# PHYSICAL-CHEMICAL CHARACTERISTICS AND ZOOPLANKTON BIOMASS ON THE CONTINENTAL SHELF OFF SOUTHERN CALIFORNIA

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## ABSTRACT

Between June 1978 and December 1984, temperature, salinity, and nutrient profiles, and data on total zooplankton biomass were collected monthly or bimonthly at nearshore stations (8-m to 75-m isobaths) throughout the Southern California Bight. Primary transects were located off Ormond Beach, Playa del Rey, Seal Beach, and San Onofre. Seasonal warming and cooling of nearshore water were generally coherent throughout the bight except near headlands where local upwelling plumes slowed spring warming by 1-2 months. Nitrate and nitrite were low throughout the water column from late summer through winter, except when strong downcoast winds caused coastal upwelling and strong cross-shelf gradients. During spring and early summer, mesoscale upwelling or longshore advection increased nutrient levels; summer thermoclines were underlain by cool, nitrate-rich waters that may be an important source of nutrients for the nearshore biological community. During spring and early summer, zooplankton biomass usually had a cross-shelf maximum at the 15-m to 36-m isobaths. Unusually warm water, as part of the 1982-83 El Niño phenomenon, was observed throughout the bight, with maximum anomalies occurring in fall 1983. Anomalously warm water persisted through most of 1984. Zooplankton biomass declined during 1983 and 1984, presumably in direct response to El Niño conditions or from reduced primary productivity. Our results and studies by others suggest that tidal mixing, internal waves, and local upwelling are important processes that distinguish the inner continental shelf of the Southern California Bight from waters farther offshore.

## RESUMEN

Los parámetros hidrográficos temperatura, salinidad, y nutrientes, y la biomasa total de zooplancton fueron muestrados mensual o bimestralmente entre junio de 1978 y diciembre de 1984 en varias estaciones costeras (8-75 m de profundidad) en la Bahía del Sur de California. Las estaciones principales están ubicadas frente a Ormond Beach, Playa del Rey, Seal Beach, y San Onofre. El calentamiento y enfriamiento estacional de las aguas costeras fue observado en toda la bahía excepto en aquellas áreas donde, a causa del relieve costero, eventos locales de surgencia retrasan en 1-2 meses el calentamiento primaveral.

Las concentraciones de nitratos y nitritos en la columna de agua fueron bajas en el período correspondiente a fines del verano y el invierno, excepto cuando los vientos fuertes, paralelos a la costa, indujeron afloramientos costeros y fuertes gradientes de concentración ubicados en forma perpendicular a la costa. Durante la primavera y comienzos del verano, los procesos de afloramiento costero o advección aumentaron las concentraciones de nutrientes. Debajo de la termoclina estival, se extendían aguas frías, ricas en nutrientes las cuales pueden ser una importante fuente de nutrientes para la comunidad biológica costera. Durante este mismo período, la biomasa de zooplancton presentó un máximo entre 15 y 36 m de profundidad.

Aguas anómalamente calientes fueron observadas en la bahía durante el fenómeno de El Niño de 1982-83, y las anomalías máximas fueron detectadas en el otoño de 1983. Estas aguas anómalas estuvieron presentes en la bahía durante la mayor parte de 1984. La biomasa de zooplancton disminuyó durante 1983 y 1984, probablemente como una respuesta directa a las condiciones vinculadas con El Niño o debido a una producción primaria reducida. La mezcla por la acción de las mareas, las ondas internas, y los afloramientos costeros parecen ser los procesos que diferencian las aguas de la plataforma continental de la Bahía del Sur de California de las aguas ubicadas mar afuera.

## INTRODUCTION

Nearshore current patterns, upwelling, and mixing processes make the zone within approximately 20 km of the coast of southern California a different marine environment from waters farther offshore. The California Current brings cool, low-salinity water south past Point Conception into the Southern California Bight (Jones 1971; Tsuchiya 1980). During April and May, this current extends farthest inshore, and flow throughout the bight is to the south (Jones 1971). During other months, a large counterclockwise gyre exists in the bight, with the southward-flowing California Current offshore and the northward-flowing

Southern California Countercurrent (SCC) inshore of the Channel Islands. However, a narrow nearshore current often exists within 10-20 km of the mainland California coast, distinct from the SCC (Tsuchiya 1980). Long-term surface flow of this nearshore current, ranging to 10 cm/s, is to the south, although near-bottom water flows northward during spring and summer (Winant and Bratkovich 1981).

Upwelling along the southern California coast has been recognized as an important process that transports deep, nutrient-rich water to the surface and thus increases local and regional productivity (e.g., Yoshida 1955; Jones 1971; Kamykowski 1974; Tont 1976; Eppley et al. 1979a; Dorman and Palmer 1981; Huyer 1983; Dykstra et al. 1984). Mesoscale upwelling, on a scale of hundreds of kilometers, is strongest from April to June (Jones 1971; Huyer 1983), when seasonal winds blow from the northwest, causing mass offshore transport of surface water through Ekman veering and replacement of nearshore surface water with deep water. Upwelling on this scale affects water conditions throughout the Southern California Bight; its influence on temperature and productivity are readily seen in satellite images (Lasker et al. 1981; Fiedler 1983, 1984). The region south of Point Conception is an area of especially intense upwelling on this scale (Fiedler 1983). Local coastal upwelling, which occurs within approximately 20 km of the shore, appears to be a major factor influencing water conditions on the inner part of the continental shelf. Dorman and Palmer (1981) summarized much of the information on coastal upwelling off southern California and described the frequency and geographic extent of summer upwellings. They found that strong coastal upwelling events, with temperature drops over 5°C, tend to occur twice each summer and are forced by local wind blowing downcoast. Stations from Balboa to San Diego experienced coastal upwelling simultaneously; areas farther north also had summer upwelling, but these events did not necessarily coincide with strong upwelling in the southern part of the bight. Upwelling events were highly correlated with strong downcoast winds (Dorman and Palmer 1981), which did not have the same intensity or direction at Los Angeles and San Diego. Downwelling events, associated with northward-moving tropical storms, tend to occur once or twice each summer (Winant 1980).

Increased tidal action on continental shelves (Riley 1967) and frequent internal waves off southern California (Armstrong and LaFond 1966; Cairns 1967; Zimmerman and Kremer 1984) also seem to be important mechanisms causing vertical and horizontal mixing, particularly within 40-50 km of the coast (Yoshida 1955). Nutrient transfer into the euphotic zone is probably the most important consequence of these mixing processes. Zimmerman and Kremer (1984) found seasonal and twice-daily components of nutrient availability near Santa Catalina Island. Frequent upward excursions of cold, nutrient-rich water were of short duration but may be important to some shallow-water species such as kelp, particularly during periods of very low nutrient concentrations (Zimmerman and Robertson 1985).

Freshwater flow from rivers and streams into the Southern California Bight is small, and rainfall is only 25-40 cm/yr; thus terrigenous nutrient input is generally low except during occasional winter storms. Large sewage outfalls are located at Santa Monica Bay, Palos Verdes Peninsula, Huntington Beach, and Point Loma, with total flows of $0.5 \times 10^6$ to $1.4 \times 10^6$ $m^3$/day (Meistrell and Montagne 1983). Other potential sources of nutrient input include tidal and subtidal flux of groundwater (Johannes 1980), refinery outfalls, and significant *in situ* regeneration (Harrison 1978; Eppley and Peterson 1979; Eppley et al. 1979b; Barnett and Jahn, in press). Nutrient input from these sources may be significant at specific sites or times.

Few long-term studies of physical and biological oceanography have been conducted in the nearshore habitat off southern California. Some exceptions are studies of temperature and currents near the shore (e.g., List and Koh 1976; Tsuchiya 1980; Winant and Bratkovich 1981), as well as work by Eppley and coworkers, who have examined nutrients and primary productivity in the Los Angeles to San Diego region. Most data collected within 20 km of the coast have been from shore monitoring stations (e.g., National Ocean Survey, Scripps Pier) or through short-term projects that address specific biological or physical questions (e.g., Cairns and Nelson 1970; Kamykowski 1974; Eppley et al. 1978; Fiedler 1983; Dykstra et al. 1984). In contrast, the CalCOFI program has been collecting physical, chemical, and biological data since 1949 in a grid off California and Baja California, Mexico (approximately 20-400 km from shore). The extensive CalCOFI data base has been used in studies of zooplankton (e.g., Fleminger 1964; Colebrook 1977), physical and biological interactions in the California Current (Bernal and McGowan 1981; Chelton et al. 1982), larval fish populations (e.g., Ahlstrom 1969; Smith and Lasker 1978; Loeb et al. 1983) and many other topics. Long-term data series, similar to the CalCOFI data set, should be valuable in understanding the coupling of biological and physical processes in the shallow nearshore zone (see Denman and Powell 1984).

This report presents physical, nutrient, and zooplankton biomass data collected in the nearshore zone of the Southern California Bight. Longshore and cross-shelf patterns will be described, and physical processes that may have caused observed patterns will also be considered. Interaction of local and oceanic processes in the Southern California Bight in determining nearshore conditions will also be discussed. "Nearshore" refers to the narrow coastal band between the 8-m and 75-m isobaths—roughly 1-20 km from the shore. "Offshore" means the region of ocean between 20 and 400 km off southern California—the area regularly sampled by CalCOFI. Some general descriptions of currents, temperature variation, and coastal upwelling in offshore waters of the Southern California Bight may be found in Sverdrup and Fleming (1941), Jones (1971), Hickey (1979), Tsuchiya (1980), and Dorman and Palmer (1981).

