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## Biological and chemical consequences of the 1997–1998 El Niño in central California waters

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### Abstract

The physical, chemical and biological perturbations in central California waters associated with the strong 1997–1998 El Niño are described and explained on the basis of time series collected from ships, moorings, tide gauges and satellites. The evolution of El Niño off California closely followed the pattern observed in the tropical Pacific. In June 1997 an anomalous influx of warm southerly waters, with weak signatures on coastal sea level and thermocline depth, marked the onset of El Niño in central California. The timing was consistent with propagation from the tropics via the equatorial and coastal wave-guide. By late 1997, the classical stratified ocean condition with a deep thermocline, high sea level, and warm sea surface temperature (SST) commonly associated with El Niño dominated the coastal zone. During the first half of 1998 the core of the California Current, which is normally detected several hundred kilometers from shore as a river of low salinity, low nutrient water, was hugging the coast. High nutrient, productive waters that occur in a north–south band from the coast to approximately 200 km offshore during cool years disappeared during El Niño. The nitrate in surface waters was less than 20% of normal and new production was reduced by close to 70%. The La Niña recovery phase began in the fall of 1998 when SSTs dropped below normal, and ocean productivity rebounded to higher than normal levels. The reduction in coastal California primary productivity associated with El Niño was estimated to be 50 million metric tons of carbon ( $5 \times 10^{13}$  gC). This reduction certainly had deleterious effects on zooplankton, fish, and marine mammals. The 1992–1993 El Niño was more moderate than the 1997–1998 event, but because its duration was longer, its overall chemical and biological impact may have been comparable. How strongly the ecosystem responds to El Niño appears related to the longer-term background climatic state of the Pacific Ocean. The 1982–1983 and 1992–1993 El Niños occurred during the warm phase of the Pacific Decadal Oscillation (PDO). The PDO may have changed sign during the 1997–1998 El Niño, resulting in weaker ecological effects than would otherwise have been predicted based on the strength of the temperature anomaly. © 2002 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

The coastal ocean off western North America is, on average, rich and productive. One view for this enhanced productivity was generated from data collected by fisheries researchers working on the California Cooperative Fisheries Investigations (CalCoFI). A correlation between transport from the north and zooplankton abundance (Chelton, Bernal, & McGowan, 1982) led to the conclusion that the nutrients responsible for stimulating primary productivity were brought south by the California Current (CC). A second view was that coastal upwelling, which occurs along eastern ocean margins when equatorward winds force surface waters offshore, was the primary source of nutrients along the North American west coast (Barber & Smith, 1981). The characteristic signature of upwelling is a cool and salty band along the coast separated from the warmer and fresher offshore waters of the CC by a series of fronts, plumes, and eddies, which can extend more than 100 km offshore. A conceptual model of biological production in upwelling systems suggested that there were two important physical processes responsible for enhanced productivity in these regions (Barber & Chavez, 1983): (1) the thermocline, and more importantly the nutricline (nitrate), must be shallow, of the order of 40–80 m or less, so that (2) upwelling-favorable winds can draw nutrient-rich waters into the sunlit zone, thereby stimulating photosynthesis. A strong coastal source of iron (Johnson, Chavez, & Friederich, 1999) is a third requirement for enhanced biological production. The CC transports lower nutrient and salinity waters, relative to those upwelled along the coast, but these waters are richer and more productive than the subtropical gyre, acting to extend the ‘coastal’ productive area further west than by coastal upwelling alone. A stronger gyre and CC circulation also results in a shallower thermocline (Wyrski & Wenzel, 1984). Nutrients provided by the combination of coastal upwelling (0–100 km), thermocline doming by a strong CC circulation, and southward transport result in high-primary productivity ecosystems that support heavily exploited fisheries. Periodically, once in every 3–8 years, El Niño disrupts this pattern of high primary productivity.

A significant proportion of the waters that feed the coastal upwelling circulation originate in the northeastern tropical Pacific (Castro, Chavez, & Collins, 2001) and are transported poleward in the California Under-

current (CUC). Off California coastal upwelling occurs seasonally (Huyer, 1983). Southward winds drive upwelling through spring and early summer; they weaken in late summer and fall and are eventually interrupted by northward winter storm winds, resulting in the cessation of upwelling (Strub, Allen, Huyer, & Smith, 1987; Strub, Allen, Huyer, Smith, & Beardsley, 1987). Based on hydrographic structure three regimes have been identified: (1) a spring (early) and summer (late) upwelling regime, (2) a fall ‘oceanic’ regime, and (3) a winter or Davidson regime (reviewed by Pennington & Chavez, 2000). During normal active upwelling, physical nutrient supply exceeds biological demand at the site of upwelling and excess nutrients are exported downstream and offshore of the upwelling site (Olivieri & Chavez, 2000). The physical characteristics (Rossby radius of deformation, horizontal currents, wind speed, etc.) determine the extent of the export and the ‘size of the productive habitat’ (*sensu* Feldman, 1986). During spring and early summer upwelling the productive habitat extends several hundred kilometers from shore. This season exhibits the highest surface nutrients and productivity, and the primary producers are small colonial centric diatoms. During the winter, when upwelling weakens and at times ceases, low productivity is the norm although nitrate is above detection limits ( $\sim 2 \mu\text{mol}$ ), and the communities are dominated by picoplankton. Horizontal gradients are very weak. The oceanic period is strongly stratified, both vertically and horizontally. Strong temperature and salinity gradients separate a narrow productive area from low productivity oceanic waters that are closer to shore during this season. It is upon this seasonal background that El Niño impinges.

El Niño was originally identified and named by the fishermen of northern Peru, who recognized warm wet years during which their fisheries changed dramatically, floods caused damage and Peruvian deserts became grassland (Eguiguren, 1894). It has since been found that El Niño is a phenomenon of global scope—it is now recognized as the world’s dominant source of climate and ocean variability on interannual time scales, with particularly dramatic oceanographic effects in the tropical Pacific (Chavez et al., 1999; McPhaden, 1999). While the prediction of El Niño remains elusive, once initiated their evolution in the tropical Pacific is relatively well-understood (Barber & Chavez, 1983; Cane, 1983; McCreary, 1976; McPhaden, Hayes, Mangum, & Toole, 1990; Rasmusson & Wallace, 1983) the equatorial dynamics of the most recent 1997–1998 event have been particularly well-described (Chavez et al., 1999; McPhaden, 1999).

El Niños are triggered by anomalies in the wind field in the western equatorial Pacific. These anomalies generate Kelvin waves that propagate eastward, depressing the thermocline and elevating sea level. A depressed thermocline favors development of warm surface temperatures since warmer water now feeds upwelling in the equatorial cold tongue (Barnett, Latif, Kirk, & Roegner, 1991; Kessler, McPhaden, & Weickmann, 1995). This warmer sea surface temperature (SST) further enhances the trade wind anomalies, again reinforcing changes in thermal structure. The Kelvin waves and the associated thermal structure anomalies lead to changes in the advective regime. Nutrient-poor waters from the western Pacific warm pool migrate eastward. Associated with this migration, less productive waters from north and south converge on the equator. The relative importance of the zonal and meridional advective processes and the eastward penetration of warm pool waters into the central and eastern tropical Pacific (ETP) are a function of El Niño intensity. Finally, the equatorial undercurrent first accelerates with the passage of the Kelvin waves and then weakens as the pressure gradient between the eastern and western equatorial Pacific first weakens and occasionally disappears. Recovery from El Niño along the equator begins with a shallowing of the thermocline. Once the trade winds re-establish, SST can drop dramatically since cool waters feed the wind-driven upwelling.

The equatorial Kelvin waves collide with South America and then propagate poleward as coastally trapped waves (Enfield & Allen, 1980). During El Niño local upwelling-favorable winds in the ETP are maintained and even intensify (Enfield, 1981). The negative effects of El Niño on biological production in the ETP have been, therefore, attributed to a deepening of the nutricline by remotely forced Kelvin waves (Barber & Chavez, 1983). Coastal upwelling continues but the waters recruited are low in nutrients, and productivity declines sharply. The coastal upwelling system of the northeast Pacific is also affected by El Niño, but the developmental sequence of events remains poorly described, and there is continued debate over the primary forcing (Norton & McLain, 1994; Simpson, 1984; Wooster & Fluharty, 1985).

For example, Simpson (1984) argued that the effects of El Niño off California are related to an expansion of the Aleutian Low, which suppresses upwelling-favorable winds. Huyer and Smith (1985) suggested that onset of the 1982–1983 El Niño was related to remotely forced oceanic perturbations, since onset off Oregon preceded changes in the Aleutian Low. Chavez (1996) argued that during the 1992–1993 El Niño remotely forced thermocline anomalies initiated the event in central California. Recently Strub and James (2002) have argued that both of these processes were important during the 1997–1998 El Niño. Remotely forced anomalies were clearly present in altimeter data, and changes in the Aleutian Low affected primarily the Alaska region. The timing was consistent with that given by Huyer and Smith (1985) for the 1982–1983 El Niño; remotely forced perturbations led the north Pacific atmospheric changes.

During El Niño, changes in the coastal California thermal structure are associated with or are a result of the advective regime. One of these effects has already been discussed; a depressed thermocline favors development of warm surface temperatures since the cold water reservoir that in normal years feeds upwelling, deepens. A second advective process is for waters from the south to be brought poleward by a stronger CUC or anomalous surface currents. A third process is associated with ‘downwelling’ or a coastal movement of offshore waters (from the subtropical gyre and the CC). Similar to the equatorial region, these effects are likely to vary in relative importance depending on El Niño intensity. In 1997–1998, a particularly strong episode of El Niño occurred. Ongoing programs monitored this major El Niño with ships, satellites and moorings. Data collected off central California have allowed us to define the developmental sequence of events in the northeast Pacific with unprecedented resolution. In this contribution we describe the evolution of El Niño along central California and assess the impact of remote, local, and advective processes on nutrient supply and biological production.

## 2. Observations and methods

The Monterey Bay Aquarium Research Institute (MBARI) initiated in 1989 a biogeochemical time series within and offshore of Monterey Bay (MB). In addition to the shipboard time series, MBARI has maintained two moorings since 1989 (M1 and M2). More recently, additional moorings have been deployed by MBARI (M3, S2, S3) and the Naval Postgraduate School NPS (M4) for shorter periods. The M moorings are equipped with meteorological, physical, chemical, and bio-optical instrumentation. The S moorings have current meters and sediment traps. Since 1997, as part of a cooperative program between MBARI and NPS (see Castro et al., 2002; Collins et al., 2002), quarterly cruises that occupy CalCOFI line 67 have been carried out. Finally, since 1997, MBARI and UC Santa Cruz have cooperated on studies of zooplankton abundance and composition (see Benson, Croll, Marinovic, Chavez, & Harvey, 2002; Hopcroft, Clark, & Chavez, 2002; Marinovic, Croll, Gong, Benson, & Chavez, 2002). The types of data collected are listed in Table 1.

### 2.1. Central California shipboard work

The sample collection, and data processing methodologies have been described in detail by Pennington and Chavez (2000); these methods are briefly outlined here. Methods not covered in that paper are treated in more detail subsequently.

