



Internal tide effects on a sewage plume at Sand Island, Hawaii

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Abstract

The variability in the vertical position of a sewage plume, far from its point of discharge, is described and explained by the forcing from an internal tide. The sewage plume, discharged from the Sand Island treatment plant in the coastal waters of Mamala Bay, Oahu, Hawaii, was mapped using ship-board towed observations collected during September 25 – October 1, 1994. Horizontal currents and temperature were measured in 1994–1995 at moorings located throughout Mamala Bay. Data at mooring D2, located close to the diffuser, suggested that the presence of an internal tide of 18 km wavelength propagating along the isobaths at speed 0.4 m s^{-1} was responsible for large (more than half the total depth) semi-diurnal vertical displacements of the isotherms. Comparison of the vertical far-field plume position and isotherm displacements at the mooring showed that the horizontal propagation of the internal tide was westward along the isobaths. These data challenge the classical view of a sewage plume “established” at a constant depth of equilibrium and are the first example showing the effects of internal tides on sewage plumes. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

An interdisciplinary study of point source and non-point source pollutants was undertaken in 1994–1995 in Mamala Bay, Oahu, Hawaii in order to track the origin of contaminants detected on nearby tourist beaches. Mamala Bay is located on the

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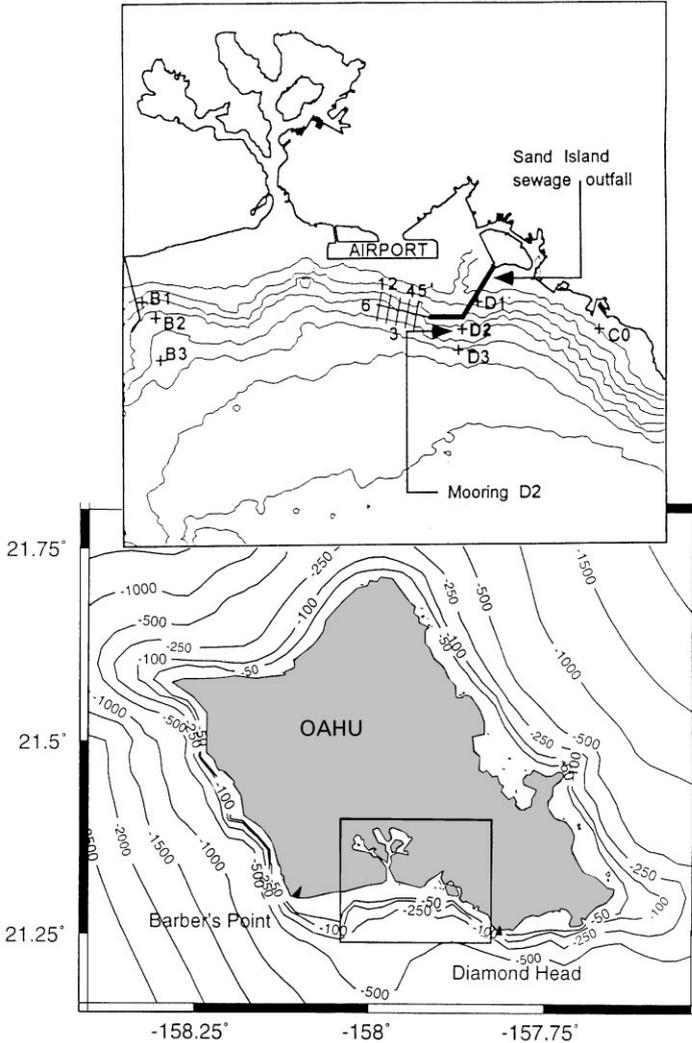


Fig. 1. The bottom map is the map of Oahu, Hawaii. Mamala Bay extends from Barber's Point (west) to Diamond Head (east). The oceanic region in the box corresponds to the study area, shown in more detail in the upper map. SAIC moorings (B1, B2, B3, C0, D1, D2, D3) are indicated by crosses. Mooring D2 and the Sand Island sewage outfall are in bold. Cross-shelf sections 1–5 correspond respectively to: (1) towoy 12; (2) towoy 26; (3) towoys 11 and 18; (4) towoys 2 and 30; (5) towoys 3, 17, and 32. Section 6 corresponds to the along-shore towoys 20 and 27. Isobaths are shown at 15, 25, 50, 100, 200, 300, 400, and 500 m.

south side of Oahu island between two headlands, Diamond Head to the east and Barber's Point to the west (Fig. 1). The sewage plume from the Sand Island Treatment Plant (SITP) was considered a potential contributor to pollution detected on the local beaches. The data forming the basis of the present study were collected for the purpose of detecting the plume and understanding its dynamics.

