water level and salinity show no coherence at any frequency between the two signals (Fig. 4).

To explore the influence of tides on currents in the study region, coherence and phase spectra were calculated over the course of the deployment period. High, significant coherence between water level and zonal currents was seen at 0.181 cycles per hour (cph; 5.5-h period) and a phase of ~20° (Fig. 4). This frequency is outside the diurnal and semidiurnal band and, when compared to the calculated tidal constituents (Table 2), failed to match significant constituent peaks. This 5.5-h period is consistent with intermittent forcing because of wind fluctuations, and its effect on water level and currents will be discussed in the next section. Significant coherence between water level and meridional currents was seen in the diurnal band at 0.0414 cph (24.1-h period) and a phase of ~100° (Fig. 4). This is suggests an ebbing tidal flow 6 h after a high tide produces a northward flow in the system.

Effects of Wind Velocity on the System

The influence of wind velocity on currents was analyzed using coherence and phase spectra. High coherence between winds and current magnitudes in the zonal directions was seen at 0.130 and 0.190 cph (7.7- and 5.3-h periods; Fig. 4). High coherence was also seen between winds and currents in meridional directions at 0.130

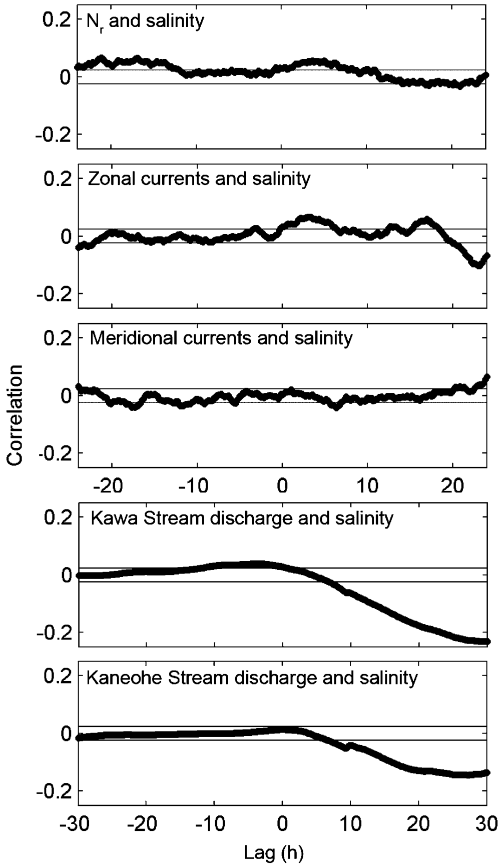


Fig. 3 Cross-correlation of N_r and salinity, zonal currents and salinity, meridional currents and salinity, Kaneohe discharge and salinity, and Kawa discharge and salinity. Lags for discharge and salinity panels are shown to 30 h. *Solid lines* represent upper and lower 95% confidence levels

(7.7-h period) and 0.177 cph (5.6-h period; Fig. 4). These results indicate that episodic storm-scale fluctuations in both zonal and meridional winds with periods of 5–8 h caused corresponding fluctuations in the current motion of the basin at the same frequencies. There was no significant coherence between wind and current velocities in the diurnal band, indicating that variations in wind velocity caused by diurnal sea breezes did not effect current motions and plume variability.

Both zonal and meridional winds were also found to be significantly coherent with water level at 0.194 and 0.181 cph, respectively (5.2- and 5.5-h periods; Fig. 4) with a phase of nearly ~100°. This suggests that winds to the northeast cause sea-level setup, while trade winds cause sea-level setdown inside the bay. As this frequency range is not represented in the calculated tidal frequencies and is not inherent in the tidal harmonics, the variability measured in the water level must be imparted from a source other than known tidal forcing mechanisms—in this system, that forcing comes from the variability in the wind. The strong out-of-phase coherence between water level and winds and between winds and currents in the period range of 5–6 h (~0.170 to ~0.190 cph), as well as the calculated phase lag in the diurnal component of the tide and meridional currents, suggests that wind forcing at this frequency significantly affects the depth of the water column as well as imparts energy to drive current motion in the system. This excitation of currents in the system because of wind influence appears to be more important in determining flow patterns near the surface than does the influence of the tide and is consistent with drifter circulation studies performed throughout the whole of the Kaneohe Bay system.

