Hydrographic and particle distributions over the Palos Verdes Continental Shelf: spatial, seasonal and daily variability

Burton H. Jonesa,*, Marlene A. Noblec, Tommy D. Dickeyc

a Department of Biological Sciences, University of Southern California, Los Angeles, CA 90089-0371, USA
b United States Geological Survey, MS 999, 345 Middlefield Road, Menlo Park, CA 94025, USA
c Ocean Physics Laboratory, University of California, 6487 Calle Real, Suite A, Santa Barbara, CA 93106-3060, USA

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Abstract

Moorings and towyo mapping were used to study the temporal and spatial variability of physical processes and suspended particulate material over the continental shelf of the Palos Verdes Peninsula in southwestern Los Angeles, California during the late summer of 1992 and winter of 1992–93. Seasonal evolution of the hydrographic structure is related to seasonal atmospheric forcing. During summer, stratification results from heating of the upper layer. Summer insolation coupled with the stratification results in a slight salinity increase nearsurface due to evaporation. Winter cooling removes much of the upper layer stratification, but winter storms can introduce sufficient quantities of freshwater into the shelf water column again adding stratification through the buoyancy input. Vertical mixing of the low salinity surface water deeper into the water column decreases the sharp nearsurface stratification and reduces the overall salinity of the upper water column. Moored conductivity measurements indicate that the decreased salinity persisted for at least 2 months after a major storm with additional freshwater inputs through the period. Four particulate groups contributed to the suspended particulate load in the water column: phytoplankton, resuspended sediments, and particles in treated sewage effluent were observed in every towyo mapping cruise; terrigenous particles are introduced through runoff from winter rainstorms. Terrigenous suspended particulate material sinks from the water column in <9 days and phytoplankton respond to the stormwater input of buoyancy and nutrients within the same period. The suspended particles near the bottom have spatially patchy distributions, but are always present in hydrographic surveys of the shelf. Temporal variations in these particles do not show a significant tidal response, but they may be maintained in suspension by internal wave and tide processes impinging on the shelf.

1. Introduction

A variety of natural and anthropogenic sources contributes to particle distributions on the continental shelves of urban regions. Natural sources of particles in the water column include phytoplankton, resuspended sediments, and surface runoff. In addition to natural sources, most coastal urban centers have major sewage outfalls where treated sewage is released through a diffuser system intended to limit the surfacing of the treated effluent. In addition to the treated human
waste, other contaminants can also enter the continental shelf through sewage outfalls. One example is the DDT found in the sediments near the Los Angeles County Joint Water Pollution Control Plant’s Whites Point ocean outfall. DDT was released through the Whites Point outfall until 1971, when the manufacture of DDT was banned in the United States. Additional anthropogenic contaminants and particulate material are released through stormwater runoff from watersheds that are dominated by the urban landscape (e.g., Bay et al., 1999), and through aeolian inputs.

Prior research on the Palos Verdes Shelf has shown that different sources of particles can be differentiated on the basis of the beam attenuation coefficient (c₆₆₀), chlorophyll fluorescence and salinity (Washburn et al., 1992; Wu et al., 1994). Three groups of particles were identified: phytoplankton, suspended particulate material associated with the effluent plume, and nearbottom particles attributed to resuspension. Results from these prior studies have suggested that nearbottom currents could be responsible for the resuspension and transport of sediments over the shelf (Washburn et al., 1992), but more recent research has indicated that besides the expected wave-induced resuspension (e.g. Cacchiione and Drake, 1990; Wiberg et al., 2002), internal solitary waves could play a significant role in resuspension events (Bogucki et al., 1997). In Santa Monica Bay, significant nearsurface turbidity plumes have been associated with the freshwater plumes from major rain events (Bay et al., 1999).

We focus in this paper on the hydrography and suspended particulate matter present in the water column over the Palos Verdes Continental Shelf. We address the spatial distributions of hydrographic variability and its seasonal transitions from late summer through late winter. The components contributing to the total load of suspended particulate matter in the water column, their spatial distributions, and seasonal changes that are evident are presented. We also examine short-term variations occurring spatially across the shelf during a 24-h period and the relationship of these changes to physical processes. The data set in this paper is from the period of September 1992–March 1993 when current meters, bottom tripods, and hydrographic mapping were utilized to evaluate the processes contributing to bottom resuspension and transport on the Palos Verdes Continental Shelf (Wiberg et al., 2002; Noble et al., 2002).

2. Methods

Current meter moorings, tripod deployments, and hydrographic mapping lines were employed in the study of the dynamics affecting the sediment near the Whites Point outfall diffusers and over the Palos Verdes Continental Shelf (Fig. 1). The current meter moorings and tripods were in place from December 1992–March 1993. Hydrographic mapping was done in September, December, January and March. Results from this paper include the observations from the tow tracks (T1–T5) and mooring B, the mid-shelf mooring located on the 60 m isobath upcoast from the outfall diffusers.