1.1. Circulation

Circulation in Mamala Bay was more complex than expected. Strong and opposed M2 tide currents were observed at the two headlands (Hamilton, 1996). Large internal M2 temperature fluctuations characteristic of the passage of internal tides were observed in the depth range of the thermocline (Petrenko, 1997). The M2 tide coming from the northeast Pacific is split by the island and merges east of Barbers Point. Hamilton (1996) proposed that the sinking and rising of the water column at the center of Mamala Bay (caused by the alternating convergence and divergence of the along-isobath M2 tidal currents) generates the observed internal tides.

Two subinertial Island Trapped Waves (ITWs) of periods 1.5 and 2 days (at the latitude of the bay, the inertial period is 33 h) have previously been observed around Oahu (Luther, 1985). Numerical simulations have indicated vertical displacements of up to 16 m for subinertial ITWs generated by direct wind forcing around the larger island of Hawaii (Lumpkin, 1995). Different ITW amplitudes would be expected around Oahu since it is smaller and its topography is different from Hawaii's; however, it is likely that non-negligible vertical displacements would also be associated with subinertial ITWs around Oahu.

1.2. Sand Island effluent plume

SITP is a primary treatment plant discharging treated waters at an average rate of $2.84 \times 10^5 \text{ m}^3 \text{ day}^{-1}$. The effluent multiport diffuser is located 4 km offshore in 70 m of water. The SITP wastewater is positively buoyant compared to ambient waters. The discharged wastewater rises as a buoyant plume, idealized as a line source of buoyancy (Koh and Brooks, 1975). The dominant processes affecting discharged plumes differ with distance away from the diffuser. In the near-field region, buoyancy processes are dominant. Dilution increases the density of the wastewater which stabilizes at its equilibrium depth, either in the water column where its density matches surrounding density, or at the surface if it remains positively buoyant relative to ambient waters. At the end of the "near-field" region, the plume reaches its equilibrium depth. The near-field behavior of the SITP sewage plume is described elsewhere (Petrenko et al., 1998). The equilibrium depth depends on the wastewater specific buoyancy flux, the stratification of the water column, and local currents. Since the plume specific buoyancy flux was approximately constant when the present data were collected (late morning or afternoon; wastewater flow around $3.8 \text{ m}^3 \text{ s}^{-1}$), temporal variations in the plume equilibrium depth were affected primarily by water column stratification and currents. In the "far-field" region, the bulk of the plume is considered "established" at its equilibrium depth, and affected only by ocean currents and diffusion.

During the cruise, the vertical position of the far-field plume was observed at depths different than its expected depth of equilibrium. Although far-field plumes are supposed to be characterized by their equilibrium depth, they reside along isopycnal surfaces. Displacements of isopycnal surfaces could also displace the plume. This hypothesis was tested by comparing the far-field plume vertical displacements with

the vertical oscillations of isotherm surfaces at a nearby mooring, and by checking the isotherm–isopycnal relationship. This study confirmed the previous hypothesis and also allowed us to gain further understanding of the physical processes taking place at this coastal site.

2. Materials and methods

2.1. Mooring data

Moorings (Science Applications International Corporation, SAIC) were positioned at chosen locations in the bay to provide continuous data (Fig. 1). Mooring D2, located just south of the center of the outfall diffuser, included a taut wire moored Aanderaa thermistor string and a bottom-mounted (75 m), 300 kHz upward-looking acoustic Doppler current profiler (ADCP). Thermistors were spaced at 5 m intervals between 13 and 63 m, and horizontal current measurements were binned at 2 m intervals from 7–65 m. These variables were sampled at 30 min intervals. Details about the other moorings can be found elsewhere (Hamilton et al., 1995).

