El Niño and the California Current System

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Introduction

The waters along the California coastline are recognized as an area of high productivity. However, it was the sudden collapse of the California sardine fishery in the late 1940's that prompted the long-term California Cooperative Oceanic Fisheries Investigations (CalCOFI) to begin routine oceanographic measurements along the California Coast. Augmented with results from other programs using moorings and satellite remotely-sensed data, these data describe the climatology of the California Current System (CCS) and changes to the CCS from perturbations such as El Niño, generally characterized by anomalous warming of the ocean waters. In recent decades there has been a seeming increase in the frequency of El Niño-Southern Oscillation (ENSO) events, perhaps a harbinger of global warming. Due to the recent interest in global warming, it is important to understand the effect of El Niño on California's oceanic productivity.

Numerous studies have attempted to determine the relationship between the physical processes and the resulting biological consequences in the CCS. This paper summarizes work describing the effect of El Niño on California waters. First, however, the effects of El Niño on the equatorial Pacific (EP) are described. The EP is a simpler system than the CCS. There is little seasonality in the circulation of the EP whereas the seasons have a distinct signal in the CCS. Understanding the ENSO impact on the EP can illuminate the effects on the more complicated CCS. The ENSO signal initiates in the EP, and propagates via Kelvin waves eastward and then poleward to the western coasts of the Americas. This paper traces the ENSO signal and its effects in the CCS in the Southern California Bight (SCB) and north in Monterey Bay. In both the EP and the CCS, El Niño has dramatic effects on the circulation and productivity of the ocean waters.

Circulation Dynamics and Biology

Light and nutrients are essential to biological productivity. Light in the water column decreases with depth, resulting in a depth-limited euphotic zone. The concentration of nutrients in the euphotic zone depends on the circulation. At a given location, nutrients will be depleted by biological consumption and settling unless they are replenished. Nutrients such as carbon, nitrate, silicate, and phosphate settle in the water and carbon dioxide is more soluble in colder temperatures. Hence, greater concentrations of nutrients are found at depth than at the surface. Vertical advection brings nutrients to the surface. Horizontal advection transports nutrients to areas away from the upwelling site. However, if the nutricline is below the Ekman depth from which upwelled water is drawn, then few nutrients will be brought to the surface. In summary, euphotic zone nutrient availability depends on the nutricline depth, upwelling conditions, and surface currents.

There are similarities between the EP and CCS waters. Under nominal conditions, the circulation of both systems is strongly influenced by winds. In the EP, the easterly Trade Winds produce Ekman upwelling along the equator. In the CCS, two wind processes produce upwelling. Nearshore Ekman upwelling is a response to seasonal (spring-summer) equatorward, alongshore winds. Offshore upwelling is due to Ekman pumping, a response to regions of positive wind-stress curl found along most of the California coast. Upwelling brings relatively cold, nutrient-rich water to the surface where the nutrients are consumed in a process called the biological pump. In the EP, the biological pump is inefficient, i.e. nutrients are upwelled at a rate faster than can be consumed by biology. Excess nutrients are advected away from the upwelling site. In the EP, the nutrients are advected northward and southward away from the equator. In the CCS, any unconsumed nutrients are transported offshore and downcurrent. Another feature common to the EP and CCS is an undercurrent. In the EP, the Equatorial Undercurrent (EUC) flows eastward in response to an east-west pressure gradient. Likewise in the CCS, the California Undercurrent (CUC) flows poleward in response to a north-south pressure gradient and the surface equatorward-flowing California Current (CC). In both systems, the undercurrent is the primary source for upwelled nutrients. Changes to the horizontal pressure gradients impact the surface and subsurface currents and the thermocline depth. These, in turn, affect the availability of nutrients. Eventually the entire food chain is impacted.

El Niño and the Equatorial Pacific

A change in the atmospheric pressure gradient between the eastern and western Pacific appears to initiate an El Niño event. The normal easterly Trade Winds lessen or cease over portions of the Pacific Basin. These westerly wind anomalies trigger westward propagating Rossby waves and eastward propagating Kelvin waves along the equator. The thermocline, which normally is deep in the west and shallow in the east, flattens, becoming shallower than normal in the west and deeper than normal in the east. The western pool of warm water moves eastward under the westerly wind anomalies. Water that normally "piles up" in the west from the Trade Winds no longer does so. The net effect of these adjustments is a reduction in the east-west horizontal pressure gradient and a lessening in the flow of the EUC. The reduced easterly winds also produce less upwelling. The upwelling that does occur draws from nutrient-poor water since the nutricline, associated with the thermocline, is now deeper than normal. The end result is less net primary production (NPP).