## METHODS

Physical-chemical and zooplankton data were collected in conjunction with a program to monitor nearshore ichthyoplankton distributions in southern California waters (Lavenberg et al. 1986). Ten transects, from Point Conception to the U.S.-Mexican border, were sampled monthly from June 1978 to July 1979 (Brewer et al. 1981). Between August 1979 and July 1980, 20 transects, including the 10 of the previous year, were also sampled monthly (Figure 1). Coordinates and descriptions of these early transects can be found in Brewer and Smith (1982). Sampling was sporadic from August 1980 until February 1982, when bimonthly sampling on four transects began (Figure 1; Table 1). Most data presented in this report were collected during 1982-84, although some temperature and salinity measurements from 1978 to 1980 are included.

During the first 26 months of the program (1978-80), two to four stations per transect were occupied (8-, 15-, 22-, and 36-m isobaths). Beginning in 1982, a fifth station at the 75-m isobath was added on each transect. Coordinates for the twenty stations occupied during 1982-84 are listed in Table 1. Temperature, salinity, oxygen, pH, nitrate, nitrite, ammonium, phosphate, and silicate data were collected from surface and depths of 2, 4, 6, 8, 10, 15, 22, 30, 36, 50, 70, and 75 m.

Temperature was measured with a Martek water quality analyzer (Mark IV) or reversing thermometers attached to Niskin bottles, which collected water samples from discrete depths. Water samples from depth were analyzed on board for salinity (Beckman induction salinometer model RS7-C), dissolved oxygen (Yellow Springs Instruments model 51A), and pH (Orion Research ion analyzer model 407A). Nutrient samples were frozen at sea and later processed by the University of Southern California Ecosystems Group using a Technicon autoanalyzer (model II).

TABLE 1
**Coordinates of Stations Occupied, 1982-1984**

| Transect (CalCOFI line) | Station (m) | N. latitude | W. longitude |
|---|---|---|---|
| Ormond Beach (84.7) | 8 | 34°07.5′ | 119°16.6′ |
| | 15 | 34°07.0′ | 119°11.0′ |
| | 22 | 34°06.6′ | 119°11.7′ |
| | 36 | 34°06.0′ | 119°12.8′ |
| | 75 | 34°04.5′ | 119°11.9′ |
| Playa del Rey (86.8) | 8 | 33°57.0′ | 118°27.1′ |
| | 15 | 33°57.0′ | 118°27.9′ |
| | 22 | 33°56.9′ | 118°28.6′ |
| | 36 | 33°57.0′ | 118°30.1′ |
| | 75 | 33°57.2′ | 118°34.0′ |
| Seal Beach (88.4) | 8 | 33°42.4′ | 118°04.3′ |
| | 15 | 33°41.2′ | 118°04.8′ |
| | 22 | 33°39.6′ | 118°05.1′ |
| | 36 | 33°37.3′ | 118°05.7′ |
| | 75 | 33°34.8′ | 118°08.9′ |
| San Onofre (90.9) | 8 | 33°21.7′ | 117°33.8′ |
| | 15 | 33°20.9′ | 117°34.1′ |
| | 22 | 33°20.4′ | 117°34.7′ |
| | 36 | 33°19.9′ | 117°35.0′ |
| | 75 | 33°18.5′ | 117°35.6′ |

Specific density (sigma-t) was calculated from temperature and salinity data using formulae given in Millero and Poisson (1981, 1982). Surface temperature "anomalies" (STA) were calculated as the difference between average cross-shelf temperature (8-m to 75-m isobaths) and the long-term (20-24 years) surface temperature for the day of the year at a nearby shore station. Long-term daily temperatures were computed from monthly means (Tekmarine 1983) by linear interpolation.

Wind-driven coastal upwelling was estimated by using an index of mass transport, $M(x)$ (Bakun 1975; Bowden 1983), computed from average daily wind speed. Wind data were from Los Angeles International Airport (NOAA 1984) near the Playa del Rey transect. Alongshore wind vectors were computed for the Southern California Bight assuming a shoreline angle of 129° from true north (Bakun 1975), and upwelling indices were computed from these vectors. Shore angle at the four major transects varies between 120° at Ormond Beach and 135° at Seal Beach, so Bakun's shoreline angle was a reasonable approximation.

Zooplankton displacement volumes were estimated from samples collected with 70-cm-diameter bongo nets (333-micrometer Nitex mesh) that were towed obliquely from the bottom to the surface (Brewer and Smith 1982). Adult and large juvenile fishes, squid,

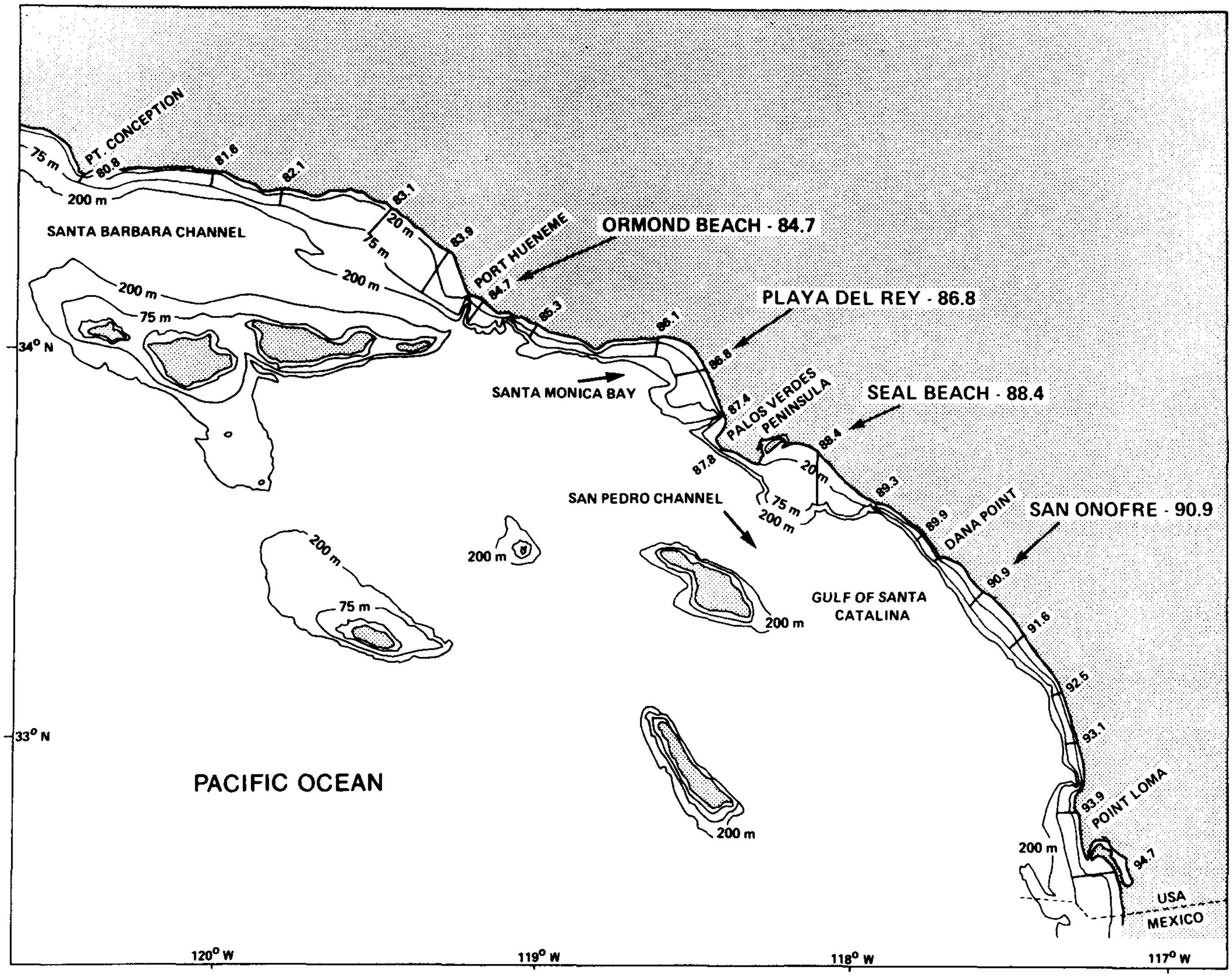

Figure 1. Location and CalCOFI numbers for all transects sampled between 1978 and 1984 in the Southern California Bight.

octopuses, and large algae were removed from fixed (buffered 5% Formalin) samples and were not considered in the volume estimates. Sample volume was adjusted to a standard level, and zooplankton was removed by draining the sample through 333-micrometer Nitex mesh. Using a buret, we added enough Formalin to the Formalin filtrate to reach the standard volume. The volume of Formalin added from the buret equaled net zooplankton displacement volume.

## RESULTS

### *Temperature and Salinity*

Seasonal warming of surface waters during spring and early summer was not synchronous throughout the bight. At Ormond Beach, seasonal warming began about 1-2 months later than at Playa del Rey, Seal Beach, and San Onofre, whose cycles coincided closely (Figure 2). Surface temperature in the nearshore zone was highest in August for all years studied, except 1983, when maximum temperatures were recorded during the October cruises (Figure 2). Annual low temperatures generally occurred during January or February, although unseasonably cold water, corresponding to intense upwelling periods, was occasionally encountered during spring or summer. Seasonal minimum water temperatures occurred at about the same time throughout the bight during any given year (Figure 2).

