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Cross-Shelf Transport at Huntington Beach. Implications for the Fate of Sewage Discharged through an Offshore Ocean Outfall

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In this study, we evaluate the potential for internal tides to transport wastewater effluent from the Orange County Sanitation District (OCSD) ocean outfall toward Huntington Beach. Results of plume tracking studies show that OCSD effluent occasionally moves shoreward into water less than 20 m deep. Analyses of current and temperature observations indicate cold water is regularly advected cross-shelf, in to and out of the nearshore, at both semi-diurnal and diurnal frequencies. Isotherms typically associated with the waste field near the outfall are observed just outside the Huntington Beach surf zone, where the total depth is less than 6 m, highlighting the extent of the cross-shelf transport. This advection is attributed to a mode 1 internal motion, or internal tide. On the basis of the analyses presented here, the OCSD plume cannot be ruled out as a contributor to poor bathing-water quality at Huntington Beach.

Introduction

Ocean outfalls are used by coastal communities to dispose of municipal wastewater. To reduce shoreward transport of waste and minimize human health impacts, outfalls are designed to dilute the waste stream roughly 100 fold and promote its submergence at a neutrally buoyant level in the water column. During months when the water column is well-stratified, the waste field resides in relatively cold, dense water at the base of the pycnocline that, in the absence of upwelling, is viewed by designers as a lid that prevents transport to the sea surface (*1*). During months when the water column is weakly stratified, and during upwelling events, dilution is the most important design criterion as the waste field is anticipated to reach the sea surface.

Several oceanographic studies conducted over the past decade have documented cases where the pycnocline does not serve as a transport barrier (*2*−*5*). Transport in these studies has been attributed to cross-shelf advection caused by tidal oscillations in isopycnal surfaces, or internal tides (*6*). These findings raise the possibility that waste fields from ocean outfalls are also susceptible to cross-shelf advection by internal tides as has been cautioned by Pineda (*3*).

Water quality in the Huntington Beach surf zone, located directly shoreward of the Orange County Sanitation District (OCSD) wastewater outfall, has frequently exceeded bathing water standards for fecal indicator bacteria in recent years. Sources of indicator bacteria have been identified, such as urban runoff and avian fecal matter, but it is difficult to explain the observed spatial and temporal variability based on these sources (*7*). It is not clear whether OCSD effluent also contributes indicator bacteria to the surf zone. On the basis of historical surveys conducted by OCSD, the effluent plume has been reported to move predominantly along the isobaths in either the upcoast or downcoast directions (*8*). However, another modeling study predicted that, during several months of the year, “the plume can be present close to the shoreline, in water less than 10−20 m deep” (*9*).

In this paper, we present results of recent plume tracking studies that point to significant variability in plume transport, and more specifically, occasional onshore transport into water less than 20 m deep. Subsequently, we evaluate whether a persistent mechanism exists, such as internal tides, that can account for the observed onshore movement of the plume. To characterize cross-shelf transport, we focus on the movement of cold water in to and out of the nearshore. This is done primarily for two reasons. First, unlike biological plume indicators (e.g., fecal bacteria), it is relatively easy to record spatially and temporally intensive measurements of temperature and currents over periods ranging from days to years, making it possible to characterize variability at time scales ranging from hours to seasons. Second, the OCSD waste field is present in relatively cold water (*8*), as will be shown in the Results and Discussion section. Hence, the onshore transport of cold isotherms raises the possibility that biological pollutants are transported onshore as well, though the presence of cold water in the nearshore does not necessarily imply the presence of the plume.

The oceanographic observations discussed in this study were recorded by Science Applications International Corporation and Moffatt & Nichol Engineers under contracts from OCSD and the City of Huntington Beach, respectively, and by OCSD. These data were shared with the authors for the present study.

Field Site Description

San Pedro shelf, shown in Figure 1, is located in the Southern California Bight, off the coast of northern Orange County. OCSD discharges treated municipal sewage near the southeastern edge of the shelf, just north of Newport submarine canyon and offshore of Huntington Beach. Approximately 10^6 m^3/d of primary and advanced secondary treated sewage is released through an outfall diffuser that is approximately 7.5 km offshore in 60 m of water. The diffuser achieves a dilution in the range of 100:1 to 300:1. The resulting waste field is characterized by salinity depressions of less than 0.2 ppt, increases in total coliform bacteria up to 1.1×10^5 most probable number (MPN)/100 mL, increases in fecal coliform bacteria up to 5.5×10^4 MPN/100 mL, and increases in *Enterococcus* bacteria up to 1.5×10^3 MPN/100 mL (*10*).