It was assumed that the D2 isotherm displacements reflected vertical motions of water parcels. Vertical mooring displacements due to horizontal currents were likely smaller than 1 m for the horizontal currents observed at D2 (about 40 cm s^{-1}). Larger isotherm displacements were observed at another mooring in the bay where the currents were much weaker (Hamilton et al., 1995), so the displacements observed at this mooring could not have been artifacts of mooring displacements.

Power spectra for temperature and current measurements were calculated by fast Fourier transforms (FFTs), using the Welch method of power spectrum estimation, for a four-month period (June 5–October 18, 1994). Spectral estimates were $\frac{1}{2}$ overlapped and tapered with a Gaussian window (Oppenheim and Schaffer, 1975). The semi-diurnal components of horizontal velocity data were calculated using a narrow-pass ($1.3 \times 10^{-3} \text{ Hz}$ full-width half-power) square cosine filter centered on the semi-diurnal frequency. The baroclinic component of this band-passed current data was isolated by subtracting the mean velocity of the vertical profile.

The theory of internal waves for two-layer flows over a flat bottom was used in order to calculate the solution for an internal semi-diurnal tide progressing horizontally along the x -axis at the interface between two layers of constant Brunt-Väisälä frequencies (N). In this case, the dispersion relation is (Leblond and Myzak, 1978):

$$\operatorname{tg}\left(\frac{kN_1}{\sqrt{\omega^2 - f^2}} h_1\right) + \frac{N_1}{N_2} \operatorname{tg}\left(\frac{kN_2}{\sqrt{\omega^2 - f^2}} h_2\right) = 0,$$

where k is the horizontal component of the wavenumber, and ω is the frequency. Depths of the upper and lower layer were $h_1 = 35$ and $h_2 = 40$ m. Density profiles were linearly approximated in each layer so that the Brunt-Väisälä frequencies were $N_1 = 0.008 \text{ s}^{-1}$ in the upper layer and $N_2 = 0.019 \text{ s}^{-1}$ in the lower layer. A Matlab

Table 1

Subset of towyos (T), with their respective date and time of acquisition, towyo type, and alongshore distance to the middle of the diffuser (Fig. 1). Plume depths (variable for the alongshore towyos, and hence not indicated) correspond to the depth of either the maximum concentration of the plume or the plume vertical range

Towyo	Date	Time	Type of towyo	Distance (km)	Plume depth (m)
T2	Sept. 25	3 pm	Cross-shelf	1.5	45–68
T3	Sept. 25	4 : 15 pm	Cross-shelf	1.0	55–70
T11	Sept. 26	8 : 00 pm	Cross-shelf	2.0	65
T12	Sept. 26	8 : 55 pm	Cross-shelf	3.0	75
T17	Sept. 27	2 : 35 pm	Cross-shelf	1.0	58
T18	Sept. 27	3 : 10 pm	Cross-shelf	2.0	52
T20	Sept. 27	4 : 40–5 : 25 pm	Alongshore	3.5–0.5	—
T26	Sept. 28	4 : 25 pm	Cross-shelf	2.5	67
T27	Sept. 28	4 : 45–5 : 30 pm	Alongshore	2.5–0	—
T30	Oct. 1	10 : 15 am	Cross-shelf	1.5	45–55
T32	Oct. 1	11 : 20 am	Cross-shelf	1.0	42–50

routine (courtesy M. Gregg) was also used to find the vertical modes in the case of a flat-bottomed ocean, given a measured density profile and its latitude.

2.2. Towyo data

A cruise to characterize the plume dynamics took place during September 25 – October 1, 1994 on the research vessel (R/V) *Kila* (University of Hawaii). Towyo transects were obtained by winching the platform between the surface and the bottom as the ship moved forward at a speed of 1–1.5 m s⁻¹, resulting in a depth-varying sawtooth pattern with horizontal resolution of approximately 250 m at mid-depth and vertical resolution of at least 0.5 m. Towyos were done on a grid pattern around the diffuser with cross-shelf towyos done at either 500 m or 1 km intervals along the coast and along-shore towyos generally following the 70 m isobath (Fig. 1; Table 1). The instrumented platform carried conductivity, temperature and pressure sensors (CTD, Sea-Bird Electronics model SBE 9/11 +), a beam transmissometer (660 nm wavelength, 0.25 m pathlength, Sea Tech, Inc.) (Bartz et al., 1978). Salinity, temperature, depth, density anomaly, beam attenuation at 660 nm (c660) were derived from these in situ measurements. The towyo data were used to map the location of the wastewater plume determined by its signature of low salinity and high c660 (Petrenko et al., 1997). The mooring data could not be used to detect the presence of the sewage plume since the ambient variability in temperature was higher than the variability of temperature associated with the effluent; moreover during the cruise the sewage plume was found westward of the diffuser and hence would not have passed by the mooring located south of the diffuser.

