

EL NIÑO 1997–98 IN THE COASTAL WATERS OF SOUTHERN CALIFORNIA: A TIMELINE OF EVENTS

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ABSTRACT

Timely detection of changes in the tropical Pacific and subsequent predictions that the west coast of North America would be impacted by a strong El Niño event in 1997 enabled CalCOFI to augment its time-series sampling to provide monthly coverage of a subset of the sample grid. The 1997–98 El Niño event in California waters is described here in terms of a preliminary timeline of events. This improved description of the timing of changes in the CalCOFI region provides new insights into the types of changes that might be expected during future events, and it also constitutes a natural experiment which can be used to test hypotheses about the cause-and-effect mechanisms linking changing physical structure with ecosystem impacts. Although some effects attributed to El Niño were evident in the summer and fall of 1997, the strongest occurred in winter 1997–98 and spring 1998. Advection and changes in ranges of mobile populations were consistent with the northward extension of the range of southern warm-water species of migratory game fish and plankton. However, the timeline observations were not consistent with predictions based upon a simple model of bottom-up trophic processes (changes in physical structure, nutrients, phytoplankton, zooplankton, upper trophic levels) as the mechanism linking changing physical and ecosystem structure. While not surprising, since few simple models have much skill in predicting structure in natural ecosystems, this suggests that ecosystem managers will have to await a better understanding of cause-and-effect linkages before improved skill in observing and predicting the physical effects of El Niño upon California waters can be directly translated into improved skill in predicting ecosystem effects.

INTRODUCTION

Observations of increases in upper ocean temperature and mixed layer depth derived from satellites and the buoy array in the tropical Pacific led to the successful prediction that the west coast of North America would be affected by strong El Niño conditions starting sometime in 1997 (e.g., NCEP 1997). Several research groups responded to these predictions by enhancing their ocean

observation programs. CalCOFI increased the frequency of the time-series sampling program. Two lines of the time-series sample grid were sampled at monthly intervals from December 1997 to January 1999, in addition to the normal quarterly sampling done during each year.

The added sampling greatly improved our knowledge of how changes in physical properties and ecosystem structure are related to each other during a strong El Niño event. In particular, the sequence of events that occurred during the onset of El Niño conditions within the CalCOFI study area was much better defined than has been possible in the past. A more detailed picture of the timing of events is interesting, if for no other reason than that it provides a better idea of the changes that might be expected during future events. However, a more important goal is to go beyond simply describing effects and attributing them to El Niño, to developing an improved understanding of cause-and-effect relations that will ultimately lead to improved predictions and models. The recent success in observing El Niño's physical conditions and predicting that they would strongly impact the west coast leads to the question of determining to what extent this new skill can be translated into ecological information that is directly useful to managers and policymakers. The existence of a better-resolved timeline constitutes a natural experiment that can be used to test hypotheses of the cause-and-effect relations linking changes in physical structure and ecosystem structure.

Here I describe the changes in structure in the CalCOFI study region during the 1997–98 El Niño. This description is organized as an overview of the timeline of events. These events are then interpreted in the context of how this new information may be useful to managers and policymakers. This description is preliminary and incomplete, in that most research groups are still working on processing and analyzing their data, and only preliminary highlights are available. It is also premature to attempt to address the larger regional issues. Sampling of other regions along the west coast of North America and studies of additional aspects of physical and biological structure by other programs will eventually be synthesized in a much more comprehensive picture

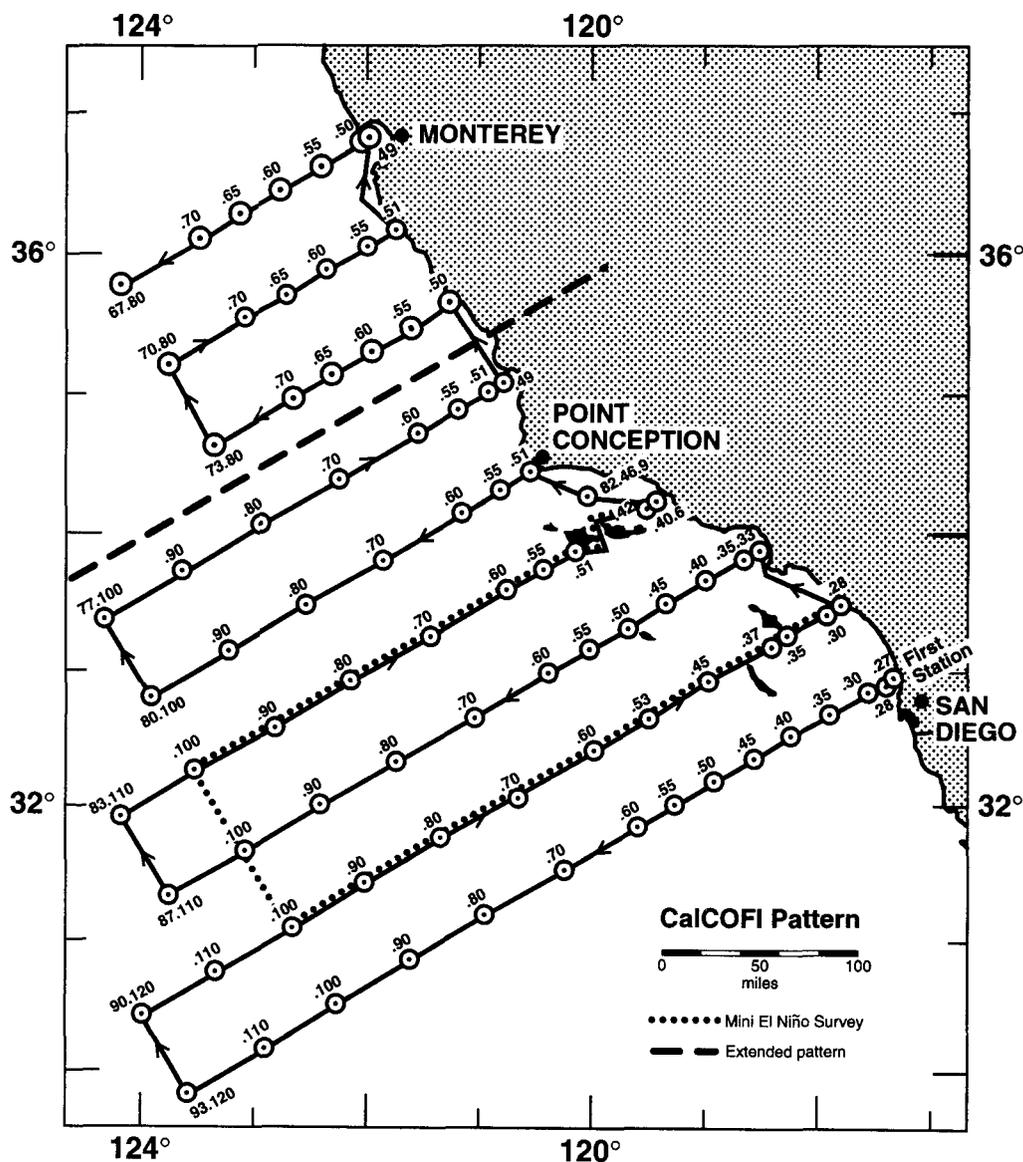


Figure 1. Sample plan for CalCOFI time-series cruises and mini El Niño cruises. The mini El Niño cruises covered lines 90 and 83 out to station 100, and are illustrated by a dotted line. On some cruises the pattern has also been extended to the north with continuous mapping to cover lines 67-73.

of this event. Some studies are summarized in other contributions to this symposium.

DATA AND METHODS

The analysis emphasizes CalCOFI hydrographic data and the high-frequency (e.g., coastal shore station) data that are widely distributed and routinely available in a timely manner. These are the types of data that will be used by managers in assessing future events. Additional information on the sources of these data, such as representative Web sites, are also listed as the data are presented.

The station plan for the quarterly CalCOFI time-series cruises and for the additional "mini" El Niño cruises added during 1997-98 is shown in figure 1.

CalCOFI hydrographic data, as well as the methods and some preliminary interpretation are available in published data reports (e.g., Scripps Institution of Oceanography 1999) and at the CalCOFI Web site (<http://www-mtrg.ucsd.edu/calcofi.html>).

One commonly used tool to detect and quantify the effects of El Niño in a time-series data set is calculation of anomalies from the long-term mean annual cycle (the climatology). This approach can be applied only when the historical data set is sufficient to calculate a representative long-term mean. The few long time series of oceanographic observations that exist have great value in this regard. The harmonic mean annual cycle (Lynn et al. 1982) was used to calculate the climatology for

CalCOFI hydrographic data and the shore station temperature data.

An additional issue becomes important when using these anomalies to interpret El Niño effects and, especially, when comparing data sets from different regions or different properties. If the base period used to calculate the climatologies differs and if there is a long-term trend in the data, the magnitude and even the sign of anomalies may differ, even from observations which are basically the same. Long-term trends have been observed for sea level (Roemmich 1992); temperature and macrozooplankton biomass (Roemmich and McGowan 1995a, b; McGowan et al. 1998); and the upwelling index (Bakun 1973, 1990). The existence of such long-term trends complicates comparison of time series of these properties made in different regions or from different data sources (e.g., temperature from shipboard measurements, shore stations, buoys, or remote sensing) where the base periods often differ greatly. It would be ideal if all climatologies were calculated with the same base period. However, the data needed to do this do not exist. The approach here is to use the timing of strong trends in a data set to define the onset and decline of El Niño conditions, rather than the time at which an anomaly time series crosses a zero line. I have also tried to avoid comparing the magnitude of anomalies based upon differing base periods. The base period used for calculating climatologies is indicated as the data are presented.

There are also constraints upon the analysis imposed by the interaction of the availability of data and the annual cycle in a given property. For example, if a fishery, such as market squid, takes place only during winter months, fishery data provide no direct information about whether the system was affected by El Niño conditions during summer.