#### 2.1.1. MBTS cruise series

Monterey Bay Time Series (MBTS) stations within and near the mouth of MB (Fig. 1) have been occupied at 2–3 week intervals since mid-1989 aboard the R/V *Point Lobos* on single-day cruises. From 1989–1992 the cruises occupied four stations (C1, H1, H3, C7), but in 1993 these stations were reduced to three along an onshore/offshore transect (C1, M1, M2). The central MB stations, H3 and M1, are

Table 1

List of sample types obtained from 1989 to present during the time series cruises and from moorings. Samples listed under ‘complete series’ were obtained over the full 10 years of the series, while samples under ‘partial series’ have been obtained over some portion of the series. Similar data sets are collected on Line 67 with CTD casts to 1000 m (modified from Pennington & Chavez, 2000)

Complete series	Partial series	Mooring
CTD cast ( $\geq 200$ m) plus downwelling PAR, fluorescence, and transmissivity	A* and HPLC pigments (0, 10, 20, 40 m)	11 Thermistors to 300 m, conductivity added in 1998. CTD, fluorometer and transmissometer at surface
Chlorophyll profile (0–200 m)	Spectroradiometer casts (PRR)	Spectral radiometers since 1995
Nutrient profile (0–200 m)	Flow cytometry profile for bacteria and cyanobacteria	Nitrate since 1997, still experimental
Total production profile ( $^{14}\text{C}$ ; 100–0.1% LPD)	Stable isotope ratios	$\Delta p\text{CO}_2$ since 1997
New production profile ( $^{15}\text{N}$ ; 100–0.1% LPD)	Zooplankton net tows with OPC (since 1997)	ADCP (horizontal currents and acoustic backscatter) since 1992
Phytoplankton taxonomy (including microzooplankton and cell counts (0 m)	Dissolvable iron	Absorption and backscatter meters since 1999
Particulate organic material (0 m)	Harmful algal species and bacterial community structure	

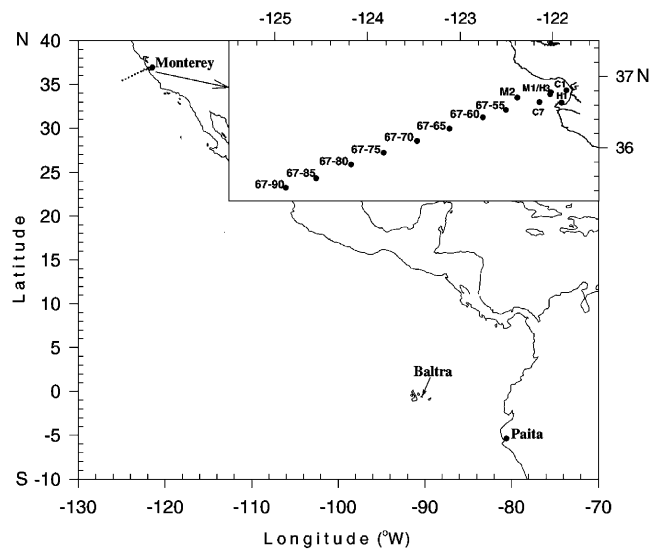


Fig. 1. Map showing locations of observations.

separated by 3 km and for 1989–1996 were treated by Pennington and Chavez (2000). In this paper data from all MBTS stations are combined into a single series.

### 2.1.2. SECRET cruise series

To extend the shipboard work across the central California upwelling zone and into the CC, the Studies of Ecological and Chemical Responses to Environmental Trends (SECRET) cruise series was begun in March 1997. SECRET cruises have been conducted at least quarterly, and occupy 10 CalCOFI Line 67 stations to 250 km offshore of MB (Fig. 1). The MBTS station C1 has been occupied as part of the

SECRET series, but MBTS stations M1 and M2 were either occupied or approximated by the Line 67 stations 67-50 and 67-55, respectively, for this cruise series. Complementing the SECRET cruise series is the PEGASUS cruise series (Collins, Garfield, Rago, Rischmiller, & Carter, 2000), which were taken during 1988–1991 and covering Line 67.

### 2.1.3. Station measurements—CTD and bottle samples

CTD casts were made to at least 200 m (MBTS) and 1000 m (SECRET cruises), and Niskin bottle samples were obtained from the surface to 200 m during each cast. This seawater was assayed for nutrients ( $\text{NO}_3 + \text{NO}_2$ ,  $\text{PO}_4$ ,  $\text{SiO}_4$ ), chlorophyll *a*, primary production, phytoplankton taxonomy and cell counts, and other parameters not presented here (see Methods in Pennington & Chavez, 2000; for phytoplankton taxonomy and cell counts see Methods in Chavez et al., 1991).

## 2.2. Central California moorings, Peru temperatures, Galapagos Island and Monterey sea level

Two moorings have been maintained by MBARI since 1989 at stations M1 and M2 (Fig. 1; moorings described in Chavez, Herlien, & Thurmond, 1994; Chavez et al., 1997). The moorings carry meteorological and oceanographic instrumentation including thermistors to 300 m. Thermistor data are normally collected every 10 min, but in April–June 1997 during El Niño the M1 system malfunctioned. CTD temperature data from rosette casts and ROV dives were used to fill this gap. Daily 60 m temperature data were also obtained from a station near Paita, Peru for the same period. These temperature data are compared to a 20 year climatology from the same location. Sea level data were obtained from monitoring stations in Baltra, Galapagos Islands and Monterey for 1997 and 1998.

### 2.3. SeaWiFS chlorophyll and primary production

We have used observations of ocean color from SeaWiFS to calculate primary production along the coast of California. We first assessed the accuracy of the chlorophyll values in the MB area by comparison with in situ measurements. Comparison was made between 1998 SeaWiFS chlorophyll and in-water chlorophyll measured during the Line 67 cruises. Shipboard coverage did not allow for calculation of monthly statistics so a seasonal comparison was deemed most appropriate. Monthly average SeaWiFS chlorophyll was obtained from NASA Goddard Space Flight Center and averaged into 3-month seasonal images. SeaWiFS data along CALCOFI Line 67 were then extracted and averaged in 25-km intervals for comparison with cruise data. The results showed good agreement, similar to those determined by Chavez (1995) for CZCS data. The satellite underestimated chlorophyll in the nearshore region and overestimated chlorophyll offshore. One exception was during the oceanic period when there appears to be an overestimate of chlorophyll nearshore, perhaps associated with low-level fog.

We calibrated satellite-based primary production models with a database of over 300 in-water measurements from the MB area. Surface chlorophyll accounted for 46% of the observed variability in euphotic zone integrated productivity. The inclusion of euphotic depth (penetration depth of 1% surface irradiance) modeled from surface chlorophyll (Morel & Berthon, 1989) increased correlation to 55%. The depth-integrated models include a measure of depth-integrated phytoplankton biomass, estimated by the product of surface chlorophyll ( $C_{\text{surf}}$ ) and euphotic depth ( $Z_{\text{eu}}$ ), as well as inclusion of an incident irradiance dependent function ( $f(E_0)$ ) and a physiological yield term ( $\text{PB}_{\text{opt}}$ ) necessary to convert the estimated biomass into a photosynthetic rate. The  $f(E_0)$  defined from the MARMAP database for the northeast US continental shelf (Behrenfeld & Falkowski, 1997) was not appropriate for MB waters (it resulted in an overestimate of primary production of a factor of 2). We found that this function reduced to a constant of 0.45 for MB waters. The model we apply here, therefore, reduces to:

$$\sum PP = 0.45 \times C_{\text{surf}} \times Z_{\text{eu}} \times PB_{\text{opt}}. \quad (1)$$

Attempts to model  $PB_{\text{opt}}$  have not been successful (Behrenfeld & Falkowski, 1997). From our database, we found that daily  $PB_{\text{opt}}$  was approximately constant along Line 67, but varied seasonally. Use of seasonal  $PB_{\text{opt}}$  substantially improved model performance over use of modeled  $PB_{\text{opt}}$ , as such we use the seasonal  $PB_{\text{opt}}$  in the results presented here.

### 3. Results

#### 3.1. The evolution of the 1997–1998 El Niño

The first indication of a developing El Niño was a weakening and reversal of the trade winds in the western equatorial Pacific in late 1996 and early 1997. Soon after these wind anomalies the equatorial Pacific became anomalously warm and remained so until mid-1998. In the tropics, El Niño was punctuated by two episodes of high sea level and deep thermocline. At the Galapagos Islands sea level began to rise in April 1997, peaked in June/July and reached a minimum in September 1997. The second and largest increase began in October 1997 and lasted until May 1998 with a maximum in late 1997 (Fig. 2A). Off Peru, SSTs closely followed the sea level signature (Fig. 2A), with some minor differences. In mid-May 1998 the trade winds abruptly returned to near normal strength in the eastern and central equatorial Pacific. The anomalously cold subsurface waters upwelled into the surface layer, and SSTs in some areas of the equatorial cold tongue plummeted 8 °C during May and June, bringing El Niño to an abrupt end (McPhaden, 1999). Ocean temperatures off Peru followed dropping over 6 °C in early June. La Niña-like conditions set in off Peru in August 1998 (Fig. 2A).

Sea level and SST were also well-correlated in coastal central California (Fig. 2B). They began to increase in late June (sea level) and late July (SSTs) reaching their maximum anomalies in late 1997–early 1998. The first large peak in sea level and SST observed in the ETP, was not as evident off California. The duration of the warm SST anomalies was also much shorter in coastal California (August 1997–April 1998) than in coastal Peru (April 1997–June 1998). By spring of 1998 the thermocline had recovered along coastal central California and small pulses of upwelling resulted in blooms of toxic diatoms (Scholin et al., 1999). Even though coastal winds were not anomalous (Collins et al., 2002) and the thermocline was shallow, spring and early summer were characterized by anomalous SST and the largest chemical and biological anomalies (Figs. 3 and 4) of the El Niño. Negative temperature anomalies became the norm during October 1998 off coastal California.

The biological and chemical response off coastal California tracked the thermal conditions. Negative anomalies in surface chlorophyll concentration began in early August 1997 with the onset of the anomalous temperatures (Fig. 3). Lower than average chlorophyll remained until October 1998 and after that, in concert with a change from positive to negative anomalies in SST, chlorophyll turned above average and remained so through 1999. Anomalies (from the 1989–1999 mean) for surface salinity, surface nitrate, integrated primary production, integrated chlorophyll, surface diatom biomass, surface dinoflagellate biomass, and surface picoplankton biomass for the higher frequency inshore time series are presented in Fig. 4. Surface salinity remained above average through 1997. In early 1998 it became significantly fresher and the freshening continued until July 1998 after which time it became saltier than average for most of 1999. Surface nitrate was above average during early 1997 and turned below average in August 1997. Negative anomalies increased reaching their maximum in May 1998 and then returned to above average in October 1998, remaining above average for the whole of 1999. Integrated chlorophyll was below average for most of 1997 and was most anomalous during spring and summer 1998. After October 1998 it remained generally

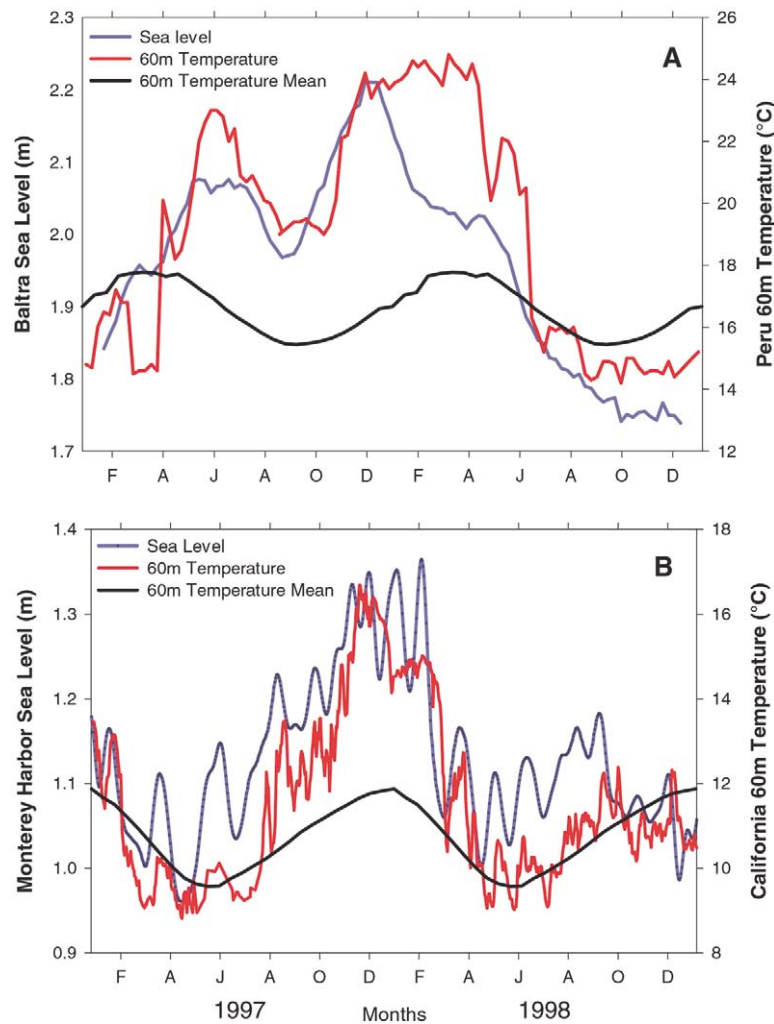


Fig. 2. A. Time series of sea level at Baltra, Galapagos Islands and 60 m temperatures at a station offshore of Paita, Peru (Barber, Kogelschatz, & Chavez, 1985) for 1997 and 1998. B. Time series of sea level at Monterey, California and 60 m temperatures at the M1 mooring in Monterey Bay for 1997 and 1998.

above average through the end of 1999. Primary productivity parallels surface chlorophyll except for a period of below average primary productivity in late 1999. Diatoms were below average during the whole of 1997 and then oscillate around the mean for the remainder of the record. Dinoflagellates were above average during the early part of El Niño and then turned below average from October 1997 to 1998. A large dinoflagellate bloom was observed in September 1999. Picoplankton followed the same pattern as dinoflagellates except for the 1999 bloom.

