Temperature Variations in the Water Column off Point Loma

During an oceanographic study off Point Loma (San Diego), water temperature measurements were collected at 30 min intervals for seven months along a cross-shore transect on the mainland shelf (SCCWRP 1992). The results were animated on a computer to show the temporal evolution of the temperature structure of the water column in two-dimensions (depth and cross-shore position). The most striking features of the animation were the dynamic nature of subsurface waters and the extent of vertical motions over a semidiurnal tidal period. This paper provides a qualitative overview of the dynamic features of the subsurface waters on the mainland shelf off Point Loma. These features have important implications for assessing the transport of wastewater, the use of data from hydrocast surveys, and the interpretation of cross-shore transport from current meter measurements and drogue tracking.

Background

Anyone watching the Pacific Ocean off Southern California is aware of the motions of waves on the sea surface and the rise and fall of the sea surface with the tides. When the water column is density stratified, as it is throughout most of the year, similar vertical motions occur below the sea surface where surfaces of constant density (isopycnal) or constant temperature (isothermal) rise and fall. These are known as internal waves and their existence has been postulated for a long time. (Ekman 1904). Internal waves were reported off Southern California in the 1950s (Arthur 1954).

Numerous mechanisms have been proposed as the source of internal waves, including the flow over or around changes in bathymetry (e.g., surface tides at slopes or over sills), diurnal winds, surface wave and internal wave interactions, shear flows, freshwater flows and discharges, currents, earthquakes, and explosions (e.g. Krauss 1966). The shelf break off the California coast may be a source of internal tides (Reid 1956) and offshore seamounts may be a source of the short period internal waves Zalkan (1970).

The density gradient of the water column bounds the frequencies of oscillation (Brunt-Väisälä frequency) of internal waves at the high frequency end of the spectrum (periods as short as minutes in strong stratification), and the inverse of the inertial period (ca. 22 h off Southern California) bounds the frequencies of oscillation at the low frequency end. There are reports of diurnal internal tides in areas where the inertial period is shorter than 24 h (Krauss 1961). The frequency spectrum is often divided into “short-period” motions associated with periods shorter than the semidiurnal tidal period, and “long-period” motions that include tidal fluctuations. Off California, there is a peak in the energy spectrum of short period internal waves at about 18 min (Roberts 1975). The amplitudes of short period motions in local coastal waters are 3-4 m (Carsola and Callaway 1962, LaFond 1962). Amplitudes of about 20 m were observed near the Straits of Gibraltar (Ziegenbein 1969) and 40 m were observed in the Andaman Sea (Perry and Schimke 1965).

Semidiurnal internal tides in 20 m of water off Mission Bay (San Diego) have amplitudes of 4-8 m in the upper 10 m of the water column (LaFond 1962). Similar amplitudes occur farther offshore and farther south (Reid 1956, Carsola 1967). Vertical excursions of 10-30 m (amplitudes of 5-15 m) of semidiurnal period were observed during a drogue and hydrocast study off Newport Beach (Hendricks 1983). Propagation speeds of internal tides are about 50 cm/sec and wavelengths range from 10-170 km (Roberts 1975).