Materials and Methods

Plume Tracking. Plume-tracking studies were conducted in May and November of 2000. On May 9, 18, and 30, 2000,

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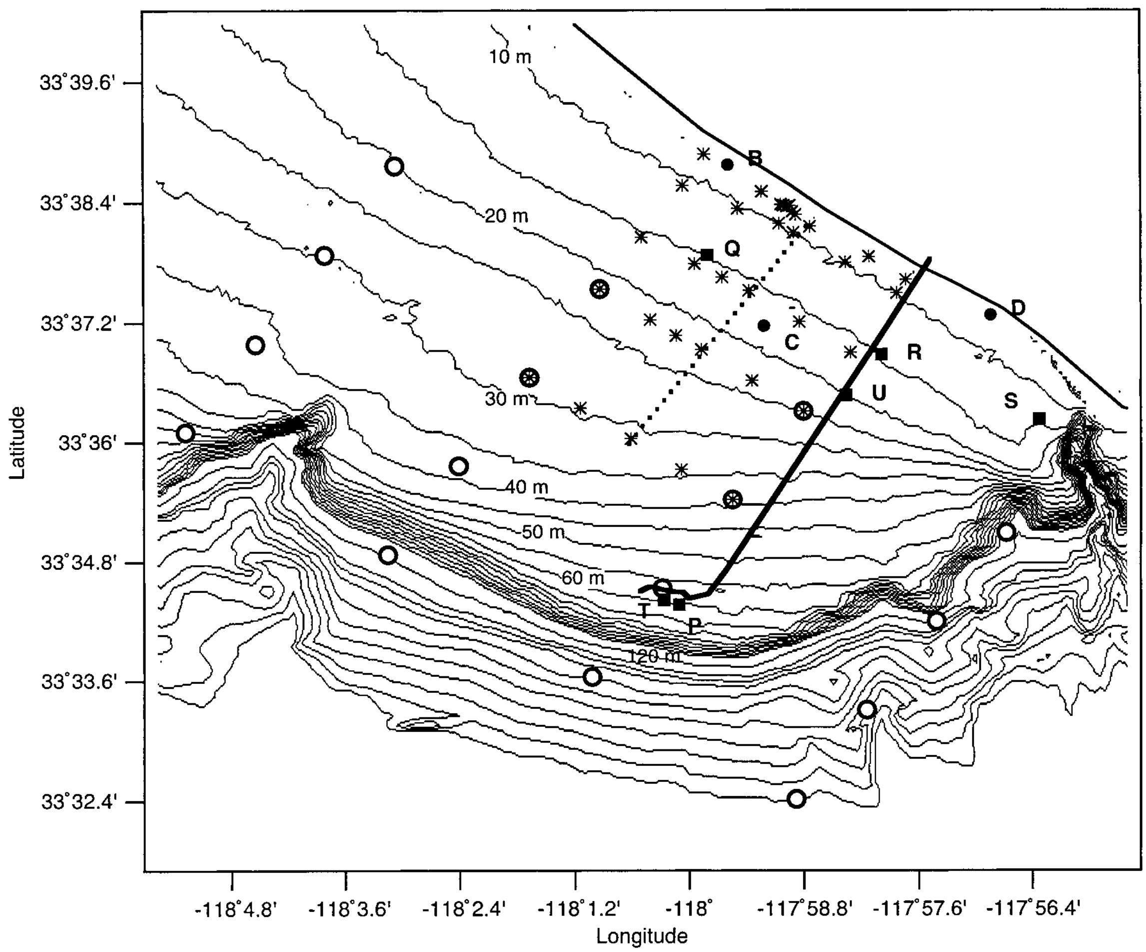

FIGURE 1. Coastal shelf offshore of Huntington Beach, California with locations of temperature and current observation stations (● and ■), and water quality monitoring stations (* and ○). Identification letters are shown where applicable. The solid black line extending from the coast line is the sanitation district's outfall pipe. The dashed line represents the transect examined in Figure 3. Contour lines on the coastal shelf and in the canyon are 5 and 20 m apart, respectively.

tracking was conducted in a region extending from offshore of the outfall diffuser to approximately the 20 m isobath which is located 3.4 km from the shoreline. On November 27, 2000, observations were confined to the nearshore region on the upcoast side of the outfall pipe, between approximately the 35 and the 5 m isobaths. Figure 1 shows the fixed grids established for each tracking study (May stations are represented by open circles and November stations are represented by black asterisks). Using one vessel, surveys began on the onshore upcoast corner of the grid and proceeded in the cross-shelf direction until sampling was complete.

At each station, temperature and conductivity were measured continuously (4–24 scans/sec) throughout the water column to the seabed and then averaged to 1-m intervals using a CTD profiler (Sea-Bird Electronics, Bellevue, WA, model SBE 9-03/SBE 11 and model SBE 25). The CTD was submerged to 3 m for 2 min to equilibrate before beginning the profile. Data were collected as the CTD was lowered at 30 to 40 cm/s.

On the upcast, water samples were collected in 1-L Niskin bottles mounted on a Rosette sampler near the bottom of the water column and then at five meter intervals. Once on board, water was transferred to presterilized 125-mL specimen jars, stored on ice at 4 °C, and transported to OCSD for bacterial analysis within the 6-h holding time limit. A 10-mL portion of each sample was analyzed using defined substrate assays for total coliform and *Escherichia coli* (a subset of fecal coliform) (Colilert-18) and *Enterococcus* (Enterolert) (Idexx, Westbrook, ME; tests implemented in a 97-well Quanti-tray format). In May, samples were not analyzed for *Enterococcus*. The detection limit for the Idexx assays is 10 MPN/100 mL.