### 3.2. El Niño along CalCOFI Line 67

Quarterly sections perpendicular to the coast to 300 km offshore along CalCOFI line 67 (Fig. 1) allowed for an onshore–offshore description of anomalies associated with El Niño. The mean 1997–1998 data are



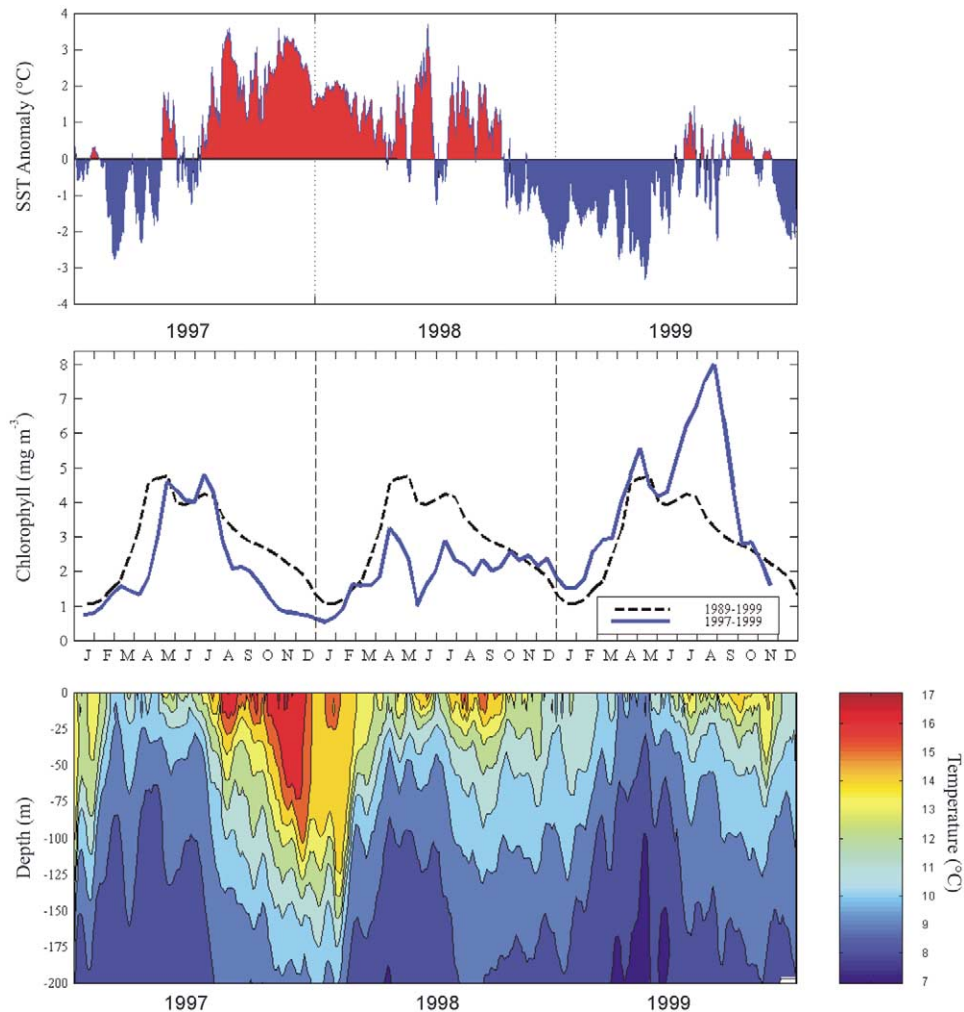


Fig. 3. Time series of daily SST anomaly from the M1 mooring (upper panel), surface chlorophyll for nearshore stations and the long-term mean (dashed line) (middle panel) and contours of temperatures to 200 m from the M1 mooring (lower panel) for 1997–1999.

compared with the mean for the normal years of 1988–1991 (Fig. 5). The temporal progression followed that described previously from the inshore moorings and time series cruises with some exceptions. In early 1997 upwelling was strong, leading to the development of abnormally cool conditions close to the coast (Fig. 5A). By early June 1997 conditions had changed but mostly offshore. The late upwelling 1997 temperature section showed the beginning of coastal thermocline anomalies and a weakening of equatorward transport in offshore waters. There was warmer, saltier water nearshore, relative to the 1988–1991 mean (Fig. 5B). Nitrate remained high nearshore, but low nitrate water ( $<0.2 \mu\text{M}$ ) was closer inshore than normal (Fig. 5C). This resulted in a narrower coastal band of high chlorophyll and primary production (Fig. 5D, E). During the 1997 oceanic and Davidson seasons the thermocline nearshore continued to deepen dramatically (Fig. 5A). Relatively high salinity, indicative of southerly water, continued to be present inshore (Fig. 5B). Low nitrate water was found along the entire transect by the oceanic season and this pool of low surface nitrate water persisted until mid-1998 (Fig. 5C). Similarly the band of high chlorophyll and primary

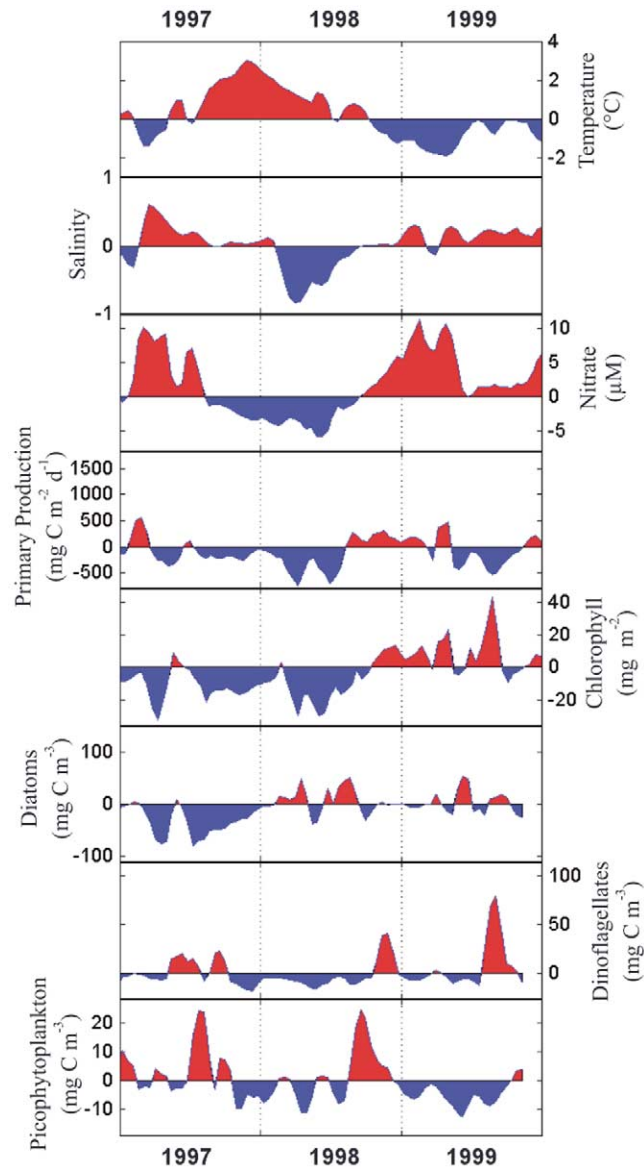


Fig. 4. Time series of anomalies (from the 1989–1999 mean) for SST, surface salinity, surface nitrate, integrated primary production, integrated chlorophyll, surface diatom biomass, surface dinoflagellate biomass and surface picoplankton biomass data from inshore stations. Data were gridded to 14-day intervals and a 3-point moving average applied. Climatological averages were calculated for each 14-day period covering 1989–1999.

productivity, that during normal times can extend to over 200 km from shore disappeared completely during the Davidson period and remained narrow through the late upwelling period of 1998 (Fig. 5D, E) The anomalous thermocline conditions near the coast began to recover during the early upwelling period of 1998, but a deep thermocline remained in the coastal transition zone (50–200 km from shore). Associated

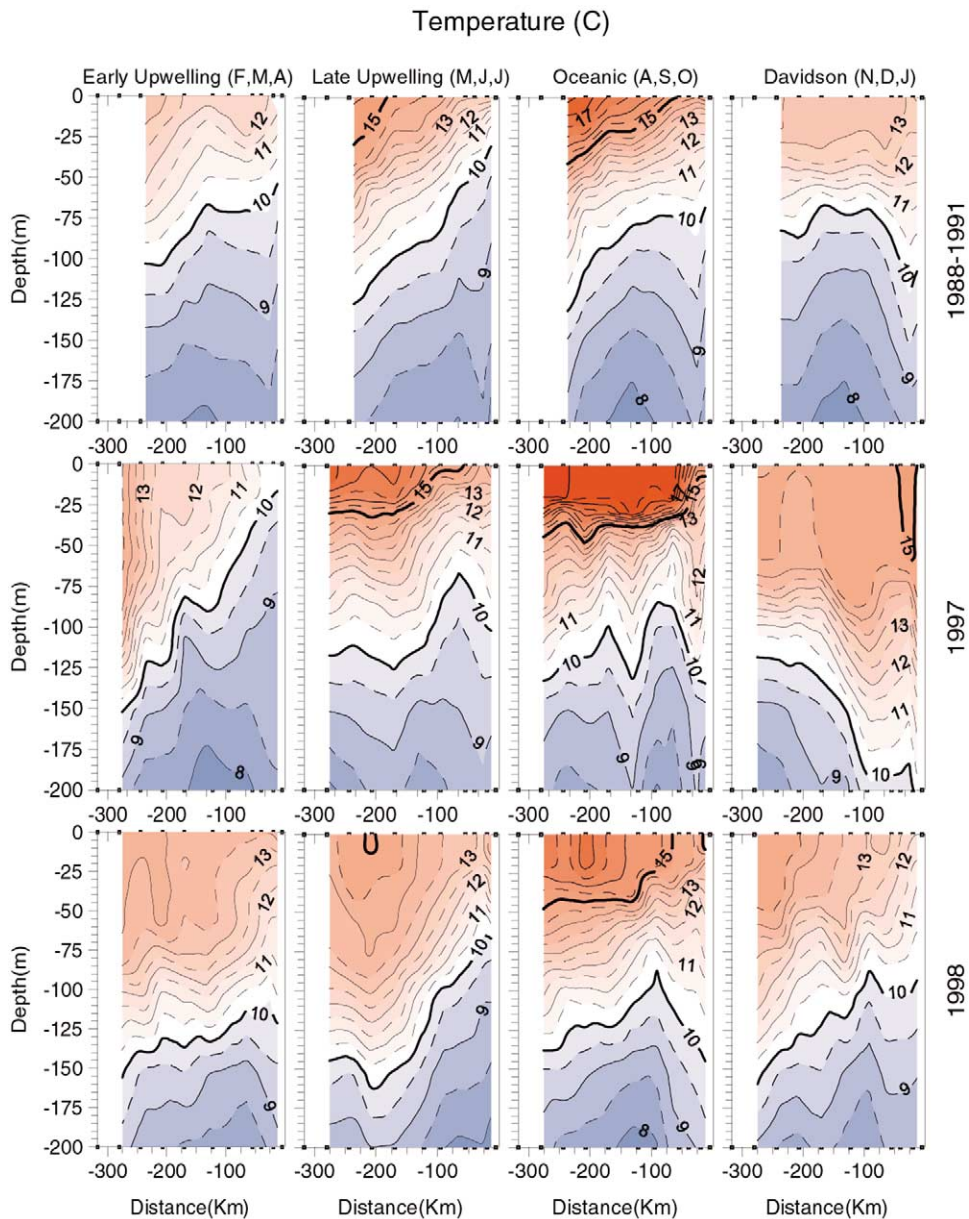


Fig. 5.a Comparison of temperature sections to 200 m along CalCOFI Line 67 for the early upwelling (FMA), late upwelling (MJJ), oceanic (ASO) and Davidson (NDJ) seasons during the normal years of 1988–1991, 1997 and 1998.