RESULTS

1. Physical Structure

Pattern in the tropical Pacific Ocean is considered first, so that the timing of changes in California waters can be compared to the timing of the events that were used to predict these changes. Conditions in the tropical Pacific are summarized by the multivariate ENSO index (Wolter and Timlin 1998; updates were taken from the NOAA Office of Global Programs Web site <http://www.ogp.noaa.gov/enso/>). Strong positive values of the multivariate index indicate El Niño conditions, and strong negative values indicate La Niña conditions. There was a sharp transition to El Niño conditions in the first part of 1997, with strong El Niño conditions evident by April–May and near maximum values by July–August (fig. 2). These very strong El Niño conditions persisted in the tropical Pacific until April–May 1998, when there

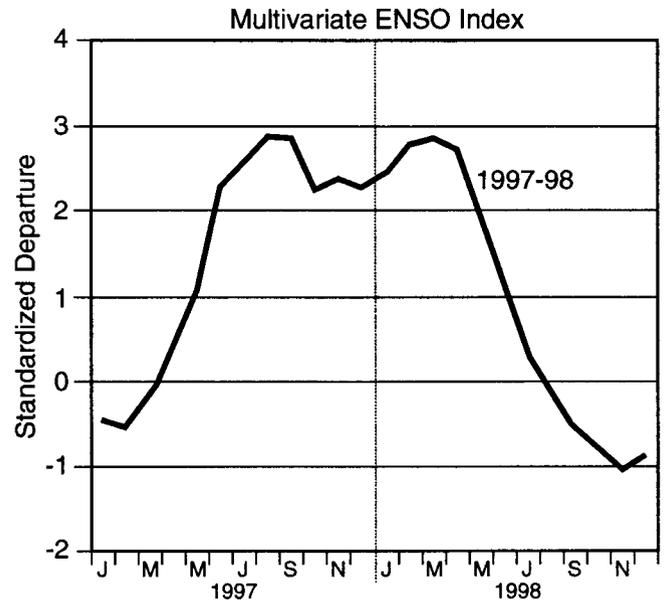


Figure 2. Multivariate ENSO index for 1997–98.

was a rapid decline and transition to La Niña conditions. The multivariate index showed negative values by July–August 1998. The period of very strong El Niño conditions in the tropical Pacific Ocean, as indicated by the multivariate ENSO index, lasted from June 1997 to April 1998.

Several indices have been used to detect El Niño–caused changes in the physical structure of the coastal waters of California. Sea-surface temperature and sea level are measured at coastal shore stations. Anomalously warm water is consistent with El Niño conditions. The pattern in SST anomalies is illustrated with data from San Diego (SIO Pier) and Pacific Grove (These data are from the SIO shore station program, Walker et al. 1994; <http://www-mlrg.ucsd.edu/shoresta/index.html>). The base period for calculating the climatologies was 1916–93 for San Diego and 1919–93 for Pacific Grove. The surface water at San Diego was anomalously warm from March 1997 to March 1998, and episodic warm pulses were seen for the remainder of 1998 (fig. 3). Early 1999 was near normal at San Diego. Pacific Grove was anomalously warm from July 1997 to March 1998, and it was cool from September 1998 into early 1999. The winter of 1997–98 was anomalously warm at both sites.

A more clear El Niño trend was evident in the pattern of sea-level anomalies (data from the University of Hawaii Sea Level Center: <http://uhslc.soest.hawaii.edu/>). The base period for calculating these climatologies was 1975–95. Coastal sea level tends to be elevated during El Niño events due to the existence of a warmer and deeper mixed layer than normal and an increase in the strength of the coastal countercurrent. Anomalies in sea

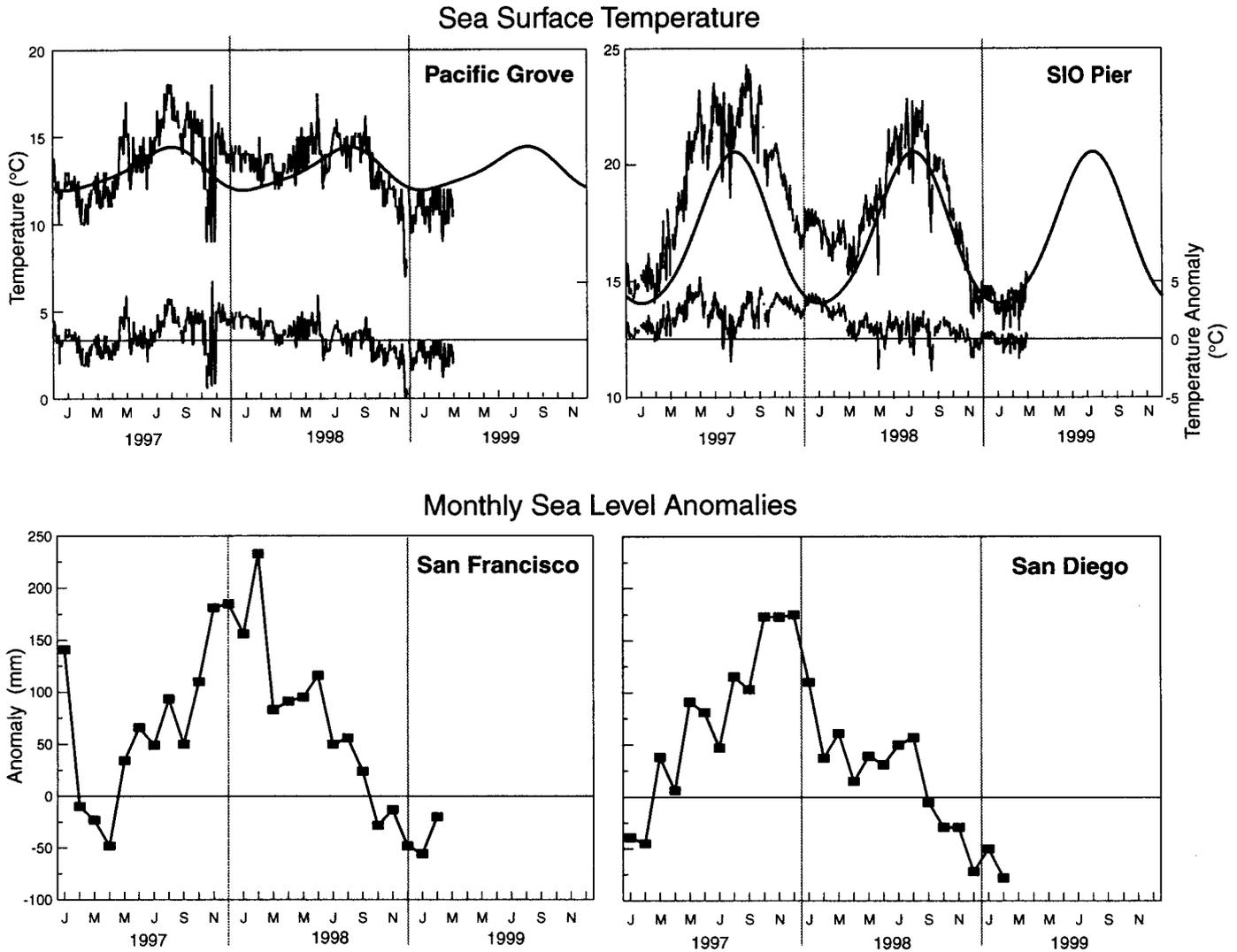


Figure 3. Upper panel: SST and SST anomalies at Pacific Grove and SIO Pier. Lower panel: Sea-level anomalies at San Francisco and San Diego.

level measured at coastal tide gauge stations have been shown to be related to both the seasonal cycle in coastal currents and nonseasonal anomalies (Reid and Mantyla 1976). Sea level was elevated at both sites from June 1997 to August 1998 (fig. 3). San Diego and San Francisco showed very similar patterns in sea-level anomalies.

The upwelling index is also commonly used as an indicator of El Niño conditions in California coastal waters. Anomalously low values of the index (negative anomalies) are presumed to be consistent with El Niño conditions. The upwelling index and anomalies for 33°N (the Southern California Bight) are illustrated here. (Data were provided by the Pacific Fisheries Environmental Laboratory: <http://www.pfeg.noaa.gov/index.html>). The base period for calculating the climatologies was 1948-67. Pattern in the anomalies should be considered in the context of the annual cycle in the upwelling index. In the Southern California Bight, the index is normally

very low in winter, and it peaks in late spring. Spring and summer of 1997 showed a variable pattern of positive and negative anomalies. The upwelling index was near normal to slightly below normal in the winter of 1997-98, the season when the index is normally low (fig. 4). The winter of 1997-98 showed values near the climatology. The large anomalies in the upwelling index were seen in the summer of 1998, when it was much lower than normal, and in 1999, when it was higher than normal.

The hydrographic data collected on CalCOFI cruises provides additional information about the circulation pattern in the coastal waters and the temperature-salinity structure below the surface layer. Past studies have shown that El Niño conditions are characterized by a stronger and broader coastal countercurrent, and by a warmer and deeper-than-normal mixed layer (McGowan 1985; Simpson 1992; Lynn et al. 1995). Detection of El Niño

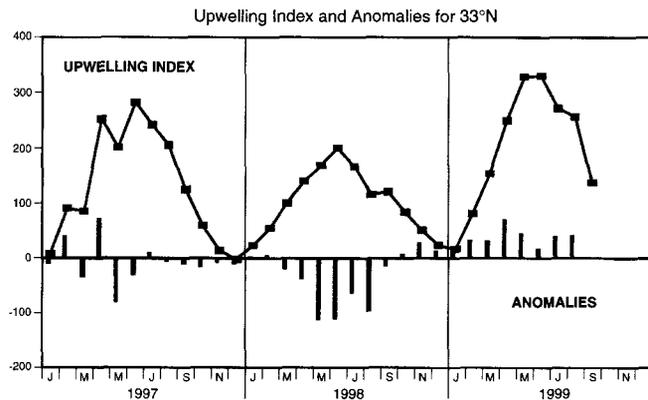


Figure 4. The upwelling index and anomalies in the upwelling index for 33°N. Units are in $\text{m}^3 \text{s}^{-1}$ per 100 km of coastline.

effects upon the circulation pattern by comparing an observed pattern with the climatological mean is a more subjective process than for temperature or sea level because there is no single index which reflects the circulation pattern. The circulation patterns measured on the CalCOFI cruises during 1997–99 are illustrated in the annual State of the California Current reports (Lynn et al. 1998; Hayward et al. 1999), and only the highlights as they relate to El Niño conditions are illustrated here.

The first cruise in which changes in the circulation pattern were attributed to El Niño was made in July 1997 (cruise 9707). The upper ocean circulation was similar to the climatology (calculated from the 1950–92 base period). However, the anomalously strong northward flow of relatively warm and saline water in the undercurrent at middepths (300–400 m) along the coast was attributed to El Niño (Lynn et al. 1998; fig. 5). The circulation on the next cruise (October 1997) was relatively similar to the climatology (data not shown here but see Lynn et al. 1998). The February 1998 pattern showed very strong northward flow, now in the upper layers in the countercurrent along the coast, and this strong northward flow continued around Point Conception (fig. 6a). The strong advection from the south is reflected in the quite high salinities along the coast. The southward-flowing, low-salinity jet that forms the core of the California Current was also located farther offshore than normal. These patterns are characteristic of prior El Niño events (Lynn et al. 1995). Interpretation of these patterns is subjective, but the differences in circulation during 1997–98 do not necessarily appear to be as pronounced as those seen in 1992 during the 1992–93 event (fig. 6b). The northward flow extended farther offshore in February 1992, making the change in circulation pattern more conspicuous, but the coastal gradient in dynamic height was stronger in February 1998 than in February 1992, indicating greater northward transport in 1998.