Physical Measurements. Locations of long- and short-term current and temperature observation stations are summarized in Table 1 and Figure 1. Long-term measurements were recorded from June 1999 to June 2000, at a total of six locations (solid black squares in Figure 1). A Sentinel Workhorse 300 kHz acoustic doppler current profiler (ADCP) (RD Instruments, San Diego, CA) with a temperature sensor was deployed at station T in 61 m of water. North and east components of the horizontal current vector were collected over 2-m thick vertical bins. Station P, also located in 61 m of water, was equipped with mini temperature recorders (Hugrun Seamon, Reykjavik, Iceland) at 15, 30, and 48 m, and doppler current sensors with temperature sensors (Aanderaa Instruments, model 3500, Nesttun, Norway) at 1 and 45 m. A mini temperature recorder was installed at station U on an anchor spindle at the bottom of the water column. Nearshore stations S, R, and Q, which span 6.2 km along shore, were equipped with current meters at 5-m (S4, Interocean Systems, Inc., San Diego, CA) and 10-m depths (2-D acoustic current meter, Falmouth Scientific, Cataumet, MA) and mini temperature recorders at 7.5 m and the base of the water column (approximately 15 m). All observations were made at 30-min intervals and then 3 h low pass filtered and resampled at 1 h intervals.

TABLE 1. Mooring Locations, Depths, and Durations

mooring	latitude	longitude	water depth (m)	distance to shore (m)	duration (mm/yy)
Q	33° 37.874′N	117° 59.804′W	14.8	2280	06/99–06/00
R	33° 36.881′N	117° 57.993′W	15.3	1810	06/99–06/00
S	33° 36.229′N	117° 56.330′W	14.6	1440	06/99–06/00
U	33° 36.473′N	117° 58.363′W	20.8	2519	06/99–06/00
P	33° 34.369′N	118° 00.110′W	61.8	7240	06/99–06/00
T	33° 34.415′N	118° 00.266′W	61.7	7150	06/99–06/00
B	33° 38.776′N	117° 59.590′W	6	220	05/00
C	33° 37.1680′N	117° 59.247′W	18	2400	05/00
D	33° 37.275′N	117° 56.838′W	6	100	05/00

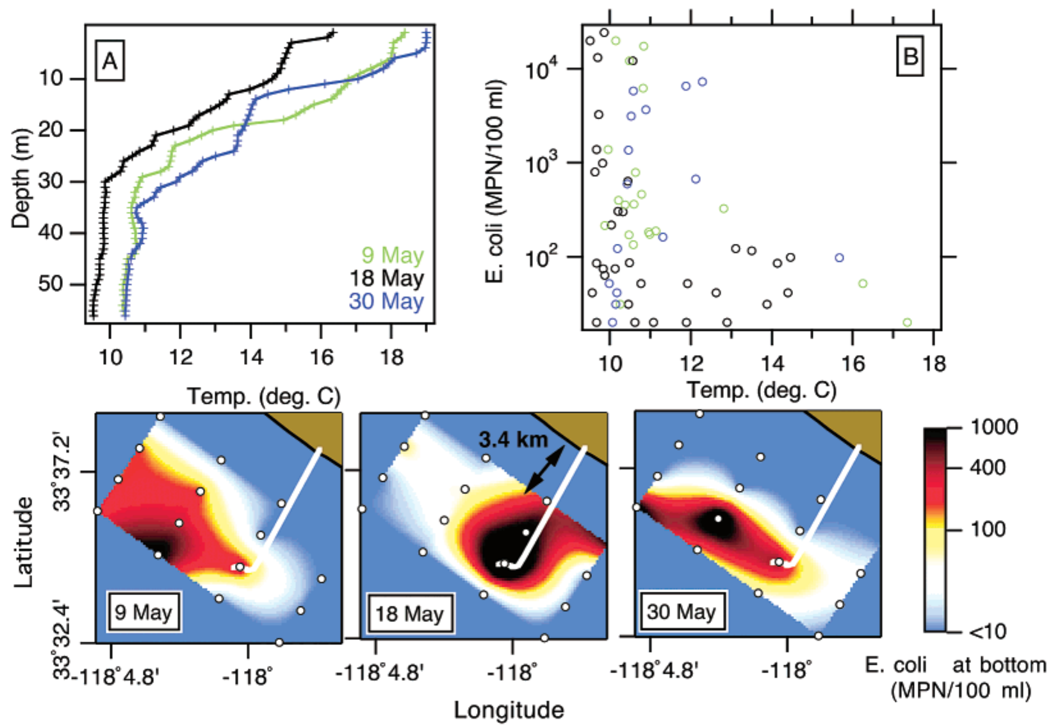

FIGURE 2. Typical characteristics of the waste field and the environment into which it is released during three plume-tracking studies conducted in May 2000. Panel A: temperature records from near the outfall diffuser. Panel B: the temperature and concentration of *E. coli* in samples collected during all three tracking studies. Samples with *E. coli* below the detection limit of 10 MPN/100 mL were not included. Bottom: location of the plume during each study based on concentration of *E. coli* (MPN/100 mL) at the bottom of the water column at water quality stations (indicated by ○). The area outside in the grid is represented by blue.

Short-term moorings were deployed during May 2000 (solid black circles in Figure 1). An S4 current meter with temperature, conductivity, and pressure sensors was deployed at the bottom of the water column at station C in 18 m of water from April 27 to May 26, 2000. Observations were recorded every 6 min. Workhorse Sentinel ADCPs (1200 kHz) equipped with temperature sensors were deployed in 6 m of water just outside the surf zone at stations B and D from May 1 to 26, 2000. Current magnitude and direction were collected in 0.25-m bins every six minutes, along with temperature within the device.