with this deep offshore thermocline, possibly resulting from reflected Rossby waves (Collins et al., 2002), was an anomalous freshening of the upper 100 m nearshore. This freshening appeared to be a product of an unusual coastal intrusion of the CC. These physical processes apparently counteracted the effects of the winds that were upwelling-favorable during that period. The chemical and biological fields during early

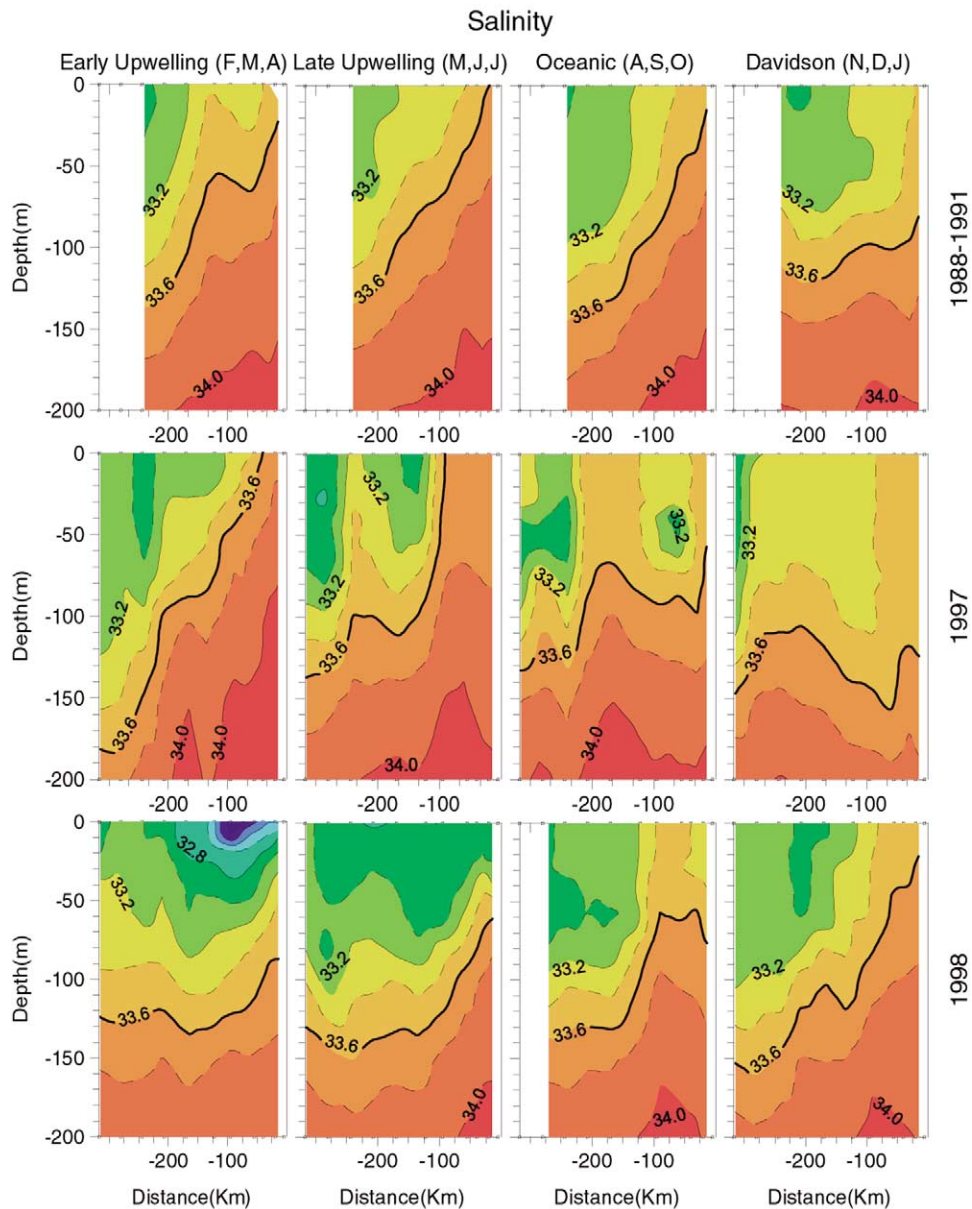


Fig. 5.b Same, but for salinity.

and late upwelling 1998 display the largest anomalies associated with the 1997–1998 El Niño (Figs. 3, 4, 5D, E). Recovery began during the 1998 oceanic season and by the 1998–1999 Davidson period anomalously cool upwelling conditions dominated. The biological response to this strong upwelling was dramatic (Fig. 5D).



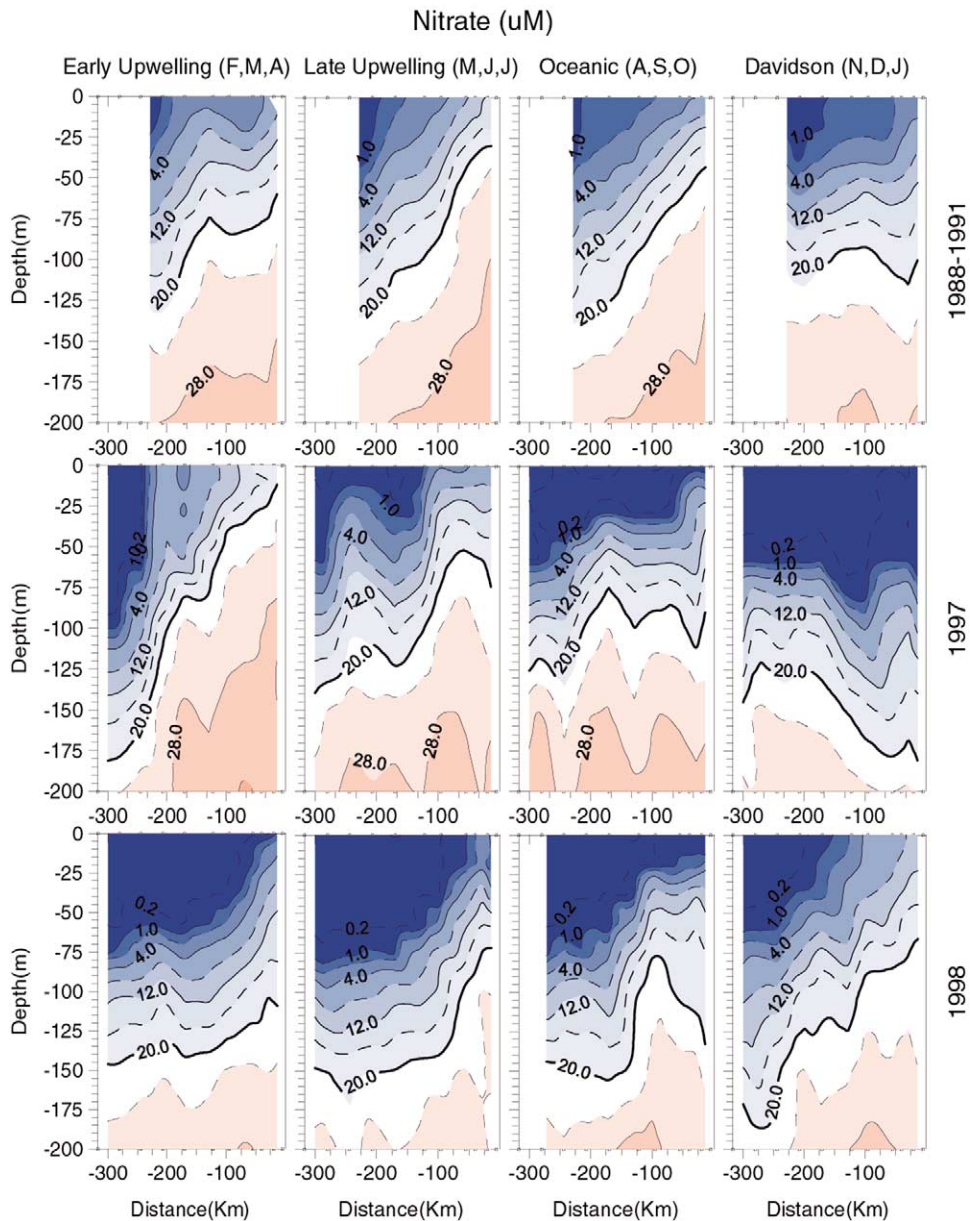


Fig. 5.c Same, but for nitrate.

### 3.3. El Niño as observed from SeaWiFS

The SeaWiFS time series began in late 1997 and only covers the second half of El Niño. Seasonal composites of chlorophyll for 1998 and 1999 are shown in Fig. 6. Decreased chlorophyll was evident during the El Niño period. We extracted a seasonal SeaWiFS time series along Line 67 and compared it to an average from Point Mendocino to Point Conception (Fig. 7). The comparison showed that, although Line 67 was more variable than the along coast average, it was a good proxy for the entire California

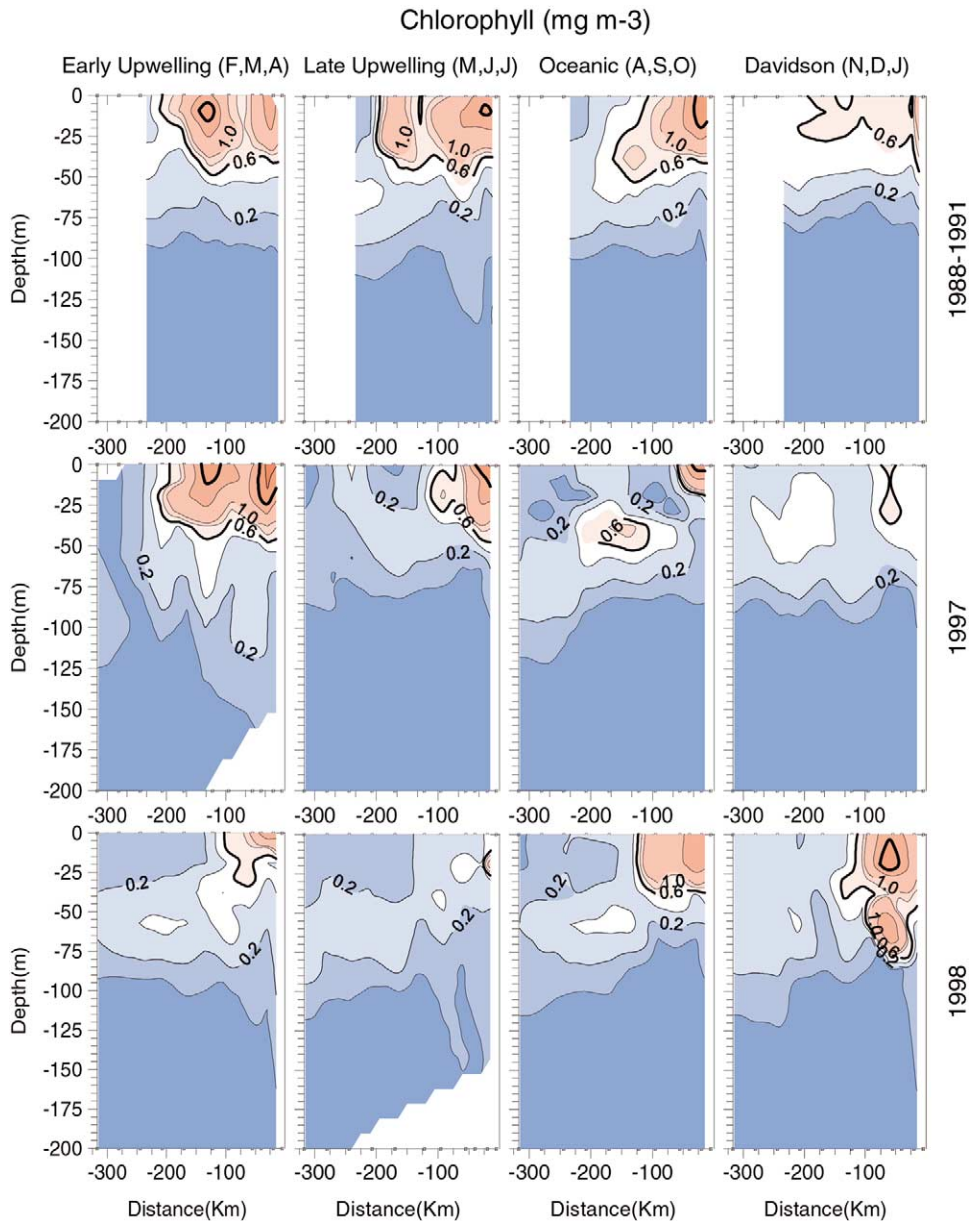


Fig. 5.d Same, but for chlorophyll.