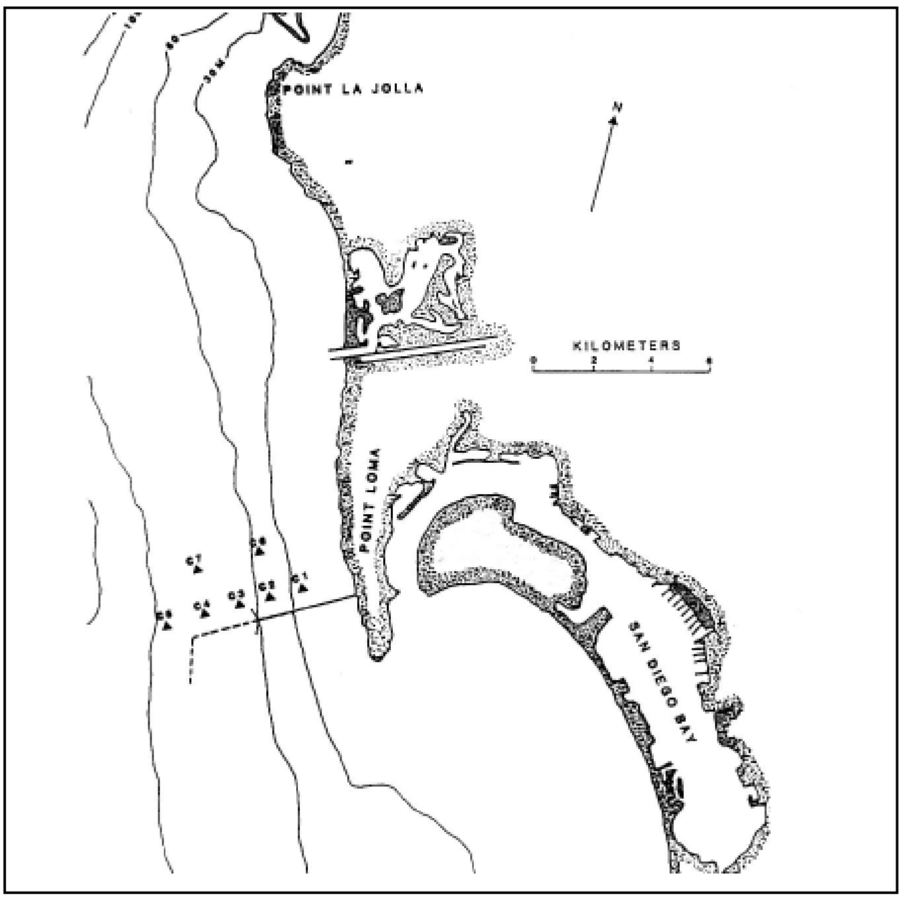
Materials and Methods

Temperature measurements were made at an array of moorings off Point Loma (Figure 1) by Engineering Science, Inc. in connection with the design of an extension of the Point Loma municipal wastewater outfall (San Diego). The moorings were deployed on 3/8/90 (calendar day 067), serviced and redeployed on several occasions, and recovered on 10/5/90 (calendar day 278). Thermistor calibrations were checked at the end of the period at the Hydraulics Laboratory at Scripps Institution of Oceanography. Eleven thermistors 5 m apart were used on moorings C3, C4, and C5 and nine thermistors were used on mooring C2. The lowermost thermistor was 1.5 m above the bottom. Water temperatures were recorded every 0.5 h for a total of about 425,000 measurements.

Temperature measurements were converted to estimates of isotherm depths to produce an isotherm depth time series. The interval between the isotherms was 0.2°C. If an isotherm temperature fell between the temperatures measured at a pair of thermistors, its depth was estimated by simple linear interpolation. If the isotherm was above the uppermost thermistor in the string, or below the lowest thermistor, isotherm depth was estimated by extrapolation from the temperature gradient between the uppermost, or lowermost, pair of thermistors. When weak gradients led to a suspect isotherm depth (e.g., above the ocean surface), the depth estimate was modified using a smoothing process based on the depths of the isotherm in a few preceding and following observations.

A 25 h running average filter was used to generate "high-pass" and "low-pass" time series. The high-pass series was obtained by subtracting the low-pass series from the original time series. Since the inertial period in the area is about 22 h, fluctuations in the isotherm depth associated with internal

Figure 1.
Location of thermistor moorings off Point Loma (adapted from Engineering Science, Inc. 1991). The dashed line is the recent outfall extension.



waves and internal tides were contained predominantly in the high-pass time series. The low pass time series contained the more slowly varying processes (i.e., up- and downwelling, vertical mixing, and longshore advection). Depths in the low-pass time series that were associated with observations outside the thermistor string depth interval were set equal to the water depth; depths in the high-pass time series associated with out-of-range values were set equal to zero.

Results

We used the data to examine the magnitude and time-scales of vertical excursions of isothermal surfaces. For simplicity, we restrict the discussion to the motion of a single or "reference" isotherm, which was chosen to maximize the number of observations between upper and lower thermistors. The motions of other isotherms were similar to the selected isotherm — except perhaps near the thermocline.

Late Summer to Fall

Variations in the depth of the 12.6°C isotherm occurred at the semidiurnal tidal frequency, at 1-2 weeks, and over times greater than the deployment (Figure 2). Variations of semidiurnal tidal periodicity (ca 12 h) were associated with internal waves (Figure 3). Amplitudes commonly ranged from 3-10 m, with occasional amplitudes of 14-24 m. The amplitudes appeared to be modulated over about two weeks — a time-scale comparable with modulation of the amplitudes of the surface tide. Typical excursions between high and low internal tides during one-half of a semidiurnal tidal period (~6 h) were 10-15 m; the greatest excursion was about 35 m (mean vertical velocity=0.16 cm/s).

The daily average isotherm depths in the slowly varying (low-pass time series) vertical motions of the 12.6°C isotherm were 20-40 m at the beginning of the period (Figure 4). Two and one-half weeks later, the daily average depth of this isotherm increased to about 65-80 m, which was suggestive of downwelling. Most of this drop occurred over two days (vertical velocity=0.025 cm/s). The increase in depth was reversed and followed by about a 20-30 m reduction in isotherm depth over a week (vertical velocity=0.005 cm/s), suggesting upwelling (or a relaxation of downwelling). The total duration of the downwelling event was about nine days.

Early Spring

Internal wave amplitudes of the 11.4°C isotherm at mooring C3 were modulated over about two weeks (Figure 5). Minimum amplitudes were 2-3 m; maximum amplitudes were 20 m. The maximum excursion over 6 h was about 39 m. These values were comparable with the excursions observed during 8/31-10/5 — even though the stratification of the water column was stronger in late summer. The maximum vertical excursions of the 11.4°C isotherm at the inner mooring (C2; Figure 6) were comparable with those at mooring C3 — except near the end of the deployment. Water depths at C2 and C3 were within the depth range of the major municipal wastewater ocean outfall diffusers off Southern California.

