THE STATE OF THE CALIFORNIA CURRENT, 1999–2000: FORWARD TO A NEW REGIME?

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ABSTRACT

This report is the latest in an ongoing series that describes oceanographic conditions in the coastal waters of the Californias. The emphasis here is on observations made by CalCOFI (California Cooperative Oceanic Fisheries Investigations) and other programs during the 1999–2000 period. The physical environment off southern California shifted dramatically between 1997 and 1999 from El Niño (warm anomalies, low productivity) to La Niña (cool anomalies, high productivity) conditions. The tropical ocean has remained in the La Niña state through 1999 and into spring 2000, while the region off southern California has been characterized by a vigorous, offshore-displaced California Current, and near-surface temperatures close to the climatological mean. Primary and secondary production in the California Current system have rebounded since the biological drought of the 1997–98 El Niño. In light of the dramatic variability observed in the CalCOFI region over the past few years, we discuss the physical and biological future of the southern California Current system within the context of a potential large-scale climatic regime shift.

INTRODUCTION

This is the seventh in an annual series of reports (Hayward et al. 1994, 1995, 1996, 1999; Schwing et al. 1997; Lynn et al. 1998) that present and synthesize recent observations of the physical and biological structure of the southern California Current system (CCS). The emphasis in this report is on observations made over the past year (April 1999 to April 2000), primarily from the quarterly CalCOFI surveys. We also present data from observational programs which sample other portions of the CCS, and which place the CalCOFI observations in a larger regional context.

The past few years constitute one of the most remarkable periods in the 50-year history of CalCOFI. One of the strongest El Niño events on record, and by far the most thoroughly monitored, affected the region during 1997–98, generating anomalously warm waters and low productivity (Lynn et al. 1998). CalCOFI responded to this event by augmenting its traditional sampling plan with monthly mini cruises between the quarterly surveys, yielding a high-resolution time series of the physical and biological response to a strong El Niño (e.g., Hayward 2000). Following this event, there was a dramatic transition to cool-water, more highly productive conditions, associated with both a strong La Niña event (Hayward et al. 1999) and anomalous upwelling-favorable wind forcing along the West Coast (Schwing et al. 2000). The tropical ocean has remained in the La Niña state through 1999 and into spring 2000. Consequently, the period 1999–2000 has been characterized by a continuation of relatively cool water conditions in the southern CCS, but with a more vigorous, offshore-displaced California Current than is expected from the CalCOFI hydrographic climatology. Primary