coastal upwelling region. The SeaWiFS data were consistent with those observed from in situ measurements along Line 67 (Fig. 5D) in that the productive habitat was narrower during El Niño (Figs. 5D, 6, 7) and expanded significantly during 1999. The narrow persistent band of high chlorophyll and the retention of the seasonal cycle in productivity (Pennington & Chavez, 2000) during El Niño were also evident in the SeaWiFS data. Our observations are consistent with those of Kahru and Mitchell (2000); we have taken the SeaWiFS data further and calculated the seasonal primary productivity for the California coast (~640,000 km<sup>2</sup>) from late 1997 to late 1999 (Fig. 8). The winter or Davidson season of 1997–1998 exhibited

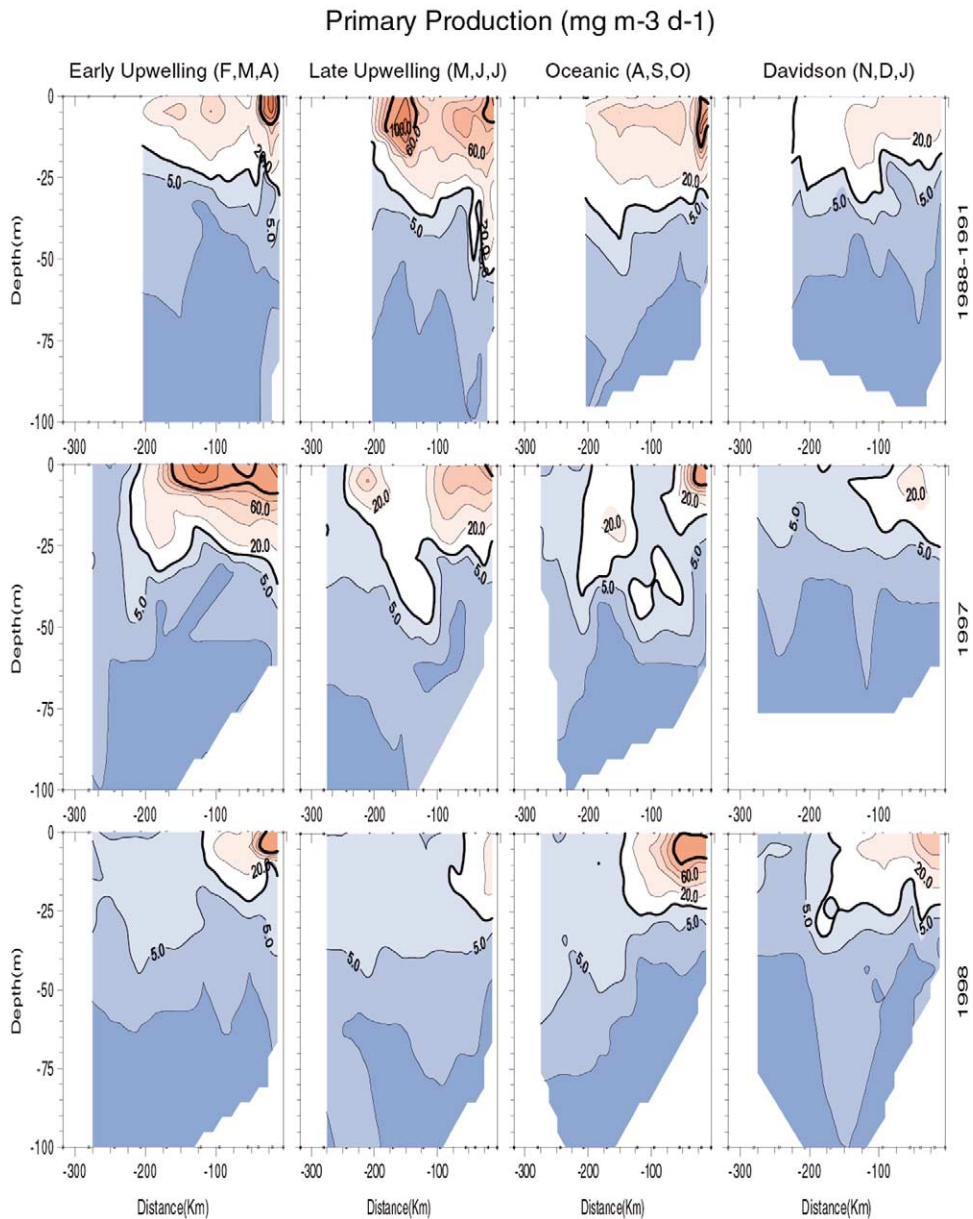


Fig. 5.e Same, but for primary production.

the lowest productivity of  $1.5 \times 10^{13}$ gC per season. The highest productivity was during the fall or oceanic season of 1999,  $4.1 \times 10^{13}$ gC. There was a generally increasing trend in primary productivity from winter 1997–1998 to fall 1999 that is interrupted by the seasonal low during winter 1998–1999. We have calculated the primary productivity anomaly associated with El Niño by taking the first year (November 1997–October 1998) as El Niño and the second year (November 1998–October 1999) as normal or La Niña. The calculated annual reduction in primary production for California waters was  $3.4 \times 10^{13}$ gC.

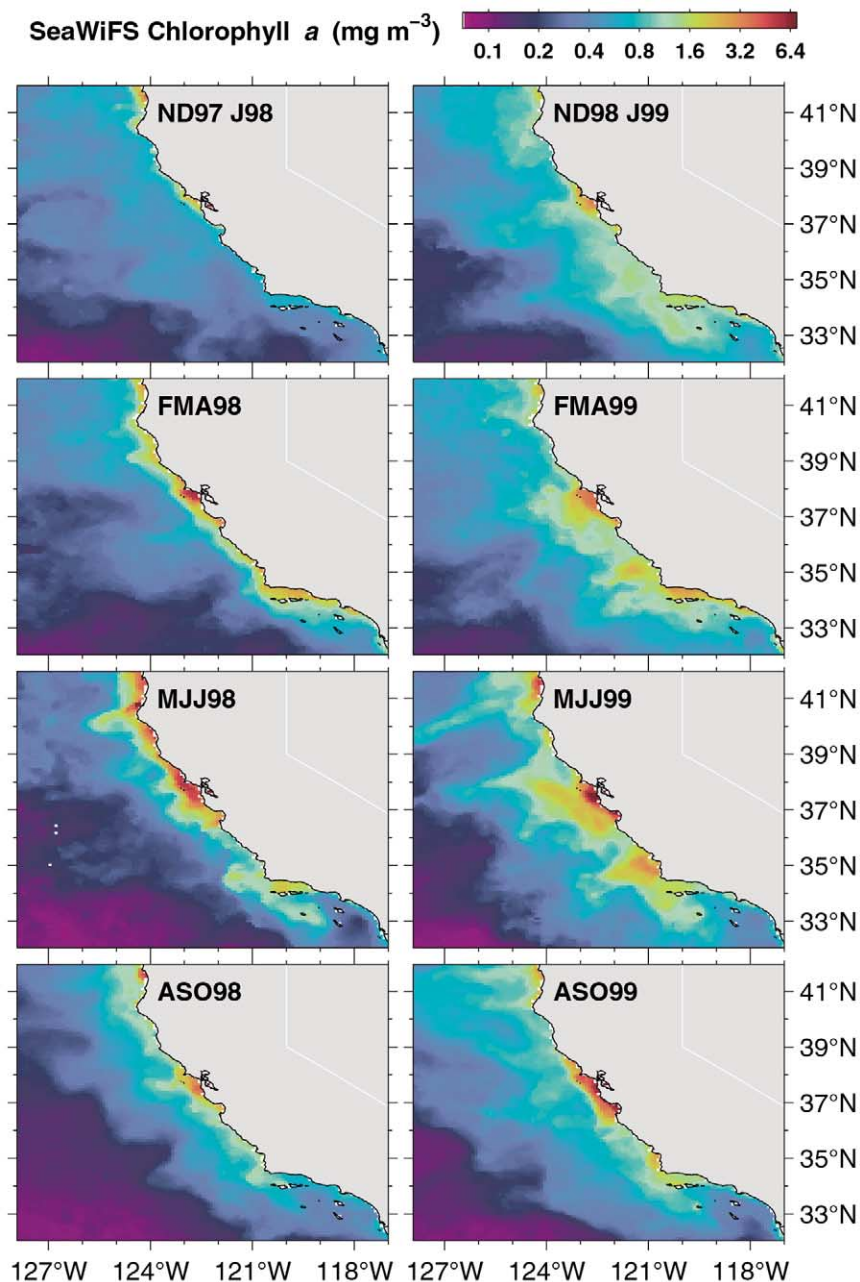


Fig. 6. Seasonal composites of SeaWiFS estimated chlorophyll from the Davidson period of 1997–1998 through to the oceanic season of 1999. The three top left panels show the effects of El Niño.



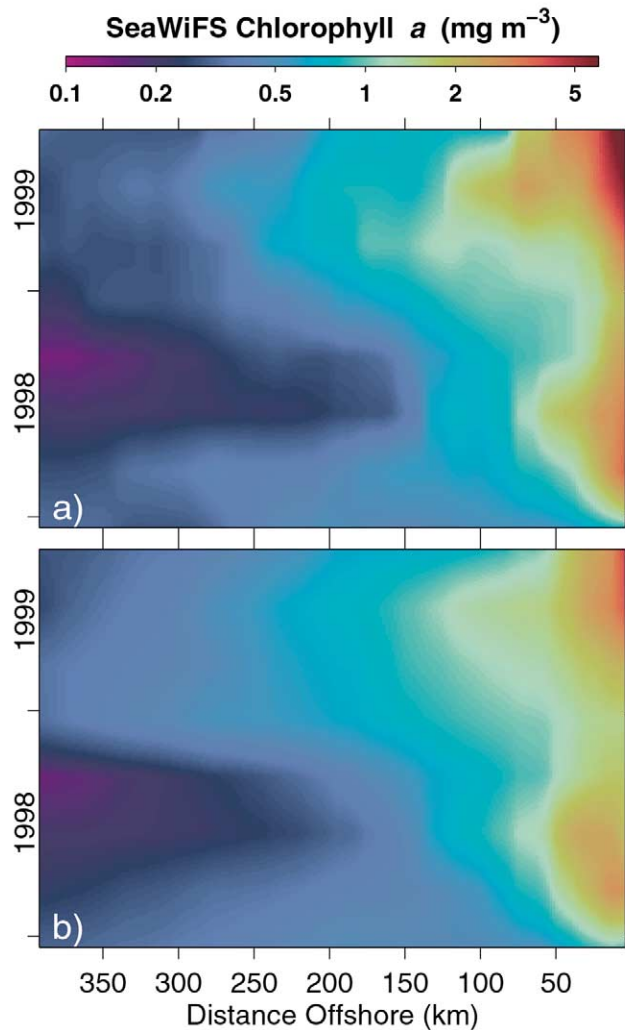


Fig. 7. Comparison of seasonal chlorophyll estimated from SeaWiFS for pixels along Line 67 and for a box extending the same distance from shore, but averaged from Cape Mendocino to Point Conception for the period from late 1997 to late 1999.