Results and Discussion

Plume Tracking. Figure 2 displays data collected during the May 2000 plume surveys and illustrates features of the waste field and the environment near the outfall. Temperature profiles near the outfall diffuser (panel A) indicate a thermocline between 15 and 30 m with weakly stratified waters above and below. Panel B shows *E. coli* concentration versus temperature, constructed using all water samples collected during the May surveys that contained detectable levels of bacteria, and it reveals the presence of the waste field in cold water. Ninety percent of the samples with detectable levels of bacteria were present in waters colder than 14 °C. Referring to panel A, this corresponds to water located within and beneath the thermocline.

Three contour plots (bottom of Figure 2) show the waste field based on concentrations of *E. coli* at the bottom of the water column. For reference purposes, California law mandates that a beach be posted as unfit for swimming if the concentration of *E. coli* in a single surf zone sample exceeds 400 MPN/100 mL. On May 9 and 30, the waste field is observed upcoast of the outfall, whereas on May 18 it is shoreward of the outfall. These plume positions are consistent with current measurements taken at station T (not shown), that indicate upcoast, slightly offshore flow during May 9 and 30, and downcoast, onshore flow on May 18. The plume on May 18 is also consistent with a previous prediction that effluent occasionally penetrates into depths ranging from 10 to 20 m (*9*).

On November 27, 2000, the plume is observed 5.3 km shoreward of the outfall, or approximately 2.2 km from the coastline (Figure 3). Depth profiles of temperature and fecal indicator bacteria are shown for five stations that span the plume in a cross-shelf direction (indicated by dashed lines in Figures 1 and 3). At the most offshore station (bottom, left

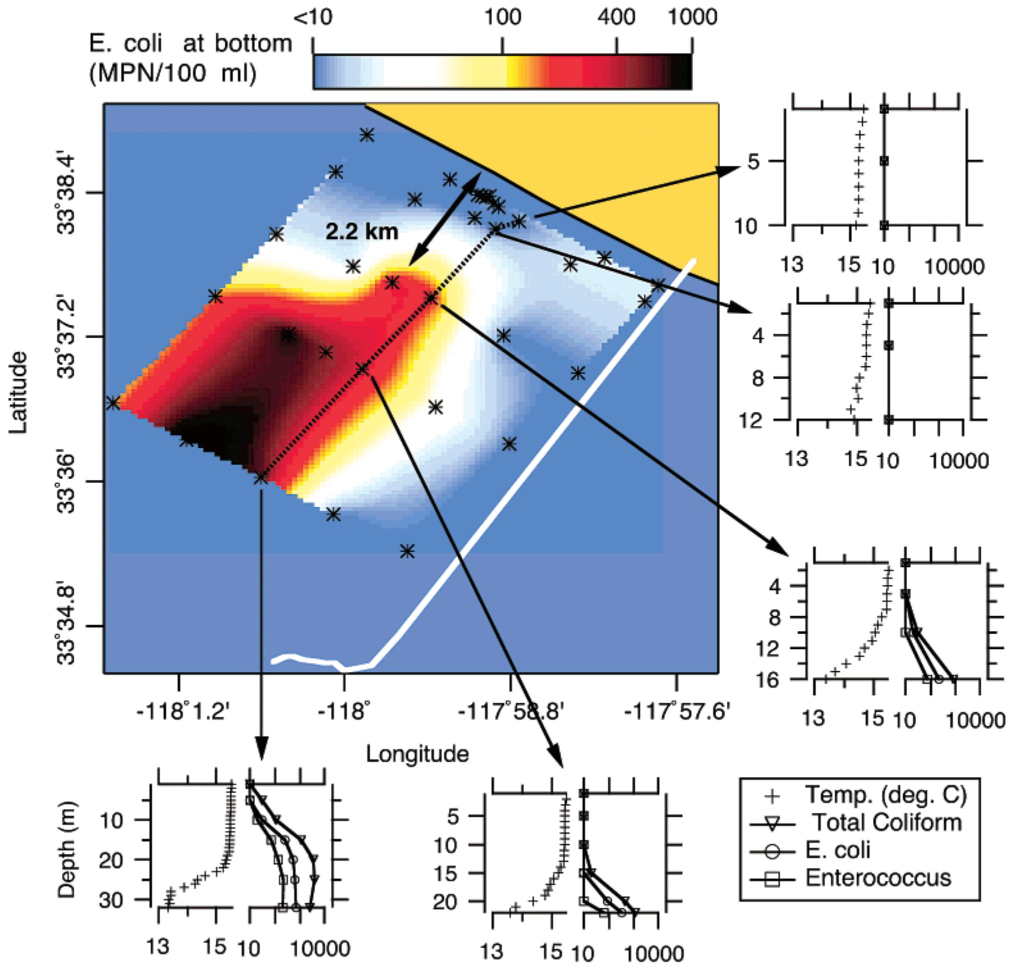

FIGURE 3. Top: Wastewater plume on November 27, 2000 as indicated by the concentration of *E. coli* (MPN/100 mL) at the bottom of the water column at water quality stations (indicated by *). The area outside the grid is represented by blue. Small panels: Depth profiles of temperature (°C) and indicator bacteria (MPN/100 mL) along a transect through the plume (dashed line). Arrows connect profiles to stations where they were measured; the most offshore station is on the bottom left, and the most onshore station is on the top right.

panel), high levels of indicator bacteria are present both above, within, and below the thermocline, while at the remaining stations, high bacteria levels are observed only in cold subthermocline water. At the two most nearshore stations (top, right panels), only relatively warm water is present and there are no detectable bacteria. Bacteria levels are relatively uniform within the cold bottom layer at the three most offshore stations.