Feely et al. (1999) and Chavez et al. (1999) detailed the changes in nitrate, chlorophyll, and carbon dioxide in the EP as a result of the 1997-1998 El Niño. During the El Niño, upwelling and the EUC ceased for several months, essentially cutting off the supply of nutrients to surface waters. As a result, nutrient concentrations declined. This is seen in Figure 1, a comparison between the spatial distributions of nutrients between non-

El Niño climatology and the El Niño period. During non-El Niño periods, there is an excess of carbon dioxide in the water, over 130 μatm at 100^o west. Even at 180^o west there is an excess of 70 μatm. In contrast, during El Niño the amount of excess carbon dioxide plummeted to less than 20 μatm over the entire region. Similar decreases are seen in nitrate and chlorophyll concentrations. Normal peak concentrations of nitrate of greater than 7 μmoles dropped during the El Niño to less than 1 μmole. Chlorophyll decreased from an average of 0.2-0.3 μgrams per liter to less than 0.05 μgrams per liter. NPP did not decrease as greatly as might be expected from the 80% reduction in nutrients. The distribution of phytoplankton species changed so that the biological pump was more efficient. All told, the changes resulted in a 50% decrease in NPP from 75 mmol C per m^2 per day to 35 mmol C per m^2 per day.

NPP in the EP recovered very swiftly after the resumption of the easterly Trade Winds. Both the EUC and equatorial upwelling resumed in response to the winds. Subsequently, the thermocline and nutricline shoaled in the central EP. Hence surface nutrient concentrations increased. The resulting NPP was estimated to be 80 to 160 mmol C per m^2 per day.

El Niño and the California Current System

The El Niño impact on the CCS is not as easily traced as in the EP. The CCS has a distinct seasonality caused by the annual wind patterns. As in the EP, the El Niño signal affects the circulation of the CCS and the depths of the thermocline and nutricline. The change in the thermocline and nutricline means warmer surface temperatures, greater stratification, and lower nutrient concentrations in upwelled water. In the EP, the winds responsible for the upwelling ceased during the El Niño. However, along the west coast of North America, the wind patterns remained normal. In this section, first the nominal conditions of the CCS are described, followed by a description of the effects of the 1997-1998 El Niño on the CCS.

The circulation of the CCS has a seasonal pattern, dependent on the winds. There are two year-round currents, the broad, surface, equatorward-flowing CC and the narrower, subsurface, poleward-flowing CUC. The two year-round currents have distinct hydrological signatures. The CC has its source in Pacific sub-arctic waters. Thus cold temperatures, high dissolved-oxygen content, low salinity, and low nutrient concentrations characterize the CC. In contrast, the CUC originates in eastern Pacific tropical waters. The CUC has high salinity and relatively-high nutrient levels. In addition to the two annual currents, there is a seasonal (winter) poleward surface current immediately adjacent to the coast, beginning in the south near the SCB and extending north past San Francisco; this flow is often called the Davidson Current or the Inshore Countercurrent (IC). In general, the CCS has weak eddying flow near the coast during the winter. The winds are variable along the coast during winter months. However in the spring, the winds are equatorward and produce coastal Ekman upwelling. In geostrophic response to the upwelling, a strong, surface, nearshore equatorward jet overtakes the poleward IC. By the summer, the equatorward flows have joined to become one broad current. The entire surface current is equatorward. The subsurface poleward CUC is nearshore and slow. Similar to the EP, the undercurrent is maintained by a horizontal pressure gradient; this gradient is enhanced when the CC strengthens. Another response to the strengthening of the CC is the tilting of nearshore isotherms. This tilting and the Ekman upwelling of the nutrient rich CUC water lead to nearshore regions of high productivity. Excess nutrients are advected downcurrent so that there is an additional region of high productivity offshore. Offshore productivity is also supported by a supply of nutrients brought to the surface by Ekman pumping, the result of nearly year-round offshore positive wind-stress curl (Chelton, 1982).

There is consensus that the El Niño oceanic signal is transmitted by Kelvin waves. These waves propagate eastward across the Pacific basin and then travel north and south of the equator as coastally-trapped waves. Chavez et al. (1999) noted several pulses in the EP, with the first pulse in early 1997, followed by several others in February, May, and August of 1997. These pulses can be detected as sea level and temperature anomalies. Dever and Winant (2002), Lynn and Bograd (2002), and Ryan and Noble (2002) detected at least 2 pulses in the CCS. They agreed on the first pulse that arrived at the SCB in June/July 1997 and a second, large pulse that arrived in late 1997-early 1998. Figure 2 shows the temperature anomalies in Monterey Bay for 1997 through 1999. The first pulse of warm water is clear in July 1997. Also evident is the extended warm pulse in late 1997 and early 1998. The distance traveled by the waves and the delays are appropriate for the phase speed of Kelvin waves (~200 km/day).

The Kelvin waves do more than transmit the El Niño signal. The waves actually advect equatorial waters poleward. This is confirmed by tracing the hydrological characteristics. Chavez et al. (2002) used N* to trace the Monterey Bay water characteristics throughout the 1997-1999 El Niño cycle. They found that the N* values matched those of Northeastern tropical Pacific waters that are characteristically very low, indicative of high denitrification. Lynn et al. (1998) measured very warm and saline waters in the SCB during July 1997. Over and near the continental slope at depths between 150 and 450 m, the salinity was greater than 34.4. These salinity values are typical of waters found 550 km to the south. The spiciness increased first at depth and then at the surface. The waters in Monterey Bay also increased in salinity during July 1997 (Collins et al. 2003), as shown in Figure 3. The largest salinity anomalies occurred in the late summer months. Marinovic et al. (2002) identified the source of water in Monterey Bay by analyzing zooplankton and euphasid communities. In July 1997, adult *Nyctiphanes simplex*, a species normally found south of Pt. Conception, suddenly appeared in the bay waters. From August to November 1997, the abundance of southern warm temperate and tropical species increased while those of northern cool water species decreased. This change in community composition is a clear sign of poleward transport of southern water.