The relationship between the wind-driven currents and salinity near the river outflow was examined by cross-correlating the time series from the whole of the deployment record. A positive correlation peak was seen between zonal currents and salinity at a lag of 4 h, while a negative correlation was seen with meridional currents and surface salinity at a lag of 6 h (Fig. 3). This suggests that currents moving toward the northwest transport low salinity water from the stream mouth through the study area with a minimum salinity reached 4–6 h after the current onset, while currents moving to the south and east transport water unaffected by stream flow from outside the study area.

Lagrangian Drifter Surveys

Trade winds dominated the conditions during the study period, with wind headings from 20 to 100° occurring 76% of the time. Winds from the south (135–225°) were measured during 8% of the days surveyed, while variable winds from the remaining directions occurred 16% of the time. Drifter surveys were conducted during southerly, trade, and variable wind conditions, and surface water response was consistently inline with the wind forcing under each wind scenario. The correlation between drifter and wind heading for all deployments was strong ($r=0.968$) and significant ($p<0.0001$; Fig. 5). This implies that the surface water of southern Kaneohe Bay responds directly to the forcing of the wind, moving along the heading of the wind under all possible wind headings.

Horizontal and Vertical Plume Structure

Horizontal and vertical distributions of salinity in a freshwater plume were examined during the period of 27–30 September, 2006, after significant rainfall (66 mm) in the preceding 24 h. The peak discharge of Kapunahala Stream (a constituent of Kaneohe Stream) was 0.61 $m^3 s^{-1}$ on the 26th of September and had returned to baseflow conditions by the 30th of September. Weak trade winds were persistent during the survey period and ranged from 3 to 7 $m s^{-1}$.

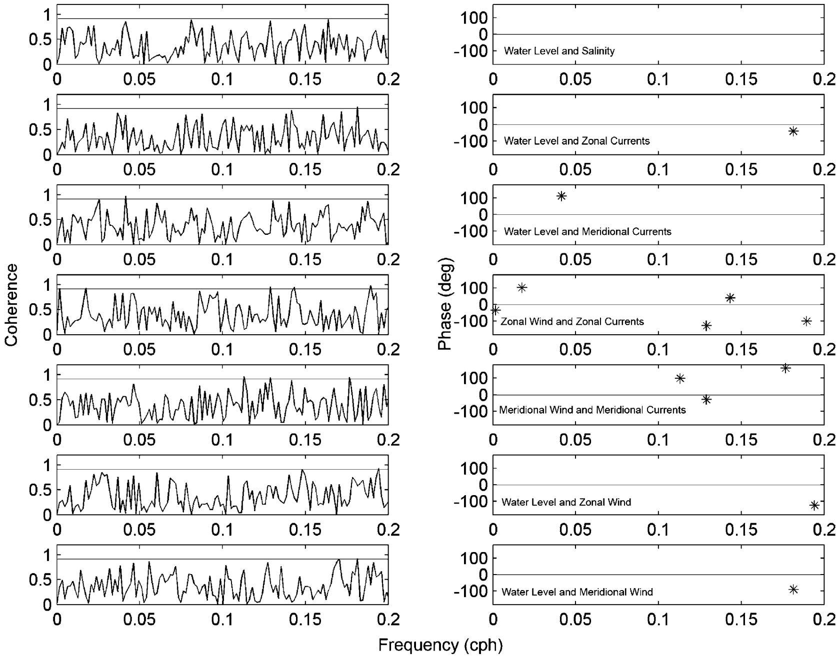


Fig. 4 Coherence (*left panels*) and phase spectra (*right panels*) between: water level and salinity, water level and zonal currents, water level and meridional currents, zonal wind and zonal currents, meridional wind and meridional currents, water level and zonal wind, and water level and meridional wind. *Solid line* in coherence plots represents 95% confidence level calculated using the Goodman formula (Drake et al. 2005; Harris 1978; Thompson 1979). Only coherence values above the confidence level are shown in phase spectra plots

The rainfall pulse on the 26th of September produced a distinct freshwater plume emanating from the Kaneohe Stream mouth. The maximum offshore extent of the plume was 0.3 km and occurred on September 29th—coinciding with a minimum in the onshore wind magnitude (see Table 3). The maximum alongshore extent of the plume was 1.5 km and was held constant during the 4 days the plume was measured. Onshore easterly winds (3–7 m s^{-1}) during the survey period confined the surface plume to a position near the shoreline (Figs. 6 and 7).