3. Results

3.1. Oceanographic conditions

Time series of temperature and horizontal velocity at the D2 mooring exhibited strong variability. At all depths, the main peak in currents and temperature energy density spectra occurred at the semi-diurnal frequency (Fig. 2). Less prominent peaks were present at periods including 24 h (K1 tide), 17, 8–9 and about 6 h (M4 tides).

During the beginning of the study period (09/25–09/28), the water column was divided in roughly two layers (upper layer 35 m; lower layer 40 m) of approximately constant Brunt-Väisälä frequencies (Fig. 3B). In both layers, alongshore currents dominated. In the shallow layer, currents were westward or eastward alternatively every 6 h approximately, while currents in the deeper layer were generally westward. The baroclinic semi-diurnal component of horizontal velocities exhibited alternation of westward and eastward currents approximately every 6 h, and opposition of

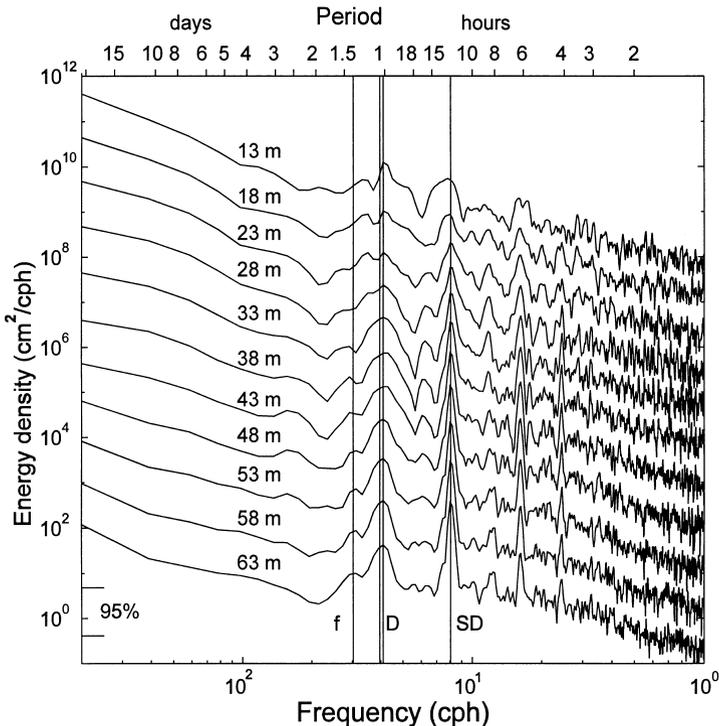


Fig. 2. Energy spectra for temperature measured at mooring D2. For ease of comparison, only the energy spectral scale for 63 m is shown. The other spectra are displaced by an order of magnitude from their lower neighbor. Inertial (f), diurnal (D), and semi-diurnal (SD) frequencies are indicated. The 95% confidence level is shown. Horizontal axis is labeled in frequency (bottom), and corresponding period (top).