The daily average depth of the isotherm in the low-pass time series increased during the deployment (Figure 7). Downwelling was not apparent. Interestingly, there appeared to be local downwelling at mooring C4 (observations 0-100 and 1535-1680) without similar events at moorings C2 and C3. It is possible, however, that downwelling at C4 near observations 0-100 was followed by downwelling at moorings C2 and C3 about three days later. There also appeared to be local downwelling at moorings C2 and C3, but not C4, near observations 1300-1490.

Late Spring to Summer

The characteristics of the internal waves were slightly different during the late-spring to summer (Figure 8). Modulation of the semidiurnal tidal

Figure 2.
Depth variations of the 12.6°C is isotherm at mooring C3 from 8/31/90 to 10/5/90. Water depth was 68.3 m; the lowermost thermistor was at 66.8 m and the uppermost thermistor was at 18.3 m. Isotherm depths <18.3 m or >66.8 m were estimated (values >68.3 m could not occur at the mooring).

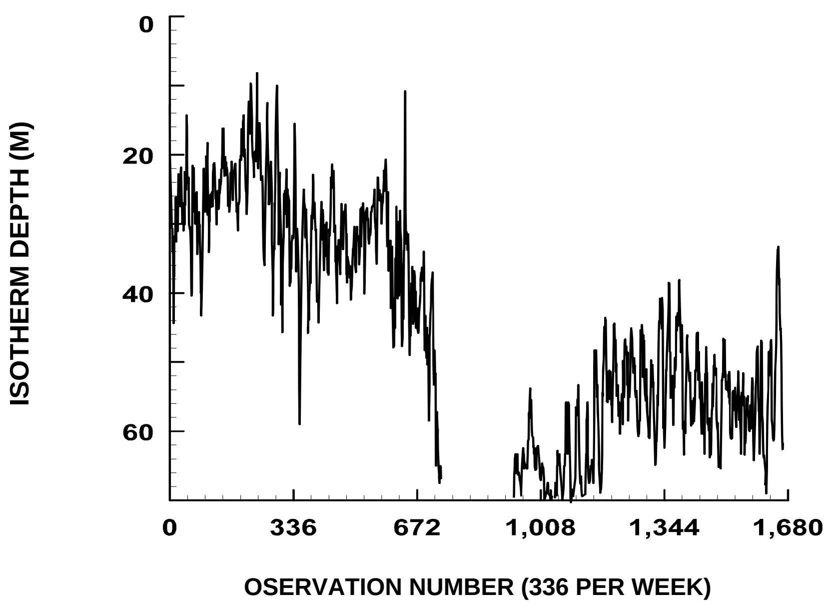
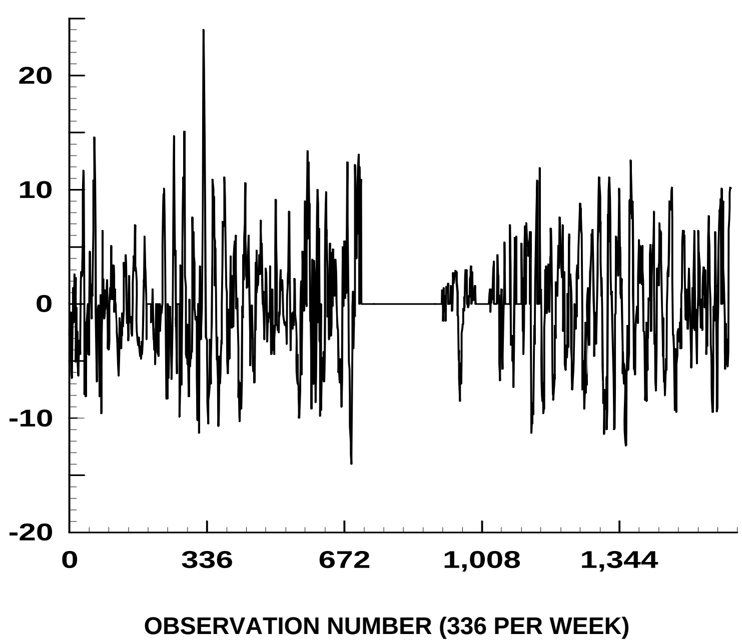


Figure 3.
Variations from the daily average depth of the 12.6°C isotherm at mooring C3 from 8/31/90 to 10/5/90. Values of 0 are associated with periods when the isotherm was outside the depth interval encompassed by the thermistors.



amplitudes was shortened closer to one week, and maximum amplitudes were slightly reduced. The maximum excursion over 6 h was about 29 m. The daily average depth of the 12.0°C isotherm increased during the deployment (Figure 9). However, there were numerous episodes of vertical excursions of 6-30 m over time-scales shorter than one week.

Discussion

Large vertical excursions of isothermal surfaces over one tidal period have important implications for assessing wastewater disposal from submerged ocean outfalls, including: 1) wastefield depth, 2) interpretation of oceanographic conditions from hydrocast surveys, and 3) estimation of wastewater transport from drogue trackings or current meter records.

Wastefield Isolation

An important function of a deep submarine outfall is to prevent intrusions of treated wastewater into environmentally sensitive areas, such as bathing waters or shellfish beds. Wastewater intrusions into protected waters can be prevented if the wastefield is confined to a depth greater than the maximum depth in the protected area. Since vertical spreading of the wastefield by vertical mixing appears small over a few

Figure 4.