A spring-summer thermocline has been described for shallow water off southern California (Cairns and Nelson 1970). Surface temperatures increased by about 1°-3°C at almost all stations between April and June (Figure 2), probably as the result of solar warming and reduced mixing. Temperature near the bottom of the water column generally declined by a few degrees as surface temperatures rose (see also Winant and Bratkovich 1981). During fall and winter, nearshore water

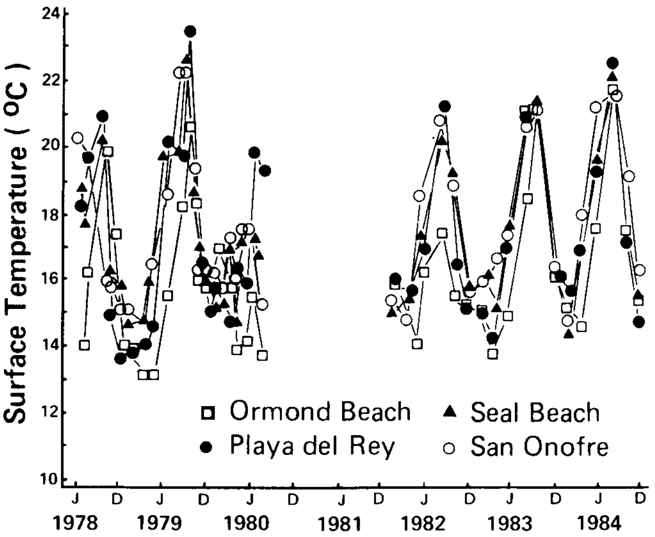

Figure 2. Average cross-shelf surface temperature at major transects. Some data points are hidden.

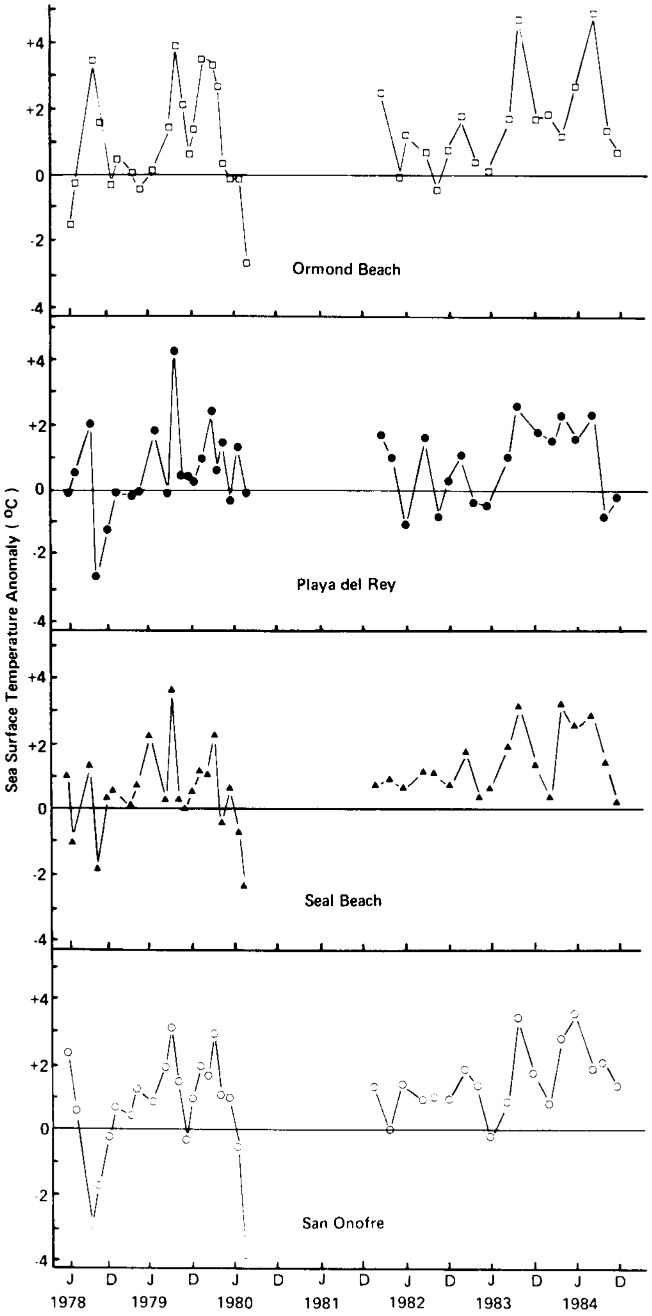

Figure 3. Sea-surface temperature anomalies at major transects.

was well mixed, and temperature and salinity were similar from the surface to the bottom.

Several anomalous (nonseasonal) warm and cool periods can be identified in transect temperature records collected between 1978 and 1984 (Figure 3). During September 1979, surface temperature anomaly (STA) was + 3° to + 4°C at all transects. During July 1980, temperatures were particularly low, being 2°-4°C below average, except at Playa del Rey, where temperatures were near the long-term average. Nearshore temperatures were only slightly above normal in the fall of 1982, and STAs during February 1983 ranged from + 1.1° to + 1.8°C. Unusually warm water was found during fall 1983 and again during spring and summer 1984; surface temperature was near normal during other periods. Of course, resolution of the start and end of these phenomena is fairly coarse, being limited by the sampling frequency of 30-60 days.

Temperature-salinity (T/S) relationships were examined to determine water mass origins, particularly during the 1982-83 El Niño. We selected October for comparison because the largest positive STA occurred in October 1983 (Figure 3), indicating strong El Niño conditions. We used long-term averages of temperature and salinity from a shallow CalCOFI station (approximately 200 m deep; number 90028 off Dana Point) to construct a reference T/S curve (Figure 4). During October 1979 and October 1984, temperature (surface to 75 m) ranged from about 12°-20°C, and salinity averaged around 33.8‰. In October 1982, temperature was similar to 1979 and 1984, but salinity had declined to about 33.4‰. This reduced salinity may have been caused by (1) diluted surface water from a rainstorm that immediately preceded sampling of the Playa del Rey and Ormond Beach transects, or (2) movement of a low-salinity water mass into the area, possibly from the north. During October 1983, when surface temperature anomalies were greatest (Figure 3), the overall temperature range had increased about 2°C over 1979, 1982, and 1984. Salinity was as low as 33.0‰ in some samples collected in October 1983 (Figure 4), suggesting a different water mass during this period. Mean salinities in the upper 50 m from June-December 1984 cruises, and preliminary data from 1985, were similar to "usual" (non-El Niño period) salinities, ranging from 33.53-33.78‰

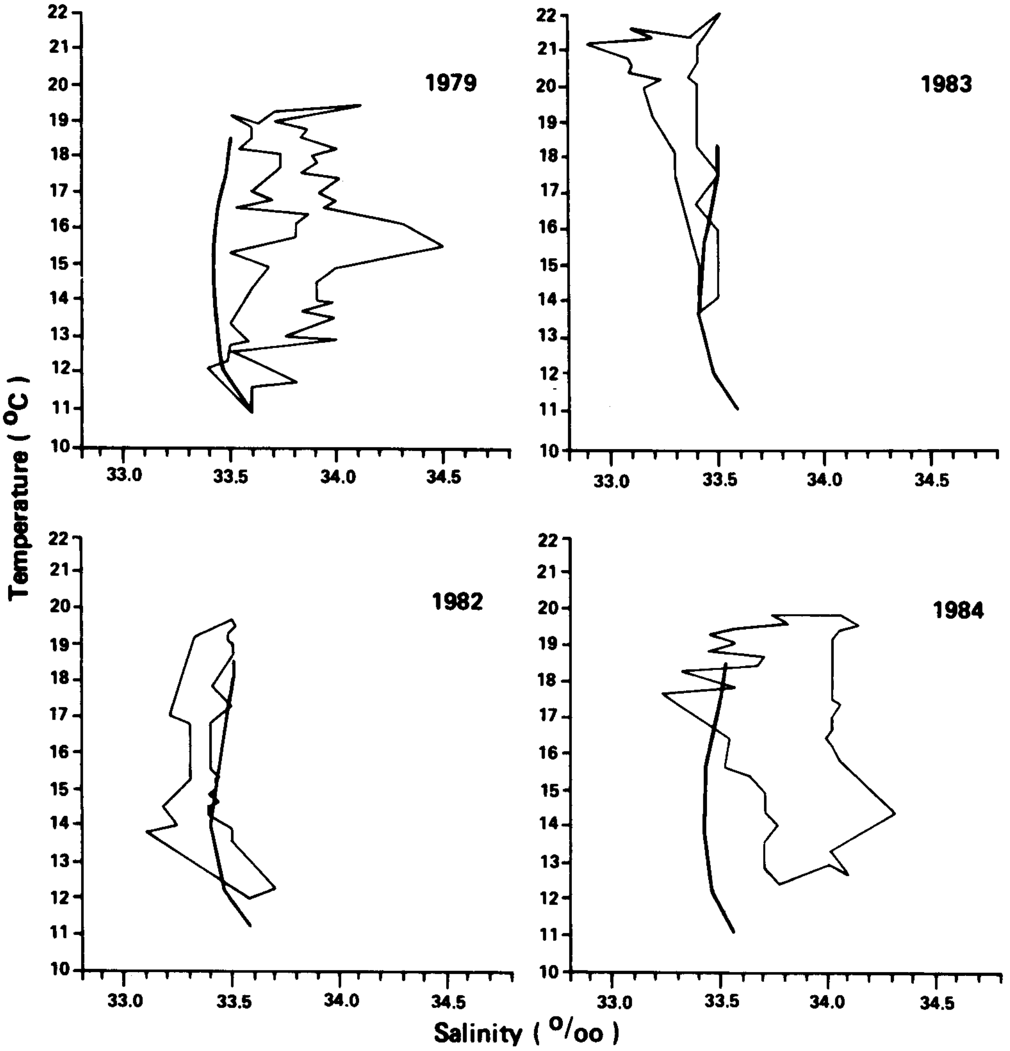

Figure 4. Temperature-salinity envelopes for October of 1979, 1982, 1983, and 1984, using data from all four major transects. The heavy line is the long-term T/S curve for CalCOFI station 90028 (data from Lynn et al. 1982).