The September 2006 plume was characterized by sharp horizontal and vertical gradients. Surface salinity near the mouth of the stream (station JD6) dropped from 35.0 to 19.7 after rainfall but was 35.0 just 0.8 km from the stream mouth (Station E). The vertical influence of the freshwater water plume was confined to the top 1 m of the water column both near the stream mouth and along the mixing edge (Fig. 6).

Plume Evolution

The evolution of the freshwater plume from Kaneohe stream was examined during three daily shipboard surveys

Table 2 Names, amplitudes, and periods of calculated significant tidal constituents in southern Kaneohe Bay

Component name	Amplitude (m)	Period (h)
Q1	0.018	26.87
O1	0.103	25.82
NO1	0.012	24.83
P1	0.058	24.07
K1	0.174	23.93
J1	0.013	23.10
N2	0.035	12.66
M2	0.152	12.42
S2	0.075	12.00
K2	0.021	11.97

Diurnal and semidiurnal components were the only tidal periods found to be statistically significant in this study.

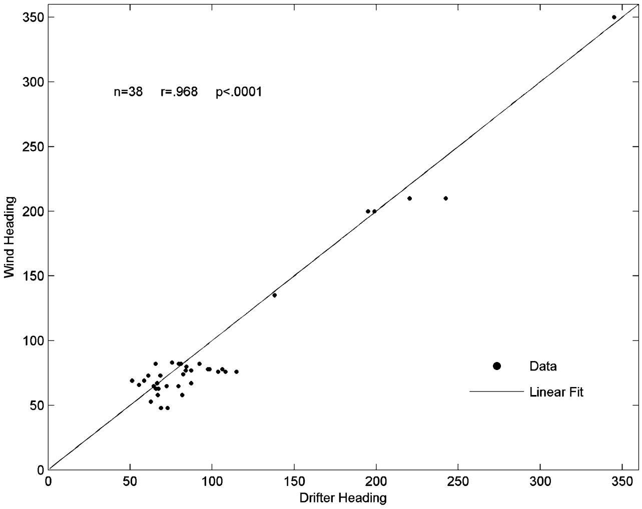


Fig. 5 Correlation of drifter and wind heading from data collected in southern Kaneohe Bay. Data represented by the *black circles* are from 38 separate deployments of the surface drifters over the course of the 19-month study. Correlation coefficient (r) and level of significance (p) were calculated from the *solid line* representing a linear fit

Table 3 Daily precipitation, stream discharge, plume extent, and wind characteristics during field survey periods

Date	Precipitation (mm)	Kapunahala Stream discharge		Wind		Plume extent	
		Average ($m^3 s^{-1}$)	Peak ($m^3 s^{-1}$)	Magnitude ($m s^{-1}$)	Direction (°)	Offshore (km)	Alongshore (m)
27 September	Trace	0.53	0.56	5.5	67	N/A	N/A
28 September	0	0.52	0.53	6.3	68	0.2	1.5
29 September	Trace	0.52	0.53	3.8	52	0.3	1.5
30 September	Trace	0.52	0.52	5.5	66	0.27	1.5

Discharge data for Kapunahala Stream is shown—data for the whole of Kaneohe Stream was not available because of instrument tampering. Location of rain gage and wind station is shown in Fig. 1. Plume extents are shown in Figs. 6 and 7. Wind characteristics listed are scalar means.

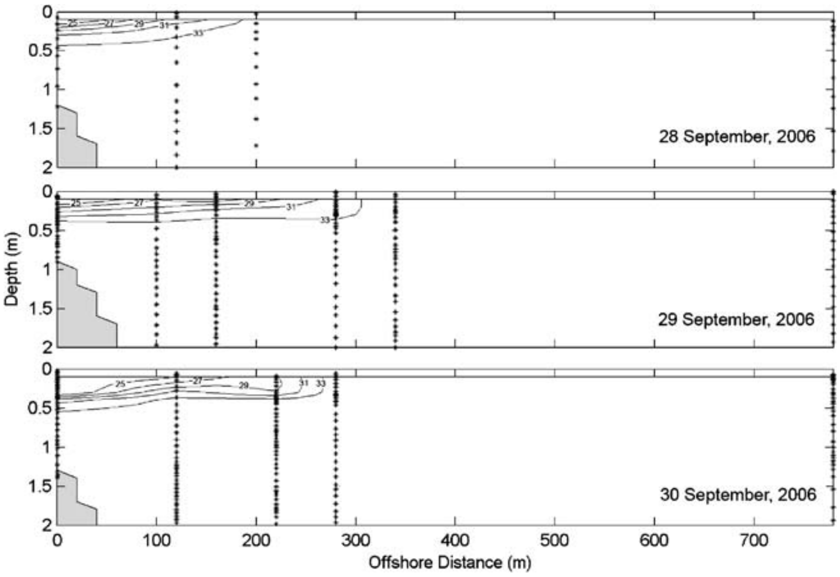
from 28 to 30 September, 2006. The discharge from the stream mouth was nearly constant at 0.52 $m^3 s^{-1}$ during the 3-day survey period. Tides during the survey period were diurnal, and the maximum range was 0.5 m. Precipitation during the survey period was trace to nonexistent.