## 4. Discussion

### 4.1. Remote forcing and the evolution of California El Niño effects

In central California, out to 300 km from shore, there were few indications of abnormal ocean conditions during the first quarter of 1997 (Fig. 5). The large scale warming described by Schwing, Murphee, deWitt, and Green (2002) was not evident in the coastal domain. Sea level and SST off Monterey were not unusual during May and June 1997 (Fig. 2) when the first set of coastally trapped waves should have reached California (Strub & James, 2002). SST did show a short-lived 1–2 °C anomaly (Fig. 3) and there was a small increase in sea level (Ryan & Noble, 2002). Collins et al. (2002) describe a deep anomaly in dynamic height during June and July 1997. We have used a time series of the geochemical tracer  $N^*$  (Fig. 9) together with the change in temperature between March and June 1997 along Line 67 (Fig. 10) to explore

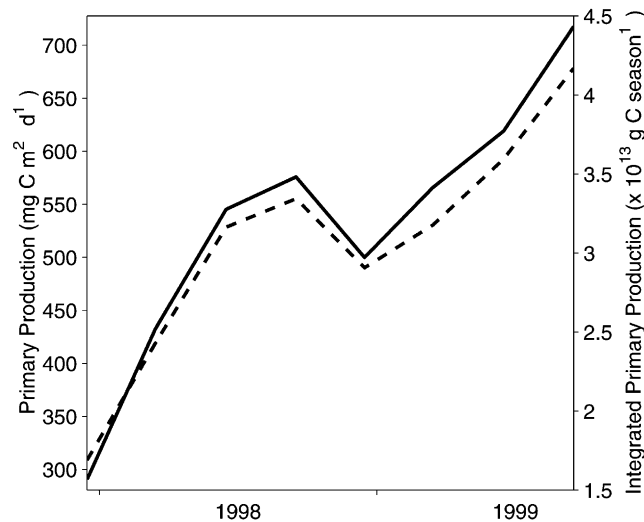


Fig. 8. Seasonal primary production estimated from SeaWiFS, a bio-optical model and measured productivity per unit chlorophyll for the domain shown in Fig. 6.

further conditions during the second quarter of 1997.  $N^*$  is a function of the inorganic nitrate to phosphate ratio and an indicator of denitrification (Gruber & Sarmiento, 1997). This signature is transported poleward from the northeastern tropical Pacific to central California via the CUC (Castro et al., 2001). The lowest  $N^*$  (higher denitrification; more water from the northeastern tropical Pacific) was observed during June and July 1997. During June 1997 anomalously warm temperatures down to 700 m ( $>1^\circ\text{C}$ ) were found along Line 67 out to 200 km from shore (Fig. 10). The characteristics (size and depth) and timing of these anomalies were consistent with an oceanic perturbation that propagated in a wave-like fashion from the tropics. The area affected (Fig. 10) exceeded what might be expected from a coastally trapped wave traveling northward along the coast. The remote forcing conclusion is further supported by the observation that winds off central California were not unusual during most of 1997–1998 (Collins et al., 2002; Friederich, Walz, Burczynski, & Chavez, 2002; Schwing & Moore, 2000). However, in sharp contrast to the South American coast (Fig. 2; Strub & James, 2002), where there was a dramatic response in coastal sea level and temperature, the effect on these properties during mid-1997 was much more subtle off North America.

The thermal anomalies reached their peak off California in late 1997 and were reminiscent of the classical El Niño effects reported for Peru (Barber & Chavez, 1983) and the equatorial Pacific (Chavez et al., 1999). The coastal thermocline progressively deepened, starting in August 1997, and attained its maximum anomaly in late 1997 (Fig. 2). Higher than average salinity (Figs. 4 and 5) and lower than average  $N^*$  (Fig. 9) continued to indicate waters of southerly origin. The thermocline recovered in early 1998 and anomalously fresh water was observed close to the coast. This freshening was partly associated with the enhanced runoff associated with El Niño-driven storms (Friederich et al., 2002) but freshwater budgets suggest there was a significant contribution from the fresher waters of the CC (Collins et al., 2002). Normally the poleward flow of the CUC acts to keep the CC about 100 km from shore (Collins et al., 2000). A nearshore weakening of the CUC is observed seasonally during February (Fig. 11) together with a surface freshening (Pennington & Chavez, 2000), presumably because of the closer proximity of the CC to shore. We surmise that during 1998 the CUC was unusually weak, perhaps because of a weakening of the alongshore pressure gradient resulting from the anomalous poleward flow during 1997. Anomalous poleward flow was reported during late 1997 in southern California by Lynn and Bograd (2002) and for the entire eastern boundary by Strub and James (2002). We propose the following sequence of events during the 1997–1998 El Niño.

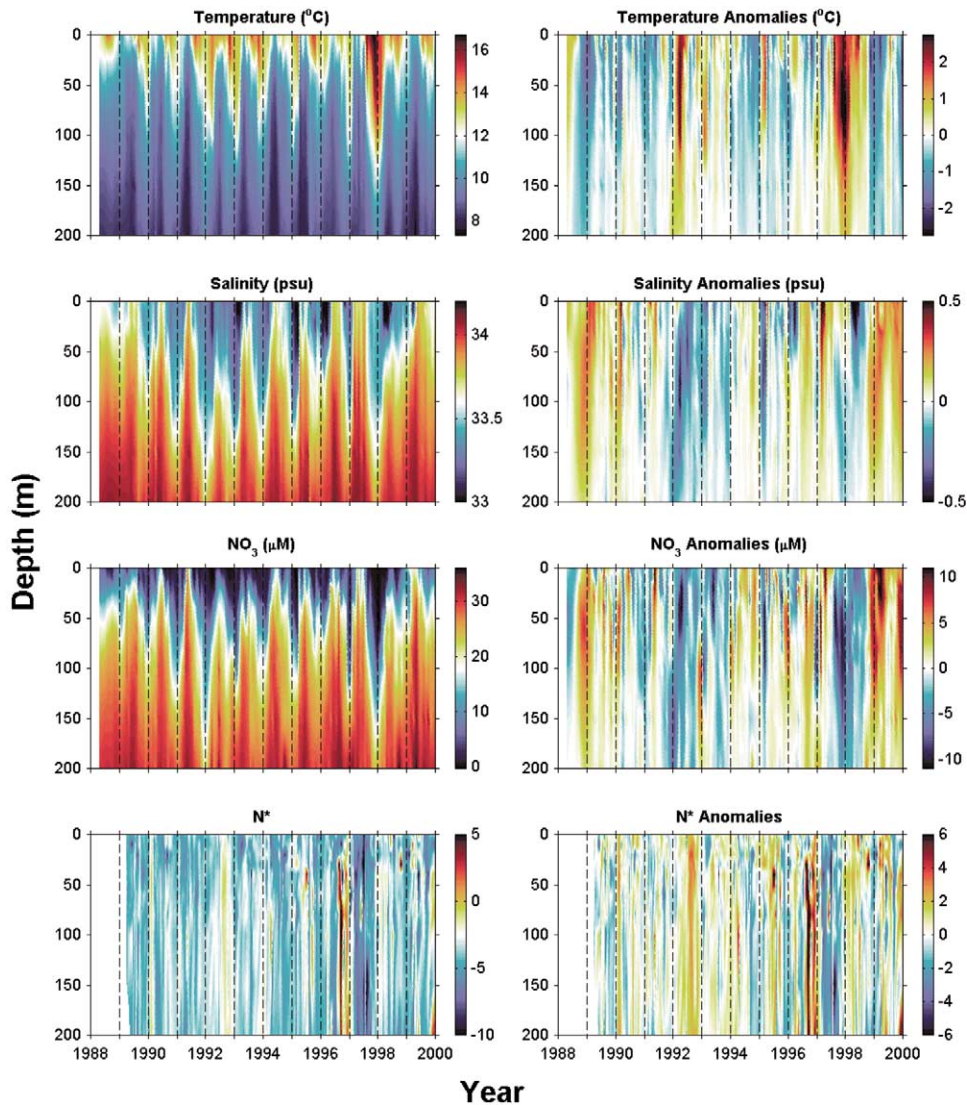


Fig. 9. Contours to 200 m of time series and anomalies (from the 1989–1999 mean) of temperature, salinity, nitrate and  $\text{N}^*$  measured from repeated shipboard occupations of the stations H3/Mooring 1.

Propagated disturbances from the tropics enhanced poleward flow (and weaken the CC) resulting in the anomalous presence of southerly waters (Durazo & Baumgartner, 2002; Lynn & Bograd, 2002). The enhanced poleward transport weakened the pressure gradient that drives the poleward flow, similar to what occurs in the equatorial Pacific where the EUC weakens significantly during El Niño. When the poleward flow weakens, the CC resumes and/or is displaced inshore from its normal position. This coastal CC together with a deepening of the thermocline that propagated offshore in a Rossby-like fashion (Collins et al., 2002) acted to extend the El Niño anomalies into the fall of 1998. By the winter of 1998–1999 conditions had changed, and strong upwelling, associated with stronger than average upwelling-favorable winds (Friederich et al., 2002; Schwing & Moore, 2000), and anomalous negative SST were evident (Figs.

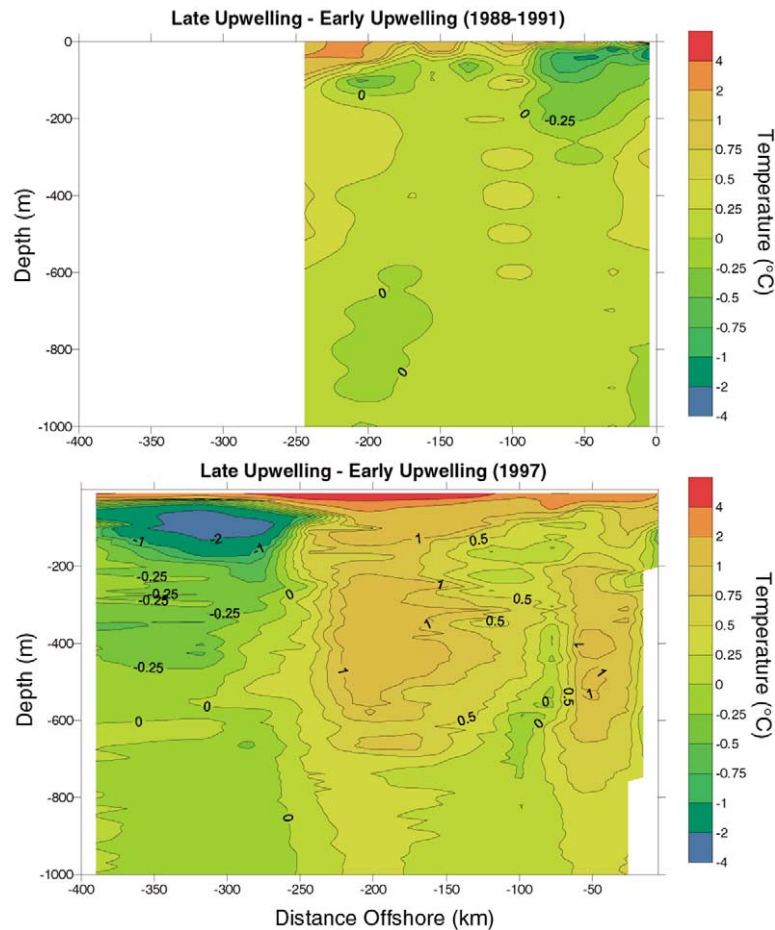


Fig. 10. Contours of the difference between climatological late and early upwelling (top panel) and June and March 1997 (lower panel) along Line 67. Two tongues of anomalously warm water ( $>1^{\circ}\text{C}$ ) were observed in June 1997 extending to at least 700 m. An anomalous layer of warm SST was also evident.