### *Nutrients*

Because nitrogen is the principal limiting nutrient of primary production in coastal waters, ammonium and nitrate distribution patterns will be emphasized. Enrichment experiments have shown that nitrogen increases algal growth and reproduction in the ocean, with very dramatic increases on the continental shelf (e.g., Ryther and Dunstan 1971; Eppley et al. 1979a; Laws and Redalje 1979). Eppley et al. (1979a), working from 0.9-107 km off the coast of southern California, demonstrated that nitrate is a major factor regulating the standing stock and production of phytoplankton in the euphotic zone. Also, concentrations of major nutrients (nitrate, phosphate, silicate, carbonate carbon) and several trace metals are linearly related to each other (e.g., Redfield et al. 1963). "Nitrate" values reported here are nitrate plus nitrite; nitrite concentrations were generally much less than nitrate concentrations, usually 5%-20% of the total nitrate-plus-nitrite value.

We calculated average ammonium and nitrate in the upper 15 m of the water column to examine longshore and temporal patterns. We selected the upper 15 m to allow computations at four cross-shelf stations (15, 22, 36, and 75 m) and so all samples would be within the euphotic zone (Jackson 1983). Station depth was not a significant factor affecting these 15-m-deep averages for nitrate (3-way ANOVA, depth not significant at $P = .05$), so we averaged means from across the shelf. Ammonium concentrations were significantly higher (3-way ANOVA, $P < .05$ for station effect) at the 15-m isobath (0.45 $\mu$g-atoms·$l^{-1}$) than at deeper stations (0.37-0.38 $\mu$g-atoms·$l^{-1}$). This cross-shelf difference was probably caused by inclusion of a "bottom" datum in 15-m means at the 15-m station, since ammonium concentrations have been shown to be higher near the bottom (Eppley et al. 1979b; Barnett and Jahn, in press). Since the cross-shelf ammonium differences were relatively small compared to the expected precision of measurements in this range (approx. 0.1 $\mu$g-atoms·l$^{-1}$; Eppley et al. 1979b), we also averaged 15-m deep ammonium means across the shelf.

Ammonium is an important source of nitrogen for plant growth in the Southern California Bight, representing about 40% of the sum of ammonium, nitrate, and urea-N assimilation by phytoplankton (McCarthy 1972; Eppley et al. 1979b). Ammonium concentration is often low relative to other nitrogenous forms because of its rapid recycling by phytoplankton. Ammonium concentrations and patterns that we observed were similar to results of other studies in the nearshore zone of southern California (Eppley et al. 1979b; Barnett and Jahn, in press). Mean concentration of ammonium between mid-1982 and December 1984 was 0.39 $\mu$g-atoms·l$^{-1}$, and there was no obvious seasonal pattern (Figure 5). Highest concentrations (2-3 $\mu$g-atoms·l$^{-1}$) were observed within Santa Monica Bay in December 1982 and February 1983, although concentrations up to 5-20 $\mu$g-atoms·l$^{-1}$ were observed by Eppley et al. (1979b) in this area in 1974-77. These differences were probably the result of station location within Santa Monica Bay and local current patterns, since sewage and refinery wastes were suggested sources of high ammonium concentrations in 1974-77 (Eppley et al. 1979b). Lowest ammonium levels were observed at three of the four transects in October 1983, during a period of unseasonably warm water (Figures 2 and 3).

Nitrate concentrations were often less than 1.0 $\mu$g-atoms·l$^{-1}$ at the surface (Figure 6), except during periods of strong upwelling. Such low concentrations in surface waters have been noted previously (e.g., Eppley et al. 1979a; Zimmerman and Kremer 1984) and may be a result of phytoplankton's rapid use of nitrate within the euphotic zone. Macroalgae, such as the giant kelp (*Macrocystis pyrifera*), are also a large sink for nutrients in the littoral zone (Jackson 1977). Profiles of nitrate at Seal Beach (Figure 6) were typical of profiles at the other three transects and will therefore be used to describe the general onshore-offshore and seasonal trends. Between August 1982 and February 1983, nitrate profiles along the Seal Beach transect were similar, with low concentrations throughout the water column at the inshore stations (8-36 m). Profiles at 75 m had low levels down to about 40 m and a significant nitrate pool (bottom cencentrations to 15.5 $\mu$g-atoms·l$^{-1}$) below 40 m (Figure 6). During the April and June 1983 cruises, the nitracline became shallower, and high nitrate concentrations were thus observed near the bottom at the 75-, 36-, and 22-m isobaths.

Nitrate levels were low from the surface down to at least 75 m during late summer to early winter of 1983. The nitracline observed during August to December 1983 was deeper, and therefore the nutrient pool was farther offshore than during the same period of 1982. Sampling at Seal Beach during February 1984 followed a strong wind event that produced intense nearshore upwelling of cold water. Finally, nitrate profiles taken in April 1984 were fairly similar to those of the previous year, with high concentrations near the bottom at 75-m and 36-m stations and moderately low levels at shallower stations. We discarded nutrient data from June to December 1984 because of equipment malfunction.

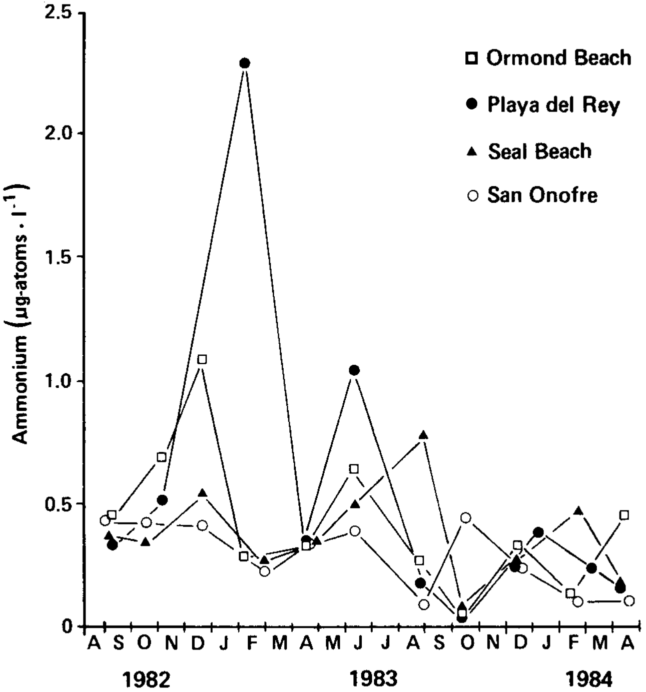

Figure 5. Average ammonium in the upper 15 m at major transects. Each point is a cross-shelf average of 15-m, 22-m, 36-m, and 75-m stations.

The temporal pattern of average nitrate suggests two major periods or events of increased nitrate concentration (Figure 7). First, three of the four transects showed increased nitrate levels during the early summer of 1983. At the Playa del Rey transect, nitrate levels increased steadily from August 1982 to a high of over 3.0 $\mu$g-atoms·l$^{-1}$ in early June 1983, whereas nitrate at Ormond Beach and San Onofre showed significant increases between April and June 1983. Nitrate at Seal Beach was relatively constant during spring-summer of 1983. Closer examination of the data indicates that increased nitrate levels at Ormond Beach, Playa del Rey, and San Onofre between April and June 1983 primarily resulted from increased concentrations in the lower part of the 15-m water column. Nitrate increased near the bottom at almost all stations of these three transects, while near-surface (surface-to-6-m) levels remained low and similar from April to June.