Spatial mapping of the hydrographic fields was accomplished by towyoing a CTD system behind the R/V Sea Watch at about 4 knots. The towyo mapping lines are indicated as T1–T5 in Fig. 1. A Sea-Bird 9/11 CTD system was used for the...
primary sensors (temperature, conductivity, and pressure), and additional sensors were logged through the CTD’s analog-to-digital conversion system. The additional sensors included a Sea-Tech chlorophyll fluorometer, a Sea-Tech beam transmissometer (25-cm pathlength, 660 nm wavelength), a Biospherical Instruments QSP-200L photosynthetically available radiation (PAR) sensor, and a Datasonics altimeter (30 m range). When the altimeter was on the package, we tried to obtain the profile between the surface and 2 m above the bottom. Without the altimeter, we generally tried to come no closer than 5 m above the bottom.

The tow vehicle carrying the above was winched in and out from the vessel at a rate of about 25 m/min to yield a zig-zag path through the water column. More detailed descriptions of the towyo and the towyo process are given by Washburn et al. (1992) and Wu et al. (1994). In this paper, tow tracks T1, T3, and T5 will be used to demonstrate the patterns of cross-shelf and long-shelf distributions. Although all tows were sampled during each cruise, examination of these three tows is sufficient to gain an understanding of the overall patterns on the shelf for the situations described herein. Thus, tow tracks T2 and T4 will not be discussed except for the 24-h time series along line T2 obtained in December 1992.

Data from USGS mooring B are used to describe the temporal variability of currents, temperature, salinity, and beam attenuation on the shelf (Fig. 1; Noble et al., 2002). Mooring B was a taut mooring with three current meter systems located near the surface (5 m), at mid-depth (31 m), and near the bottom (57 m). The near-surface current meter was an EG&G vector measuring current meter (VMCM) and the two deeper current meters were EG&G vector averaging current meters (VACM). All the current meters measured temperature. Additionally, the 5 and 31 m instruments included Seabird conductivity sensors for measurement of salinity. SeaTech 25 cm transmissometers were placed at 31 and 57 m to measure beam attenuation and inferentially suspended particulate load. Current vectors displayed within the paper are relative to 300°, the approximate orientation of the topography. Thus, currents toward 300° are upcoast and currents toward 120° are downcoast.

A bottom boundary layer tripod (BBLT) was deployed in 60 m of water off Long Point (Fig. 1). This tripod was deployed three times during the winter of 1992–93, each for a period of approximately 1 month. The tripod was equipped with four thermistors and three transmissometers located within 2 m of the bottom. Other sensors included Marsh–McBirney current meters, a Sea-Bird conductivity sensor, and chlorophyll fluorometer. Only the thermistor and transmissometer data are discussed in this paper. Data from these two sensors were acquired at a rate of 1 Hz for the entire deployment. The temperature and beam attenuation data were then averaged to 1-min intervals before performing statistical analysis.

The Sea Tech transmissometers used in this field study measured inherent optical property of the beam attenuation of light over the fixed path length of 25 cm at a wavelength of 660 nm. Beam attenuation, also referred to as $c_{660}$, is calculated from the light transmission in percent ($T$) by the relationship

$$c_{660} = -\ln(T/100)/L,$$

where $L$, the pathlength of the instrument, is 0.25 m. Bishop (1986) demonstrated that in the conditions characterized by suspended particles from a common source, the load of suspended particulate material is linearly proportional to the beam attenuation coefficient. Within this manuscript beam attenuation and $c_{660}$ will be used interchangeably.

### 3. Observations

#### 3.1. Summertime conditions

Observations from September 1992 provide a view of the hydrographic and particulate distributions over the Palos Verdes Shelf in the late summer when the water column is still well stratified. The region over the Palos Verdes Shelf was surveyed on September 15, 1992 over a period of about 12 h. Towyo sections T1, T3, and T5 (Fig. 1) are used here to provide an overview of the
hydrographic and particulate distributions over the shelf.

Off Pt. Fermin (Towyo T1), the water column was thermally stratified in the upper 20 m where nearshore (offshore) temperature decreased rapidly from $>16^\circ C$ (19$^\circ C$) at the surface to about 14$^\circ C$ at 10 m (20 m) (Fig. 2). Salinity increased monotonically with the depth from 33.2 to 33.28 psu in the upper 10 m to $>33.5$ psu at 100 m. When towyos T1 and T3 are compared, cooling and thinning of the upper layer are apparent toward Pt. Fermin. The alongshelf section, towyo T5, shows this even more clearly (Fig. 3). The alongshelf gradient suggests that some upwelling may occur near the southeast end of the peninsula. (Figs. 2 and 3)

Fig. 2. Cross-shelf towyo sections T1 off Pt. Fermin, and T3 near Long Point. Positions are as shown in Fig. 1. Towyo T1 occurred between 0848 and 0949 PDT; tow 3 occurred between 1342 and 1430 PDT. Distances in these plots is relative transect distance. The sea bottom is indicated by the black area in the lower right of the panels.
In all the sections obtained on September 15, a clearly defined chlorophyll maximum was observed at the base of the surface layer between 10 and 20 m depths (Figs. 2 and 3). This location is probably the region of the water column, where sufficient nutrient concentrations from deeper in the water column overlap with the euphotic zone, where there is sufficient light for photosynthesis to allow phytoplankton growth to occur (Cullen and Eppley, 1981).