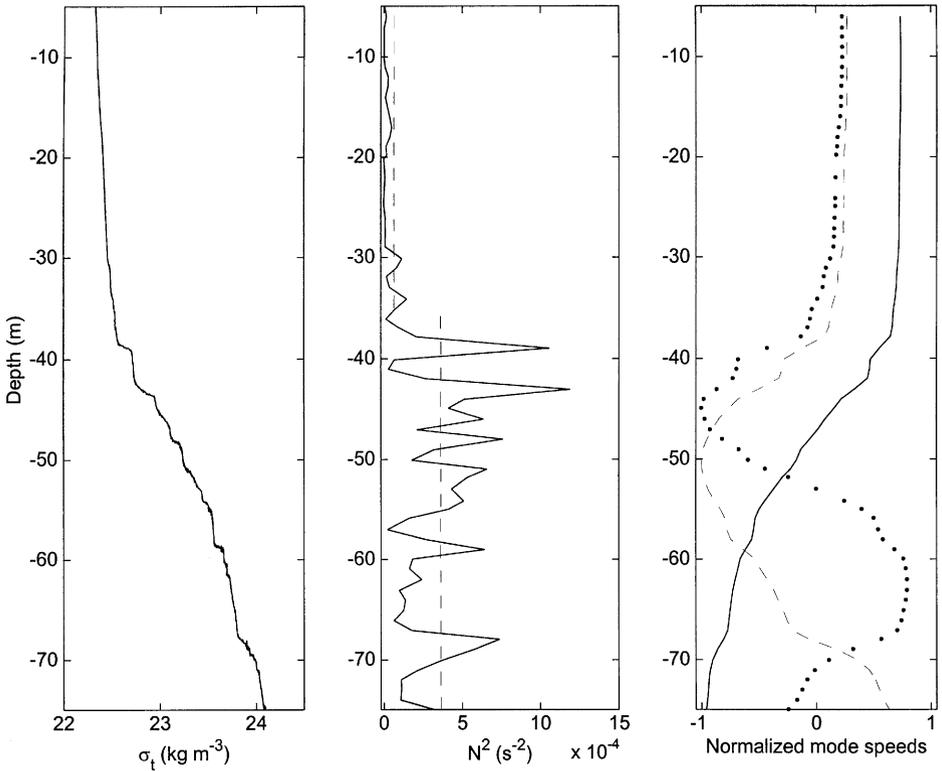


Fig. 3. (A) Typical density anomaly profile outside the plume during the first part of the cruise; (B) corresponding N^2 profile (N_1^2 and N_2^2 are indicated in dashed lines); (C) normalized mode speeds (for the first three modes).

currents above and below the thermocline, both characteristic of semi-diurnal internal tides (Fig. 4). The baroclinic semi-diurnal velocity vectors rotated in a counter-clockwise phase polarity. Resolving the dispersion relation for two-layer internal waves provided a first mode eigensolution: $k = 3.4 \times 10^{-4} \text{ rad m}^{-1}$ for $\omega = 1.4 \times 10^{-4} \text{ rad s}^{-1}$ (semi-diurnal M2 frequency). This corresponded to a semi-diurnal wave of phase speed 0.41 m s^{-1} and wavelength 18.4 km. The first eigenmode calculated with the realistic density profiles gave a wave speed of 0.43 m s^{-1} confirming the validity of the above simplistic two-layer approach (Fig. 3C). Sensitivity analyses did not lead to significant differences in these numerical solutions.

3.2. Plume positions and isotherm motions

At depth at mooring D2, large variations in temperature had an approximately 13-h period (Fig. 5B). Vertical displacements were calculated based on these isotherm displacements. The largest vertical displacements occurred within the thermocline and

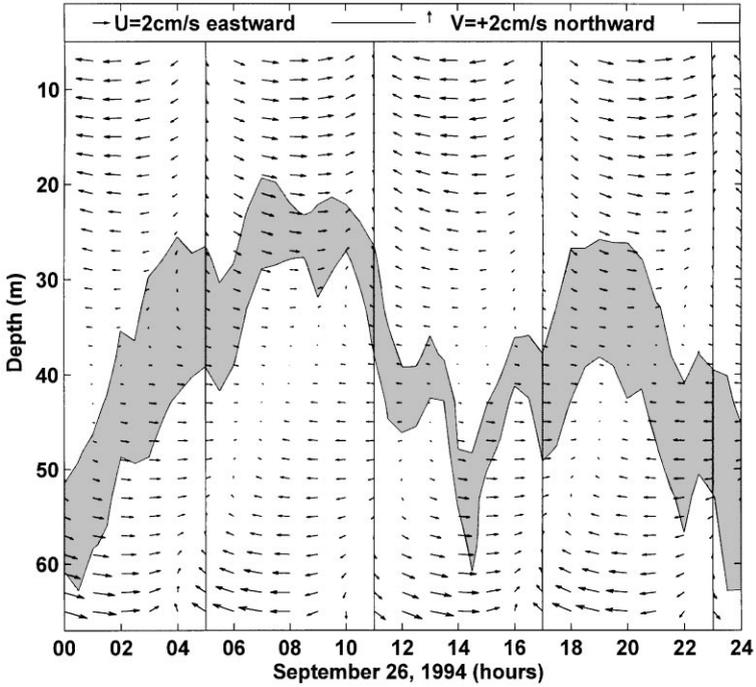


Fig. 4. Baroclinic component of the semi-diurnal horizontal velocities at the mooring D2 on September 26, 1994. The interval between the 26 and 27°C isotherms is shaded.