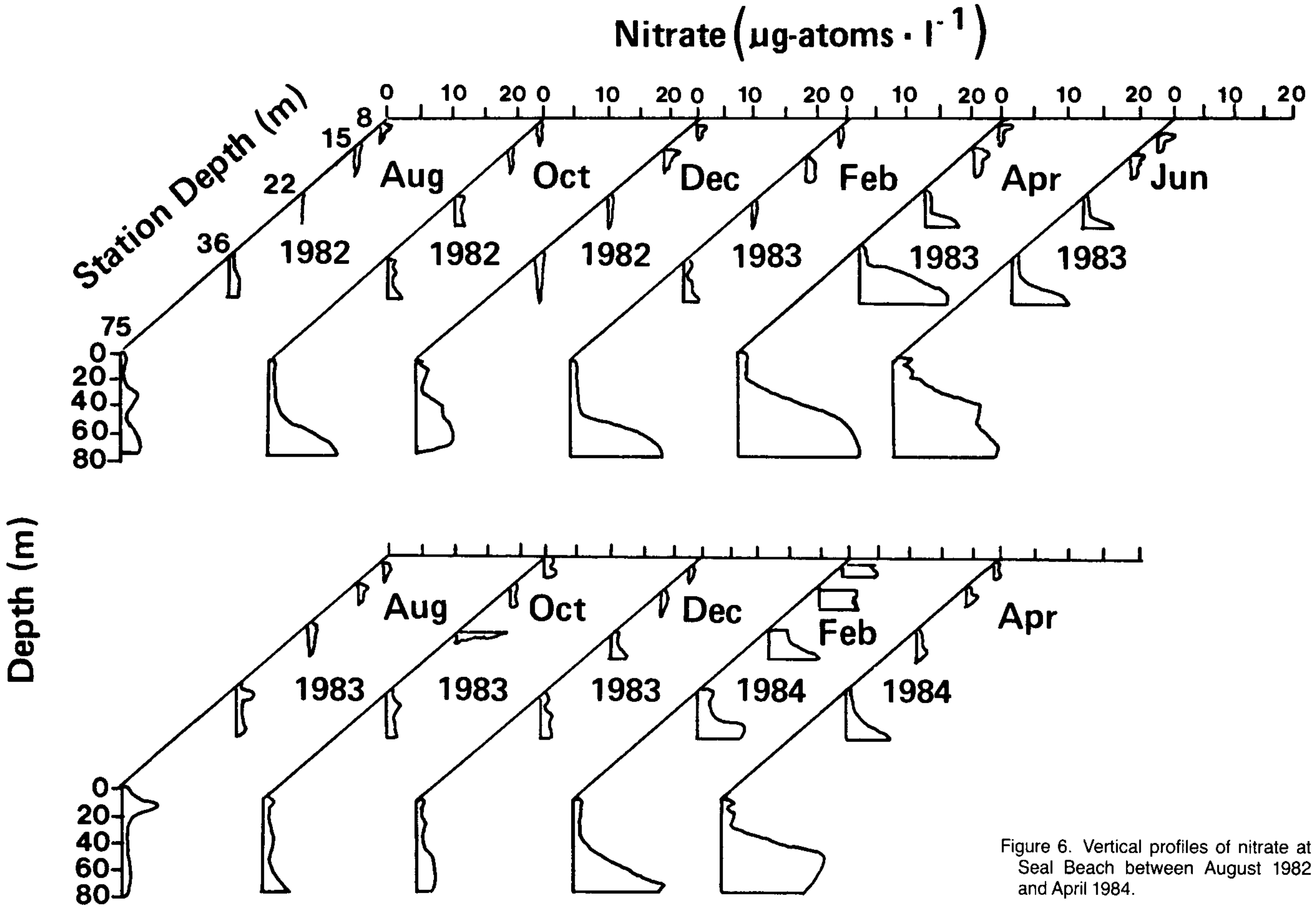

Figure 6. Vertical profiles of nitrate at Seal Beach between August 1982 and April 1984.

The second period of increased nitrate levels occurred during February 1984 (Figure 7). Nitrate increased slightly at Ormond Beach and San Onofre between December 1983 and February 1984 but showed a dramatic rise at Seal Beach—from 0.3 µg-atoms·l$^{-1}$ to 5.5 µg-atoms·l$^{-1}$ at the 15-m isobath. Bightwide sampling during February 1984 was interrupted by a strong, brief windstorm that caused nearshore upwelling and significant cross-shelf gradients in temperature, salinity, and nutrients. Normal sampling protocol called for the ship to begin on the northernmost transect (Ormond Beach) and proceed south to successive transects over a period not to exceed 10 days. Ormond Beach was sampled on February 15, 1984, but strong winds and heavy seas forced the ship off the scheduled Playa del Rey transect, which was finally sampled on March 7. Average daily wind speed at Los Angeles International Airport (LAX) increased from 2.8 m/sec on February 15, 1984, to 7.9 m/sec on February 16 (NOAA 1984). Winds remained strong on February 17, averaging 6.8 m/sec. During the storm, the wind blew steadily from the northwest. Winds from this direction were parallel to the shoreline of the Southern California Bight and produced strong offshore transport of nearshore surface waters, as suggested by the upwelling index calculated for this period (Figure 8). Seal Beach and San Onofre transects were sampled soon after the wind event, on February 20 and 22, respectively.

Specific density (sigma-t) and nitrate profiles at Seal Beach (Figure 9) for the February 1984 cruise indicate intense movement of surface water away from the shore and replacement of this water from depth. Water from the 8-m station was significantly more dense than

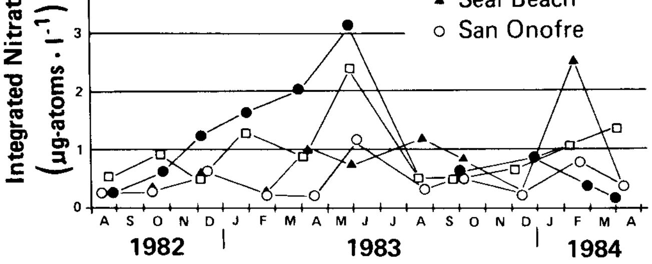

Figure 7. Average nitrate in the upper 15 m at major transects. Each point is a cross-shelf average of 15-m, 22-m, 36-m, and 75-m stations.

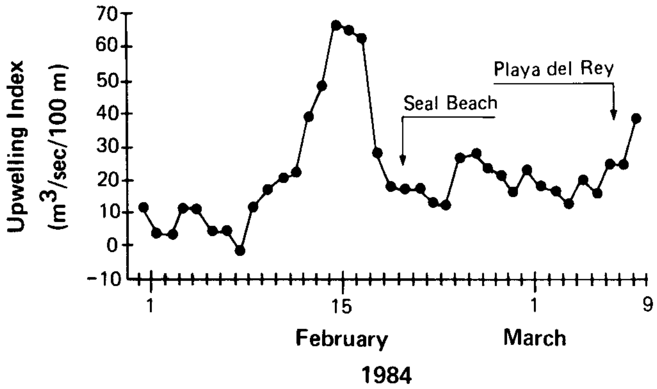

Figure 8. Upwelling index, $M(x)$, during cruise 47. Each point is a 3-day running average. Dates when the Seal Beach and Playa del Rey transects were sampled are indicated. $M(x)$ was computed from daily wind data at Los Angeles International Airport and has units of cubic meters per second per 100 m of coastline.

water from similar depths farther offshore, and isopycnal lines showed strong inshore sloping. Nitrate in near-surface water reached very high levels (5.1 µg-atoms·l$^{-1}$) at 8 m, while comparable surface water over the 75-m contour had only 0.7 µg-atoms·l$^{-1}$, a more typical concentration for the coastal zone during winter (Kamykowski 1974; Eppley et al. 1978; unpublished data; see Figure 7).

To assess the persistence of local upwelling caused by the storm of February 15-17, we compared the vertical structure of the water column at the Playa del Rey transect with Seal Beach profiles. The continental shelf is similar at these transects (Figures 1, 9, and 10), although Seal Beach is located just south of a large headland, the Palos Verdes Peninsula, in a semipermanent upwelling area (Dorman and Palmer 1981; Dykstra et al. 1984). Winds at Seal Beach and Playa del Rey during and after this wind event were compared using the alongshore component of daily winds (NOAA 1984) measured at LAX and Long Beach Airport, near Seal Beach. The alongshore wind components, which may cause upwelling or downwelling, were significantly correlated ($r$ = 0.73; $P$ <.001) between LAX and Long Beach Airport for February and early March 1984, implying that wind speeds and directions in the nearshore zone were similar during this period. Profiles of sigma-t and nitrate from the Playa del Rey transect, measured 17 days after the storm and following a relatively calm period (Figure 8), indicate that the effects of the windstorm were short-lived, since near-coast water conditions were stable and there were no indications of upwelling (Figure 10).

Infrared satellite images showing relative sea-surface temperature suggest that nearshore upwelling was widespread in the Southern California Bight during the mid-February 1984 windstorm (Figure 11). Just

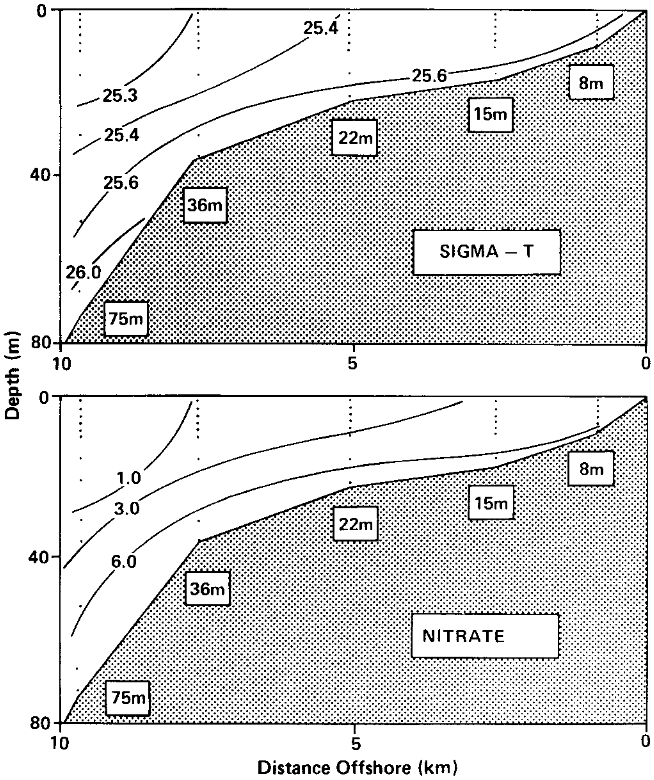

Figure 9. Cross-shelf distribution of sigma-t and nitrate (µg-atoms·l$^{-1}$) at Seal Beach on February 20, 1984.