3 and 5). Re-establishment of the poleward flow moved CC waters offshore. The negative anomalies in SST persisted through the spring of 1999 (Fig. 3).

#### 4.2. Biological and chemical consequences

During normal active upwelling deep waters low in phytoplankton are brought to the surface at a rate that exceeds phytoplankton growth, so the populations remain low at the site of upwelling (Chavez, 1995; Olivieri & Chavez, 2000). Phytoplankton increase offshore or downstream of the upwelling site and biological uptake eventually consume the surface nutrients. Nitrate depletion typically occurs about 200 km from shore off California (Figs. 5C, 12). The highest coastal (0–25 km) concentrations of phytoplankton are found during weak upwelling or after strong upwelling-favorable winds relax and phytoplankton blooms are brought onshore (Fig. 12). During early 1997 normal active upwelling was in place and the size of the productive habitat (defined here as concentrations greater  $1\ \mu\text{M}$  nitrate or  $0.6\ \mu\text{g}$  chlorophyll per liter

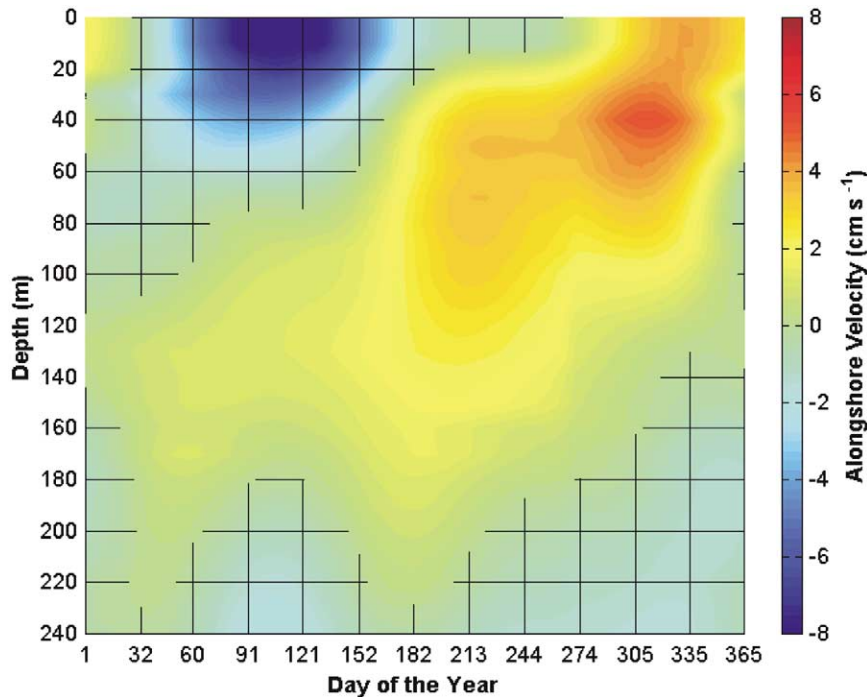


Fig. 11. Annual cycle of alongshore currents (0–200 m) at the M1 mooring. Filtered seasonal along-shore ADCP current velocities at M1 are shown. The data spans from 15 January 1992 to 22 September 1998. Gaps in the record were filled in with data that are statistically similar to the rest of the data set. (i.e. statistically 'neutral' data). The data were filtered with a 112 day low frequency band pass filter. The filtered data were then averaged to get the daily average for a 'typical' year. The North and East components were rotated so that the along-shore axis runs along the 330–150 degree line. The figure shows the progressive intensification and annual surfacing of the undercurrent, and its disappearance early in the year.

at the sea surface) extended to 200 km from shore (Fig. 5D). During normal years the 200 km productive area extends into the late upwelling period. However, during the late upwelling period of 1997 this area was reduced by half. This reduction continued during the following seasons and a small productive area was maintained through the late upwelling season of 1998. During El Niño continued coastal upwelling-favorable winds (and coastal runoff during winter) sustain enhanced production around the regions of active upwelling (close to M1 for example) but the area affected is reduced dramatically (Figs. 5D, 12). The greatest anomalies in chlorophyll and primary production occurred in the spring and summer of 1998 and coincided with the greatest nitrate anomalies (Fig. 4). Coastal (0–25 km) diatom populations were not anomalously low during this period. During the typical seasonal cycle diatoms account for over 90% of the variance in chlorophyll and primary production yet during El Niño their variability was not correlated to either. The high diatom abundance supports the conclusion that coastal processes (e.g. upwelling) that favor diatoms (through retention or resuspension) must have remained active during El Niño. However, carbon to chlorophyll ratio increased greatly and primary production per unit carbon decreased dramatically, indicative of nutrient-limited phytoplankton. Neither dinoflagellates nor picophytoplankton increased during El Niño.

The nitrate (and phosphate and silicate, not shown) consequences were tightly coupled to physical perturbations described previously. Early in 1997 enhanced upwelling resulted in above average surface nitrate

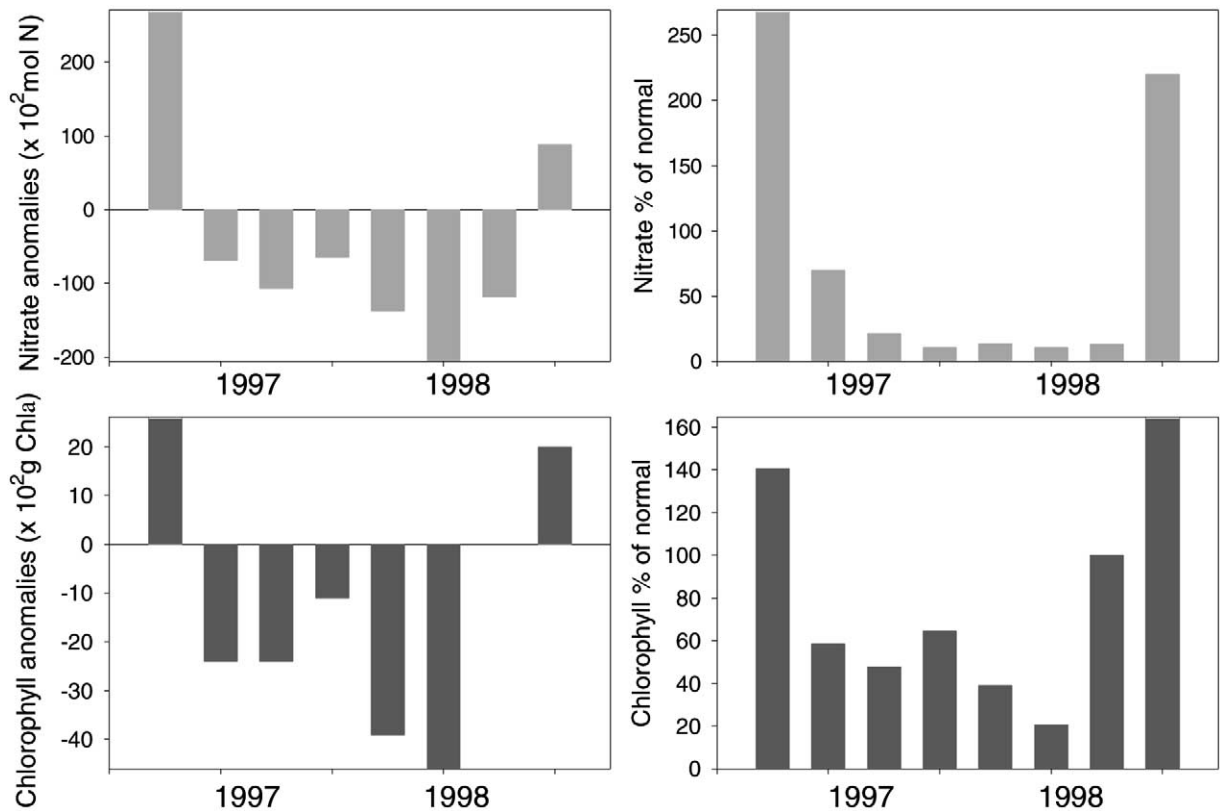


Fig. 12. Seasonal nitrate and chlorophyll for 1997–1998, integrated from the surface to 20 m and from the coast to 240 km from shore compared with the same integration for the 1988–1991 data (see Fig. 5C, D) to calculate anomalies (top panel) or percentages (bottom panel).

concentrations (Figs. 5C, 13). The late upwelling period of 1997 continued to exhibit above average concentrations close to the coast (Fig. 4). However, the isoline of  $1 \mu\text{M}$  nitrate had moved onshore from 200 to 100 km, and nitrate in the upper layer integrated over the Line 67 transect was below average (Figs. 5C, 13). The nutricline deepened with the thermocline and the expansion of the area of low nitrate continued and in late 1997 occupied the entire coastal zone (Fig. 5C). Surface nitrate turned lower than average close to the coast by August 1997 and remained below average until October 1998 (Fig. 4). A large pool of low surface nitrate water was evident from late 1997 through the oceanic season of 1998 (Fig. 5C), and nitrate in the upper layer was reduced by as much as 90% relative to normal conditions (Fig. 13). The nitrate in surface layers was 28% of normal on an annual basis. Coastal upwelling was evident during spring 1998, but the area affected was restricted to less than 50 km from shore compared to the normal 200 km. By late 1998 the near-coastal nitrate had become above average (Fig. 13) and the large pool of low nitrate water had practically disappeared.

The seasonally integrated nitrate and chlorophyll for 1997–1998 along Line 67 (from the surface to 20 m and from the coast to 240 km from shore) were compared to the 1988–1991 mean (Fig. 13). In the early 1997 upwelling period nitrate and chlorophyll were well above average. In the late 1997 upwelling period both turned below average and remained that way until the Davidson period of 1998–1999 when