vanished in the quasi-homogeneous upper layer. For example, in the night of September 25–26, the drop in temperature of 4°C detected at 63 m over a 10-h period (Fig. 5C) coincided with a rise of the 26.7°C isotherm of 40 m (from 65 m depth to 15 m). If the magnitude of this displacement is considered as twice the amplitude of the semi-diurnal internal tide, the amplitude of the internal tide was, in this case, 20 m. More commonly, the amplitude of the internal tide was of the order of 15 m. Further offshore at the D3 mooring, the amplitude of the internal tide was as large as 75 m (data not shown).

A linear relation was obtained between density anomaly, σ_t , and temperature, T , measured outside the wastewater plume throughout the cruise ($\sigma_t = -0.43 T + 34.22$, $r^2 = 0.997$), indicating that temperature variations dominated the density signal. The T/S relation calculated from seasonal CTD casts also showed very little scatter (Hamilton et al., 1995). Therefore, isotherms correspond very closely to isopycnal surfaces.

The variability in the vertical position of the far-field plume was examined between far-field cross-shelf towys (located from 1–3.5 km west of mooring D2) for the five days when towyo mapping was performed (Table 1). This vertical variability was then compared with the concurrent D2 isotherm motions. The investigation was limited to the far-field component of the plume since the rising plume and momentum-driven

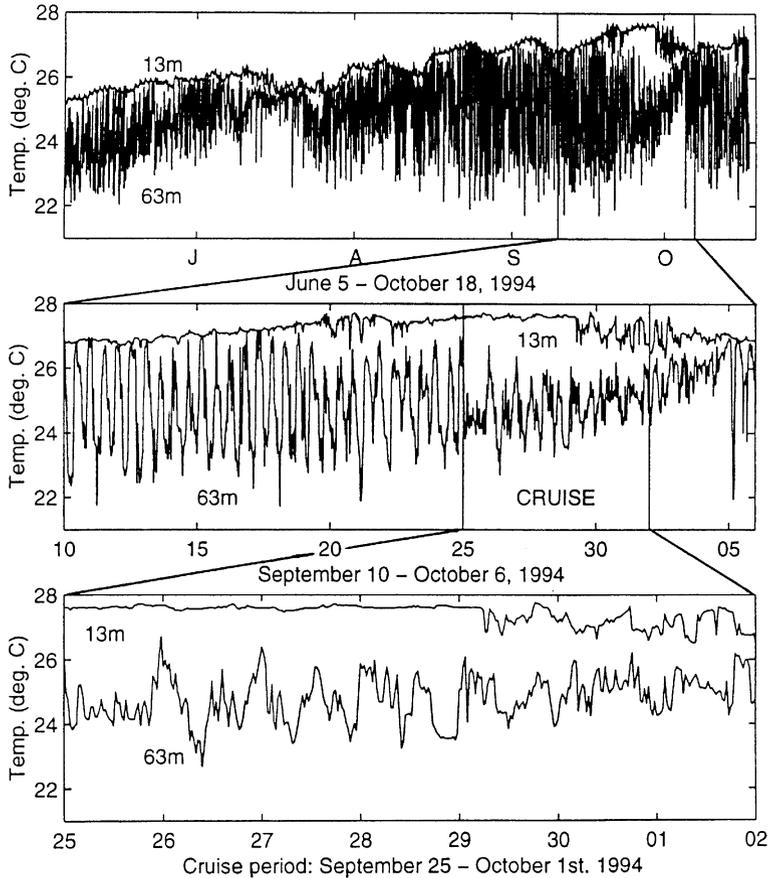


Fig. 5. Time series of temperature at 13 and 63 m collected at D2 mooring: (A) from June 5 to October 18, 1994, (B) from September 10–October 6, 1994 and (C) during the cruise from September 25–October 1, 1994.

overshooting produce local distortions of the density field. The plume and the isotherms shoaled, respectively, between T17 and T18 on September 27, between T26 and T27 on September 28 (Table 1; Fig. 6), and between T30 and T32 on October 01. The plume and the isotherms deepened between T2 and T3 on September 25, and between T11 and T12 on September 26. Hence the far-field plume followed the isotherm displacements measured at mooring D2, which are, as demonstrated above, equivalent to isopycnal motions.