Daily average 12.6°C isotherm depths at moorings C2 (water depth 55.5 m), C3 (68.3 m), and C4 (80.5 m) from 8/31/90 to 10/5/90. Missing values were periods when the isotherm occurred outside the depth interval encompassed by the thermistors. [Mooring C5 in 95 m of water was not included because the reference isotherm was above the upper thermistor (44.5 m) a significant fraction of the time.]

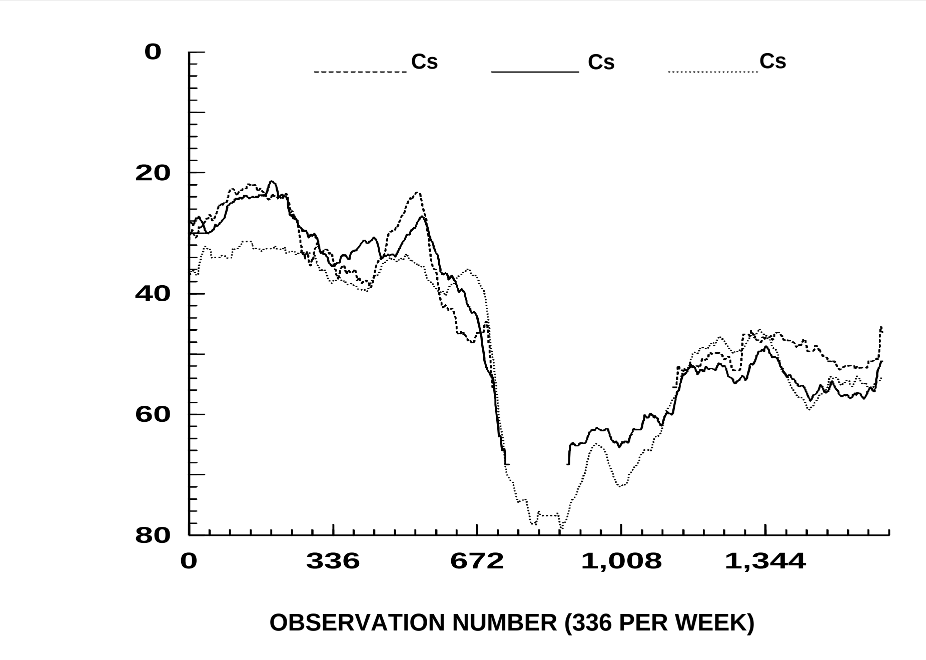
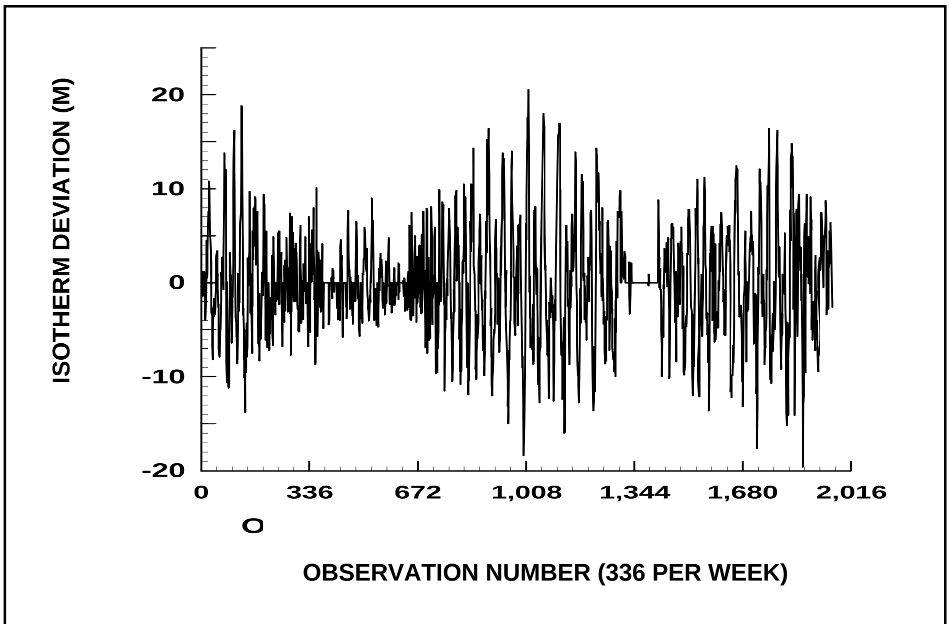


Figure 5.

Variations from the daily average depth of the 11.4°C isotherm at mooring C3 from 3/8/90 to 4/18/90. Values of 0 are associated with periods when the isotherm was outside the depth interval encompassed by the thermistors.



days, the upper face of the wastefield will stay with essentially the same isothermal surface as at the end of initial dilution. In the absence of internal waves and upwelling, it may be sufficient to ensure that the depth of the top of the wastefield at the end of initial dilution is below the maximum depth of the protected waters. Some additional depth may be required by the shoreward shoaling of isotherms associated with vertical shear in the longshore component of long-term net flows above and below the thermocline.