The more frequent hydrographic sampling during the 1997–98 event provided a good example of how rapidly the circulation pattern and related biological structure can change during an El Niño event. By April 1998, the circulation had changed from the pattern seen in February (relatively strong and broad northward-flowing countercurrent along the coast) to strong southward flow of the low-salinity core of the California Current along the coast (Hayward et al. 1999; fig. 6a). Sampling along CalCOFI line 83 during the March 1998 mini El Niño cruise showed that the change in circulation took place relatively rapidly between February and March 1998. There was a strong increase in chlorophyll along the coast, related to the change in circulation pattern (Hayward et al. 1999). A similar pattern was observed during the 1992–93 El Niño event, when the circulation pattern reversed in a similar manner and chlorophyll concentration increased rapidly from low values in January to normal spring levels in April (Hayward 1993). In each case the increase in chlorophyll was attributed to the dramatic shoaling of the pycnocline and nutricline, associated with the change in circulation. The circulation patterns on the July and September 1998 cruises were relatively similar to the long-term mean (Hayward et al. 1999).

Additional insights from the hydrographic data can be gained by plotting data from individual stations over time. Although spatial information is lost, this provides better temporal resolution of structure, since the data from the mini El Niño cruises can be included. T-S plots from station 90.30 show the evolution of water-mass structure in the coastal waters (fig. 7). The individual cruise data are compared with the 1950–92 climatology. The first strong El Niño signal is again seen in July 1997. The anomalously warm, saline water associated with the strong northward flow in the undercurrent is clearly evident in the T-S plot. However, note that the T-S structure in the upper layers is similar to the climatology (as was the circulation).

The data in December (cruise 9712) show the first strong El Niño signal in T-S structure that affected the full water column. The T-S plots show that the entire water column is warmer and more saline than normal. The February to April 1998 structure continued the trends from December, and the anomalies increased in magnitude. By May 1998 the surface layer was slightly cooler and fresher than normal, but the thermocline continued to be anomalously warm and saline, and this pattern continued in June. By July 1998 the surface layers were much fresher than the climatology and near normal in temperature, and the T-S structure in the lower layers was similar to the climatology.

The hydrographic data are also illustrated by plotting the vertical structure of temperature anomalies (again

CALCOFI CRUISE 9707

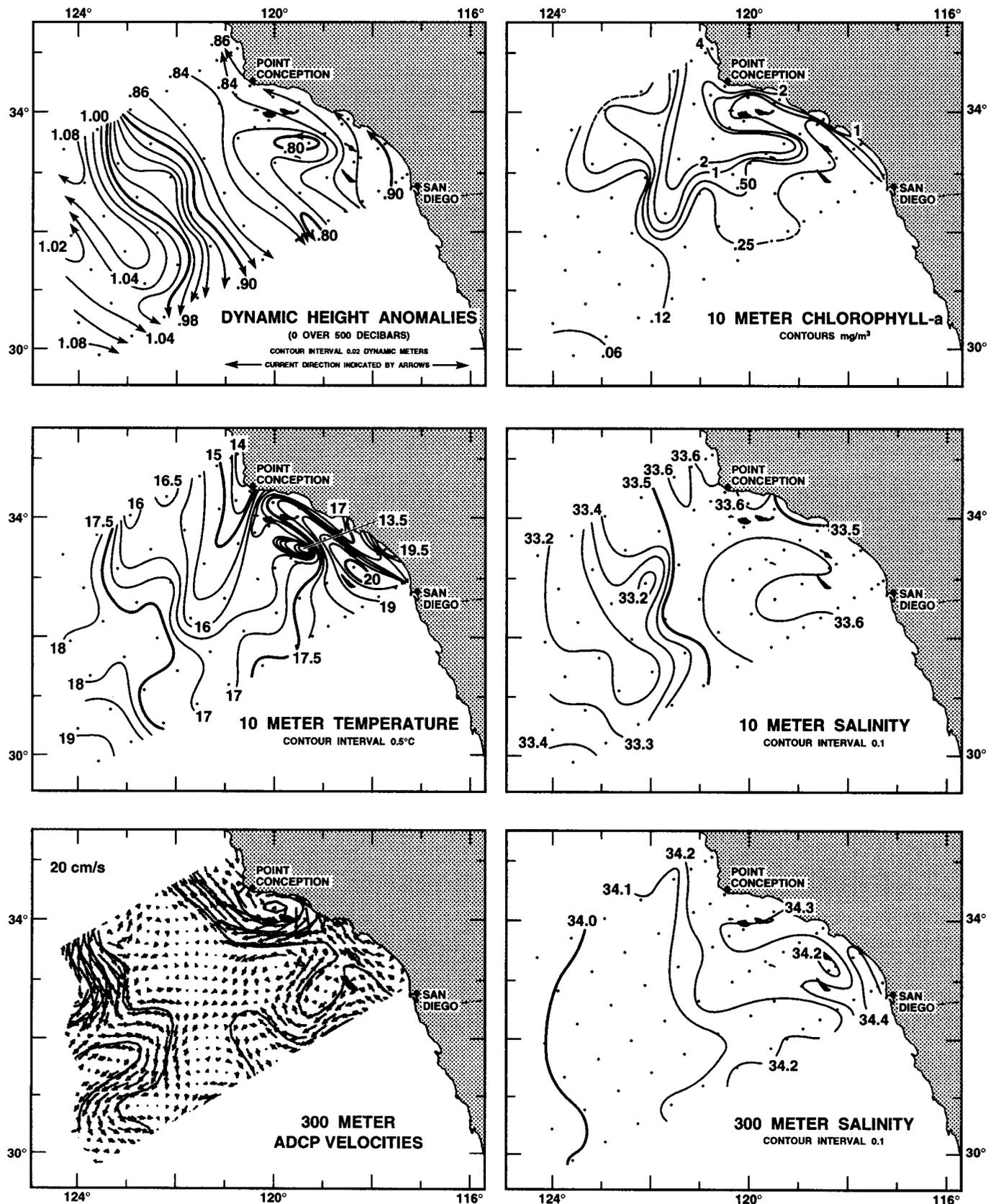
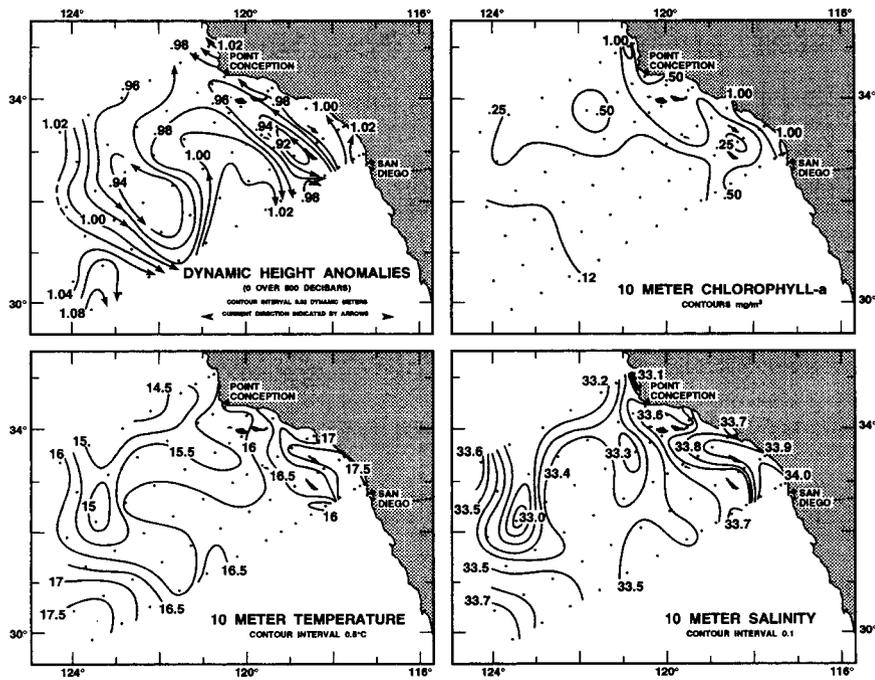


Figure 5. Spatial distribution of properties on CalCOFI cruise 9707.

CALCOFI CRUISE 9802



CALCOFI CRUISE 9804

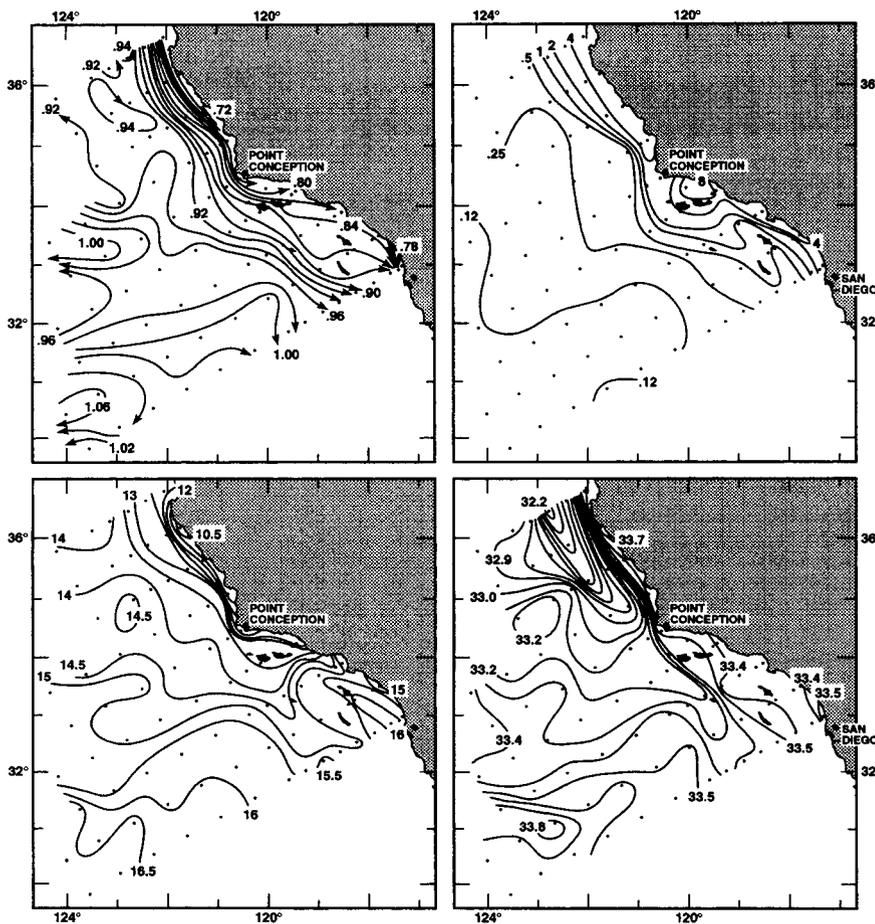


Figure 6a. Spatial distributions of dynamic height, salinity, temperature, and chlorophyll on CalCOFI cruises 9802 and 9804.