The CCS typically has net equatorward transport. The broad surface equatorward CC flow is greater than the subsurface poleward CUC flow. Even in the winter, the poleward IC is too narrow and shallow to tip the balance of net transport. However, during the El Niño the net transport did change to being poleward. Beginning with the first El Niño pulse in July, the surface equatorward transport lessened. Lynn and Bograd (2002) saw 2 distinct pulses of strong poleward flow in the subsurface CUC, the first in July 1997 and the second in November 1997. Between July 1997 and February 1998, the surface IC and the CUC strengthened and broadened. Figure 4 shows this evolution of the CCS transport between CalCOFI lines 80 and 90 in the SCB. At its peak, the poleward flow extended from the coast to 387-km offshore and from the surface to at least 500-m depth. The result was a net poleward flow of the CCS.

The passage of the Kelvin waves also affects the thermocline and nutricline depths. Bograd and Lynn (2001) noted that the nominal nearshore depth of the nutricline (the depth of 10 μmol/L of nitrate) in the SCB is less than 60 m, and even shallower near Pt. Conception. Beginning in July 1997, the nutricline was depressed to depths greater than 80 m, even at the coast. This continued through February 1998. The deepening of the thermocline and nutricline began inshore and propagated offshore in a manner consistent with Rossby wave dynamics. July's sudden depression of the nutricline is obvious in Figure 5, which shows the time history of the nutricline depth for CalCOFI lines 80 and 90 in the SCB. Similar deepening of the nutricline was observed in Monterey Bay, as depicted in Figures 6 and 7.

As mentioned previously, upwelling and the nutricline depth are particularly important to NPP. Without a supply of nutrients, primary production in the euphotic zone cannot occur. Figure 8 shows the upwelling indices and the upwelling anomalies for the U.S. west coast. California experienced winds strongly favorable to upwelling during the spring and summer of 1997. However, the nutricline was below the Ekman depth. Also, as seen in Figure 7, except for a very narrow nearshore region, the upper 60 m of water had nitrate concentrations less than 1 μmol/kg. The depletion of nutrients in the upper water column continued through the end of 1998. Plots of chlorophyll and zooplankton abundance reflect the lack of nutrients. Figure 9 compares the Monterey Bay surface chlorophyll concentrations during the El Niño cycle to the climatological values. Beginning in July of 1997, the concentration of chlorophyll dropped below mean levels, continuing to be lower than normal until nearly the end of 1998. Figure 10 shows the time history of the zooplankton abundance in the SCB. There is a dramatic absence of zooplankton from September 1997 through February 1998. Bograd and Lynn (2001) measured normal nutricline depths in the SCB beginning in March 1998; this coincides with the reappearance of zooplankton.

The return of zooplankton in surface waters is just one sign of the beginning of the recovery from the El Niño. Starting in March 1998, water temperatures began dropping towards normal values. The surface waters freshened, signaling a strengthening of the CC. The current first redeveloped nearshore and then moved offshore at ~1.4 km/day, the phase speed of a Rossby wave. By April 1998, the net transport of the CCS was equatorward. The poleward subsurface flow had diminished to 10% of its normal value within a narrow inshore region. Throughout the spring and summer of 1998, increasing numbers of oceanic euphasiid species (*Nemotoscelis difficilis*) indicated the onshore movement of the CC (Marinovic et al., 2002). This onshore movement coincided with a period of atypical downwelling-favorable winds. As a consequence, nitrate levels and chlorophyll concentrations continued to remain lower than normal until November 1998.

The final phase of the El Niño cycle began at the end of 1998 and continued through 1999. Cold water anomalies and very shallow thermoclines and nutriclines characterize a La Niña. In the SCB, the nutricline shoaled, especially at Pt. Conception, evident in Figure 5. There was enhanced coastal upwelling in the spring of 1999, when record values of nitrate, 11.5 μmol/L, were measured at the surface. These concentrations extended 200 km offshore (Bograd and Lynn, 2001). Biology benefited from the ample supply of nutrients. April 1999 saw the highest values of NPP in a 50-year history. Figures 9 and 10 show the blooms in chlorophyll and zooplankton (respectively) in 1999.