3.3. Deduction from the spatial and temporal variability of the plume

The previous section showed excellent agreement between isotherm displacements and variability in plume depth. The isotherm data were collected at mooring D2 and

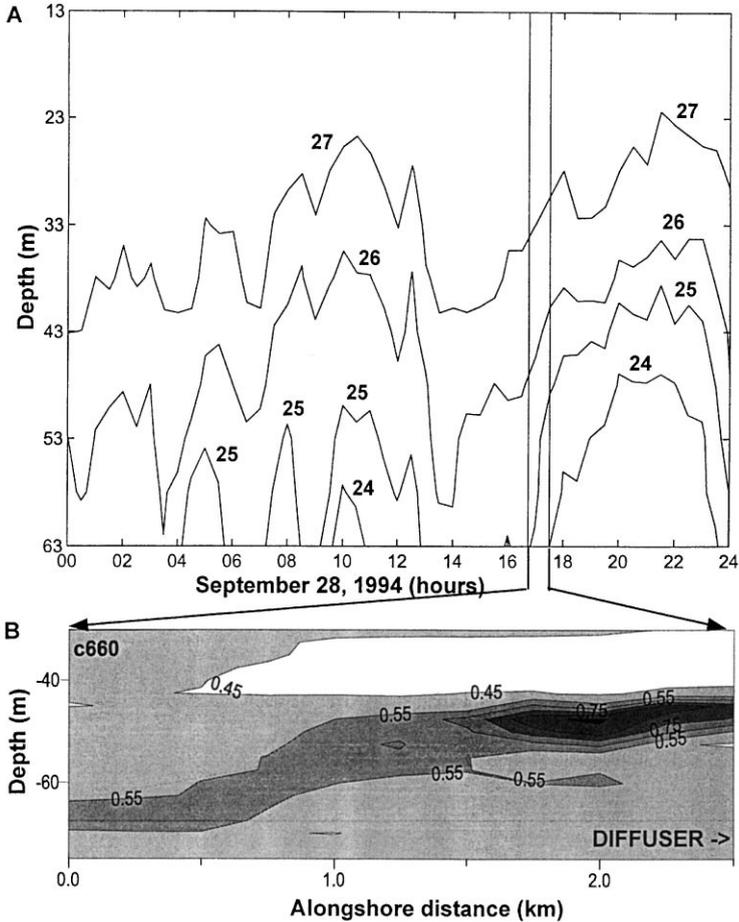


Fig. 6. (A) Isotherms (at 1°C intervals) at mooring D2 on September 28, 1994; (B) section of c660 contours (at 0.1 m^{-1} intervals) for along-shore towyo 27, collected between the times indicated by arrows.

were used to interpret the motions of the plume detected in the far-field region, at a distance ranging from 1–3 km from mooring D2. Including spatial information on the plume shape provides additional information on the physical processes taking place at this coastal site. If the plume deepens with distance west from the diffuser, two cases are possible: (1) if the D2 isotherms are rising, the horizontal propagation of the semi-diurnal internal tide is westward; (2) eastward, if the D2 isotherms are falling. The opposite results are found if the plume shoals with distance west from the diffuser. The along-shore towyos provided the best data for examining the spatial configuration of the plume. During the cruise, three alongshore towyos were done (towyo 13, 20 and 27); only towyos 20 and 27 were used since, during towyo 13, the plume position and isotherm motions did not vary monotonically and hence could not be

correlated. The far-field plume of along-shore towyo 20 rose in the water column with distance west of the diffuser; during the collection of that towyo, the isotherms at mooring D2 deepened. The far-field plume of along-shore towyo 27 deepened with distance west from the diffuser, while the isotherms at D2 rose (Fig. 6). Both cases show that the horizontal component of the semi-diurnal internal tide was westward.