On September 28, the plume at Kaneohe Stream reached 0.2 km offshore (Fig. 7) at the southernmost transect and 1.5 km alongshore to the northwest of the stream mouth. Minimum salinities in the plume were ~19.7, while salinity outside the plume was oceanic (~35.0). The wind on September 28 was northeasterly and had an average magnitude of 6.3 m s^{-1}. On September 29, the plume extended 0.3 km offshore (Fig. 7) and had a maximum alongshore extent of 1.5 km. The alongshore distribution of the plume was unchanged from the previous day, while the plume's offshore extent increased by 100 m. This offshore excursion coincided with a decrease in the wind magnitude to 3.8 m s^{-1}, while the origin of the wind remained northeasterly. Salinity values inside the plume reached a minimum of ~19.3, while salinity outside the plume was again nearly constant at 35.0. By September 30, winds had regained strength and were from the northeast at 5.5 m s^{-1}. The plume on the 30th had advected slightly back toward shore and had a maximum offshore extent of 0.27 km (Fig. 7). The alongshore extent again remained unchanged at 1.5 km. Salinities in the plume reached a minimum of 22.4, while salinity in the bay was oceanic (~35.0).

Conclusions

River discharge is the primary avenue for the transport of terrigenous material and anthropogenic inputs from the continents to the world's oceans. While the physical variability of large river plumes greatly impacted by large coastal population centers has been well documented in the literature; relatively little attention has been paid to describing the physical forcing mechanisms that govern the dynamics of small river plumes discharging into coastal environments. Works by Devlin et al. (2001) and Gaston

Fig. 6 Vertical sections of salinity in southern Kaneohe Bay, Hawaii for 28 September, 29 September, and 30 September, 2006. *Black crosses* in panels indicate location of measured salinity. Zero offshore distance represents the mouth of Kaneohe Stream as shown in Fig. 7