Summary

An El Niño event greatly impacts the circulation and hydrological and biological signatures of water. In both the Equatorial Pacific and the California Current System, an El Niño causes the depths of thermocline and nutricline to deepen. In both systems, this results in an increase in water temperature and stratification, and a decrease in surface nutrient concentrations. In the EP, the undercurrent ceases to flow and upwelling stops, cutting off the supply of nutrients to the surface. In the CCS, the upwelling may continue, but the nutricline is below the Ekman depth so fewer nutrients are vertically advected. Consequently, NPP plummets. The recovery from El Niño begins in the EP with the resumption of the easterly Trade Winds. This shifts the east-west horizontal pressure gradient such that the EUC resumes flow. Upwelling also resumes. As a result, large quantities of nutrients are available and NPP peaks. Chavez et al. (2002) suggest that recovery in the CCS takes a different route. The strong poleward flow that delivers the El Niño signal overwhelms the normal equatorward flow in the CCS. This weakens the normal north-south pressure gradient. Like a teeter-totter, the balance tips and the surface equatorward flow strengthens, returning the north-south pressure gradient to its normal state, allowing the undercurrent to resume. The strong equatorward flow also causes the isotherms to tilt steeply, bringing nutrients closer to the surface. Finally, coastal upwelling delivers the nutrients to the surface. The 1999 La Niña resulted in the highest recorded primary productivity in the CCS and EP.

Discussion

In the EP, the primary source of nutrients is the EUC. The nutrients are delivered to the surface through Ekman upwelling. The 1997-1998 El Niño shut down both the source and the agent of delivery, tremendously reducing NPP as a result. However in the CCS, the CUC is the source of nutrients and this subsurface flow is enhanced by the El Niño oceanic signal. Also, during the first year of the 1997-1998 El Niño, upwelling winds were stronger than usual. Despite having a source of and method to deliver the nutrients to the euphotic zone, NPP off the California coast also plummeted. Salinity is a conserved quantity; on the other hand, nutrients are not. A sudden rich supply of nutrients south of California may have been consumed before the water reached the northern region. Kahru and Mitchell (2002) used satellite remotely-sensed data to estimate NPP throughout the CCS during the 1997-1998 El Niño. They found decreased NPP from the coast to 1000-km offshore in Central and Southern California. Conversely, the NPP increased by 20-30% off Northern and Southern Baja California in the 0-1000-km offshore region. Within the 100-300-km offshore Southern Baja California band, the NPP increased by 60% in early 1998, the same period during which California saw its lowest NPP values (Figure 11). Kahru and Mitchell hypothesized that nitrogen-fixing cyanobacteria composed the offshore blooms. Unfortunately, the studies summarized in this paper did not include in situ measurements from Baja California, so there is no way of determining whether southern biology depleted the nutrients before the water was advected northward to California and what type of southern phytoplankton prospered during the 1997-1998 El Niño.

Bograd and Lynn (2001) posed another curiosity. They noted that in the SCB, the zooplankton recovered 3-4 months earlier than the phytoplankton. They suggested that the CC carried zooplankton to the SCB. While the CC was strong during that period, chlorophyll and nutrient levels were still lower than normal further north. The unexpected order of the two recoveries remains unanswered.

The physical responses of the EP and the CCS to an ENSO event seem to be well understood. A lessening of the easterly Trade Winds causes the formation of westward Rossby waves and eastward Kelvin waves. These waves carry a signal that causes the flattening of the thermocline and nutricline across the Pacific basin and a deepening of the thermocline and nutricline along the west coast of the United States. This, in turn, reduces the supply of nutrients that can be advected to the surface. The undercurrent in each region is affected, but in opposite manners: weakening in the EP and strengthening in the CCS. A resumption of the winds restores the thermoclines and the undercurrents to their nominal states.

The biological response to an ENSO event is less understood. Certainly production will suffer if the supply of nutrients decreases. However, more efficient phytoplankton species may dominate during times of lower nutrient supply. While remote-sensing offers a cost-effective method to monitor NPP over large spatial and temporal periods, it cannot distinguish between phytoplankton species nor can it measure depth-dependent nutrient levels. These quantities must be determined with in situ measurements. The questions about the biological and chemical responses to an ENSO event will likely remain unanswered until a well-instrumented experiment captures another El Niño.

Figures

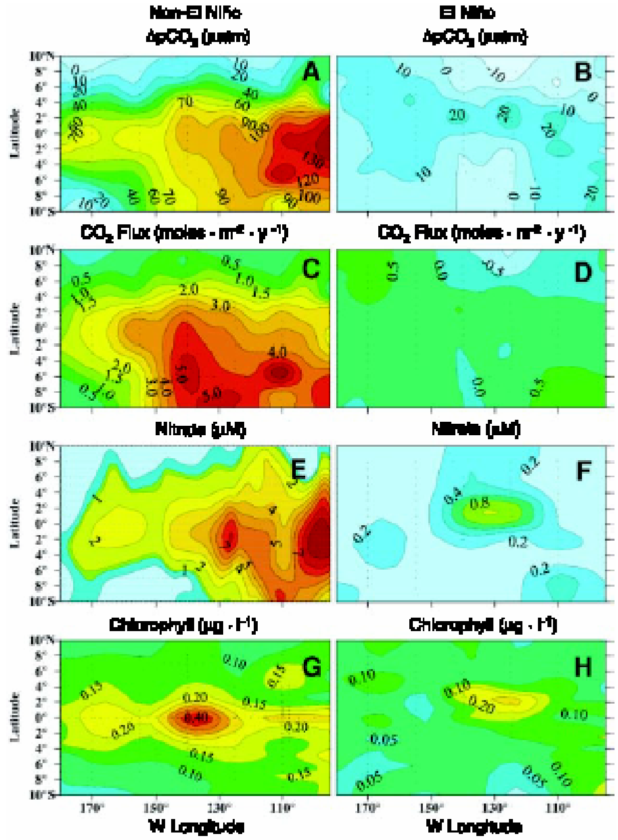

Figure 1. Maps of the distribution of ΔpCO2 (in μatm) and CO_2 flux (in moles per m^2 per year) in the central and eastern equatorial Pacific during the 1995–96 non–El Niño (**A** and **C**) and the 1997–98 El Niño event (**B** and **D**). Maps of nitrate (in μmole) from Levitus climatology (**E**) and during the 1997–98 event (**F**). Maps of surface chlorophyll (in μgm per liter) from climatology (**G**) and the 1997–98 El Niño event (**H**). Chavez et al. (1999)