4. Discussion

The Sand Island wastewater plume was shown to follow the vertical displacements of isopycnals generated by a semi-diurnal internal tide propagating alongshore. These data challenge the classical view of a sewage plume “established” at a constant depth of equilibrium and are the first example showing the effects of internal tides on sewage plumes. Spectral EOF analysis of the temperature data collected at the moorings throughout Mamala Bay suggested the presence of a Kelvin-like wave, of phase speed 0.8 m s^{-1} and wavelength 35 km, propagating westward (Hamilton et al., 1995). The phase speed and wavelength of the first baroclinic mode presented in this paper were half the magnitude of the Kelvin wave. The difference is attributed to the fact that Hamilton’s calculations assumed deeper depths. Due to the location of the D2 mooring just at the edge of the slope (Fig. 1), waves from deeper waters could easily influence water motions at the D2 mooring site.

Semi-diurnal internal tides with amplitudes up to 70 m were previously observed at 2.8 km off the leeward side of Oahu, where the water depth is 220 m (Düing, 1969). In the present study, the maximum amplitude observed was 20 m at D2 (75 m deep) and 75 m at D3 (250 m deep). The temperature oscillations were not pure sinusoids as their crests were flattened (Fig. 5C). This phenomenon was first observed by LaFond (1961), who distinguished two cases: flattened crests when the thermocline is shallow, and peaked crests when the thermocline is deep. In this study, the flattening of the crests is indeed linked with a shallow seasonal thermocline (about 35 m depth). Another interesting feature of the isotherm oscillations observed at mooring D2 was their asymmetry. The rate of temperature increase (descending isotherms) was greater than the rate of decrease (rising isotherms) (Fig. 5B and C). Düing (1969) observed this feature and described it as resulting from non-linear waves. This explanation seems appropriate at the D2 mooring site since shoaling of internal tides could be taking place at the top of the continental slope. This may also explain the presence of secondary M4 peaks in the energy spectra (Fig. 2) caused by non-linear interactions.

The baroclinic semi-diurnal velocity vectors unexpectedly rotated in a counter-clockwise (CCW) phase polarity since a clockwise rotation is normally characteristic of internal tides in the northern hemisphere (Levine and Richman, 1989). In fact, the hodographs of the semi-diurnal tide themselves rotated CCW (Hamilton et al., 1995). Some reversals from clockwise to CCW rotation of tidal ellipses have been observed at the transition to the bottom boundary (Marchuk and Kagan, 1984), but these boundary layers are typically about 10–15 m thick. However, at the Mamala Bay site this phenomenon was also observed at the surface. Uncertainties in the harmonic analysis of the small onshore/offshore current component could give rise to a spurious

CCW rotation, but this error is unlikely since the hodographs rotated the same way at all depths and since CCW tidal rotations were also observed elsewhere around Oahu (Lumpkin, 1995). Interactions with the steep topography complicated by the potential presence of other internal waves could be responsible for these CCW rotations.

Temperature density spectra exhibited a distinct peak at about 16–17 h between 29 and 43 m (Fig. 2), which could correspond to the low azimuthal order propagating wave of period 17 h previously found in Oahu sea-level spectra (Lumpkin, 1995). Such narrowband, superinertial oscillations are poorly understood. It seems that they are not accompanied by significant currents in contrast to their subinertial counterparts (Luther, 1995). Various hypotheses including pseudo-resonant scattering of internal waves (Wunsch, 1972), harmonics of lower frequency motion, and wave trapping by refraction on a steeply sloping island (Lumpkin, 1995) have been suggested to explain these superinertial oscillations. Both subinertial and superinertial processes may contribute, in addition to the influence of the semi-diurnal internal tide, to the vertical position of the wastewater plume in the water column.

Regardless of their origins, the vertical isopycnal (isothermal) oscillations have a strong influence on the plume's position within the water column. Omission of processes contributing to vertical isopycnal displacements may account for the discrepancies sometimes found between results of plume modeling and in situ observations. Models of plume dynamics around Mamala Bay should include alongshore internal tide forcing mechanisms in order to provide accurate predictions of sewage plume fates.

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