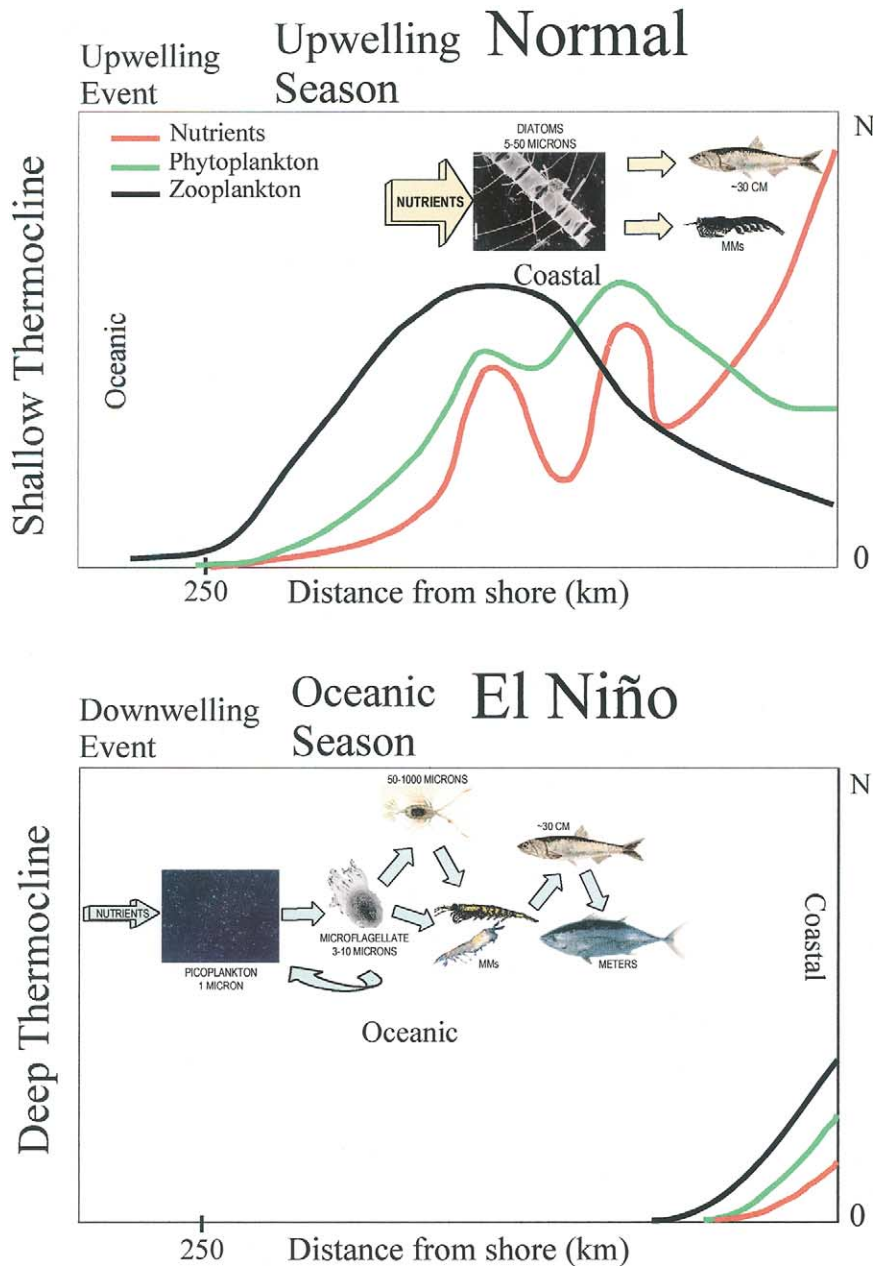


Fig. 13. Conceptual model of offshore-onshore ecosystem changes associated with El Niño. The coastal ecosystem exhibits high biomass and primary productivity as a result of an ample supply of nutrients (micro and macro). It is dominated by large phytoplankton, typically colonial centric diatoms, supports a food web with large zooplankton (i.e. euphausiids) and small pelagic fish that can graze directly on phytoplankton. During normal years this ecosystem occupies an area extending ~200 km from shore with variability associated with filaments. There is a spatial and temporal separation of sources (nutrients, phytoplankton) and sinks (phytoplankton, zooplankton). This coastal ecosystem is thought to be leaky in that a significant fraction of the primary production may escape the upper mixed layer to midwater and the sediments. An oceanic low biomass and primary productivity ecosystem is found offshore of the coastal ecosystem, when nutrients are drawdown. It is dominated by picophytoplankton whose grazers are protists with similar growth rates creating an efficient recycling system. A complex food web evolves with a smaller proportion of the primary production reaching the upper trophic levels. During warm years the productive coastal area is reduced dramatically and the oceanic ecosystem impinges on the shore.

they were once again well above average. From nitrate and chlorophyll we can define the El Niño period as extending from late upwelling 1997 to the oceanic 1998 seasons. During much of this period nitrate was reduced to below 20% of normal (Fig. 13). Chlorophyll was reduced on average to less than 50% of normal and was down to 20% of normal during the late 1998 upwelling season. The anomalies of nitrate and chlorophyll were highly correlated ( $r = 0.88$ ,  $p < 0.01$ ) suggesting a tight coupling between nitrate supply and biological production. There was no taxonomic data for Line 67 but size-fractionated chlorophyll data (not presented) showed a decrease in the larger fraction (diatoms) in the offshore waters associated with El Niño. During the 1998–1999 winter or Davidson season we observed large blooms of phytoplankton that are otherwise rare during this season.

The available SeaWiFS data also showed a reduction in the size of the area of high chlorophyll during El Niño (Fig. 6). The near-coastal, Line 67 and SeaWiFS data support the conceptual model that onshore–offshore changes are a fundamental part of El Niño-generated productivity anomalies (Fig. 12). From SeaWiFS we have estimated the productivity anomaly for California coastal waters for the 1997–1998 El Niño to be at least  $3.4 \times 10^{13}$  gC. If we further assume that the productivity anomalies for the late upwelling and oceanic seasons for 1997 (not measured by SeaWiFS) were equal to the average of the other seasonal anomalies then productivity declined by  $5.1 \times 10^{13}$  gC for the 18-month period of El Niño. We argue that this anomaly can be directly related to a decrease in the supply of nutrients and that this was also the decline in new production. We have estimated new production from wind-driven coastal upwelling for the California coast following Chavez and Toggweiler (1995) (1 Sverdrup per 1000 km of coast and 20  $\mu$ M nitrate in the source water) to be  $5 \times 10^{13}$  gC per year. Given that the productivity decrease was associated with a reduction in the supply of nitrate then new production was reduced by 68% (from 5 to 3.4) during the 1997–1998 El Niño. This value compares well to the decrease in nitrate calculated previously. Since new production supports the upper trophic levels as well as the midwater and benthic communities, these must have suffered extensively during 1997–1998.

In summary, first as a result of remotely forced coastally trapped waves and then as a result of a weaker CC circulation, a deepening of the nutricline reduced the supply of nutrients to the surface waters off western North America. The observed decreases in primary production were directly linked to changes in nutrient supply. Thus, there was a clear evidence of physical forcing driving a biological response. The effects off central California were similar in nature to those in the equatorial Pacific (Chavez et al., 1999); Bograd and Lynn (2001) also noted this for Southern California. An important aspect of the El Niño (and La Niña) physical anomalies was that they were most pronounced during the winter, the period of lowest seasonal production (Fig. 3). Should the strongest perturbations have occurred during the spring and summer upwelling seasons then the effects on biological production could have been greater.

#### 4.3. Comparison with the 1992–1993 El Niño

Our records encompass one other named event (1992) although persistent El Niño-like anomalies were evident in the tropics from 1991 to 1995. The onset of the 1992 El Niño occurred in the spring (Fig. 14) (Chavez, 1995; Ramp, McClean, Collins, Semtner, & Hays, 1997). The strongest positive temperature anomalies were observed during 1992 with weaker, intermittent anomalies persisting through 1993. The onset of positive temperature anomalies during 1997–1998 was later in the year and anomalies were stronger, and appear as one cohesive set of positive anomalies. In both cases greatest temperature anomalies were subsurface, at the depth where the thermocline is found normally. Anomalies ( $>1$  °C) extended deeper during 1997–1998. The 1992–1993 temperature anomalies extended longer than during 1997–1998. Notable differences can also be found in the salinity fields. During 1992 coastal salinity was fresher than normal at onset indicating water from offshore. The N\* data support the conclusions drawn from the salinity field. During 1992 (or 1993) there was little evidence of enhanced transport of denitrified waters. N\* anomalies were mostly positive indicating the presence of water of northern or offshore origin. In 1997 on the other



## Anomalies

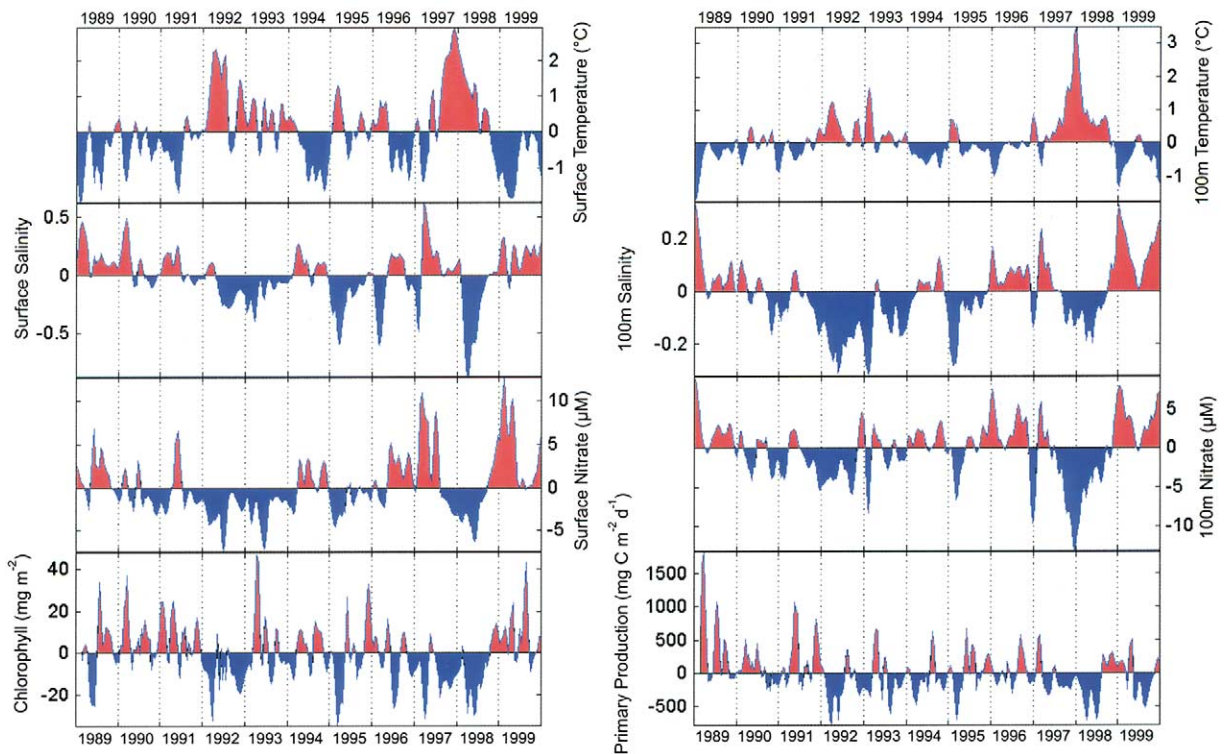


Fig. 14. Time series of surface (left panels) and 100 m (right panel) temperature, salinity and nitrate for the inshore stations of the MBTS. Also shown are time series of integrated chlorophyll (lower left) and primary production (lower right). There is strong correspondence between physical and chemical properties but these are not well correlated with the biological time series.

hand there was a large positive salinity (negative  $N^*$ ) anomaly, which we have associated with enhanced poleward transport. The salinity anomaly during 1992, while not as intense at the surface as 1998, penetrated deeper into the water column (Fig. 14). During strong events, like 1997–1998, enhanced poleward flow early in the event kept the fresher waters offshore. Later in the event, onshore flow dominated as the CUC weakened. This sequence was consistent with the description of the 1982–1983 El Niño off Oregon (Huyer & Smith, 1985). The relative importance of onshore versus poleward transport then seems to be related to El Niño intensity and perhaps timing of onset. There may also be latitudinal changes in the relative importance of these transports.

The longer duration of the 1992–1993 El Niño, relative to 1997–1998, was more evident in nitrate and salinity than in temperature (Fig. 14). The amplitude of the nitrate anomalies was greater in 1997–1998. The largest anomalies were subsurface and a second surface nitrate anomaly was associated with lower salinity in 1998. Finally, the 1997–1998 El Niño started and ended much more abruptly than the 1992–1993 El Niño. The 1992–1993 El Niño was bounded by weak warm anomalies both prior to and after the event. On the other hand early 1997 and late 1998 were abnormally cool. The strongest (negative) temperature and (positive) nitrate anomalies for the entire record occurred in 1999. Fish catch records from the

coast of Peru show that there was a remarkable recovery of anchoveta after 1998, whereas no similar rebound occurred after the 1983 or 1993 events. Pearcy (2002) reports a similar phenomenon for salmon off Oregon. So the different ecosystem responses to El Niño are perhaps related to the longer-term background climatic state of the Pacific Ocean (Fedorov & Philander, 2000). The 1982–1983 and 1992–1993 El Niños occurred during the warm phase of the Pacific Decadal Oscillation (PDO), a 20–40 year cycle of Pacific temperatures (Chao, Ghil, & McWilliams, 2000; Mantua, Hare, Zhang, Wallace, & Francis, 1997). The PDO appears to have changed sign in the late 1990s apparently ameliorating the biogeochemical and ecological impact of the 1997–1998 El Niño.

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