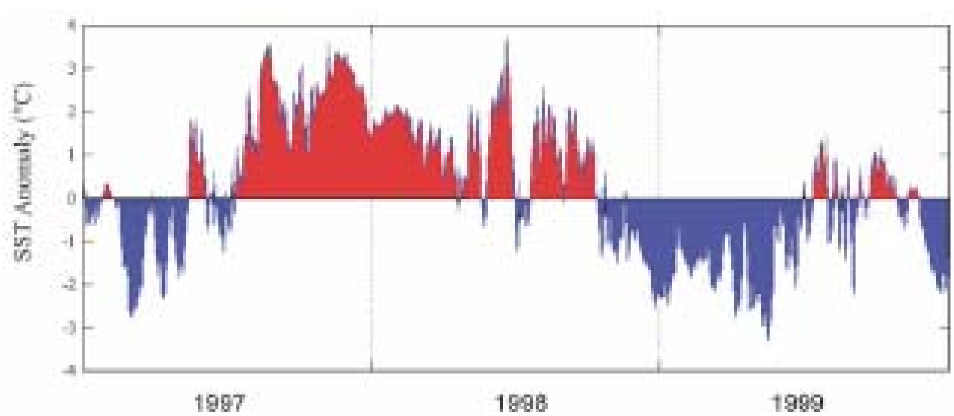

Figure 2. Time series of daily SST anomaly from the M1 mooring for 1997-1999. Chavez et al. (2002)