The presence of the plume in the nearshore in a near-bottom layer of cold water could be a result of transport by internal tides. This raises concern about the potential for bathing water quality impairment in the surf zone if internal tides further advect the cold, subthermocline water containing the waste field into the surf zone as has been reported for nutrients (*2*), plankton (*3*), and chlorophyll (*11*) at other locations.

Temperature Near the Outfall. Year-long observations as station P characterize temperature changes over seasonal and shorter time scales (top panel of Figure 4). Because salinity co-varies with temperature, the temperature field serves as a proxy for the density field. The year can be divided into two periods. The first period runs from December through mid-April when the surface temperature is approximately 14 °C, and the temperature difference across the 60-m deep water column is about 2 °C, corresponding to a relative density difference of 0.5 ppt. The rest of the year, from mid-April through November, the surface temperature is about 18 °C, and the vertical temperature difference is near 8 °C, with a relative density difference of 2 ppt. According to monitoring reports issued by OCSD in 1990 (*12*) and 1993 (*8*), these seasonal variations are typical for the study area.

Upwelling events, defined by periods when the upper water column cools for one to several weeks, occurred in late August and September 1999 and May 2000 (Figure 4). In areas of active upwelling, the cross-shelf circulation forced by equatorward wind is understood to bring cold subthermocline water to the surface. Upwelling can also reduce the vertical stability of the water column during summer and fall to levels comparable to those that occur during winter. In the vicinity of the outfall, this process alone could be responsible for effluent transport to the nearshore. The upwelling process is distinct from the internal tidal transport that is the focus of this paper. The latter are illustrated by the high-frequency variability that is evident in the 15-m temperature record.

An expanded view of the temperature record for May 2000 is shown in the bottom left panel of Figure 4 along with the sea surface level. This period is chosen because it is when observations are available for stations B, C, and D in shallow water. Temperature fluctuations 1 m beneath the surface exhibit slow changes associated with the upwelling process described earlier, and diurnal changes that have been associated in similar observations on the southern California shelf with the diurnal heating and cooling cycle. That cycle is limited to a shallow near-surface layer (*13*). In contrast, the 15-m record is characterized by temperature changes that occur on both diurnal and semi-diurnal periods, and are synchronized with the surface tide such that maximum