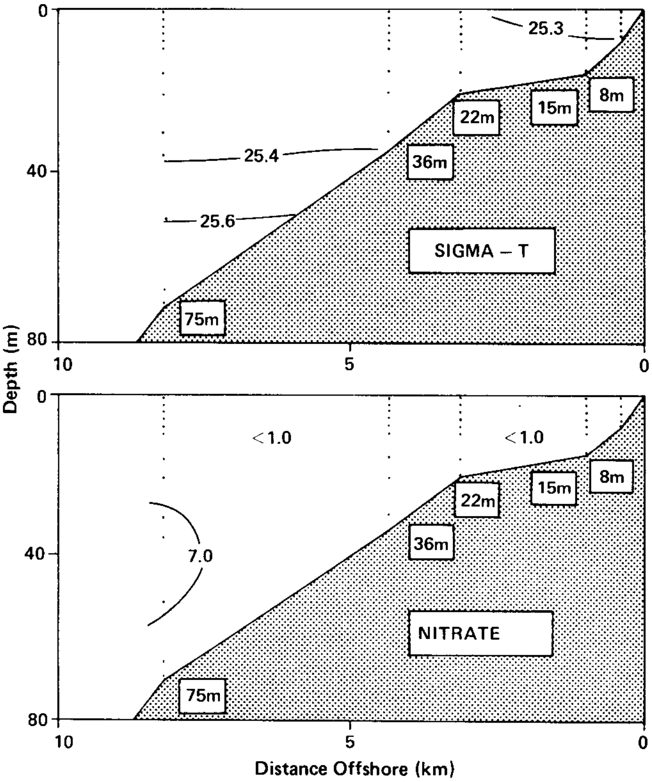

Figure 10. Cross-shelf distribution of sigma-t and nitrate (µg-atoms·l$^{-1}$) at Playa del Rey on March 7, 1984.

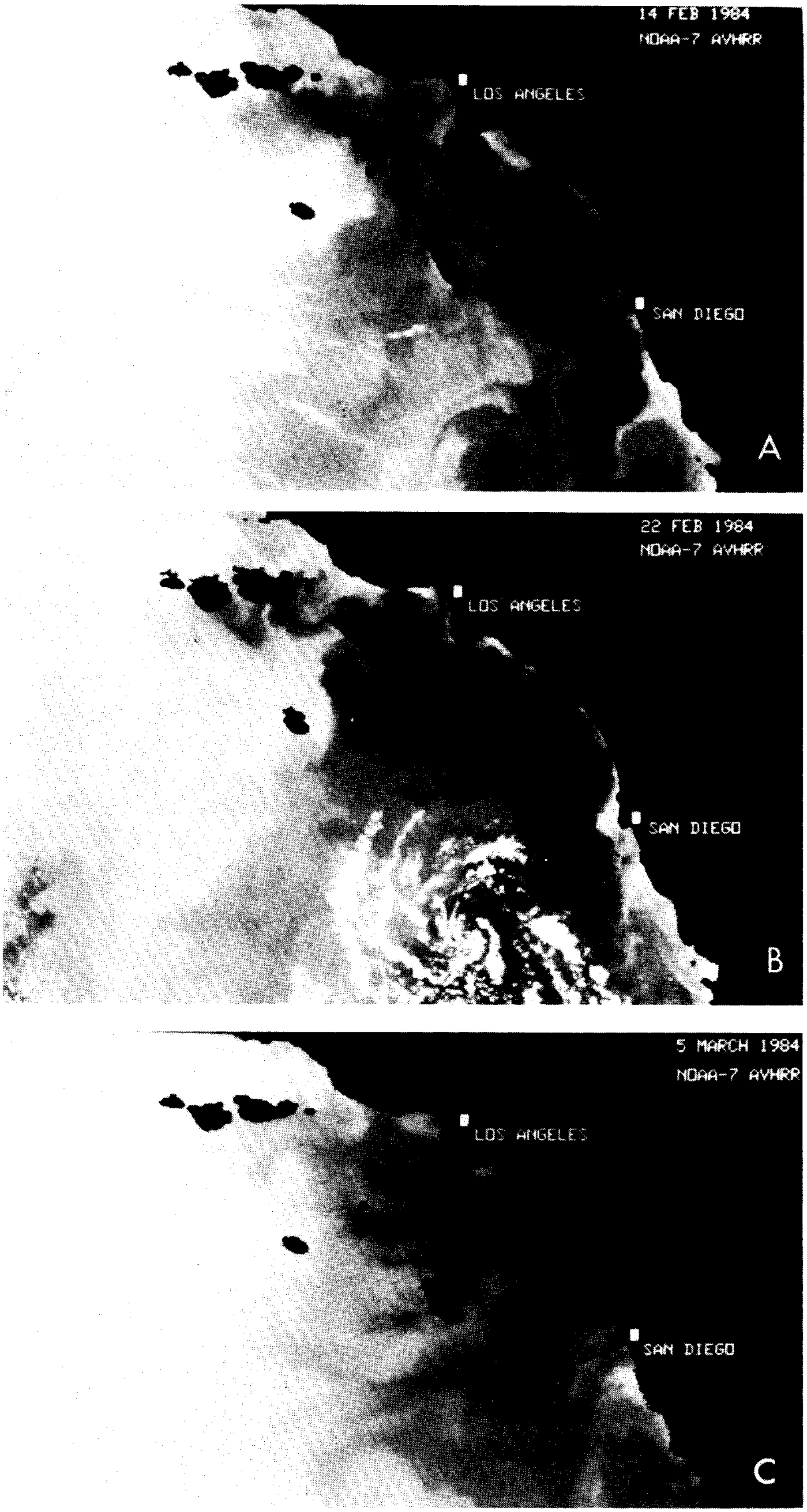

Figure 11. Infrared satellite imagery of relative sea-surface temperature before and after the windstorm of February 15-17, 1984. White areas show relatively cold water; gray-to-black areas are warmer water.

prior to the storm, a long plume of cold water stretched southeast of the Palos Verdes Peninsula, but other nearshore areas of the bight had surface temperatures similar to areas farther offshore, or only slightly cooler (Figure 11a). Five days after the storm, strands of cold surface water were observed off Point Dume, in the northern part of Santa Monica Bay, south of Palos Verdes Peninsula, and in the Point Loma area (Figure 11b). Upwelling occurred along much of the coast from Point Dume to San Diego during the windstorm. In agreement with transect data, no well-defined patches of cold water were present along the coast on March 5, indicating that upwelling had relaxed and surface waters had warmed by solar heating or horizontal advection (Figure 11c). Satellite images from other days during this period could not be used because of cloud cover.

### *Zooplankton Biomass*

Zooplankton volumes were first averaged over each transect to examine seasonal, annual, and geographic variability (Figure 12). Nearshore zooplankton biomass showed strong seasonality, with highest volumes during April-June and minima during December-February. Analyses of the variation of zooplankton volumes for each month (Feb, Apr, June, Aug, Oct, Dec) indicated a significant transect-by-year interaction for all months except February (Table 2), suggesting that zooplankton communities at different transects responded asynchronously during 1982-84. The seasonal pattern of biomass observed at Seal Beach seems to have differed from the other three transects during this 3-year period (Figure 12). Ormond Beach, Playa del Rey, and San Onofre zooplankton volumes followed similar patterns through the 36 months of sampling, having been somewhat lower during 1983 and 1984 than during 1982. Biomass levels appeared to be about the same during 1983 and 1984 at these three transects. In contrast, Seal Beach zooplankton volumes were similar during 1982 and 1983 but dropped sharply during the spring and summer of 1984. June 1984 zooplankton volume at Seal Beach was lowest of the four transects, whereas estimates were generally higher at Seal Beach than the other three transects during 1982 and 1983.

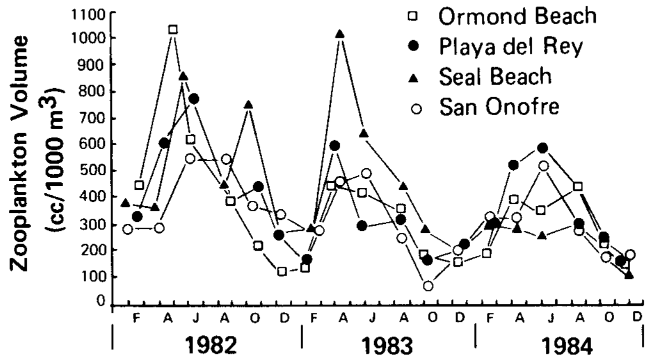

Figure 12. Average zooplankton displacement volume along the major transects.

Cross-shelf zooplankton biomass averages for all nearshore transects were higher very near the coast than at the 75-m depth contour, particularly from August through December (Figure 13; Table 2). Zooplankton biomass at the 75-m stations was always lower than at stations closer to the shore, being only 38.5% of the nearshore maximum in October. From February to August, peak zooplankton biomass was found at stations from the 15-36-m depth contours, although the trend for February, April, and June was not statistically significant (Table 2). During the period of increasing zooplankton abundance—February through June—the mode of maximum zooplankton biomass shifted progressively from inshore (15-m isobath) to mid-transect (36-m isobath), suggesting that the zone of highest zooplankton production and/or survivorship near the coast gradually shifts farther offshore as the season develops (Figure 13). This seasonal movement of the zooplankton biomass mode was observed during 1982 and 1983, but zooplankton volumes, within a sample period, were similar from the 8-m depth to the 36-m station in 1984. Between June and August, zooplankton volumes declined at each depth across the shelf. Minimum zooplankton biomass was observed in December.