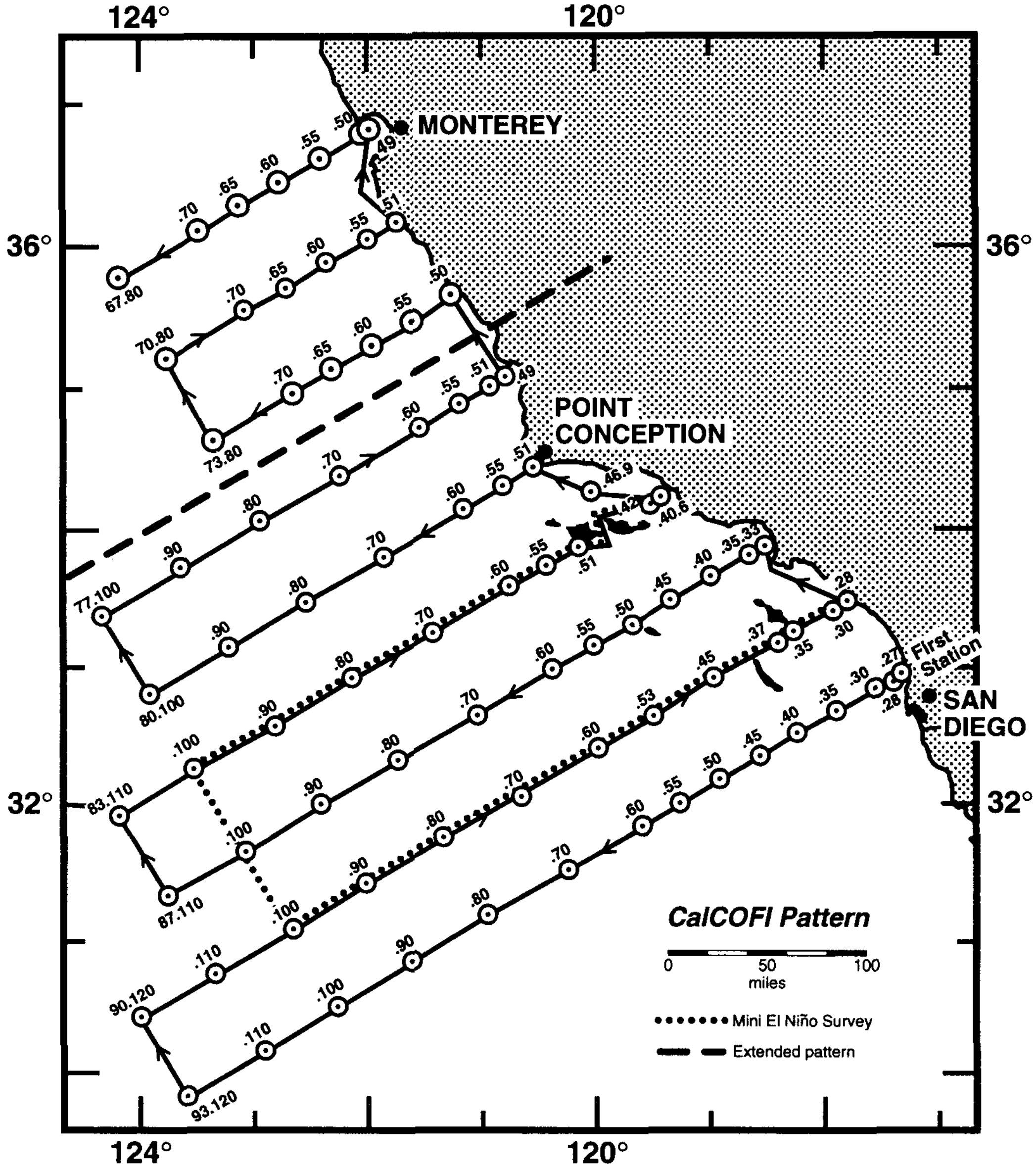

Figure 1. The standard CalCOFI sampling grid. The regular 66-station pattern occupied by CalCOFI since 1985 (lines 77, 80, 83, 87, 90, and 93) is shown by a solid line. The stations for the 1997–98 mini El Niño cruises on lines 83 and 90 are shown by a dotted line. The area of additional underway sampling north of the regular pattern is above the dashed line (lines 67, 70, and 73).

and secondary production have rebounded following the biological drought of the 1997–98 El Niño.

We begin our report with a summary of the large-scale atmospheric and oceanic conditions that have affected the CCS during 1999–2000. We then describe general patterns of ocean circulation and water properties in the CCS as revealed by survey cruises off southern California (CalCOFI) and Baja California (IMECOCAL). The corresponding biological patterns are then summarized, focusing on the near-surface chlorophyll a patterns, cruise-mean macrozooplankton biomass, and seabird communities in the CCS. The biological response to the recent environmental variability is further explored by comparing satellite-derived and in situ chlorophyll estimates from the CalCOFI region. Finally, we conclude the report by speculating on the future of the California Current in the context of an anticipated large-scale climatic regime shift.