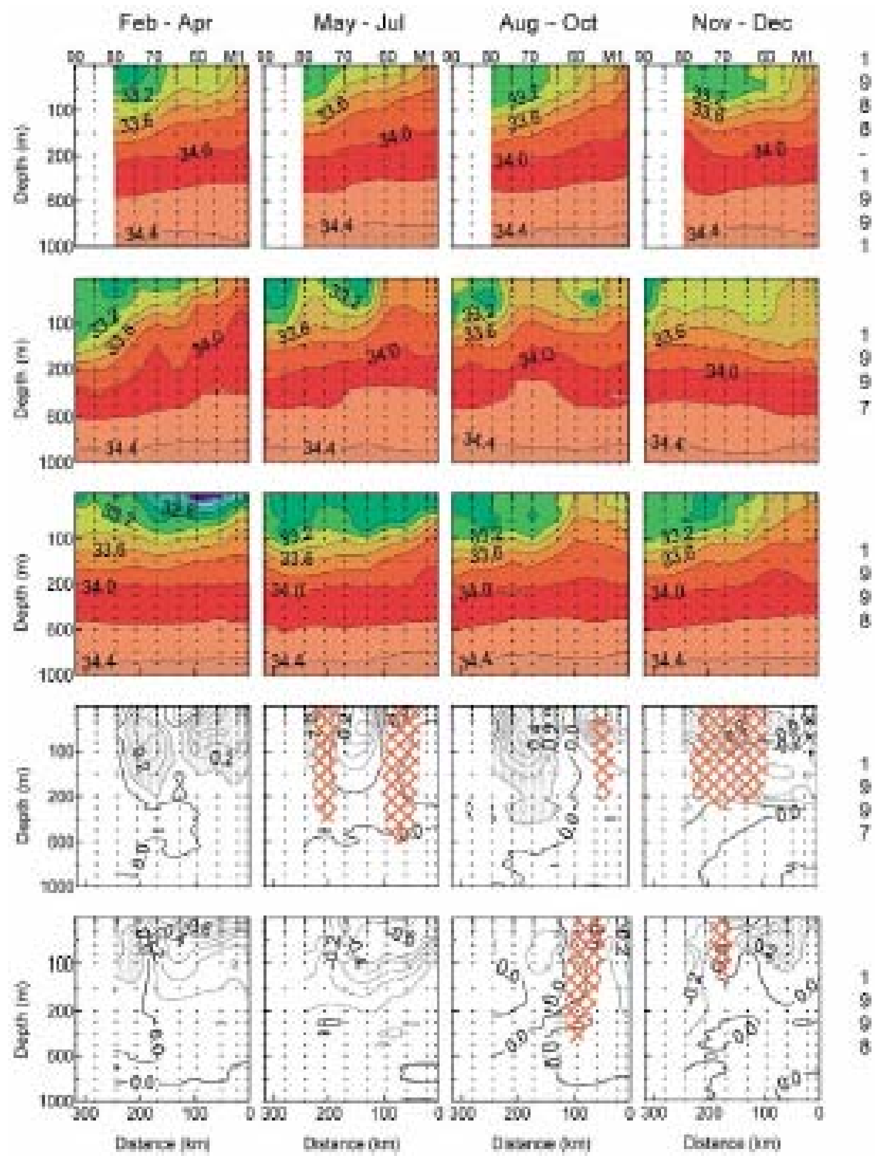

Figure 3. Vertical distributions of salinity for three-month seasons from the surface to 1000 dbar. The upper panel shows seasonal mean conditions observed from April 1988 to April 1991. The second and third panels show results from measurements made during 1997 and 1998, respectively. The lower two panels show anomalies for 1997 and 1998, respectively, which were computed by subtracting the seasonal means in the upper panel from observed conditions. The contour interval for the upper three panels is 0.2 and for the lower two panels is 0.1. The upper 200 dbar have been expanded five times. Poleward velocities >5 cm/s are overlaid in red in the lower two panels. Castro et al. (2002)

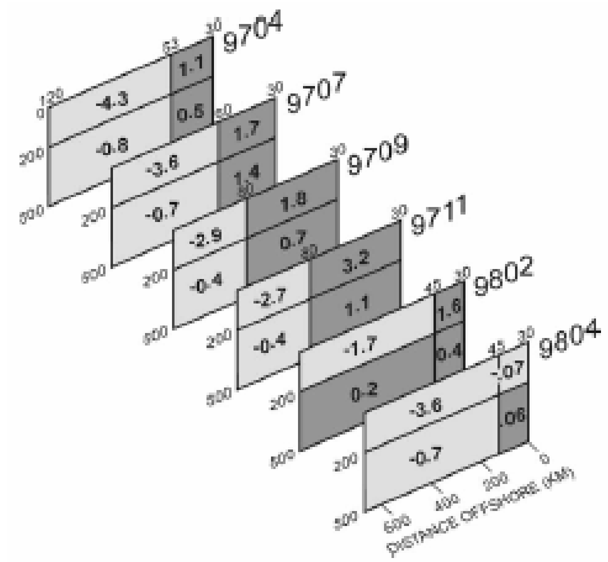

Figure 4. Transport (10^6 m^3/s) for selected surveys divided into quadrants by depth (0–200 m; 200-500 m) and by the position of the dynamic height minimum that divides the California Current from the Inshore Countercurrent. The six panels trace the sequence from the maximum equatorward transport in early 1997 to the maximum equatorward transport in early 1998. Negative (positive) numbers and light (dark) shading indicate equatorward (poleward) transport. Lynn and Bograd (2002)

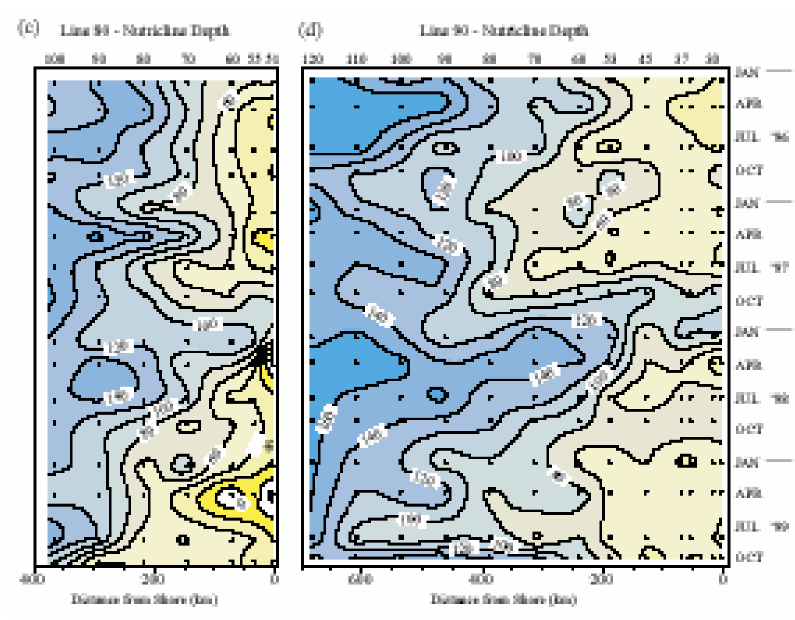

Figure 5. Time-distance sections of depth (m) of the 10 μmol/L nitrate value for CalCOFI lines 80 (c) and 90 (d). Areas of white in (c) represent regions where the 10 μmol/L nitrate outcrops (surface values are 10 μmol/L). Nutrient data were collected only on the quarterly cruises. Stations are marked by a dot, and their labels are given on the top axis of each plot. Bograd and Lynn (2001)