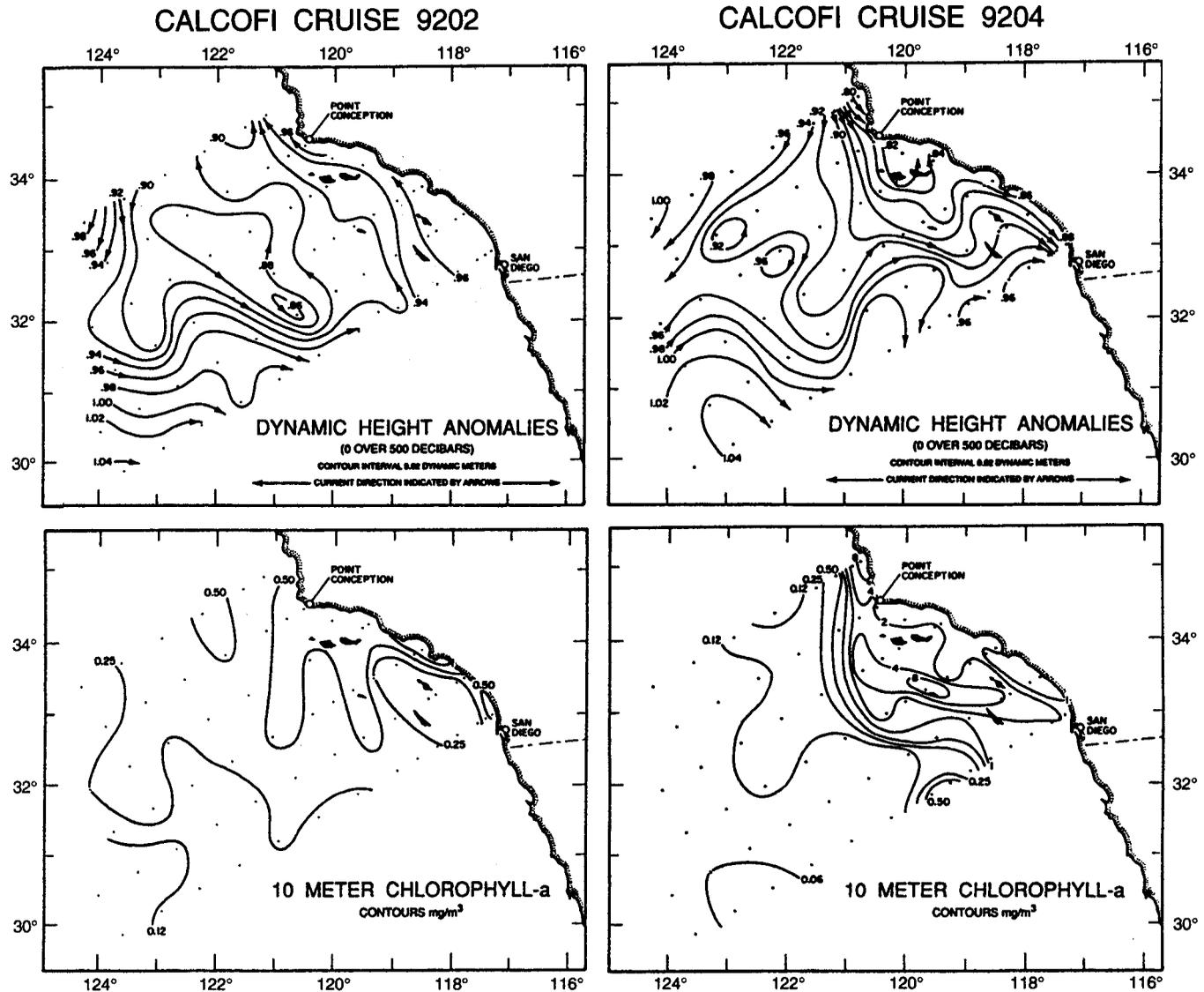


Figure 6b. Spatial distributions of dynamic height and chlorophyll on CalCOFI cruises 9202 and 9204.

based upon comparison with the 1950–92 climatology) over time. This illustrates the warming of the upper layers and the deepening of the thermocline. The deepening of the thermocline associated with El Niño can be seen in the characteristic subsurface maxima in temperature anomalies (McGowan 1985; Lynn et al. 1995). Stations 90.30 and 96.60 showed similar patterns (fig. 8). Warming of the surface layer was evident at both stations in the spring and summer of 1997, but note that the waters in the thermocline were normal to cool during this period. The absence of a subsurface maximum in temperature anomalies shows that the thermocline was not shallower than normal in the summer of 1997. The thermocline deepened dramatically in December 1997 at both stations, and positive temperature anomalies of greater than 4°–6°C were seen in the thermocline. These thermocline temperature anomalies are quite

large by historical standards. Thermocline anomalies of greater than 4°C that were seen in January and March 1983, during the 1982–83 El Niño event, were 9 standard deviations from the long-term mean calculated at that time (Simpson 1983). Anomalies greater than 2° were seen in January 1993, during the 1992–93 event (Hayward et al. 1994). The strong El Niño signal in thermocline temperature anomalies persisted until about September 1998, when there was a rapid transition to negative temperature anomalies in the upper layers and thermocline. It is interesting to observe that during both the onset of El Niño conditions and the transition to La Niña conditions, the change in temperature anomalies first took place in the mixed layer and then penetrated downward into the thermocline. At the onset of El Niño the thermocline was normal to cool while positive temperature anomalies developed in the mixed layer, and

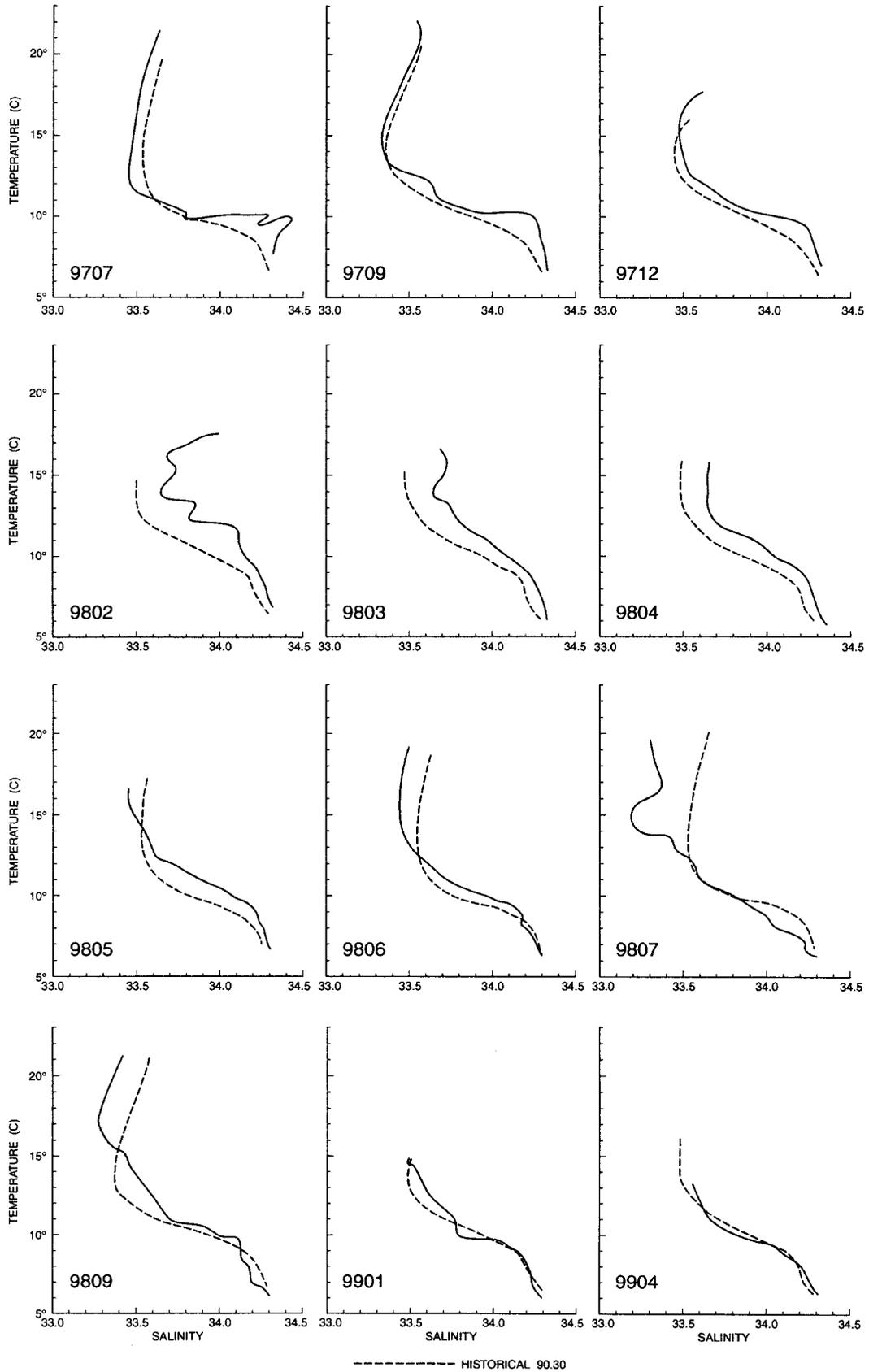


Figure 7. T-S plots for CalCOFI station 90.30. The historical mean T-S structure for each month is also shown (dashed line).