However, the temperature data collected off Point Loma recorded the presence of internal waves and internal tides that could produce vertical wastefield excursions comparable to the initial height-of-rise of the plume above the diffuser, or the initial depth of the wastefield below the surface. Isolation of protected waters from wastewater intrusions by water column density stratification may be substantially less than a static analysis would indicate.

Interpretation of Hydrocast Data

The vertical movements of sub-thermocline isotherms over 6 h were typically 6-15 m, and occasionally reached 35-40 m. Hydrocast data from a grid of stations must be collected nearly simultaneously if two- or three-di-

Figure 6.
Variations from the daily average depth of the 11.4°C isotherm at mooring C2 (in 55.5m of water) from 3/8/90 to 4/18/90. Values of 0 are associated with periods when the isotherm was outside the depth interval encompassed by the thermistors.

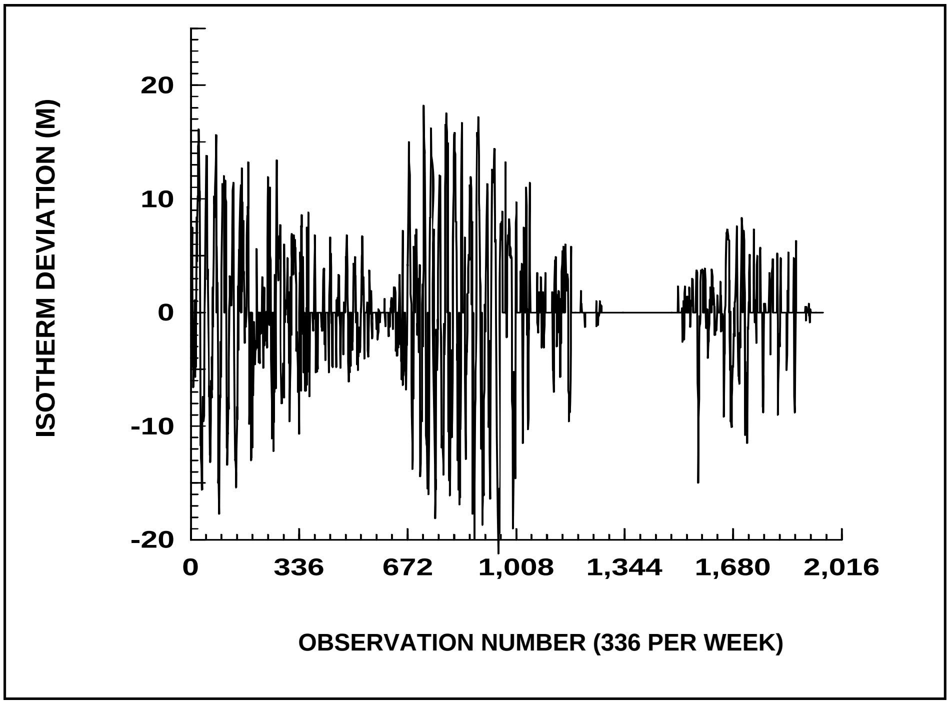
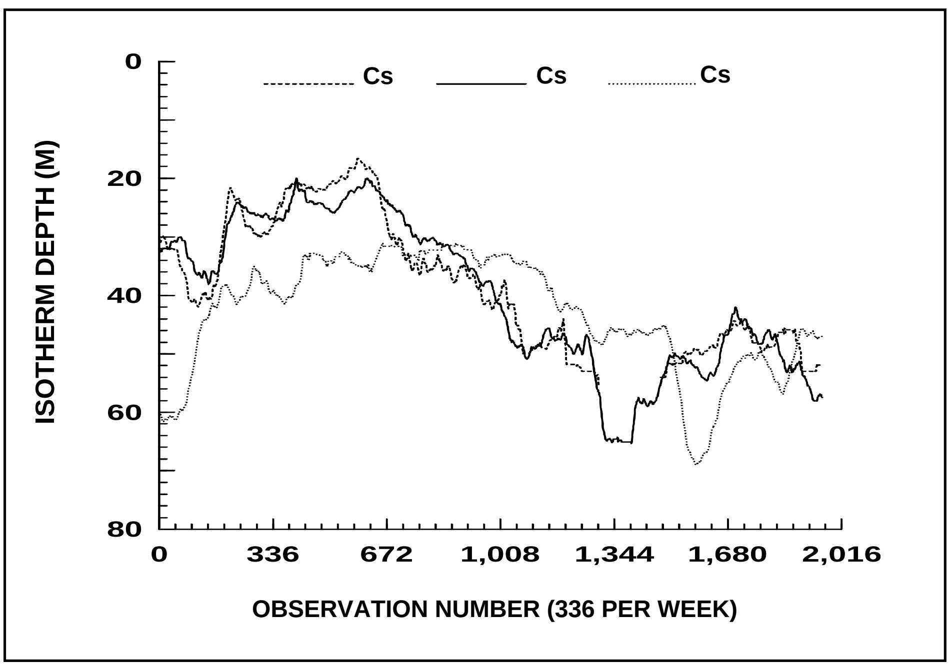


Figure 7.
Daily average 11.4°C isotherm depths at moorings C2 (water depth 55.5 m), C3 (68.3 m), and C4 (80.5 m) from 8/31/90 to 10/5/90. Missing values were periods when the isotherm occurred outside the depth interval encompassed by the thermistors.



mension contours of water quality parameters (temperature, salinity, dissolved oxygen) are used as a quasi-synoptic picture of the water column. This is especially important if slopes of isopleth surfaces (surfaces of constant value), or the vertical distribution, of water quality parameters are used as evidence for processes with long time-scales (e.g., up- or down-welling), which assumes that the isotherms move up and down in unison across the transect or grid.