Two additional particle types, a nearbottom turbidity layer and the sewage outfall plume, were present in the water column along all the lines sampled on September 15, 1992. Nearbottom high turbidity is present in the beam attenuation measurements from all lines (Figs. 2 and 3). However, in towyo T1 off Pt. Fermin, resuspension appears only at the nearshore end of the transect. Highest beam attenuation and, hence, suspended load occurred at water depths of <30 m, where the base of the thermocline (pycnocline) intersects with the bottom. Internal waves propagating along the pycnocline onto the shelf could interact with the bottom and cause resuspension in the nearshore region (e.g. Cacchione and Drake, 1986). Along all other transects including tows T2 and T4 (not shown), significant resuspension is apparent near the bottom in water depths up to 75 m.

Lower salinities and higher suspended particulate material at mid-depth in towpys T3 and T5 characterize suspended particulate material released from the Whites Point sewage outfall. In most transects, the outfall plume is centered between 20 and 30 m depths, beneath the seasonal pycnocline (Figs. 2 and 3). In towyo T1, there is a region located about 2.5 km offshore, 10 m depth and within the pycnocline where salinity is depressed, beam c is elevated, and chlorophyll is elevated as well. Conceivably, the effluent plume may have become trapped in the pycnocline, and as the pycnocline was elevated higher into the euphotic zone nearshore, phytoplankton grew within the patch utilizing the available nutrients.
contained within the plume water. But there is little other evidence of effluent plume water in towyo T1 (Fig. 2). Sections of salinity anomaly (not shown) indicate that there is little or no influence of the plume within towyo T1, but a large influence between 20 and 60 m in towyos T3 and T5.

The $T-S$ diagram in Fig. 4 shows two major regions within the data set. The deeper permanent pycnocline occurs at densities $>25 \text{ kg m}^{-3}$, where salinity increases and temperature decreases with increasing depth. The thermally stratified upper layer occurs at densities $<25 \text{ kg m}^{-3}$. This layer is comparatively isohaline (33.2–33.5 psu), except for a low salinity region at the interface with the permanent pycnocline, and a higher salinity region near the surface where temperature is $>18^\circ \text{C}$. The higher nearsurface salinities of nearly 33.3 psu may result from summer evaporation where the warm temperatures prevent convective overturning of the water. The lower salinity water near the interface of the upper and lower layers is the region of the effluent plume, where the effluent–seawater mixture has reached density equilibrium. This area is outlined with a black line in Fig. 4.

Three sources of particles account for the patterns observed during the late summer mapping of the Palos Verdes Shelf. In the right panel of Fig. 4, nearbottom resuspended sediments appear as beam attenuation coefficients greater than about $0.8 \text{ m}^{-1}$ at salinities $>33.3 \text{ psu}$. The higher salinities in this range correspond to deeper depths on the shelf (cf. Figs. 2 and 3). Phytoplankton are characterized by high chlorophyll fluorescence and salinities $<33.3 \text{ psu}$ within the upper layer and pycnocline. The region of the chlorophyll maximum where chlorophyll fluorescence was $>0.8$ is indicated by the box between 33.17 and 33.27 psu and beam attenuation $>0.8 \text{ m}^{-1}$. Particles from sewage effluent are indicated by the box that

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**Fig. 4.** Property-property relationships from towyos T1, T3 and T5 on September 15, 1992. The left panel shows temperature–salinity relationship and the right panel shows the beam attenuation ($c_{660}$)–salinity relationship. The various water mass regions and particle types are outlined and identified within the figure.
extends from beam attenuation coefficients of 0.49 m\(^{-1}\) to an upper bound of 0.92 m\(^{-1}\), at the boundary between the seasonal pycnocline and the permanent pycnocline (Fig. 4). Within the effluent plume, beam attenuation generally increases with decreasing salinity. The plume is especially evident in towyos T3 and T5 where salinity is low and beam attenuation is high between 25 and 40 m depths (Figs. 2 and 3), indicating upcoast dispersion from the outfall during the period of sampling.