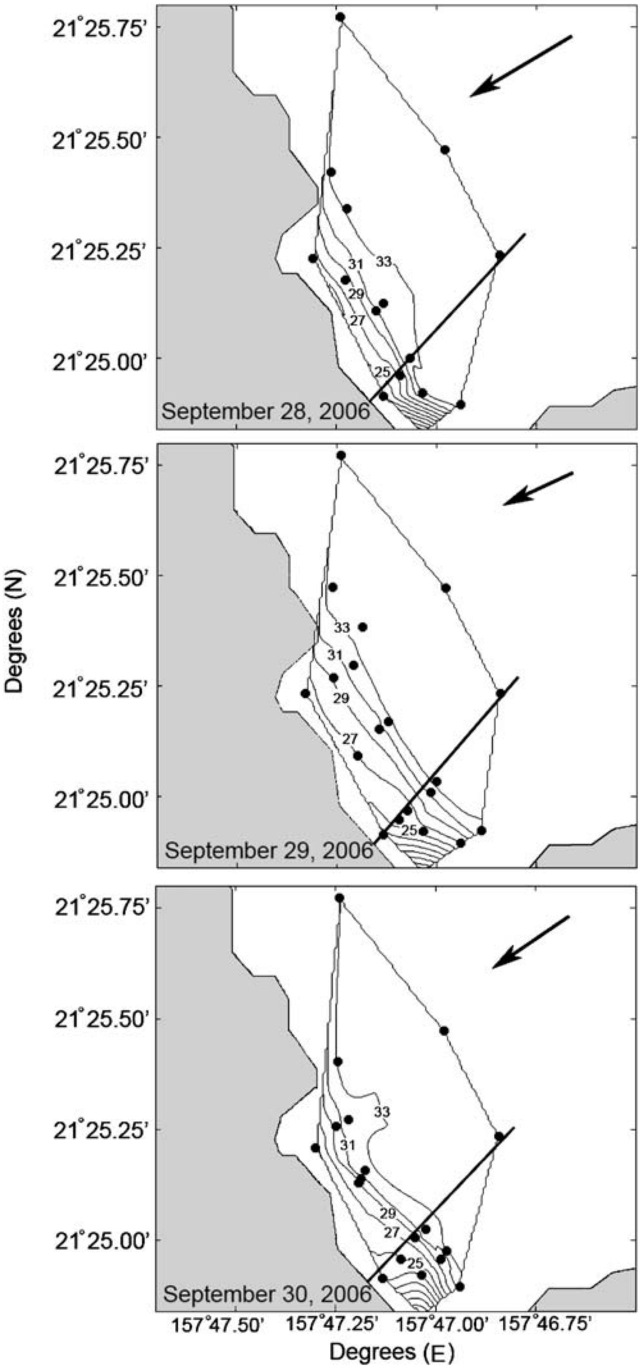


Fig. 7 Surface salinity contours in southern Kaneohe Bay, Hawaii for 28 September, 29 September, and 30 September, 2006. *Arrows* in panels indicate wind direction and average magnitude during time of shipboard survey. *Filled circles* indicate location of high-resolution vertical profiles. *Dark bar* through study area indicates the location of the vertical transect depicted in Fig. 6

et al. (2006) have shown that the size and physical variability of small river plumes from coastal systems is primarily governed by wind regimes and river discharge. However, the systems described by Devlin et al. (2001) and Gaston et al. (2006), while similar to the scale of discharge in Kaneohe Bay, occurred over the continental shelf of the ocean—not in a semienclosed basin. While the systems might respond similarly to physical forcing, a close examination of the possible forcing mechanisms is necessary to substantiate this assumption.

The consistent and predictable response of the surface waters of the south bay to the drifter releases over the 19-month duration of this study and the spatial response of the September 2006 freshwater plume to changes in wind forcing are consistent with the results of Kimmerer et al. (1982) who found that the spatial persistence of buoyant effluent plumes from sewage outfalls near Kaneohe Stream in the south bay was governed by the strength and persistence of onshore wind stress. This onshore wind stress is instrumental in creating opposition to the pressure gradient force of the lower-density spreading surface layer and can be the primary agent in preventing the horizontal spreading and mixing of freshwater discharge. In addition to the drifter and plume response, the influence of this wind stress can be seen again in the strong coherence over a range of frequencies between current magnitude and direction and wind magnitude.

The lack of coherence between salinity fluctuations and water level at diurnal and semidiurnal frequencies indicates that tidal variations did not have a significant impact on plume dynamics. The tidal range of the system is very small, and tidal currents near the stream mouth are weak (<10 cm s^{-1}) both in the horizontal and vertical planes. The lack of a tidal correspondence to salinity and the correlation between wind-driven currents and the persistence of salinity near the stream mouth indicate that spatial dimensions of freshwater plumes emanating from Kaneohe stream are largely controlled by wind forcing. According to the characteristics observed in this study and the theory of plume advection put forth by Yankovsky and Chapman (1997), plumes emanating from Kaneohe stream are most likely "pure surface-advected plumes." A plume of this nature will respond readily to changes in forcing direction—observations in Kaneohe showed a clear response in surface currents and plume motion to changes in wind forcing. A plume of this nature will also depend heavily on stream discharge to supply it with the low-salinity water that affords its existence. The strong correlation between both stream outflows and the persistence of freshwater in the system implies that the temporal persistence of the plume under consistent physical forcing is largely controlled by the stream discharge. These results are consistent with other examinations of microtidal systems in Europe and the Americas (Forget et al. 2001; Piñones et al. 2005; Washburn et al. 2003), which found that wind and stream discharge comprise the main influences on the dynamics of freshwater plumes in coastal systems.

This study provides an initial examination of the physical forcing mechanisms that govern freshwater plume variability in southern Kaneohe Bay, Hawaii. To understand the full range of physical variability associated with freshwater plumes in this system, additional research is needed to determine the processes leading to the eventual fine-scale mixing of the plume and its advection out of the study area.

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