While the wavelengths of internal tides are long compared to the dimensions of the cross-shore transect in this study, internal tides did not always display uniform movement. This is illustrated by the cross-shore distribution of an isotherm in June (Figure 10). There was a brief period early in the day when the isotherm depth decreased offshore. However, by observations 6-12, the slope was reversed and the isotherm depth increased offshore. Another reversal occurred later in the day. If a hydrocast survey had been made along this transect on this day, the slope of the isotherm could have suggested either upwelling or downwelling depending on when the hydrocasts were made.

Although these date were collected off Point Loma, similar motions are likely over other areas on the mainland

Figure 8.
Variations from thedaily average depth of the 12.0°C isotherm at mooring C3 (water depth 68.3 m) from 6/25/90 to 8/31/90. Values of 0 are associated with periods when the isotherm was outside the depth interval encompassed by the thermistors.

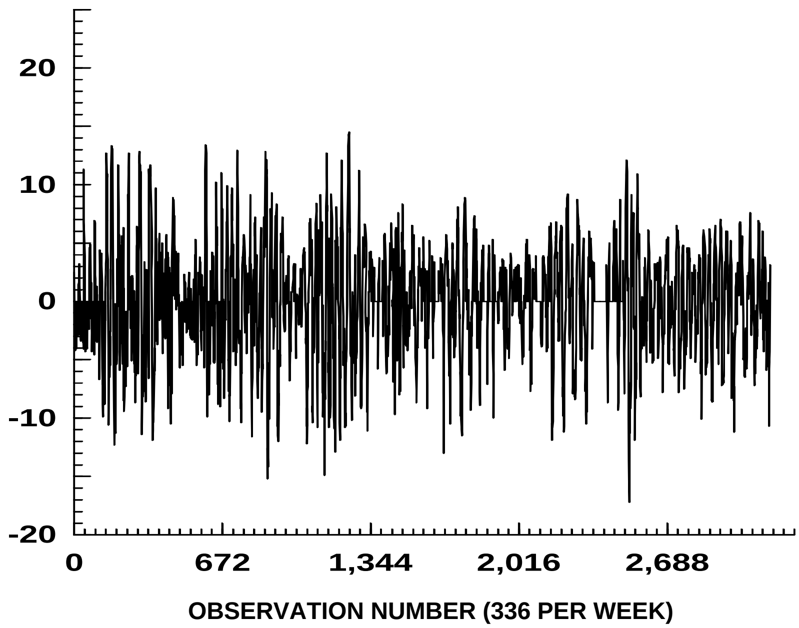
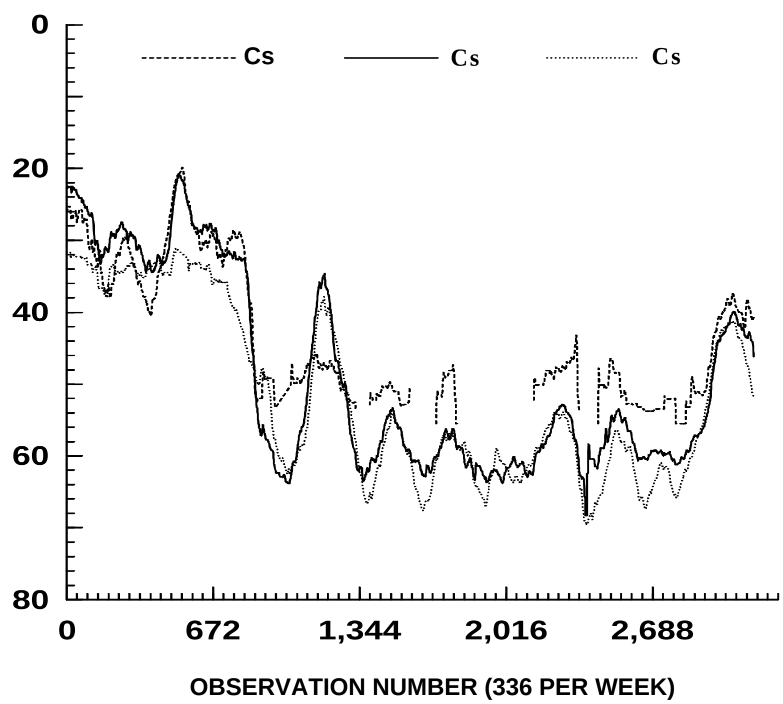


Figure 9.
Daily average 12.0°C isotherm depths at moorings C2 (water depth 55.5 m), C3 (68.3 m), and C4 (80.5 m) from 6/25/90 to 8/31/90. Missing values were periods when the isotherm occurred outside the depth interval encompassed by the thermistors.



shelf off Southern California with a comparable bottom slope and water column density stratification. In the presence of a density gradient, the energy associated with an internal wave propagates along a ray that has a slope from the horizontal. This slope depends on the density gradient, the period of the internal wave, and the inertial period for the area. If the slope of the bottom is greater than the slope of the ray, the wave will be reflected; if the bottom slope is less, internal wave energy will propagate inshore and intensify. Most ray slopes in the lower portion of the water column at the outer transect edge off Point Loma are greater than the slope of the bottom over the outer and middle of the shelf (Figure 11). Therefore internal tidal energy will propagate onshore and intensify within this region. Inshore from mooring C2 (and offshore from the kelp bed), the bottom slope steepens and the energy will be reflected.