3.2. Early winter structure and short-term variability

The Palos Verdes region was mapped on December 15, 1992 with four cross-shelf lines (T1–T4) and one longshore line (T5) shown in Fig. 1. The towyos on December 15 extended only from the surface to about 80 m, rather than 100 m depth as was done in September. During the shelf mapping period, the surface currents were \(<5\text{ cm}\text{s}^{-1}\) and reversed direction, perhaps due to tidal fluctuations in the longshore currents (Fig. 5). Mid-depth currents were mostly downcoast during the mapping phase of the sampling, but decreased to near zero during the last part of the day, especially during the period when we sampled the alongshelf line over the outfall. Currents near the bottom remained downcoast at speeds of \(10–20\text{ cm}\text{s}^{-1}\) throughout most of the 36 h of observations on the shelf. In addition to the mapping, line 2 was sampled at approximately hourly intervals for the 24-h period following the completion of the mapping (labeled “Diel Towyo” in Fig. 5). During that period, surface currents became strongly upcoast at \(10–20\text{ cm}\text{s}^{-1}\), and mid-depth currents also became upcoast for at least a part of the period (Fig. 5).

On December 15, the water column was continuously stratified below 20 m and weakly stratified in the surface layer that ranged from \(<10\text{ m}\) to \(\sim20\text{ m}\) thickness (Figs. 6–8). For the cross-shelf towyos there was a low salinity, turbid nearsurface layer nearshore (Fig. 6). This low salinity, turbid water may be the residual from a

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**Mooring Site B: Dec. 14–18, 1992 (GMT)**

![Graphs showing temperature, salinity, and beam attenuation over time](image)

**Fig. 5.** Four-day time series at mooring B for the period of December 14–18, 1992, centered on the towyo mapping study. The periods of mapping of the shelf (lines T1–T5) and the repeated towyo time series along line T2 (Diel Towyo) are indicated on the plots. The depth of the sensors for temperature, salinity and beam attenuation \((c_{660})\) is indicated by the line type as identified in the temperature panel. The current vectors are relative to 300°; upcoast is toward 300° and downcoast is toward 120°.
large rain event 8 days earlier when 7 cm of rainfall was recorded at the Los Angeles Civic Center. Chlorophyll fluorescence was highest within the upper layer. Although the concentration and distribution of chlorophyll was probably influenced by the rainfall through both nutrient and buoyancy inputs, there does not seem to be a strong coupling between the phytoplankton distribution and the low salinity, turbid nearshore water.

Effluent from the outfall is readily apparent in towyo sections T1 and T5 where salinities were <33.3 psu below 30 m depth (Figs. 6 and 7). This water was also characterized by a higher beam attenuation (>0.7–0.8 m⁻¹) similar to characteristics that have been previously documented for
the White’s Point outfall (Wu et al., 1994). Although the plume is not readily apparent in towyo T3, the $T/S$ relationship (Fig. 8) suggested that some effluent may be present over a broad area between 0 and 3.2 km transect distance and between 22 and 62 m depth.

Property relationships for the above transects are shown in Fig. 8. The most obvious differences from the September observations are the reduced temperature and salinity ranges. Temperatures are 4–5°C cooler than in September and salinities are not as high as those shown in Fig. 4. The lower temperatures in the surface layer are the result of seasonal cooling and the lower range of salinity at depths simply results from sampling only to 80 m in December compared with 100 m in September. The effluent plume is delineated from the background ambient water in both the $T/S$ and the $c_{660}/S$ plots. In the $T/S$ panel, points lying below and to the left of the line are waters that contain some effluents. The data that fit into the effluent portion of this figure are highlighted with white boxes in Figs. 6 and 7. The affected areas in towyos T1 and T5 are consistent with what we have already described. However, as stated above, the region of effluent-affected water in towyo T3 is much larger than the area that is immediately apparent from visual inspection of Fig. 7. This region probably contains residual plume that was advected upcoast from the diffuser prior to our sampling of the region. Two periods of upcoast flow occurred at both 31 and 57 m in the day prior to sampling (Fig. 5).

3.2.1. Short-term variations

From previous studies and from the observations presented above, a nearbottom turbidity layer of several meters thickness is often observed along some portion of the region under most conditions (Washburn et al. (1992); Wu et al., 1994). A fundamental question is how variable is this layer over time and what processes contribute to this variability. While fixed measurements from moorings and tripods resolve the temporal
variations well, they do not resolve the spatial variations well. To address this question we repeatedly sampled Line T2 adjacent to the USGS mooring and tripod array (Fig. 1), by towyoing back and forth across the shelf for 22.5h at approximately hourly intervals beginning at ~1930 PST on 15th December and continuing until 1800 on 16th December. The transects began 0.5–0.8 km from the shore, where the water depth was ~20 m and extended to about 4.5 km offshore from the coast, where the depth was >300 m. During this period 26 cross-shelf towyos along line 2 were completed.