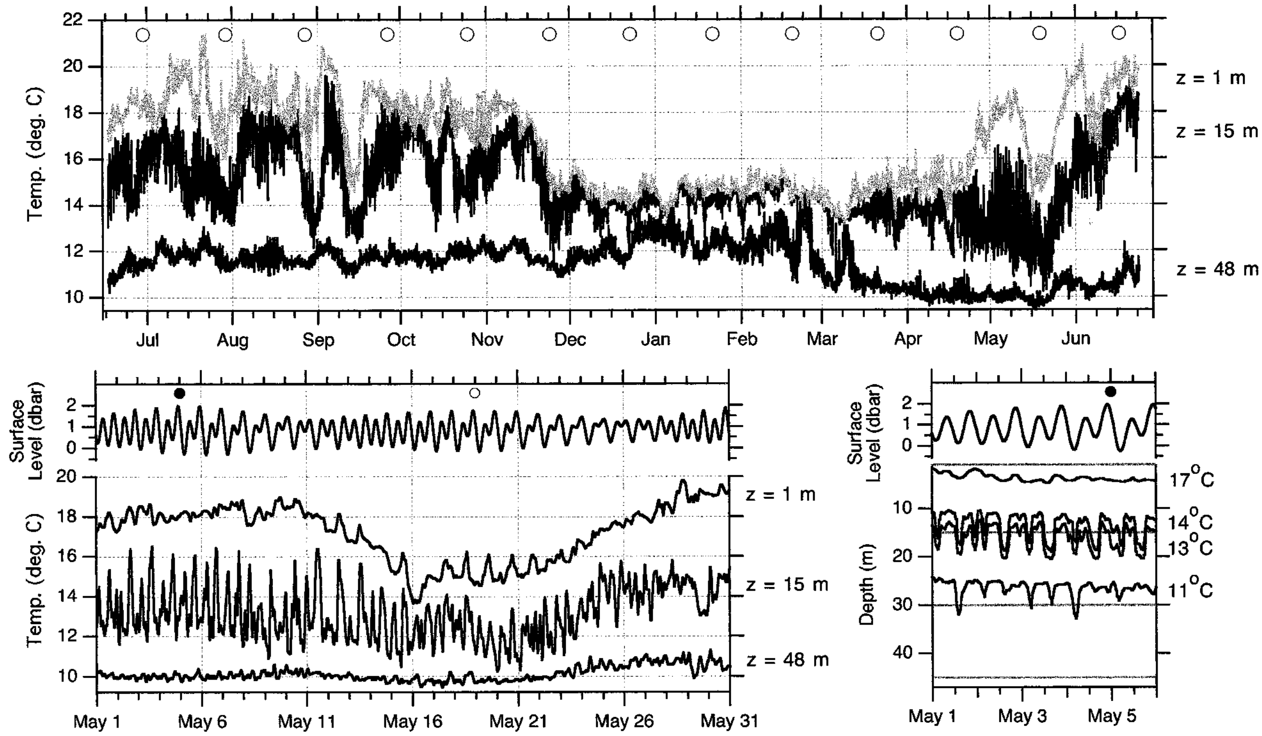

FIGURE 4. Top: Year-long temperature observations at 1, 15, and 48 m at station P, located in 61 m of water near OCSD's outfall, and the lunar record. Bottom, left: Temperature variability during May at the same location, and depths and sea surface level. Bottom, right: Expanded contour plot of temperature from May 1 through May 5, along with sea surface level and lunar record. Note that the scale for the surface tide is magnified by a factor of 5 compared to the scale for the internal tide. Open circles (○) represent full moons and solid circles (●) represent new moons.

temperatures occur when sea level is low and vice-versa. Because these are internal motions that take place at the tidal periods, they are frequently called internal tides. The temperature record does not show the spring-neap cycle associated with the beat between lunar and solar semi-diurnal periods that is clear in the sea level record. This suggests that the energy associated with temperature fluctuations is spread over a broader range of frequencies in the semi-diurnal band than is the energy associated with sea level.

The amplitude of the isotherm displacements at station P can be estimated using a contour plot of all temperature observations between May 1 and 6 (Figure 4 bottom, right panel). During the period shown, the 13 and 14 °C isotherms were displaced by as much as 10 m, at the same time that the surface displacement was between 1 and 2 m. Water temperatures above 10 m and beneath 30 m remained relatively unchanged. The patterns described for this brief period and for the month of May 2000 are typical of all months when stratification is strong (mid-April through November).

Nearshore Temperatures. The nearshore is defined here as the area of the shelf where the total depth is less than 20 m, where the bottom is above the mean depth of the thermocline in an average sense. Temperature measurements at stations C (18 m), R (15 m), and B (6 m) are illustrated in Figure 5 with the record from station P at 15 m for the month of May 2000. The observations at station R are representative of those at stations Q and S, also on the 15-m isobath, and the observations at the bottom at D are very similar to those at B.

The temperatures in Figure 5 show a high degree of correlation between all stations in the nearshore. An empirical orthogonal function (EOF) analysis was performed on May 2000 nearshore temperature measurements and filtered to retain diurnal and higher frequency fluctuations. The largest mode of co-variability was found to account for 66% of the total variance, pointing to a high degree of coherence between stations. This analysis suggests that most of the temperature fluctuations in the nearshore occur in unison. EOF analysis of the cross-shelf currents in the tidal frequency band at all nearshore stations was also performed, and a single mode of co-variability was found to account for 36% of the total variance. Furthermore, the co-variability in cross-shelf current was found to be 90 degrees out of phase with the co-variability in temperature, in such a way that bottom currents are directed onshore while temperatures are cooling.

The time series of temperature demonstrates that relatively cold water is frequently present in the nearshore. For example, the average near-bottom temperature at C is 12 °C. At station R, the average near bottom temperature is approximately 13 °C, which is equivalent to the average temperature in 15 m at station P, near the outfall. Several degree fluctuations in temperature are evident at all nearshore stations, even at station B located 220 m from shore at a point just outside the surf zone. During the upwelling event (May 15−16), minimum temperatures at B are less than 12 °C.

The vertical structure of temperature and currents is evaluated from observations at stations Q, R, and S. Temperature fluctuations are in phase across the water column, with the maximum amplitude at mid-water, while the cross-shelf currents above mid-water are a half-cycle out of phase with those below mid-water. This is the expected vertical structure for either an interfacial wave or a mode 1 internal wave in a linearly stratified ocean.

Cross-Shelf Transport. Comparing the preceding offshore and nearshore temperature records, fluctuations at both diurnal and semi-diurnal frequencies are observed at both stations though the ratio of diurnal to semi-diurnal energy is observed to be greater in the nearshore. The station C record in Figure 5, for example, illustrates semi-diurnal variability from May 2 to 7 and from May 22 to 26, but diurnal variability from May 9 to 12. Cross-spectral analyses between