The source of nutrients, particularly nitrate, that

TABLE 2
**Monthly Means and Effects of Transect, Year, and Station Depth for Zooplankton Displacement Volume (1982-1984)**

| Month | Mean (S.D.) (cc/1000m$^3$) | 3-way ANOVA results | | | | | |
|---|---|---|---|---|---|---|---|
| | | Transect (T) | Year (Y) | Station (S) | T × Y | T × S | Y × S |
| February | 278.8 (140.1) | NS | ** | NS | NS | NS | NS |
| April | 518.7 (319.5) | — | — | NS | *** | NS | NS |
| June | 520.4 (273.0) | — | — | NS | * | NS | NS |
| August | 370.8 (147.5) | — | — | *** | ** | NS | NS |
| October | 264.5 (234.1) | — | — | ** | ** | NS | NS |
| December | 189.1 ( 95.4) | — | — | ** | * | NS | NS |

NS = not significant; *$P < .05$; **$P < .01$; ***$P < .001$

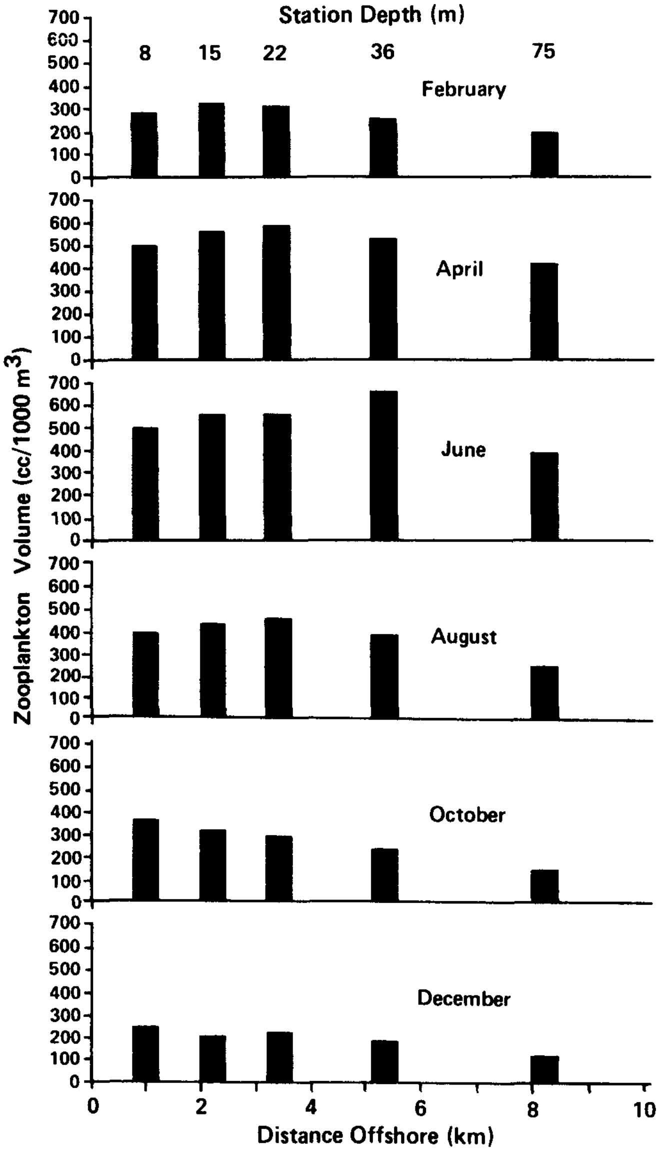

Figure 13. Average monthly zooplankton displacement volume for all four major transects during 1982-84.

could stimulate increased primary production and, ultimately, increased secondary production (zooplankton biomass) on the inner continental shelf appears to be moderately deep water (Figure 14). Mean zooplankton volumes across the shelf were significantly correlated with nitrate levels at the 75-m station and the 36-m station ($r^2 = 0.25$) but not at shallower stations ($P > .10$; $r^2 < 0.07$). Although we do not have data to relate increased primary production with increased nutrients in the nearshore, other studies have shown this relationship (e.g., Ryther and Dunstan 1971; Eppley et al. 1979a). Processes that mix outer-shelf water into the shallow nearshore zone should be important mechanisms for explaining primary and secondary production in shallow coastal waters off southern California.

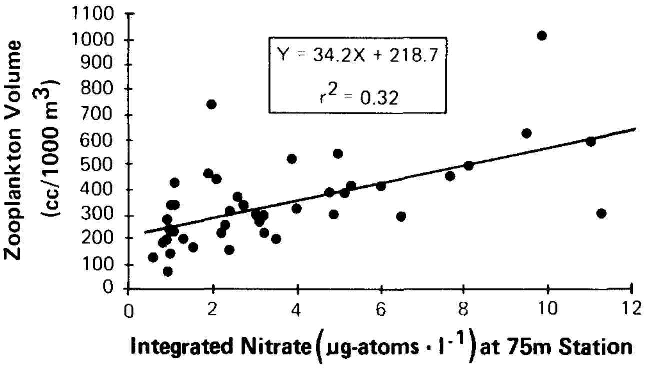

Figure 14. Effect of offshore nitrate (75-m station) on cross-shelf zooplankton volume. The regression equation is significant at $P < .001$.

## DISCUSSION

### *Seasonal Patterns*

Two important seasonal processes related to nutrient mixing off southern California are temperature stratification and upwelling. Seasonal development of the thermocline in nearshore water begins in April or May and persists through September (Cairns and Nelson 1970; Winant and Bratkovich 1981). Several physical and chemical changes accompany this process. Surface water becomes warmer during these months, but near-bottom temperatures usually decline. Mean vertical temperature or heat content changes little during the year in shallow water, but the vertical structure of the current field shifts dramatically (Winant and Bratkovich 1981). During fall and winter, the water column is well mixed, and water flow is toward the south. In spring and summer, surface water continues flowing southward, but water below the thermocline usually moves in the opposite direction.

The cool, offshore water mass observed beneath the summer thermocline is almost certainly the major source of nutrients for primary production in nearshore waters. Internal waves that propagate onto the continental shelf are thought to be a major contributor to mixing in the upper part of the water column (Gregg and Briscoe 1979). Recent studies on other continental shelves have shown how large-amplitude internal waves may "pump" deep-water nutrients across the shelf edge and into shallow water on the inner continental shelf (Sandstrom and Elliott 1984; Holloway et al. 1985). Large temperature fluctuations, representing surges of cold water moving onshore, occur at approximately tidal frequencies in shallow waters off southern California (Cairns 1967; Winant 1974; Zimmerman and Kremer 1984). Isotherms on the leading edge of cold surges are often vertical, or even pass vertical and become inclined toward the shore, with cold water overlaying warmer water in an unstable configuration (Cairns 1967; Winant 1974). Such instabilities probably cause vertical mixing by shear or convective (overturning) processes.

Barnett and Jahn (in press), working between 8 and 100 m near San Onofre, also observed a spring-summer encroachment of nutrient-rich water onto the shallower parts of the shelf, and mixed, nutrient-poor water in the upper part of the water column during fall and winter. A deep pool of nitrate-rich water was also common, but not always present. Eddy diffusion of nitrogen from depth and regeneration of nutrients were offered as likely explanations of nearshore enrichment, although Barnett and Jahn also considered longshore transport of water from semipermanent upwelling centers (e.g., Palos Verdes Peninsula, Dana Point, and San Mateo Point) as a possible mechanism supplying nutrients.

Nearshore upwelling off southern California occurs during several months of the year and may affect primary production by transporting nutrient-rich water into the euphotic zone (Kamykowski 1974; Dorman and Palmer 1981). In all cases, local winds have been the putative cause of nearshore upwelling off southern California (Kamykowski 1974; Dorman and Palmer 1981; Dorman 1982), although other mechanisms are possible, such as continental shelf waves or internal Kelvin waves (Bowden 1983).

Nearshore winds off San Diego have a strong diurnal component, blowing offshore from late night to early morning and onshore at other hours (Dorman 1982). Mean seasonal winds at San Diego are generally toward the east and southeast (Dorman 1982). Tropical storms, which occur once or twice from mid to late summer, move north along the coast of Baja California causing strong northward winds and downwelling near the shore (Winant 1980). Other summer wind events cause strong southeastward wind flow and significant upwelling (Dorman and Palmer 1981). Relatively weak coastal winds (e.g., 7 m/sec) over a narrow continental shelf result in nearshore upwelling that is 30 times as intense as the typical open-ocean upwelling observed off San Diego (Dorman 1982). Wind stress increases with distance from shore, often by a factor of three or four (Dorman 1982). Therefore large-scale analysis of wind data collected at offshore (beyond about 20 km) ship stations (e.g., Bakun 1975) is not representative of nearshore winds and wind-forced processes.

Storm-driven upwelling events have been observed in the nearshore zone during several months of the year (Kamykowski 1974; Dorman and Palmer 1981; this study, and unpublished data). Kamykowski (1974) described a nearshore upwelling event off La Jolla, California, during February 1971. Winds of 5.5 m/sec, with gusts up to 9.7 m/sec, produced upwelling at a station 1 km offshore. Increased nutrients from upwelled water caused increased primary production and a phytoplankton succession that was followed for three weeks. An average of two upwelling events occur during summer months in the southern part of the bight (Dorman and Palmer 1981). Nearshore upwelling events produce strong cross-shelf gradients in nutrients, temperature, and, probably, zooplankton distribution patterns. These gradients are within approximately 10 km of the shore and are created by conditions that do not cause strong offshore mesoscale upwelling.

### *El Niño Conditions in the Nearshore Zone*

The most significant long-term phenomenon observed during sampling was the El Niño event that began in the tropical Pacific in 1982 (Philander 1983). This was an exceptionally strong meteorological and oceanographic event that produced very warm surface waters throughout the Central and Eastern Tropical Pacific Ocean. Anomalous, large-scale atmospheric circulation presumably caused warm ocean conditions off the coast of California and Mexico during the 1982-83 El Niño (Lynn 1983; Simpson 1983, 1984a, 1984b). Unusually warm temperatures were first observed at offshore stations in the California Current during the fall of 1982, with full development of large-scale warming by January 1983 (Auer 1982-83; Simpson 1983) and persistence of the phenomenon to at least January 1984 (McGowan 1984; Simpson 1984a). Monthly mean sea level, an indicator of an El Niño event, was about 0.2 m above the long-term mean at Scripps Pier during the fall of 1982 (Dykstra and Sonu 1985), signifying the beginning of this El Niño event.