Rather than present a detailed discussion of the time series, we summarize the observations with the average property distributions for the section and their associated variances (Fig. 9). The averages and variances were calculated by combining the data from all the towyos into 0.5 km × 5 m bins.

The water column was stratified in both temperature and density with a 20–40 m thick upper layer where temperature was >14°C and density was <24.8 kg m⁻³ (Fig. 9). A broad salinity minimum where salinity was <33.25 psu extended across the entire transect (Fig. 9). At the offshore end of the transect, this minimum was centered at about 30 m and within 3 km of the coast it extended to the surface. A thinner, narrower low salinity feature (S<33.2 psu) defines the core of the effluent plume that was located between 2 and 3.5 km offshore at a depth of about 30 m.

The particle distributions, as indicated by beam attenuation and chlorophyll fluorescence, show several patterns. Both chlorophyll and beam attenuation increase from the depth toward the surface indicating the distribution of phytoplankton (Fig. 9). The distribution of chlorophyll...
fluorescence is fairly uniform across the entire transect and accounts for only a portion of the variability in the beam attenuation. Between 2.5 and 4 km offshore, a beam attenuation maximum occurs between 20 and 40 m, coinciding with the subsurface salinity minimum. This region appears to be the mean location of the effluent plume during the 24-h study. High beam attenuation also occurs in the lower 10 m of the water column between 2.5 and 1 km offshore. Offshore of 2.5 km, a tongue of beam attenuation > 0.7 m$^{-1}$ extends offshore to almost 3.5 km in the depth range between 20 and 60 m. The nearbottom high turbidity and the tongue extending offshore are likely to be resuspended surficial bed sediments that are fairly light, easily resuspended, and remain in suspension sufficiently so that they can be advected away from the shelf. Nearshore beam attenuation > 0.9 m$^{-1}$ extends through the entire water column. The individual sections of beam attenuation (not shown) suggest that this nearshore region of high attenuation was separated from the nearbottom layer and was advected through the region.

The variances indicate the regions of maximum variation of the properties and provide indications of what processes may be contributing to the variance. All the properties have a higher variance in the region between 2 and 3.5 km, and between 50 and 70 m depth, the depth of the sharpest density gradient (Fig. 9), at the intersection between the upper layer and the top of the permanent pycnocline. Thus, internal waves and tides would contribute to vertical excursions of

Fig. 9. The mean and variance statistics for 26 tows obtained along line T2 during the period between 1927 December 15 and 1800 December 16, 1992 PST. The statistics are calculated based on all the data in boxes that are 0.5 km wide 5 m deep in the region between 1 and 4.5 km offshore.
this interface resulting in increased variance in all variables that have a gradient in this region. Salinity demonstrated a high variance between 2 and 4 km, 15 and 35 m depth, the region that we have attributed to the effluent plume based on the salinity minimum and a higher beam attenuation. During the study, the plume moved back and forth across the shelf with the variations in current speed and direction in the lower part of the water column (Fig. 5). In fact, the mooring record shows that a decrease of about 0.15 psu occurred at the 31-m instrument during the diel towyo study (Fig. 5). Chlorophyll fluorescence variance is greatest at about 20 m depth, at the base of the maximum chlorophyll fluorescence. Therefore, fluctuations in the depth of this base are the primary cause of this variance. The phytoplankton concentrations in the upper layer were spatially varying and much of the variance is due to advection of horizontally varying phytoplankton concentrations across the transect.

3.3. Effects of winter storms

The winter of 1992–93 was exceptionally rainy for the Los Angeles Region as >25 in of rain was recorded at the Los Angeles Civic Center. Rainfall is significant because it affects the density structure of the upper ocean and carries a large suspended particulate load and inorganic nutrients into the coastal ocean (Bay et al., 1999).

Eleven inches (28 cm) of rain fell during the period of January 6–18, 1993 (Fig. 10). Initially, small decreases in surface salinity were the primary indications of surface runoff in the coastal water over the Palos Verdes Shelf (Fig. 10). Beginning on January 13, surface salinity dropped to <32.5 psu and on January 18 values of <30 were observed briefly. Prior to January 13, salinity at 31 m showed no response to the rain events that began on January 6. During 7 days of rainfall beginning on January 12, salinity at 31 m decreased to about 33 psu and remained near 33 psu for the duration of the deployment. Suspended load, indicated by the beam attenuation coefficient, increased simultaneously with decreases in salinity at 31 m. While absolute values of the beam attenuation are questionable due to fouling of the transmissometer, the relative increase and spikiness during this period reflect increased suspended load at mid-depth in the water column.