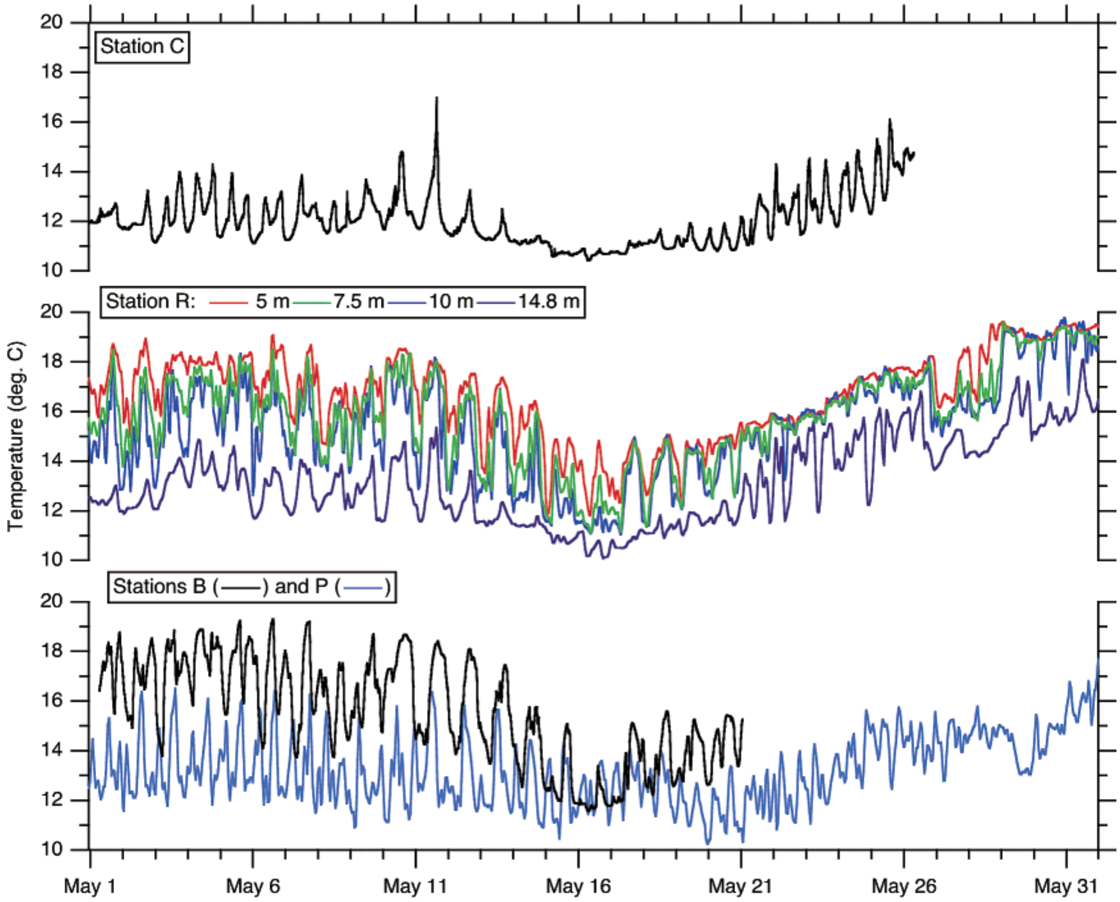

FIGURE 5. Temperatures recorded at stations C, R, B, and P during May 2000.

temperature fluctuations at P (15 m) and mid-depth observations in the nearshore show that the coherence is significant in both the diurnal and semi-diurnal frequency band. In addition, the phase lag is zero for the diurnal band, but it is a half cycle for the semi-diurnal band. This corresponds to a general heaving up and down of the isotherms at one cycle per day, and a rocking back and forth of the isotherms at two cycles per day such that the isotherms are rising in the nearshore when they are falling near the outfall. Because the inertial period at this latitude is shorter than 1 day, internal tides forced at diurnal frequencies cannot propagate and are in phase across the shelf. On the other hand, internal tides forced at semi-diurnal frequencies can propagate.

In the simplest model of the shelf, where the depth H is taken to be constant, the coastline enforces a no-flow condition, and motion is forced from offshore, the ratio of vertical to horizontal scales of motion, α, is given by Gill (*14*)

$$\alpha = \sqrt{\frac{N^2 - \omega^2}{\omega^2 - f^2}} \tag{1}$$

where N is the buoyancy frequency, f is the inertial frequency, and ω is the semi-diurnal frequency. The wavelength of the mode 1 wave is then $\lambda = 2\alpha H$. For the area of interest, during the summer, the wavelength is 14 km which is almost twice the distance from the outfall to the coast. Thus, semi-diurnal temperature fluctuations at the offshore and nearshore sites are expected to be out of phase by a half cycle.

Heat Budget. There is no external heat sink that can explain the cooling observed in the nearshore, and the only source of cold water is from offshore, so it is reasonable to expect that advection brings cold water into the nearshore. Near the bed, where the vertical velocity tends to zero, an equation for the temperature changes due to advection is

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} \approx 0 \tag{2}$$

where u is the onshore (x) component of velocity (20° clockwise from true north) and v is the upcoast (y) component, all relative to the local bathymetry.

To evaluate the relative contribution of cross-shelf and alongshore advection to nearshore cooling, we estimate each of the terms in eq 2 using nearshore observations from May 2000. The local change in temperature $\partial T/\partial t$ is calculated from the observed temperature at C. The cross-shelf and longshore velocity, u and v, are taken from the near-bottom measurements at C. Stations U and R, and R and S, were used to estimate $\partial T/x$ and $\partial T/y$, respectively, because of their proximity to station C and their orientation with the coastline.