Nearshore processes that mix cool, deep water with surface water presumably created a complex temperature signal close to the shore during the 1982-83 El Niño (Figure 3). During the first few months of the El Niño event (fall 1982), surface temperatures measured at Scripps Pier and on our nearshore transects were near normal or slightly above normal (North 1985). Surface temperatures were 1°-2°C above normal in the first few months of 1983 (Dayton and Tegner 1984). During spring and summer of 1983, nearshore surface temperatures were again near normal. The strongest nearshore development of El Niño conditions was observed during fall 1983 and again during spring and summer 1984; surface temperature was a little warmer than average during the winter of 1983-84, with some significant events of below-normal cold water (North 1985). Thus periods of near-normal hydrographic conditions (surface temperature and presumably other variables) were imposed upon the strong El Niño nearshore, and the near-normal temperatures during part of 1983 were probably the result of intense nearshore mixing and upwelling processes that advected cool, high-salinity, deep water to the surface. Warm "El Niño-like" conditions persisted in the Southern California Bight through most of 1984, suggesting that a considerable time lag is necessary for regional temperatures to return to normal following a global El Niño event (J. Simpson, MS).

Simpson (1984a) showed that water properties within the inner part of the Southern California Bight were probably caused by onshore movement of Pacific subarctic water from the offshore part of the California Current. Subarctic water is distinguishable by low temperature, high nutrient concentrations, and low salinity (Reid et al. 1958). After subarctic water enters the California Current around 48°N, it warms as it moves south, but remains recognizable by its relatively low salinity as far south as 25°N (Reid et al. 1958; Simpson 1984a). Conditions in the fall of 1983 suggest the presence of this subarctic water mass in the nearshore zone. No long-term averages of nitrate were available for comparison with nitrate concentrations measured during 1983 and 1984, but nutrient levels may have been lower, since a strong inverse relationship exists between temperature and nutrients (Zimmerman and Kremer 1984; Barnett and Jahn, in press).

The lower zooplankton biomasses at most transects during 1983 and 1984 were most likely caused by the 1982-83 El Niño. Fiedler (1984) has shown that reduced phytoplankton production off the coast of southern California during El Niño was associated with weakened mesoscale upwelling. Reduced nutrients over the continental shelf may have caused slower phytoplankton growth following the onset of El Niño conditions in late 1982, and therefore less input to the zooplankton food chain. Zooplankton biomass was lower at all transects in June 1983 than in June 1982 (Figure 12), although unusually warm water was not observed until September and October of 1983. Temperature, per se, was probably not regulating zooplankton abundance, and other factors such as nutrient limitation or increased offshore transport were probably responsible for low zooplankton biomass. Continued anomalous conditions in the nearshore zone through most of 1984, although the tropical El Niño phenomenon ended in 1983 (Cane 1983), may have caused primary productivity and zooplankton biomass to remain low during 1984.

### *Cross-Shelf Patterns*

Cross-shelf gradients were particularly obvious for zooplankton biomass. Zooplankton studies off southern California generally emphasize biological interactions (grazing, predator-prey relationships) or species-distribution patterns (vertical, horizontal, patchiness). However, zooplankton biomass estimates made in the California Current have also been used to study interannual variability and the effects of large-scale physical processes on the planktonic community (Bernal and McGowan 1981; Chelton et al. 1982). Biomass estimates of many broad taxonomic categories (total copepods, chaetognaths, decapods, euphasiids, etc.) are highly correlated throughout the region (Colebrook 1977), and biomass fluctuations have been common during the last 200 years (Soutar and Isaacs 1969, 1974). High correlations among taxa on a regional scale suggest that zooplankton biomass may be used as a measure of community response to large or mesoscale physical or chemical phenomena (Bernal and McGowan 1981). Biological interactions undoubtedly cause fluctuations of populations of some zooplankton species, but time series of zooplankton biomass, interpreted in light of major physical processes, should give a reasonable picture of community "condition," particularly when most major taxa respond simultaneously throughout the ecosystem.

Zooplankton biomass shows an offshore peak in abundance at about 100-200 km off the coast of central and southern California (Smith 1971; Bernal and McGowan 1981). Chelton (1982) has shown that the offshore zooplankton peaks are associated with offshore upwelling driven by the wind stress curl. Bernal and McGowan (1981) described the onshore-offshore distribution of zooplankton biomass in the California Current and discussed the possible existence of an additional nearshore maximum within approximately 50 km of the shore. Using data from special CalCOFI stations within 50 km of the coast (also, see maps in Smith 1971), they observed no nearshore peak in zooplankton. Our nearshore data are not directly comparable to the CalCOFI data, since different mesh sizes were used (333 μ vs 505 μ), and offshore (CalCOFI) tows sampled below the euphotic zone, whereas our nearshore tows did not. We can, however, examine our data for cross-shelf pattern and compare these results to those of Bernal and McGowan (1981) in a qualitative manner.

We observed zooplankton biomass peaks, for most months of the year, that were inside the 75-m isobath. The low zooplankton volumes found at 75-m depths may be the result of a real nearshore maximum or, possibly, sampling bias caused by sampling through water columns of different depth. The lower portion of the 75-m sample was probably below the 1% surface light level, thus some of the water strained on these tows was relatively unproductive and not strictly comparable to shallower stations. However, other workers' results suggest that dynamics are different nearshore and that zooplankton is denser very near the coast. Beers and Stewart (1967) found a decline in the density of microplanktonic metazoans between 25 and 200 m in the upper part of the water column. Barnett and Jahn (in press) distinguished nearshore and offshore assemblages of zooplankton, with the change occurring at about the 30-m isobath. Nearshore taxa shifted slightly seaward in spring and summer at the San Onofre transect (Barnett and Jahn, in press), a phenomenon that may be related to the shift of biomass peaks noted above. Other studies of mysids, copepods, ctenophores, and fish larvae have also found large abundance peaks within 10 km of the coastline (e.g., Clutter 1967; Barnett 1974; Hirota 1974; Barnett et al. 1984).

Failure of Bernal and McGowan (1981) to see a nearshore zooplankton maximum was probably caused by the close proximity of the abundance peak to the shore and the offshore location of "nearshore" CalCOFI stations. CalCOFI stations nearest the shore (in Smith 1971), used by Bernal and McGowan (1981) as a test of an inshore zooplankton peak, appear to be in 200 m of water, well offshore of waters shown here and elsewhere to be strongly influenced by shelf processes.

The nearshore zooplankton biomass peak that we observed, and other nearshore distribution patterns cited above are probably the combined result of recycling and vertical mixing in shallow water that keeps nutrients available in the euphotic zone and increases phytoplankton growth, relative to that of deeper waters. Mesoscale hydrographic processes in offshore waters, such as seasonal upwelling and storm-induced mixing, transport nutrients from deep water into the euphotic zone throughout the bight, and local upwelling increases nutrients on the shelf at times when offshore waters may remain stratified. Once nutrients have been mixed or advected onto the shelf, turbulent mixing and recycling probably maintain higher nutrient concentrations in the shallow waters, increasing the standing stock of plankton (Walsh 1981).

### *Bightwide Coherence of Processes*

Results from our nearshore cruises, and long-term (20-63 years) temperature records from shore stations between Gaviota and San Diego (Jones 1971; Tekmarine 1983; E. Stewart, pers. comm.) indicate that nearshore continental shelf waters usually show coherent patterns throughout the Southern California Bight, except near headlands. Delayed warming occurs at major headlands throughout the bight, particularly at Point Conception, Port Hueneme-Point Dume, and Palos Verdes Peninsula (Tekmarine 1983; this study). Local upwelling near headlands, which is particularly active during spring and summer (Roden 1972; Dorman and Palmer 1981; Huyer 1983), brings cool water to the surface in these areas and may produce slower warming of the surface layer. List and Koh (1976) analyzed shore temperatures collected between Neah Bay, Washington, and La Jolla, California, with most stations being in the Southern California Bight. Data were separated into three frequency components identified as low (seasonal; several months), intermediate (two weeks to one season), and high (less than two weeks). Seasonal and intermediate time-scale temperature events were highly correlated in southern California, with many temperature phenomena occurring almost simultaneously at stations throughout the bight. List and Koh (1976) did not observe slower spring warming at headlands because none of their stations were near major promontories. Occasional events within the intermediate temporal component had a smaller spatial scale on the order of 200 km. High-frequency phenomena tended to be local and were most likely associated with internal waves (Winant 1974) or wind (Cairns and La Fond 1966).

## CONCLUSION

Oceanic, mesoscale, and local processes combine within the Southern California Bight to produce the physical and nutrient conditions observed in the nearshore zone. Basin-wide phenomena like the 1982-83 El Niño affect waters throughout the bight, although local processes such as coastal upwelling occasionally seem to dominate in the nearshore zone, resulting in "normal" hydrographic conditions at certain locations during a large-scale anomalous period. Mesoscale upwelling forced by strong offshore winds brings nutrient-rich water to the surface over large areas of the bight, including the nearshore waters. Such upwelling is a seasonal phenomenon, being most intense in spring and early summer. Local upwelling, often observed near headlands, has been observed at other times of the year, however, and greatly changes nearshore conditions and gradients. Nearshore mixing of waters from depth by tidal action and internal waves also brings important nutrients into the euphotic zone and increases production compared to waters farther from the coastline. Longshore advection may also enhance phytoplankton populations through higher nutrient levels and may cause increased nearshore productivity compared to productivity on the outer continental shelf and areas farther offshore. These observations and other studies from the nearshore zone suggest that physical processes often distinguish "nearshore" waters from "offshore" waters.

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