On January 27, 9 days after the end of the rain event, a towyo mapping survey was conducted in the study area. Significant evidence of stormwater input into the coastal ocean was still present on the Palos Verdes Shelf. Evidence of the rainfall event was clearly shown in the mooring record where salinity at 5 m was 32.5–32.6 psu and salinity at 31 m was about 33.1 psu (Fig. 11). Although the nearsurface salinity depression was not as large as that on January 27–28 as it had been during the rainfall period of January 6–18, the 5 and 31 m salinities remained below their values prior to January 6 for the duration of the record.

Currents were upcoast throughout the water column during the period of the towyo mapping on January 27 (Fig. 11). Velocities at 31 and 57 m were approximately 20 cm s⁻¹. Vertical shear was small through the water column. The vertical gradients in both temperature and salinity resulted in a stratified water column on the day of the towyo mapping.

The towyo sections confirm the stratification indicated by the mooring for both temperature and salinity. Temperatures decreased from >15 °C nearsurface to 11 °C below 80 m (Figs. 12 and 13). Salinities were <33 psu above 20 m throughout the area. Both beam attenuation and chlorophyll fluorescence were high in the upper and low salinity layer.

Lack of a subsurface salinity minimum in towyo T1 suggests that the effluent was not present downcoast from the diffuser (Fig. 12). There is some evidence of plume evident in towyo T3, upcoast from the diffuser (Fig. 13). Effluent plume was observed at about 60 m along the 13 °C isotherm, where a small region of salinity <33.2 psu was observed (Fig. 12). The plume from the diffusers is more evident in the alongshelf section, towyo T5 (Fig. 13), where salinities <33.2 below 30 m extend upcoast, to the left in the figure, from the diffusers consistent with the current direction observed in the mooring record.

The property relationships for this set of sections indicate that temperatures <14.25 °C and salinities <33.2 psu characterize the effluent
Fig. 10. Time series of the rainfall at the Los Angeles Civic Center and temperature, salinity and beam attenuation from mooring B during the winter deployment from December 10, 1992 through March 30, 1993. As in Fig. 5, the depths of the measurements are indicated by the line type with is identified in the $c_{660}$ panel at the bottom. The beam attenuation in the bottom panel has not been corrected for drift due to lens fouling. The effects of fouling become evident beginning about June 30 for both the 31 and 57 m sensors.
plume (Fig. 14). Temperatures >14.25°C and salinities <33.2 psu characterize the recent stormwater runoff. Both freshwater sources have elevated beam attenuation coefficients, i.e. increased particulate and dissolved matter, but show distinct slopes and occur at different salinity ranges.

The highest beam attenuation coefficients occur at about 50m depth at the upcoast end (0–0.5 km) of towyo T5 (Fig. 13). This particular maximum is outside the low salinity water from the outfall plume and probably results from bottom resuspension. Other areas of resuspension were apparent in towyos T1 and T3 between nearshore and the 60m isobath.

Chlorophyll fluorescence, indicative of phytoplankton abundance, is usually highest within the upper 10m of the water column, where the stormwater-derived salinity minimum is present. During December the chlorophyll maximum was between 5 and 15 m. The chlorophyll fluorescence/salinity relationship for January shows that the highest chlorophyll concentrations coincide with the lowest salinities (Fig. 14). The chlorophyll fluorescence/c₆₆₀ plot shows two clearly defined regions: a correlated region of increasing fluorescence and increasing c₆₆₀ characteristic of phytoplankton; and a region of low fluorescence, but high c₆₆₀. The region of low fluorescence corresponds to both the outfall plume and resuspended sediments. The strong salinity/fluorescence relationship is probably the result of the addition of nutrients and stratification from the stormwater. When the stormwater initially enters the ocean, the particulate and dissolved matter associated with the runoff would attenuate sunlight rapidly and prevent initial phytoplankton growth. After the terrigenous suspended particulate matter sinks from the upper layer, phytoplankton growth would occur and result in a highly correlated negative relationship between c₆₆₀ and salinity.
4. Discussion

We have used moored and towed undulating observation methods to study the variability of currents, hydrographic characteristics, and particulate fields in the coastal ocean over the Palos Verdes Continental Shelf. Each of these methods allows us to examine a different aspect of the variability that is observed on the shelf.

4.1. Particulate groups

Four major particulate groups have been observed on the Palos Verdes Shelf using the sampling methods that we have employed. The four groups include phytoplankton, nearbottom suspended particles that are likely due to resuspension of lighter surficial sediments, particles in the sewage effluent, and terrigenous suspended...
Fig. 13. Alongshelf towyo section T5 along the 60 m isobath on January 27, 1993. The bars along the bottom centered at 2 and 4 km indicate the locations of outfall diffusers.

Fig. 14. Property relationships for towyos T1, T3, and T5 from the mapping cruise on January 27, 1993. The diagonal black lines in the T/S panel (top left) delineate the ambient water, stormwater runoff, and effluent plume. The other panels show particulate relationships with salinity and the chlorophyll fluorescence/c660 relationship.
particles that are transported into the region during major rain events. The methods for differentiating the particulate material over the shelf were discussed previously (Jones et al., 1991; Wu et al., 1994; Petrenko et al., 1997).