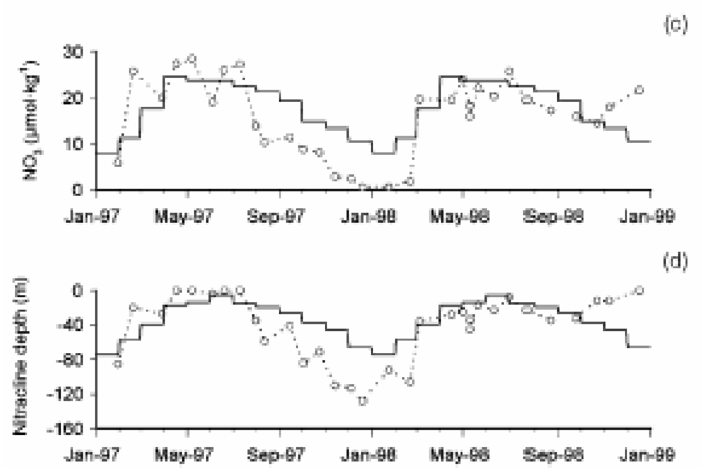

Figure 6. (c) Nitrate concentration at 60 m depth at coastal station M1 (open circles) superimposed on the monthly average, 1989–2000 (solid line), μmol/kg. (d) Nutricline pressure (10 μmol/ kg isopleth) at station M1 (open circles) superimposed on the monthly average, 1989–2000 (solid line), dbars. Castro et al. (2002)

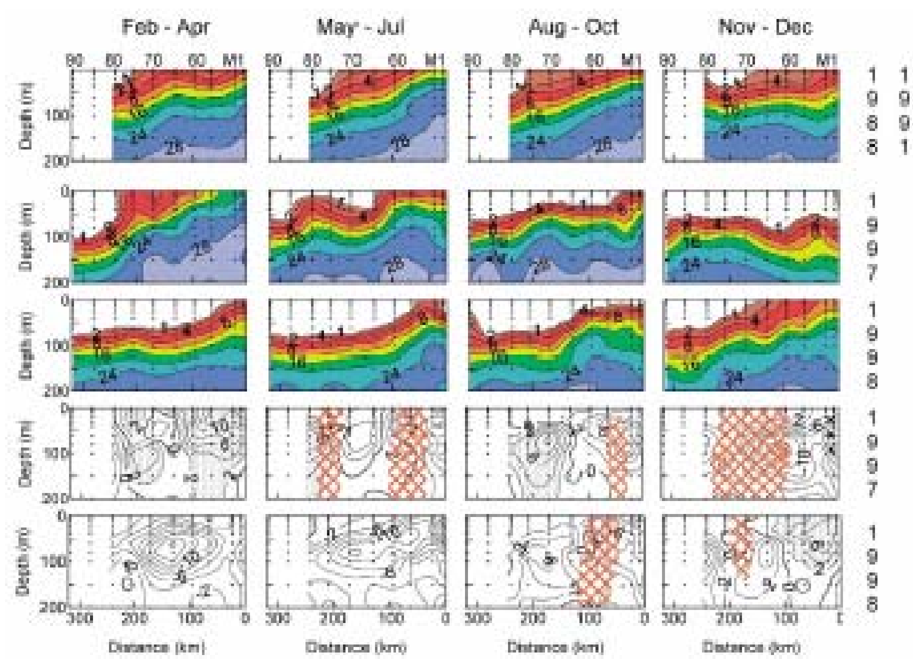

Figure 7. Vertical distributions of nitrate for three-month seasons from the surface to 200 dbar. The upper panel shows seasonal conditions observed from April 1988 to April 1991. The second and third panels show results from measurements made during 1997 and 1998, respectively. The lower two panels show anomalies for 1997 and 1998, respectively, which were computed by subtracting the seasonal means in the upper panel from observed conditions. Units are in μmol/kg. In the upper three panels, 1, 2, and 4 μmol/kg are contoured and for nitrate levels greater than 4 μmol/kg, the contour interval is 4 μmol/kg. In the lower two panels, the contour interval is 2 μmol/kg. Poleward velocities >5 cm/s are overlaid in red in the lower two panels. Castro et al. (2002)

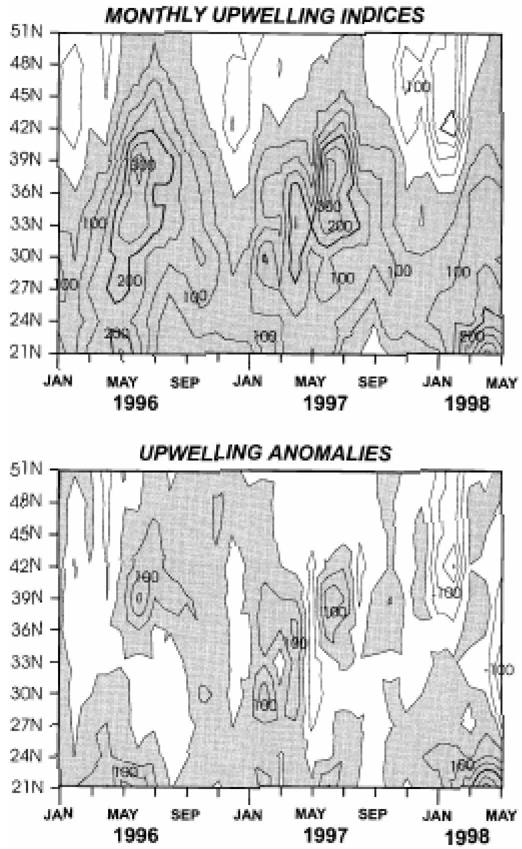

Figure 8. Monthly upwelling index and upwelling index anomaly during 1996-98. Positive values imply coastal upwelling. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948-67 monthly means. Units are in m^3 per sec^{-1} per 100 km of coastline. Lynn et al. (1998)