Figure 6 presents terms in eq 2 from May 1 to 6, and illustrates that the local change in temperature (red line) closely tracks cross-shelf advection (black line). Based on all estimates made for May, the average magnitudes for $\partial T/\partial t$ and $-u\partial T/\partial x$ are 5.81×10^{-5} and 5.44×10^{-5} °C/s, respectively, while the average magnitude of $-v\partial T/\partial y$ is 1.12×10^{-5} °C/s. In addition $-u\partial T/\partial x$ correlates well with the $\partial T/\partial t$ ($r = 0.71$), while $-v\partial T/\partial y$ and $\partial T/\partial t$ correlate poorly ($r = -0.12$). These comparisons show that the nearshore cooling cycle is dominated by cross-shelf advection.

Pollutant Transport. The onshore transport of cool water raises the possibility that pollutants are transported as well. Figure 2, panel B illustrates that in May, the plume is present in waters with $T \leqslant 14$ °C, based on the presence of *E. coli*. During the first two weeks of May before upwelling occurred, temperature observations at station P (Figure 4) indicate that

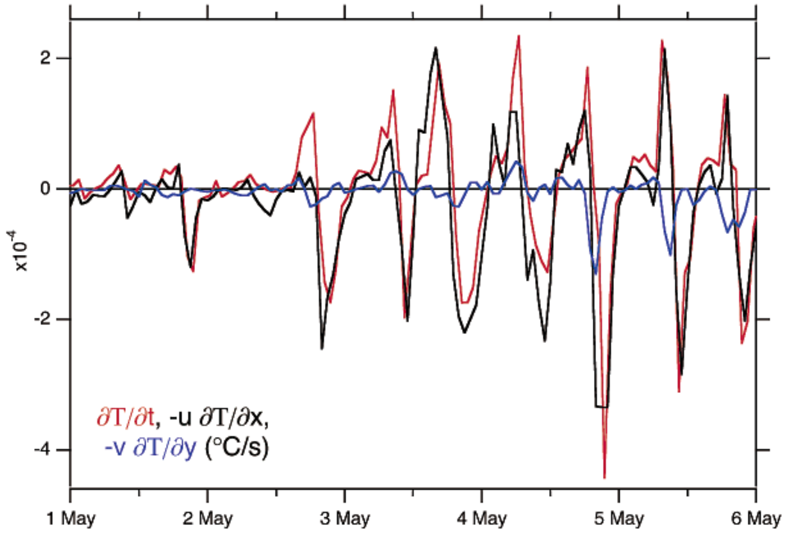

FIGURE 6. The local time rate of change of temperature at C [$\partial T/\partial t$, (red)] with the cross-shelf [$-u\partial T/\partial x$, (black)] and alongshore [$-v\partial T/\partial y$, (blue)] advective contributions from May 1 to 6, 2000.

the 14 °C isotherm is present near a depth of 15 m at the outfall diffuser. During the same period at the 15 m isobath, the station R record shows that the 14 °C isotherm was routinely present in water 10 m deep. At the 6-m isobath just outside the surf zone, station B and D records show the occasional occurrence of the 14 °C isotherm at the bottom of the water column during the largest high-frequency cooling events. These observations indicate that even in the absence of upwelling, isotherms associated with the plume are transported to isobaths as shallow as 6 m.

Implications

Plume-tracking studies presented here demonstrate that the OCSD waste field is occasionally advected into the nearshore with relatively cold water. Results from November 27, 2000 show that the plume was transported 5 km onshore from the outfall to a point roughly 2 km from the shoreline, and results from May 2000 show that onshore transport of the plume with cold water occurs at other times during the year as has previously been predicted (*9*).

Analyses of temperature and current observations taken in May, that are typical of conditions between mid-April and November, show that internal motions regularly cause cold water to be advected onshore and offshore at both semi-diurnal and diurnal frequencies. This implies that onshore transport from the OCSD outfall is possible, for pollutants that typically reside in cold water, throughout the late spring, summer, and fall when the internal motions are energized. We speculate that the susceptibility of the OCSD effluent to onshore transport by these recurring internal motions is linked to the magnitude and direction of currents near the outfall. That is, relatively stronger alongshore currents may dominate transport in some instances and sweep the waste field upcoast and offshore as was observed on May 30, 2000, whereas onshore currents at the outfall may facilitate subsequent transport to the nearshore by internal tides.

Although the length of observations available for this study is too short to reach statistically significant conclusions about upwelling, we note that the most shoreward extent of the plume observed during May (May 18, Figure 2) occurred during an upwelling episode. In the absence of tidal period motions, upwelling circulation could by itself advect water from the outfall to the nearshore, and at the same time reduce the stability of the water column.

On the basis of these analyses, it remains unclear whether OCSD effluent impairs surf-zone water quality. However, it is clear that the plume occasionally resides offshore of Huntington Beach near the bed in water less than 20 m deep, where cross-shelf transport by internal tides occurs. Hence, we cannot rule out the possibility that OCSD effluent is contributing to the elevated indicator bacteria levels at Huntington Beach.

These findings underline the need for a comprehensive characterization of oceanic variability over time scales sufficiently long to capture interannual variations, sufficiently short to capture high-frequency internal motions, and over the entire area affected by the outfall. This is necessary not only to better understand the impact of ocean outfalls on coastal water quality, but also to design monitoring programs that protect bathing-water quality. Extensive monitoring was initiated by OCSD in the summer of 2001 for this purpose.

Acknowledgments

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