Phytoplankton are always present within the upper layer and are defined by regions, where high chlorophyll fluorescence is associated with elevated particulate concentrations. Their distributions change on a seasonal basis as a function of water mass variability and hydrographic stratification of the water column. During summer stratification, nutrient utilization by phytoplankton depletes nutrients from the surface layer and a subsurface chlorophyll maximum develops at a depth, where the euphotic zone and nutricline overlap (e.g. Mullin, 1986). On September 15, 1992, the chlorophyll maximum was located at a water temperature of \( \sim 14^\circ \text{C} \), or on the 24.8 kg m\(^{-3}\) isopycnal (Fig. 15). Various data sets indicate that nitrate becomes \(<1\mu\text{M}\) above \( \sim 14^\circ \text{C} \). Below this temperature, nitrate generally increases linearly with decreasing temperature (Dugdale et al., 1990; Jones et al., 1983; CalCOFI).

In December 1992 and January 1993, the chlorophyll maximum was nearer to the surface where water temperatures were 14.5–15\(^\circ\)C. The chlorophyll maximum in January occurred in the low salinity surface layer, where terrigenous runoff was present. We attribute this maximum to nutrient and buoyancy (stratification) input associated with stormwater. This situation is analogous to the blooms that occur in response to persistent river runoff (e.g. Lohrenz et al., 1999).

Resuspended sediments are the second naturally occurring particulate components that are present in all the observations from the Palos Verdes Shelf. This was first characterized by Washburn et al. (1992) in describing some initial studies from this region. In our observations, resuspended particulate material generally occurred within 5 m of the bottom. Evidence of resuspended sediments near the bottom was present in all our spatial maps (Figs. 2, 3, 6, 7, 9, 12 and 13). Levels of resuspended material were less during the periods when we performed spatial mapping than during some of the storm periods (e.g. Wiberg et al., 2002), since these were periods when the sea state was appropriate for sampling. Other papers in this volume discuss the temporal variability associated with storm events and the enhanced resuspension due to storm-induced waves (Wiberg et al., 2002; Sherwood et al., 2002).

The nearbottom particulates that we observe over the shelf have been observed over a range of current velocities. Washburn et al. (1992) suggested that this layer was caused by nearbottom shear of the typical currents. Because currents often have significant tidal components, we hypothesized that tidal fluctuations would account for the resuspension of this material. We calculated the power spectra for a 1-month record of temperature and beam attenuation from the BBLT near Long Point. The spectral analysis used 1-min averages of the 1 Hz data. The spectra (not shown) show significant tidal peaks for temperature, but no significant peaks for beam attenuation at tidal or higher frequencies. It is likely that these particulates are relatively light materials that are either easily resuspended or stay in suspension near the bottom and can be transported off the shelf by cross-shelf currents. Cacchione and Drake (1986) had also observed similar nepheloid layers near Newport Canyon. They proposed that shoaling and perhaps breaking of internal waves might cause this resuspension. The elevated beam attenuation and high variance between 40 and 60 m near the bottom during our 24-h study are at least consistent with this explanation.

The major anthropogenic source of suspended particulate load in the water column is the treated sewage discharged from the two outfall diffusers located on the Palos Verdes Shelf. This effluent has also been previously characterized and is identified by low salinity, increased beam attenuation and elevated nutrients at mid-depth in the water column (Jones et al., 1991; Washburn et al., 1992; Wu et al., 1994). Effluent can typically be resolved clearly in property plots as a region of negative salinity anomaly at mid-depth and negative beam attenuation–salinity relationships within this negative salinity anomaly (e.g., Figs. 4, 8 and 14).

Stormwater input has not been previously documented for the Palos Verdes Shelf, but it has a clear signature and significant effect on the
The primary characteristic of stormwater runoff is low salinity and high beam attenuation in the surface layer with little change in temperature as seen in the mooring time series (Fig. 10). Like sewage effluent, the beam attenuation coefficient increases with decreasing salinity. Unlike sewage effluent, this water is generally found at the surface and the slope of the salinity-$c_{660}$ relationship may differ from the sewage effluent relationship depending on the relative concentrations of suspended particulates in the source waters. On January 27, stormwater was ubiquitous in the surface layer over the shelf (Figs. 12 and 13). Stormwater penetrated 15–30 m into the water column based on the $T-S$ properties in Fig. 14. Evidence from stormwater plume studies in Santa Monica Bay indicates that the signature of stormwater plumes can be present for at least 3 days following a storm (Jones et al., 1997; Bay et al., 1999), but the results of the towyo measurements indicate that both the salinity and $c_{660}$ signatures of the stormwater plume can remain for a much longer period following a large rainfall event. Salinity measurements from mooring B suggest that the salinity signature can remain beyond the period indicated by the towyo measurements. Additional rain events may have contributed to the persistence of the salinity signature. The data set does not indicate how long the phytoplankton bloom lasted and contributed to the large beam attenuation signal.
4.2. Processes and scales affecting particulate groups