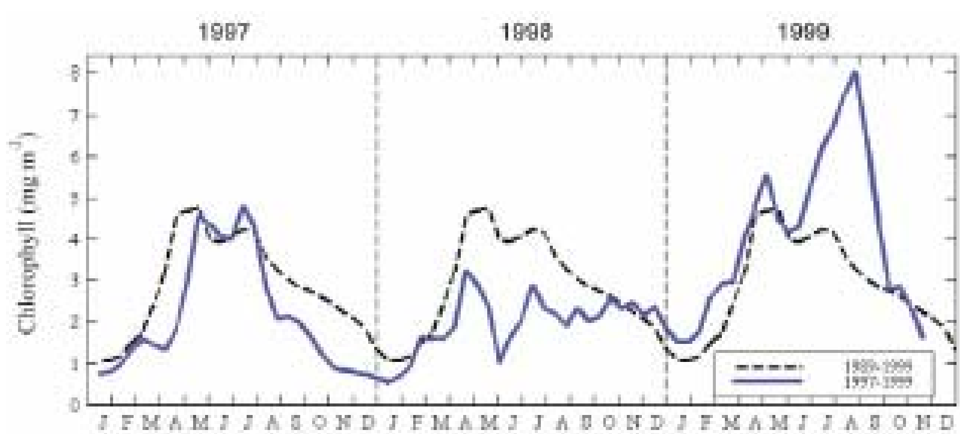

Figure 9. Time series of daily surface chlorophyll for nearshore stations and the long-term mean (dashed line) from the M1 mooring for 1997–1999. Chavez et al. (2002)

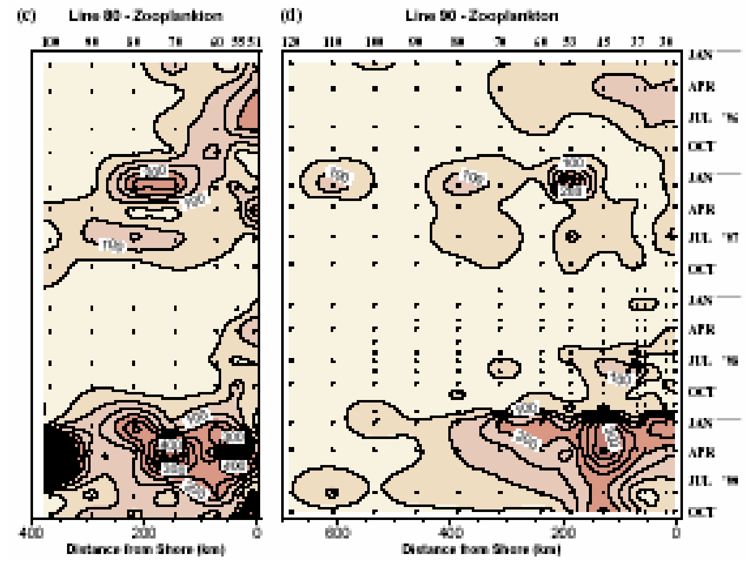

Figure 10. Time-distance sections of the macrozooplankton displacement volume ($cm^3/1000m^3$) for CalCOFI lines 80 (c) and 90 (d). Stations are marked by a dot, and their labels are given on the top axis of each plot. Bograd and Lynn (2001)

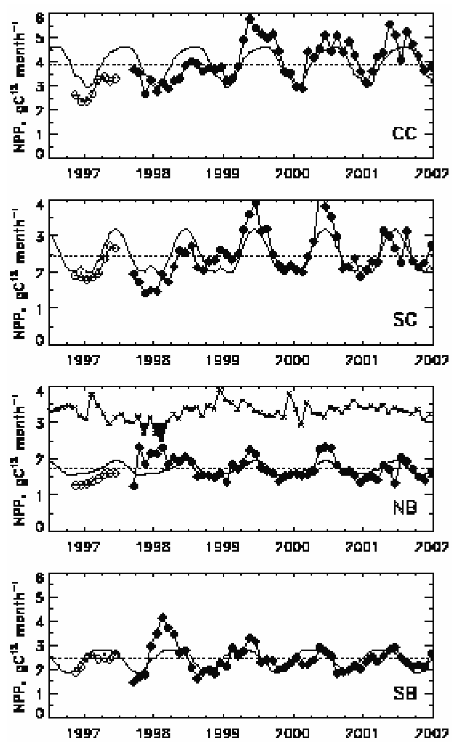

Figure 11. Time series of NPP in 100–300 km band in zones CC, SC, NB, SB calculated with C_{sat} from OCTS (◊) and SeaWiFS (♦) and compared with the mean annual cycle (solid line). The dotted horizontal line is the long-term mean. Minima in the Northern Oscillation Index (x, relative scale) correspond to peaks in the El Niño (filled black areas). Kahru and Mitchell (2002)

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