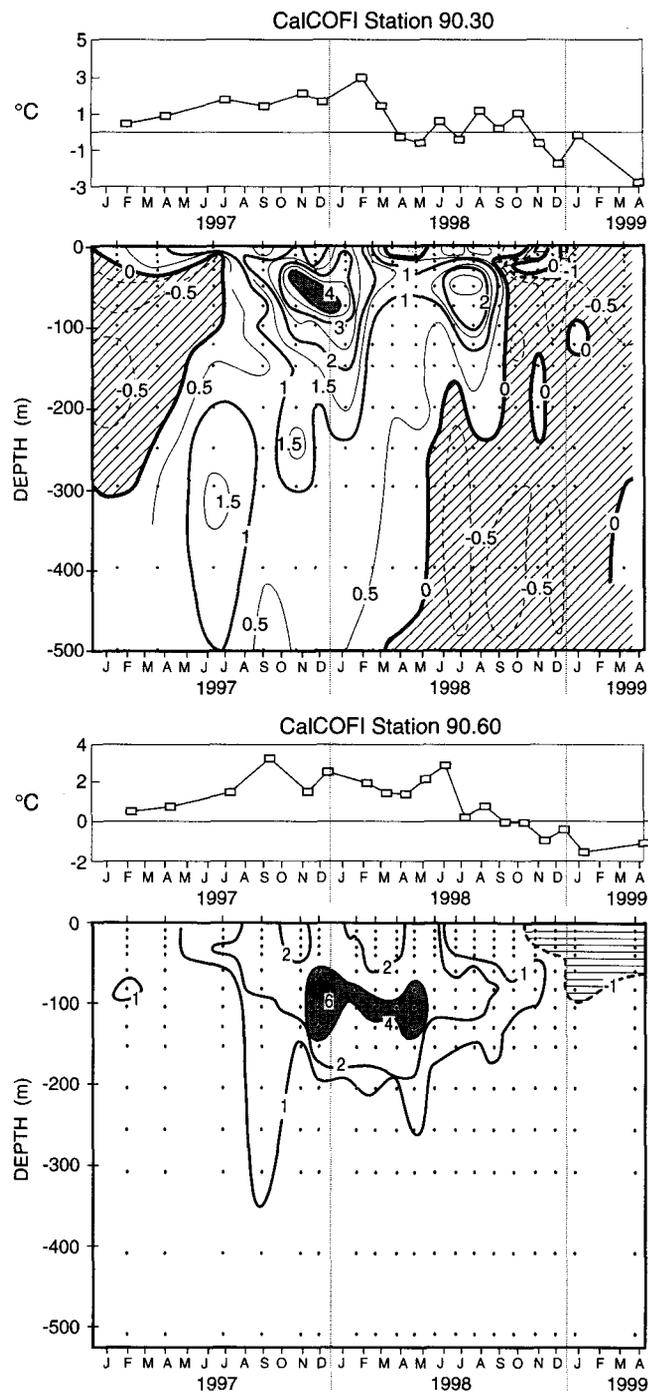


Figure 8. Vertical sections of temperature anomalies versus time for CalCOFI stations 90.30 and 90.60. SST anomalies are also illustrated above each section.

the converse was true during the transition to La Niña. In contrast to the impression that might be gained from surface data, the thermocline temperature anomalies were much larger in July 1998 than they were in July 1997. The surface (mixed layer) signal will give a different impression of the timing of events than the thermocline signal.

Much additional analysis remains to be done on the hydrographic data. The reader should be aware that there are some inconsistencies in the preliminary interpretation presented here. In particular, the abrupt change in the circulation in April 1998 when cool, fresh water appeared along the coast (fig. 6a) does not appear to be reflected in the sections of temperature anomalies over time (fig. 8) or in the time series of T-S plots (fig. 7). Plotting vertical sections and making temperature anomaly sections and T/S time series at additional stations will help to reveal the spatial pattern of changes in hydrographic structure associated with El Niño.

2. Ecosystem Structure

This analysis of changes over time in ecosystem structure begins with a summary of the trends in chlorophyll concentration. El Niño effects on chlorophyll are more difficult to quantify than the trends in physical properties because the long-term data set is limited. CalCOFI has made routine measurements of chlorophyll concentration only since 1984, although measurements were made on some individual cruises prior to this.

Perhaps the most interesting and surprising aspect of the chlorophyll data is that the measurements made during the 1997-98 El Niño event do not appear to be anomalous when considered in the context of the 1984-99 period. Since this finding is unexpected and it bears upon the mechanisms by which El Niño affects other aspects of ecosystem structure, I illustrate this in several ways. First, the cruise mean values for vertically integrated chlorophyll (typically based upon sampling 14 depths at each station and averaging 66 stations per cruise) for 1997 and 1998 do not stand out in the scatter of the cruise means for the 1984-99 period (fig. 9). These data are from the quarterly sampling cruises covering the full CalCOFI grid. Including data from the mini El Niño cruises provides better temporal resolution during 1997-98 along line 90. Here I illustrate the average vertically integrated chlorophyll on the 7 stations from the coast to station 90.60 for 1996 to 1999 (fig. 10). The 1997-98 period does not differ from 1996. Indeed, the unusual aspect in this period is the quite high chlorophyll seen in December 1998 and April 1999 (during the transition to La Niña conditions; Hayward et al. 1999). These figures illustrate the spatial average of vertically integrated chlorophyll.

El Niño may also affect the vertical distribution and spatial pattern of chlorophyll (McGowan 1985). Vertical structure and spatial pattern in these chlorophyll data are still being analyzed, but the first analysis again does not show any obvious trends during the 1997-98 period. This is illustrated by comparing the spatial pattern of 10 m chlorophyll on the spring CalCOFI time-series cruises from 1996, 1997, 1998, and 1999 (fig. 11). The spatial

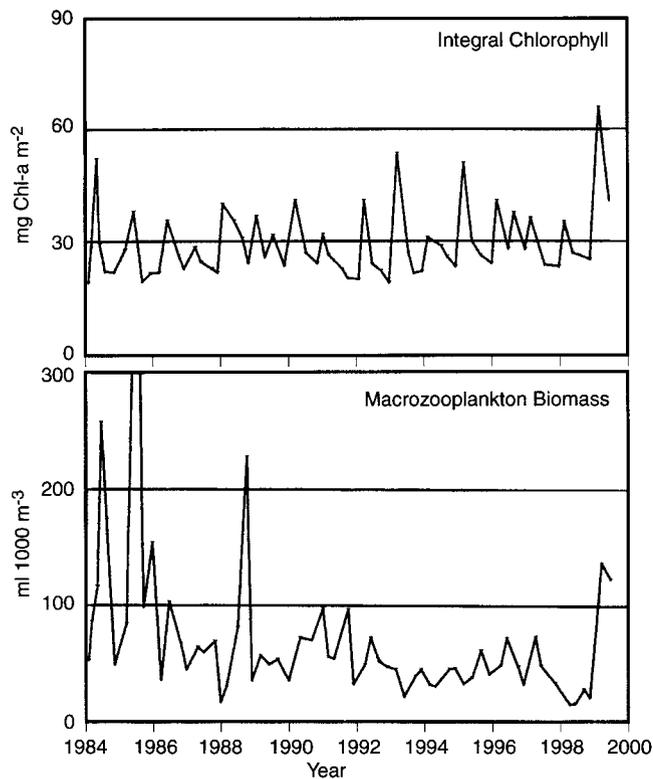


Figure 9. Cruise means of vertically integrated chlorophyll and macrozooplankton biomass for CalCOFI cruises from 1984 to 1999, for the cruise grid covering lines 77 to 93 (fig. 1).

pattern and concentration of near-surface chlorophyll during the springs of 1997 and 1998 do not look unusual when compared to springs of the other years.

An additional aspect of pattern in the distribution of chlorophyll during the 1997–98 El Niño is worth emphasizing. Chlorophyll increased rapidly from January to April 1998 (fig. 6a). This is surprising in light of the strong thermocline temperature anomalies which were observed at this time (fig. 8). However, a rapid transition in hydrographic structure also took place between February and April 1998 (Hayward et al. 1999). The California Current moved inshore along the coast, resulting in a strong upward tilt to the thermocline, and this nutrient input appeared to fuel the increase in chlorophyll. This is a common event during spring, but it is interesting to observe that it can still take place and result in a normal increase in chlorophyll even during strong El Niño conditions when the thermocline and nutricline are unusually deep. It is possible that a normal cycle in the circulation pattern and a strong spring increase in chlorophyll related to the changing circulation is a normal event, even during El Niño conditions. This same general pattern was also observed during the 1992 El Niño event, and in each case chlorophyll concentrations were elevated along the coast (fig. 6b).

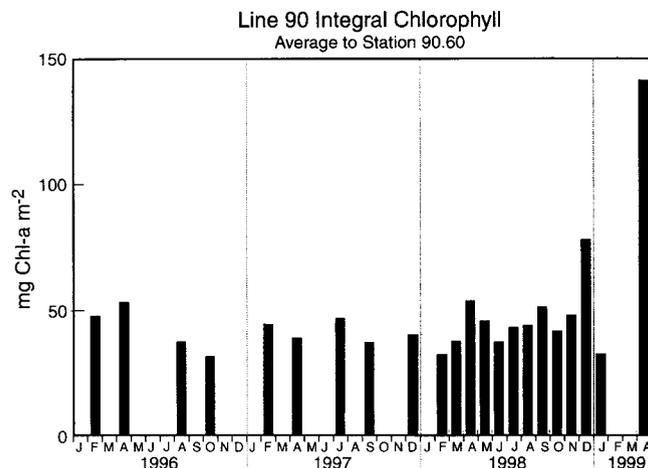


Figure 10. Averages of vertically integrated chlorophyll for the six stations along line 90 from the shore to station 90.60.

The apparent lack of a trend in chlorophyll during the 1997–98 El Niño event differs from the common dogma, and it is worth asking why. There are few direct observations of chlorophyll during prior events, and there are even fewer long-term data sets to compare these observations to. McGowan (1984, 1985) summarized the shipboard observations made by CalCOFI during the 1982–83 El Niño event. He reported a large decrease in surface chlorophyll, and concluded that there was a redistribution of the vertical structure in chlorophyll. The chlorophyll maximum became deeper in association with a deepening of the nutricline. Fiedler (1984) compared a CZCS image of near-surface chlorophyll made during the 1982–83 El Niño (15 March 1983) with an image made on 19 April 1982. He concluded that near-surface chlorophyll during El Niño was reduced to less than half of the 1982 values.

The question of whether chlorophyll concentration changed or its vertical or spatial distribution changed during the 1997–98 El Niño event remains open. Analysis of the vertical and spatial distributions is continuing. It will be important to resolve this to the extent possible given the available data, because El Niño–caused changes in the nutrient distribution, chlorophyll, and primary production are presumed to be one of the main ways in which changing physical structure impacts the ecosystem. Given the range of interannual variability, only relatively large effects can be detected. Comparison of the 1997–98 El Niño period with only the immediately preceding and following periods may give a misleading impression. The quarterly CalCOFI time-series cruise in October 1996 was quite unusual in that high chlorophyll was observed. Fall is generally a time of low chlorophyll, and the chlorophyll measured on this cruise was the highest measured in the 1984–96 period (Schwing et al. 1997). Very high chlorophyll was also measured in