A similar bottom slope occurs over the middle and outer shelf off Orange County where evidence for internal tides of comparable amplitude was detected during drogue trackings (Hendricks 1983). In contrast, the average bottom slope on the Palos Verdes Shelf is 0.03-0.04. As a result, semidiurnal internal tides may be reflected to a greater degree resulting in

Figure 10.

Cross-shore depth variations of the 12.8°C isotherm at moorings C2, C3, and C4 on 6/25-6/26/90. Each slice through the axis labeled observation number is the depth at each of the moorings along the cross-shore transect. Planes parallel to the right-rear face of the box are slices in time (constant observation number).

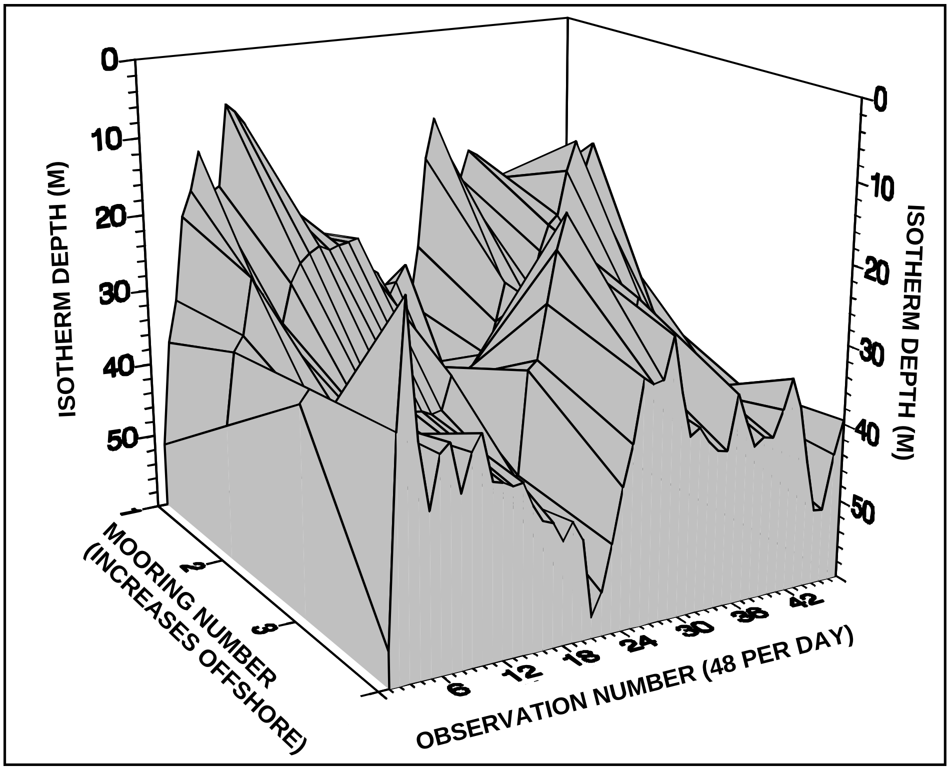
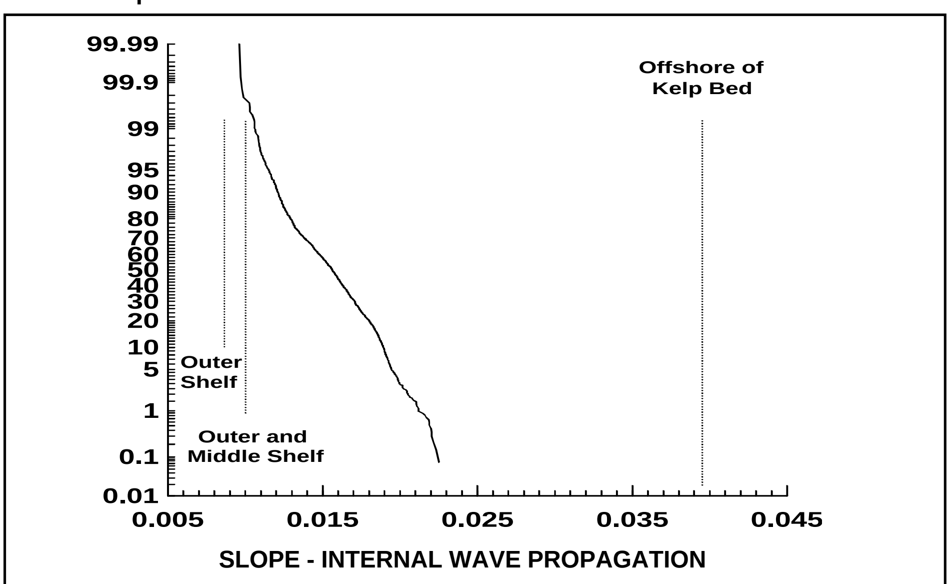


Figure 11.