The shortest time scales (~1 h) that we can examine using the towyo data set come from the diurnal towyo series on December 15–16, 1992 along line 2 and mooring measurements (Figs. 5 and 10). This data set demonstrates significant variability in the water column over the course of 24 h. The region of highest variance for temperature, salinity, density, and beam attenuation was centered at about 60 m where the top of the permanent pycnocline intersected the upper layer. The second area of high variance was at the base of the chlorophyll maximum layer. Although some variation may occur due to diurnal fluctuations in photosynthesis and photoadaptation of the phytoplankton, advection probably accounted for much of the variability. The other area of higher variance was in the region affected by the sewage effluent plume. Both salinity and beam attenuation show some variance in the 20–40 m depth range, between 2 and 4 km offshore. These fluctuations are consistent with tidal and subtidal variations in current velocity and direction at mid-depth.

The mooring and towyo observations indicate that the signatures from surface runoff plumes can remain for periods in excess of 1 month for salinity and for at least several days for suspended particulate material. The towyo mapping on January 27th followed the major rain event on January 12–18, by 9 days. Within this 9-day period, terrigenous suspended particulate matter disappeared from the water column, presumably due to sinking. Simultaneously, a significant phytoplankton bloom developed within the runoff layer. For a brief period of time, the Palos Verdes Peninsula functioned as a coastal region with significant riverine input, where fresh, turbid, nutrient-enriched water enters the coastal zone and spreads out as a buoyant plume. As terrigenous SPM sinks out, water transparency increases, and phytoplankton growth results from the increased light and available nutrients (e.g., Lohrenz et al., 1999).

Water mass characteristics indicate seasonal changes in the water column from September 1992–March 1993. In September 1992, the water column was strongly thermally stratified (Fig. 15). The nearly isohaline upper layer extended to a density of about 24.8 kg m\(^{-3}\). For nearsurface where temperature was >18°C, salinity increased slightly due to evaporation. The major change in T–S characteristics from September to December is cooling of the upper layer by about 3°C. The maximum temperature on December 15 was <16°C compared to nearly 19°C on September 15. In both September and December, the plume was centered near the 24.9 kg m\(^{-3}\) isopycnal. On January 27, 1993, the plume occurred again on approximately the same isopycnal. The upper layer had cooled to an additional 0.6°C, and most strikingly, a nearsurface low salinity layer was present having a minimum salinity of <32.4 psu. This created a strongly stratified upper layer where density varied by >0.5 kg m\(^{-3}\) similar to the density range in the upper layer in September, but caused by salinity rather than temperature. Observations from March 18, 1993 have not been presented in this paper, but the T–S data are included in Fig. 15. By March 18, much of the low salinity water found in the upper layer had mixed downward in the water column to a density of 25 kg m\(^{-3}\), consistent with the conductivity observations in the current meter record of reduced salinity at 31 m (Fig. 10). The very low nearsurface salinity had disappeared, but the low salinity signature penetrated deeper into the water column thus influencing a greater part of the water column.

5. Summary

We have identified four sources of particulate material over the continental shelf of the Palos Verdes Peninsula that are associated with the water mass characteristics of the region. Phytoplankton occur in regions where there is a nutrient supply to the euphotic zone either from ambient nutrients beneath the surface layer or from seasonal input from runoff. Particles from the outfall effluent are associated with the low salinity signature of the plume and their distributions readily reflect the stratification and current varia-
bility over the shelf. The nearbottom turbid layer has been observed on numerous occasions. This layer does appear to advect seaward at times and indicates the potential for a broader dispersion of particles from the shelf. Terrigenous particles are most obvious during major storm events. The increase of beam attenuation associated with the freshwater input indicates a large suspended load from the runoff. The absence of this terrigenous suspended material in the low salinity surface layer after 9 days indicates that the suspended load has sunk from the water column thereby contributing to the short-term sediment flux. The nutrient input associated with the stormwater results in a phytoplankton bloom within the nearsurface stormwater plume. Although the bloom is a major source of particles within the water column, it may not be a major source of particulate input into the sediments compared with the direct inputs from stormwater and outfall effluent.

Much of the hydrographic variability in the upper layer is due to seasonal variations in insolation, air temperature, day length and seasonal rainfall. The seasonal transition from late summer to early winter reflects the loss of heat from the upper layer. Later, in winter, significant freshwater input reestablishes the stratification that was observed in late summer, but due to salinity stratification rather than temperature stratification.

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