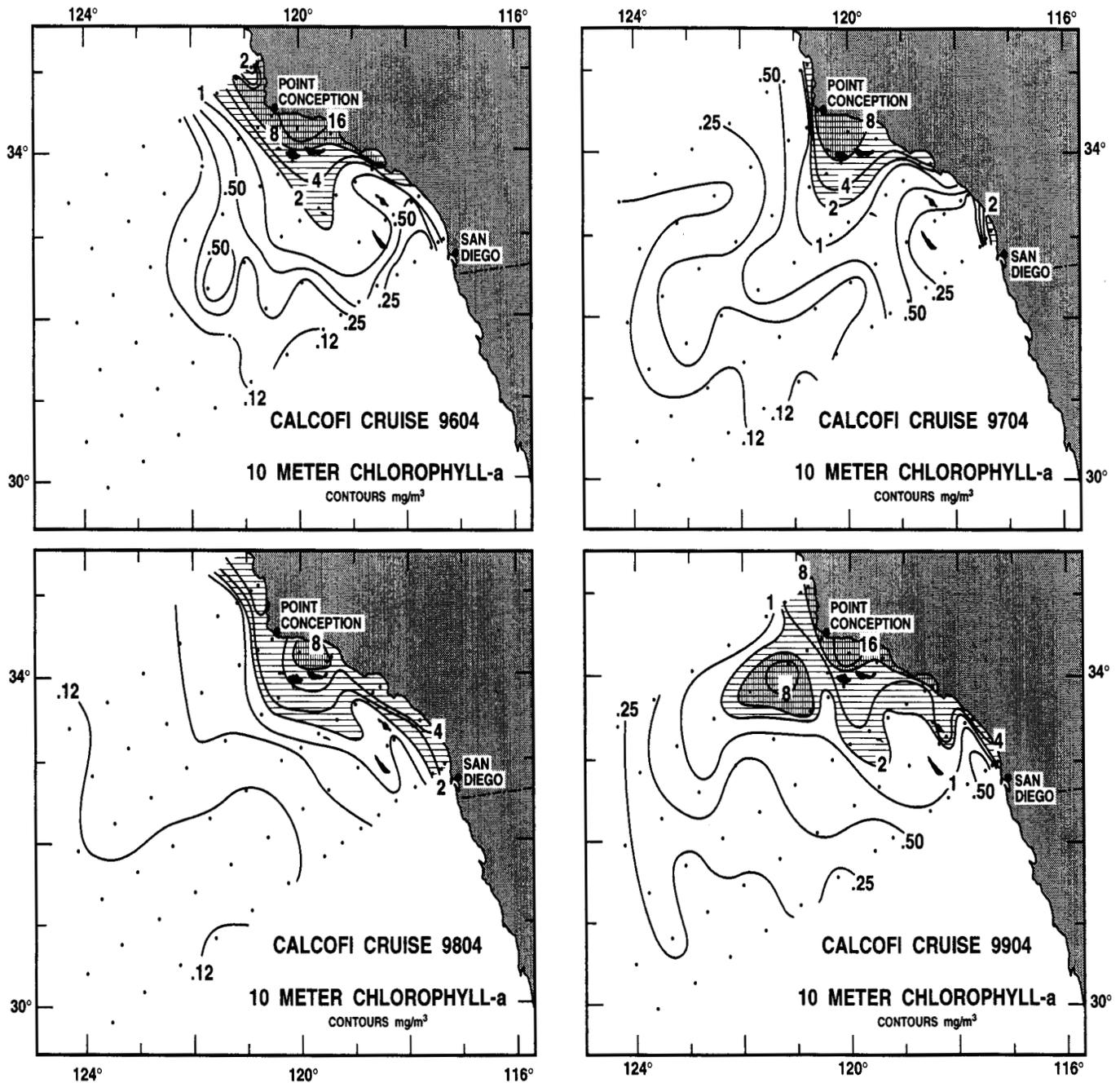


Figure 11. Spatial pattern of 10 m chlorophyll for spring CalCOFI cruises in 1996, 1997, 1998, and 1999.

the spring of 1999 in association with the transition to La Niña conditions (Hayward et al. 1999). Hence comparison of chlorophyll concentrations in the 1997-98 El Niño period with the periods immediately preceding and following it might lead to the impression that chlorophyll declined during the El Niño event, whereas analysis of the 15-year data set leads to the impression that the real anomalies were in the preceding and following years. Shipboard and remote sensing data will have to be carefully compared in order to answer the question

of whether observed changes are due to changes in vertically integrated chlorophyll or a redistribution of vertical structure.

Zooplankton is the most thoroughly sampled biological property in the CalCOFI data set, having essentially the same spatial and temporal coverage as the hydrographic data. During past events, macrozooplankton biomass has shown a strong El Niño signal. Very large declines in macrozooplankton biomass during prior strong El Niño events (particularly 1958-59 and 1982-83) have

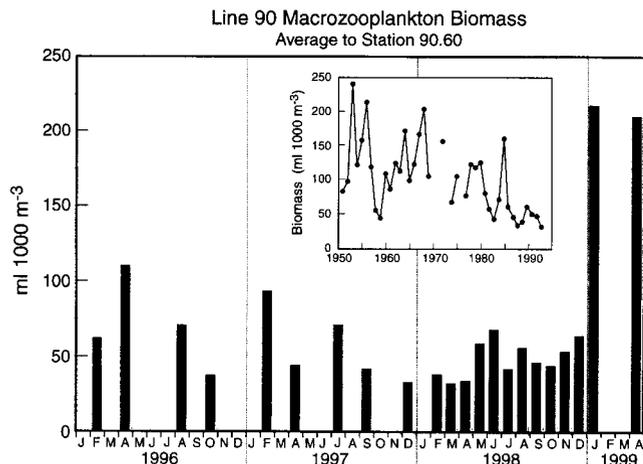


Figure 12. Averages of macrozooplankton biomass for the six stations along line 90 from the shore to station 90.60; inset, the long-term trend in macrozooplankton biomass.

been described (Roemmich and McGowan 1995a, b; McGowan et al. 1998). The 1997–98 event also affected macrozooplankton biomass. The cruise means of macrozooplankton biomass during 1998 were all the lowest in the 1951–98 record (Hayward et al. 1999; figs. 9 and 12). However, calculation of anomalies from the long-term (50-year) mean may in some senses overstate the impact of this event. There has been a strong (70%) long-term trend of declining values of macrozooplankton biomass (Roemmich and McGowan 1995a, b). The relative effect of El Niño upon macrozooplankton biomass can be illustrated by comparing El Niño periods with the preceding and following years. (In contrast to the situation with chlorophyll, the El Niño signal in macrozooplankton biomass is very clear in the long-term record. The comparison with adjacent years is not intended to ask whether an El Niño signal can be detected over the variability on other space-time scales, but rather, given that such a signal has already been detected: What is the short-term impact of each event?) The 1958–59 and 1982–83 El Niño events reduced macrozooplankton biomass to about 20%–30% of the preceding and following years (fig. 12). These were very strong events by this measure. The relative decline in macrozooplankton biomass during 1997–98 (about a 50% decline in comparison to 1994–96 period) is smaller than during the prior strong events (fig. 9). It is hard to say when an El Niño-related decline in macrozooplankton biomass began, because the signal is superimposed upon significant interannual variability and patchiness. The large increases in 1999 in association with the transition to La Niña conditions are also evident.

In addition to changes in biomass, zooplankton species composition in the CalCOFI study area may also be affected by El Niño. Due to a combination of advection

TABLE 1
 Preliminary Summary of El Niño Effects on
 Euphausiid Populations in the CalCOFI Study Area

Year	Abundance
<i>Euphausia pacifica</i> (an abundant cool-water species)	
1996	High
1997	Decline from high 1996 values to typical values
1998	Very low—lowest in the record
1999	Strong increases from 1998 levels
<i>Nyctiphanes simplex</i> (a southern species)	
1997	Not abundant in CalCOFI sample region
1998	Average in winter—high in spring
1999	Average to low

Note: Data from winter (January–February) and spring (March–April) cruises only. Thanks to Ed Brinton, Marine Life Research Group, Scripps Institution of Oceanography.

and changes in habitat structure, southern “warm-water” species tend to become more abundant and northern “cool-water” species less abundant during El Niño events (Brinton and Reid 1986). Without data from the entire range of a population, it is difficult to separate local changes in population size (due to changes in the distribution of a species) from trends in the overall abundance of the species. Some preliminary information on the El Niño effect on the distributions of individual euphausiid species during 1997 and 1998 is also available (thanks to Ed Brinton, SIO). Data are presently available only for winter and spring cruises during this period (table 1). The California Current dominant cool-water species *Euphausia pacifica* was extremely abundant in the winter and spring of 1996. This species then declined in abundance in 1997 to nearly normal values, and the decline continued in 1998 to the lowest values on record. The winter and spring of 1999 showed strong increases from the low values of 1998. For *E. pacifica*, 1998 was certainly a year of unusually low abundance, but it is hard to know whether to attribute the 1997 data to El Niño forcing or to a decline from the unusually high 1996 density. Shifts in springtime abundances of *E. pacifica* from highest to lowest recorded extremes followed by abrupt (one-year) recoveries were previously associated only with the 1957–59 and 1980–84 periods, which were also El Niño events. *Nyctiphanes simplex*, a southern, warm-water species, was not abundant in the CalCOFI study region in 1997, but it was quite abundant in 1998, and it returned to normal to low abundances by 1999. The euphausiid data thus generally show the expected declines in the northern, cool-water species and increases in the southern, warm-water species in winter and spring of 1998 and a reversal in 1999. But the 1997 data are ambiguous as to whether there was an early El Niño signal in the euphausiid distribution.

Pinnipeds in the northern Channel Islands were strongly affected by El Niño conditions in both 1997

TABLE 2
Preliminary Summary of El Niño Effects
on Pinniped Populations in the Channel Islands

1997
Northern fur seals and California sea lions: Pup mortality increased dramatically; few pups born during 1997 survived.

1998
Northern fur seals: Pup production low; increased mortality in adult females. California sea lions: Few pups born; pup mortality high.

1999
Improved conditions for pinnipeds.

Note: The pupping and breeding season is from June to September. Thanks to Robert DeLong et al. (National Marine Mammal Laboratory, AFSC, NMFS, Seattle).

and 1998. (Robert DeLong, pers. comm.) The breeding and pupping season runs from June to September (table 2). This is the part of the annual cycle for which information is available, but changes seen during the pupping season presumably reflect an integration of the population response to environmental conditions over some longer period of time. The poor survival of northern fur seal and California sea lion pups born in June and July 1997 (most were dead by October) means that pinniped populations experienced a dramatically different environment in California waters in the summer of 1997. The poor conditions for pinnipeds continued into 1998. Pup production was low; pup mortality was high; and there was increased mortality in adult females of northern fur seals. The onset of the El Niño effect on pinnipeds appeared to precede the onset of the effect on thermocline and nutricline depth by several months. Conditions improved for pinnipeds in 1999. The El Niño signal must also be interpreted in the context of the long-term trend of population increases in pinnipeds.

Observations made at seabird colonies provide information on trends in abundance and physiological state. (Thanks to Bill Sydeman, Point Reyes Bird Observatory, and collaborating projects; table 3). Some effects on seabirds nesting in the Channel Islands during the summer of 1997 were attributed to El Niño. These included nest abandonment and a greater than 50% reduction in productivity (chicks/pair) in double-crested cormorants, and significant chick mortality in brown pelicans. The effects were even greater during the summer of 1998, and central and southern California were affected.