Comparison of internal tide energy propagation slope and bottom slope at the offshore mooring (C5) off Point Loma. Semi-diurnal tidal period, density distribution within the lower portion of the water column (wastefield plume entrainment region of the extended Point Loma outfall). Thermistor data combined from all periods.



reduced amplitudes inshore of the shelf break. This expectation is consistent with a report of isotherm excursions of "several meters" associated with internal tides in this area (Steele 1987).

Cross-shore Component of Currents

Currents can also isolate the wastefield from protected waters. Transport by currents is often estimated from current meters measurements (measurement location fixed in three dimensions) or by tracking movements of drogues (measurements made at a fixed depth below the surface). However, the transport of a wastefield segment is associated with the flow between the isopycnal surfaces bounding the upper and lower faces of the segment. These surfaces move up and down with the passage of internal waves and tides. Neither transport estimated from current meter records, nor transport estimated from drogue movements, will simulate the movement of wastewater unless vertical shear in the horizontal component of the currents (at wastefield depth) is negligible or predictable.

Slowly varying fluctuations (subtidal frequency band) dominate transport over distances greater than 1-3 km off Point Loma (Hendricks 1990). The longshore component of subtidal flows is highly correlated: between current meters on a transect across the shelf (mean r=0.82, range: 0.65-0.93, n=10), between current meters at the same depth and distance offshore but separated by 1.6 km (mean r=0.82, range: 0.74-0.92, n=4), and between current meters separated by 20 m on the same mooring (mean r=0.76, range: 0.59-0.89, n=10). The high correlations are consistent with other results for the area (e.g., Hendricks 1977, Winant 1983) and lend support to the use of current meter data and drogue movements to estimate longshore transport. The situation is not so good for cross-shore transport. Net flows over a month or more often are not significantly different from zero, and correlations of the cross-shore component of currents in the subtidal frequency band are about half that for longshore flows (Hendricks 1990).

Off Point Loma, vertical excursions of an isotherm, and hence a wastefield, can be 15-20 m. However, cross-shore motions in the subtidal frequency band are often poorly correlated over this interval. Therefore, to use current measurements to estimate cross-shore transport of wastefield segments, one should know vertical correlation length-scales for the subtidal frequency band of the cross-shore component of the currents, and collect simultaneous current and temperature measurements at intervals shorter than this length-scale.

Vertical Mixing

The daily average depth of the reference isotherms increased during each deployment. This could be caused by: 1) persistent weak downwelling, 2) downward diffusion of heat from the warmer surface layer, or 3) advection of a water mass with upward sloping isothermal surfaces in the down-current direction. If the change was due to downwelling, the average downward vertical velocity was 0.0008-0.0011 cm/s, or about 0.8 m/day. We lack the information necessary to estimate the velocity due to the diffusion of thermal energy. However, by assuming that the movement was associated with the spread of a semi-gaussian distribution due to Fickian diffusion, the time-averaged vertical diffusivity was about 10 cm^2/s.

Active mixing was measured with a conductivity microstructure probe near the outfall diffusers on the Palos Verdes Shelf, but only occasional patches of mixing were observed farther away (Wu *et al.* 1993). Within a patch, vertical diffusivity was about 1 cm^2/s and the patches covered about 5% (0.4-7.4%) of the area. Assuming horizontal isotropy for turbulent vertical mixing, the patches occupied about 1% of the water column volume. Over time periods greater than a mixing event, and vertical lengths greater than patch thickness, temporally averaged vertical mixing would be about 0.01 x 1 cm^2/s, or about 0.01 cm^2/s. This is three orders of magnitude lower than our rough estimate of the diffusivity required to move the reference isotherm down about 30 m over six weeks. Hence, persistent downwelling, or the advection of a sloping isothermal surface through the study area, probably caused the increase in isotherm depth during the deployments.

Conclusions

Internal waves and internal tides in the coastal waters off Point Loma caused 10-20 m, and occasionally 35-40 m, vertical excursions of isopycnal surfaces in 55-70 m of water. These movements should be considered when assessing the likelihood of wastewater intruding into protected nearshore areas. Further, internal wave motions may distort the spatial distribution of water quality parameters in hydrocast surveys unless the sampling is accomplished over a period substantially shorter than one-half a semidiurnal tidal period (<6 h). Vertical motions associated with internal waves do not always move up and down as a unit and hydrocast surveys may not be appropriate for deducing the presence of upwelling or downwelling. Time series measurements of temperatures from moorings are probably required.

Vertical motions may also cause serious problems in estimates of cross-shore transport from current meter data or drogue tracking. Vertical correlation-length scales for cross-shore motions in the subtidal frequency band are comparable to, or shorter than, vertical movements associated with semidiurnal internal tides. Estimates of cross-shore transport over distances greater than 1-2 km will be poor without good vertical spatial resolution for water temperature and ocean current time series.

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