El Niño effects on seabird populations are also being studied by examining long-term patterns of seabird distribution and abundance at sea (Ainley et al. 1995; Veit et al. 1996; Hyrenbach and Veit 1999). Routine surveys made on CalCOFI cruises during 1997–98 revealed that overall seabird abundance between July 1997 and April 1998 remained consistently low when compared to long-term seasonal means (Lynn et al. 1998; Hayward et al. 1999). Additionally, the seasonal cycle of seabird abun-

TABLE 3
Preliminary Summary of El Niño Effects
on Seabirds in Southern and Central California

Southern California

1997
Brown pelican and double-crested cormorant: Near normal nesting effort, but significant chick mortality (brown pelican) and nest abandonment (double-crested cormorant).
Greater than 50% reduction in productivity (chicks/pair) for double-crested cormorant.
No signal in productivity for Cassin's auklet, Xantu's murrelet, or western gull.

1998
Greater than 50% reduction in breeding populations of brown pelican, double-crested cormorant, Brandt's cormorant, pelagic cormorant, and Cassin's auklet; but no signal in Xantu's murrelet.
50% reduction in productivity (chicks/pair) for brown pelican but no signal in productivity for Cassin's auklet, Xantu's murrelet, or western gull.

Central California

1997
No apparent signal.

1998
Reduction in nesting effort; significant delay in breeding; reduction in productivity.
Amplitude of response is species dependent.

Thanks to Bill Sydeman, Point Reyes Bird Observatory, and collaborators: Point Reyes Bird Observatory, University of Washington, Channel Islands National Park, UC Davis, San Francisco Bay National Wildlife Refuge.

dance was disrupted during 1997–98. Instead of the usual summertime maximum, overall seabird abundance peaked in the fall of 1997 in response to the transient immigration of southern warm-water species (i.e., black-vented shearwater and black and least storm petrels; Lynn et al. 1998; Hayward et al. 1999). These fluctuations in seabird community composition resemble similar changes observed during the 1992–93 El Niño (Ainley et al. 1995; Veit et al. 1996). However, it is difficult to separate a clear El Niño signal during 1997–98 from the long-term trend of declining seabird abundance (fig. 13; Veit et al. 1996; Hayward et al. 1999; Hyrenbach and Veit 1999).

Squid populations also respond to El Niño events, and understanding the effects is an important management issue. Market squid was the most economically valuable fishery in the state of California in 1996 (California Department of Fish and Game 1997, 1998). The market squid data (thanks to Marci Yaremko, California Department of Fish and Game) can be best considered in the context of a five-year record of landings. The fishery in the northern Channel Islands normally occurs during winter (November–March), and the data are thus shown for the winter periods spanning two years (fig. 14). There has been a steady increase in the fishery since at least the mid-1990s, to the

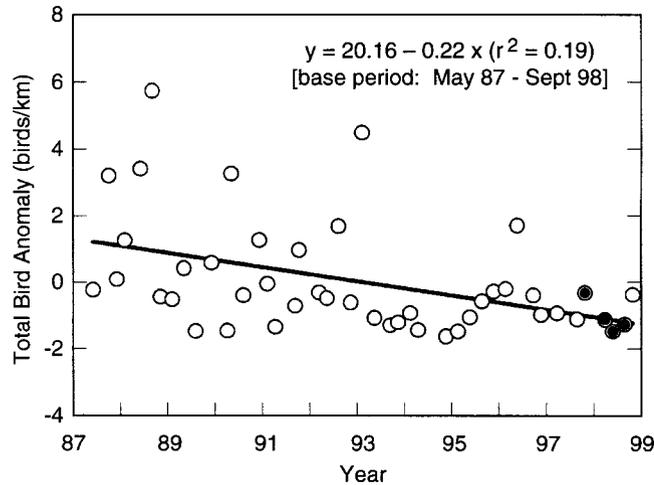


Figure 13. Seasonal anomalies in overall seabird abundance obtained by subtracting the average abundance from each cruise from the long-term (1987-98) seasonal mean. Values for cruises between July 1997 and April 1998 are depicted by filled circles.

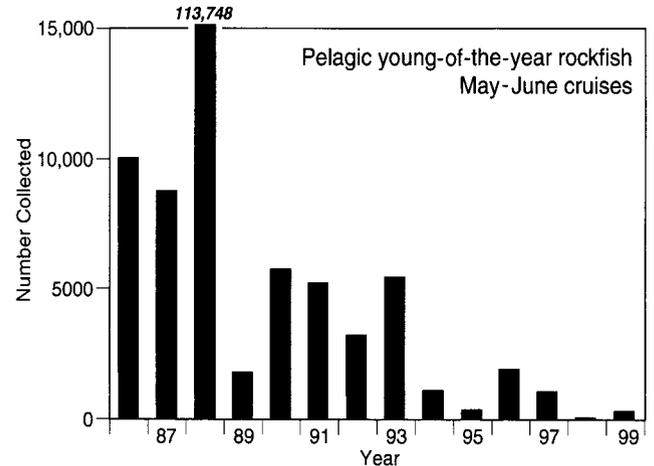


Figure 15. Abundance of pelagic young-of-the-year rockfish collected by midwater trawl in the Monterey region during spring, 1986-99.

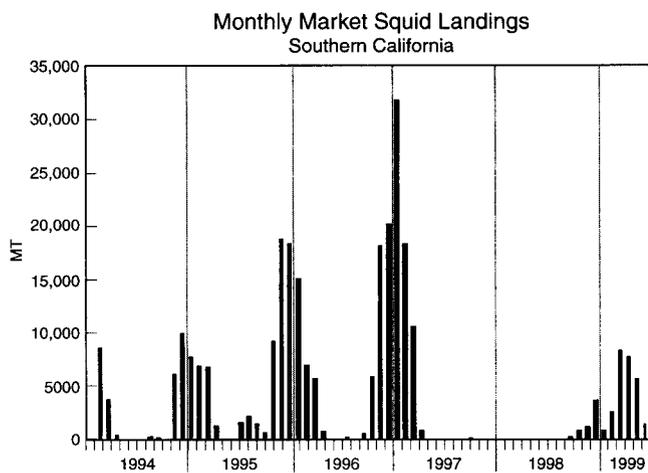


Figure 14. Monthly landings of market squid in the southern California region, 1994-99.

quite high landings of the winter of 1996-97. There were virtually no landings from the Channel Islands fishery in the winter of 1997-98. Landings were low in the winter of 1998-99, but there was an unusually significant catch in the spring of 1999. The squid data are consistent with strong El Niño effects in the winter and spring of 1997-98 and a recovery in the winter and spring of 1998-99.

Pelagic young-of-the-year rockfish are another group with important implications for fishery management and for which there are time-series data that can be used to look for an El Niño signal and its relation to longer-term trends. Recent data on rockfish (thanks to David Woodbury, NOAA-NMFS Santa Cruz/Tiburon Laboratory, <http://www.pfeg.noaa.gov/tib/index.htm>) must be

considered in the context of the longer-term trend of a strong decline over the last decade. Abundance was low in the years 1997, 1998, and 1999, but it is not necessarily clear that an El Niño signal can be detected over the longer-term trend of declining values (fig. 15).

Long-term studies have shown that kelp forest communities tend to be affected by changes in physical structure associated with El Niño events (Tegner et al. 1996). The cause-and-effect relations linking changes in physical structure and kelp forests may be better understood than is the case with pelagic populations. Kelp forests respond to changes in nutrient inputs, which are correlated with trends in coastal temperature anomalies. Kelp forests are also affected by disruptions caused by El Niño storm events. Time-series observations in the Point Loma kelp forest (thanks to Mia Tegner, SIO) show that kelp density and the stipe index (an index of physiological state, Tegner et al. 1996) were both strongly affected from the fall of 1997 through calendar year 1998 (fig. 16; Hayward et al. 1999). The decline in abundance was attributed to direct impacts by storm events and indirectly by reduced growth rates due to nutrient stress during warm-water conditions.

DISCUSSION

Managers and policymakers are concerned with better understanding how and why the ecosystem in our local waters changes during El Niño events. With respect to physical impacts, it is important to have an objective way to determine when physical structure changed, how strong the impacts were, and when they ended. Improved understanding of the ecological consequences, including determining which observed ecosystem changes should be attributed to El Niño as opposed to something else, and better determining the specific physical causes of ecosystem effects are impor-

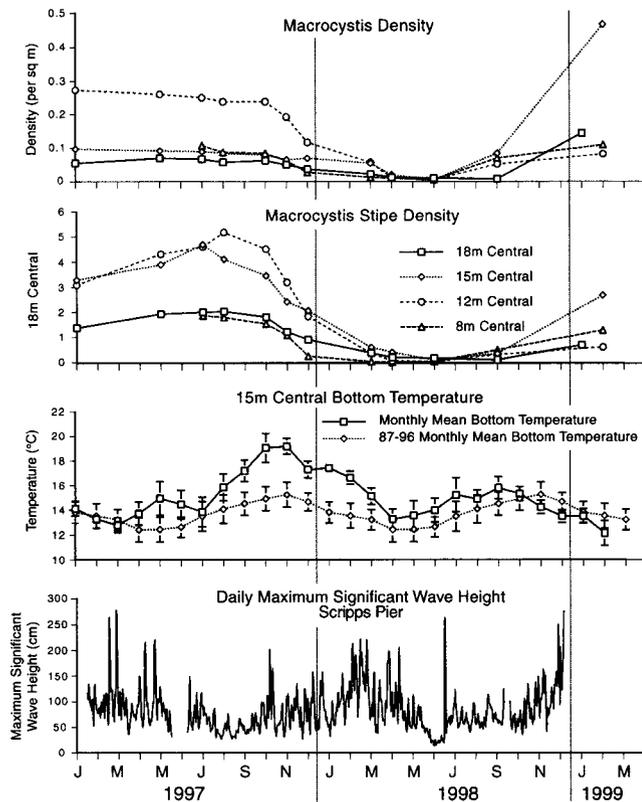


Figure 16. A. Changes in density of *Macrocystis* adults (defined as four or more stipes), and B, stipe density from permanent sites at 18, 15, 12, and 8 m in the center of the Point Loma kelp forest, January 1997 through March 1999. See Tegner et al. (1997) for sampling details. C, In situ temperature at 15 m for 1997–99 and the mean for 1987–96; error bars represent one standard deviation. D, Daily maximum significant wave height from the Scripps Institution of Oceanography Pier. Gaps in the data are due to equipment failure (Coastal Data Information Program).

tant scientific goals that support management and policy objectives.

The 1997–98 El Niño event affected different aspects of structure at different times. Hence, the question of when El Niño conditions started to affect California waters, and, specifically, the question of whether the system was affected by El Niño forcing during the summer and fall of 1997, depends upon which aspects of structure are considered. Elevations in sea-surface temperature and sea level, and the intensification of the undercurrent and related changes in T-S structure showed that some effects on physical structure were detectable by the summer of 1997. There was thus a short time lag for these aspects of the system to respond to (or at least be associated with) the dramatic changes which took place in the tropical Pacific that summer (fig. 2). However, the timing of changes in other aspects of local structure, particularly thermocline depth, T-S structure in the upper layers, and the upwelling index, showed that the full suite of physical effects of El Niño did not occur in California waters until the winter of 1997–98.

Managers considering how to respond to future El Niño events will generally have the easiest access to such widely and rapidly distributed physical data as SST anomalies and sea-level anomalies. The question is how such information is related to the overall trends in physical structure. The timeline showed that the El Niño impact upon these indices preceded the impact upon thermocline structure by a period of several months. The difference in timing of surface versus thermocline signals is particularly evident in the vertical section of temperature anomalies versus time (fig. 8). The onset and decline of temperature anomalies in the thermocline lags the surface layer by about six months. The upper thermocline (e.g., 50 to 150 m depth) was normal to cool in the summer of 1997, well after positive SST anomalies were evident. The converse was also true during the transition to La Niña conditions. Relatively large positive anomalies persisted in the thermocline during spring and summer 1998 as the surface layer became anomalously cool. Generally, however, the suite of physical indices examined here was in better agreement about the timing of the decline of El Niño conditions and that there was a relatively rapid transition to La Niña conditions in the summer of 1998.

Advection associated with the enhanced flow in the undercurrent in summer 1997 may be the explanation for the unusual northward range extension of southern warm-water species that summer. The strongest impacts upon upper ocean physical structure started during the winter of 1997–98. The deepening of the thermocline that started in November 1997 is probably the physical change which is most directly related to the nutrient distribution and primary production. The upper ocean physical structure suggests that primary production and related aspects of biological structure should have been most strongly affected during spring 1998 rather than summer 1997.

As with physical structure, there is ambiguity in the extent to which El Niño conditions affected ecosystem structure in California waters during the summer of 1997. Effects on pinnipeds and seabirds and northward extensions of the range of warm-water species in the summer of 1997 were attributed to El Niño forcing. However, El Niño effects during spring and summer 1998 were more pronounced in that more ecosystem properties were affected and the impacts were greater.

The observation that a few aspects of both physical and ecosystem structure were affected by El Niño conditions in the summer of 1997, while others were not affected until winter and spring of 1998 makes it difficult to develop a multivariate “California El Niño” index that could be used to define the timing of the onset or the intensity of El Niño conditions in California waters for a broad range of management and policy decisions.

It is not clear what criteria should be used to select the physical aspects of structure used to define El Niño conditions for the index. For many purposes those physical aspects which most strongly affect ecosystem structure would make good components of such an index. However, it is not clear what these are. There is a clear chicken-and-the-egg problem in defining cause-and-effect linkages between physical and biological trends by correlating timelines. If an aspect of ecosystem response is first used to define physical aspects of El Niño forcing, one cannot then turn around and use a timeline of that physical property in an El Niño index to detect the ecosystem response by correlation. Ambiguity in defining indices of physical forcing and ecosystem response should not necessarily be surprising, since attributing cause-and-effect relations to observed ecosystem changes is one of the great challenges in ecology and fisheries oceanography.

The timeline can be used to further study cause-and-effect linkages by examining whether the observed temporal patterns are consistent with those expected from theory. A range of mechanisms which link changing physical and ecosystem structure has been proposed (table 4). In each of these mechanisms changes in physical structure are expected to affect ecosystem structure following some time lag. The theories are better developed for some mechanisms than for others, and the time lags are generally not well defined. Testing these theories is also complicated because they are not mutually exclusive and more than one may affect a given population. Different mechanisms may also affect different populations. In spite of these complications, it is still useful to examine the timeline and determine the predictive skill that can be attributed to a basic approach a manager might use to implement these theories. Even when the expected time lags are not well known, an effect should follow its cause.

Changes in range due to advection of plankton and migration of mobile species have been invoked to explain the popular reports of northward extensions of the range of southern, warm-water plankton and game fish species. This general explanation has also been invoked to explain shifts in the local abundance of planktonic species, such as euphausiids, with northern and southern affinities. However, the timing and nature of the trends in circulation pattern are not necessarily consistent with this explanation. The strong northward flow in the summer of 1997 occurred at middepths. There was quite strong northward flow along the coast in February 1998, and the high salinity was consistent with strong advection from the south. The role of physical forcing in changing the range of mobile species will be hard to deal with until more is known about the specific aspects of physical structure to which these species

TABLE 4
Summary of Mechanisms by Which El Niño Conditions May Affect Ecosystem Structure, and Expected Effects

Bottom-up Forcing
Physics → nutrient inputs → phytoplankton–primary production → zooplankton grazers → higher trophic levels.
Expect effects to occur in sequence (e.g., with time lags) following the physical change of an increase in mixed-layer (thermocline/nutricline) depth.
Advection
Changes in spatial distribution (especially plankton) due to changes in ocean circulation pattern.
Expect changes to occur at the same time and be correlated with changes in circulation pattern and water mass (T/S) structure.
Changes in Range and Location of Preferred Habitat
Changes in physical environment (temperature and salinity) cause mobile species to migrate and change their range. This will be seen as a change in abundance as species move in and out of the study area.
Expect changes in abundance of mobile species within the study area correlated with changes in habitat structure. This is best studied by looking at a larger area and documenting changes in range.
Top-down Forcing and Changes in Community Structure
Advection, migration, and changes in the range of top predators lead to changes in abundance of prey and competitor species (changes in community structure).
These mechanisms will be difficult to evaluate until the roles of predation and competition in structuring the pelagic community are better understood.
Internal Changes in Habitat Structure
Changes in other aspects of habitat structure such as changes in the vertical distributions of phytoplankton (e.g., depth and intensity of chlorophyll maximum layer) and zooplankton, changes in the size distribution or taxonomic composition of phytoplankton or zooplankton, or changes in horizontal distributions and intensity of patchiness on a range of scales could all affect abundance and pelagic community structure.
The impact of El Niño upon these mechanisms will also be difficult to evaluate until the processes influencing pelagic community structure are better understood.
Direct Thermal Effects
Changes in abundance or limits in range due to direct thermal effects.
Such changes will occur where the biogeographic boundary (or limit of the range of a species) is directly associated with temperature, and El Niño changes make the temperature of the habitat unsuitable for a species.
Examples include coral reef bleaching and direct temperature effects on kelp forests in the southern part of the range off Baja California, Mexico.

respond. It is also difficult to separate trends in local abundance due to trends in overall population size from trends in local abundance caused by changes in range, although a regional synthesis will help with this. Planktonic populations, such as the euphausiids, also show long-term trends in abundance whose causes are not well understood. Even when, as in 1998, it appears that there was an El Niño effect, it is difficult to determine the precise timing or magnitude of El Niño changes and separate them from trends due to processes on other time scales. Additional research is needed in several areas. It would be helpful to have a quantitative index of upper ocean transport (an advection index) which could be

used for comparison with population trends. A synthesis of the data from regional programs along the west coast of North America will help in showing whether changes in local abundance are due to changes in range or changes in overall population size. Development of a time series which reflects the preferred habitat structure of mobile species for comparison with population trends would be helpful, as would the development of additional time series of ecosystem structure.

Bottom-up trophic forcing is probably the most commonly cited cause-and-effect mechanism linking in situ changes in physical properties with ecosystem structure. In this mechanism, El Niño is hypothesized to affect the system by deepening the thermocline (and nutricline) and thus reducing the nutrient input, primary production, and phytoplankton abundance. This, in turn, is presumed to reduce the abundance of grazers upon the phytoplankton and their predators in the food chain above them. The link between physics and nutrients, at least, is clear. In the CalCOFI study region, there is a strong correlation between temperature and nitrate (Hayward and Venrick 1998). Changes in thermocline depth are thus a very good indicator of changes in nutricline depth. In the most simple implementation of the bottom-up theory, the strong impacts of El Niño on nutricline depth should be indicated by anomalies in thermocline depth as indicated by thermocline temperature anomalies. Warm water in the thermocline (e.g., 100–150 m) indicates that the nutricline is deeper than normal, and cooler water indicates that it is shallower than normal. Waters in the thermocline were normal to cool in July 1997, and the strong positive thermocline temperature anomalies did not develop until November–December 1997 (fig. 8). These warm thermocline anomalies persisted into summer 1998, and the greatest negative effect on production should have been during the time of the 1998 spring phytoplankton bloom.

The timeline observations are inconsistent with the expectations of a simple model of bottom-up trophic forcing in several ways. The effects on pinnipeds and seabirds in summer 1997 preceded the deepening of the nutricline. Further, the lack of a decrease in chlorophyll (and thus primary production, since the two are strongly correlated in the CalCOFI study region; Mantyla et al. 1995) in 1998, coupled with a decrease in macrozooplankton biomass, presents an ambiguous picture of whether even the first link in this presumed sequence of events following a deepening of the nutricline can be documented. Recall also the remarkable change in circulation in the spring of 1998, when the California Current swept shoreward along the coast, and shoaling of isopycnals and the nutricline resulted in a sharp increase in chlorophyll to what appear to be normal

spring levels (fig. 6a). The facts that some of the presumed responses to bottom-up forcing preceded the forcing and that the first change in the presumed sequence of responses cannot be detected, indicate that this very basic implementation of a bottom-up model may have little skill in predicting the types of changes in ecosystem structure that managers and policymakers need to understand.

The above is clearly not a sufficient test of the bottom-up hypothesis; nor is it intended to be. The intent is to illustrate the level of predictive skill about ecosystem structure associated with the most simple implementation of a bottom-up model based upon observed trends in physical structure. Given that physical trends now can be predicted, this is the approach that would be used as a first step in the absence of other information. The theory may be correct, but a more complicated implementation may be required. El Niño may change phytoplankton taxonomic composition, size, or distribution in a way that affects food quality or availability to grazers but which is not reflected in the simple phytoplankton index used here (vertically integrated chlorophyll). However, Mullin (this volume) shows that large phytoplankton were anomalously abundant since the depression of the nutricline. It may also be that the grazer community changes in some way, such as taxonomic composition or vertical distribution, that affects the higher trophic levels that feed upon them but which is not correlated with the nutrient distribution or chlorophyll concentration (Mullin 1995, 1997). Preliminary evidence from the seabirds and pinnipeds suggests that nutrition is an issue. El Niño-induced changes in the food chain remain a likely candidate for linking changes in physical structure and the ecosystem. However, simple implementations of the bottom-up model appear to have little predictive value usable by managers or policymakers.

Although much more analysis of these data remains to be done, this is an appropriate place to end this analysis. The mechanisms listed in table 4, other than bottom-up control, would probably be difficult to test because the theories for these mechanisms are generally not developed to the point that predictions can reasonably be tested with existing data. Theoretical development, ecosystem modeling, and new types of observations will all be required. Future work will also include a more detailed analysis of the timeline, particularly to address the aspects of the data which appear to be inconsistent. The timeline presented here is just one way to consider the new data that were collected during this event. Development of a coastwide synthesis and consideration of how these new findings contribute to understanding individual populations and aspects of structure will be exciting next steps.

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