DATA SETS AND METHODS

The CalCOFI program maintains quarterly (normally January, April, July, and October) survey cruises that occupy a geographically fixed grid of 66 stations off southern California (fig. 1). This grid has been expanded in recent years to include three northern lines in winter and spring, where underway measurements are made,

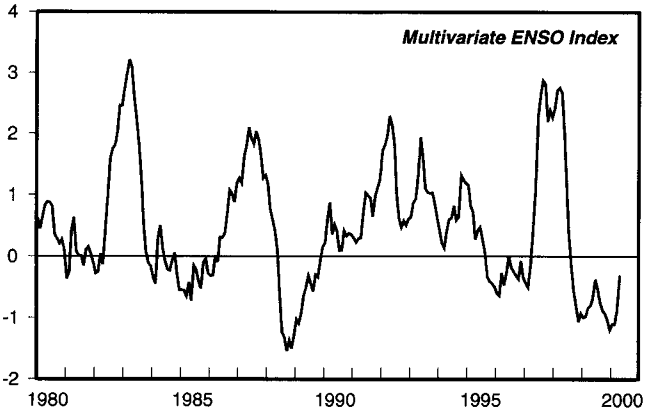

Figure 2. Monthly time series of the multivariate ENSO index, or MEI (Wolter and Timlin 1998), for January 1980–April 2000. The series highlights the rapid transition from El Niño to La Niña in 1998, and the extended negative phase of MEI associated with the 1998–2000 La Niña.

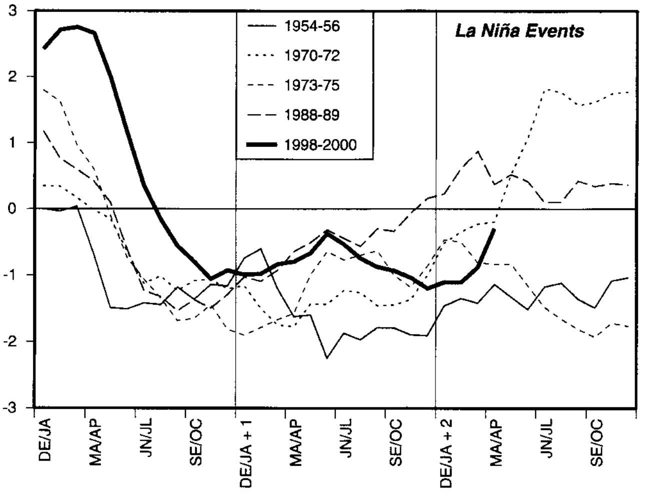

Figure 3. Monthly multivariate ENSO index, or MEI (Wolter and Timlin 1998), comparing the intensity and duration of the 1998–2000 La Niña to four previous strong La Niña events. Multiyear La Niña events are not uncommon.

and the additional occupations of lines 83 and 90 during the 1997–98 El Niño event. Standard station sampling includes a CTD/rosette cast, with water samples collected at 20–24 depths in the upper 500 m to determine salinity, dissolved oxygen, inorganic nutrients, phytoplankton pigments (chlorophyll a and phaeophytin), and primary production (^{14}C uptake at one station per day). Continuous underway sampling of surface temperature and salinity is carried out, and high-resolution measurements of upper ocean currents are made with an acoustic Doppler current profiler (ADCP). The continuous underway fish egg sampler (CUFES; Checkley et al. 1997) is used to track fish eggs and larvae along the transects. Oblique and surface (neuston) net tows (0.505 mm mesh) are taken at each station.

We also present data from a Mexican sampling program, Investigaciones Mexicanas de la Corriente de California (IMECOCAL), which has occupied historical CalCOFI lines off Baja California since 1997. These cruises are planned to coincide closely with the timing of the CalCOFI cruises, and use complementary sampling methods. Additional data sets presented here include seabird observations conducted on the CalCOFI surveys, and ocean color from the OCTS (ocean color and temperature scanner) and SeaWiFS (sea-viewing wide field-of-view sensor) satellites. Details of sampling methods and data sources are briefly described as these observations are presented.

OBSERVATIONS

Large-Scale Atmospheric and Oceanic Patterns

After a dramatic transition in 1998 from one of the strongest El Niño events of this century to a strong La Niña event, 1999 and early 2000 were marked by a continuation of La Niña conditions in the tropical Pacific. The multivariate ENSO index (MEI; Wolter and Timlin 1998) dropped from an El Niño peak in spring 1998 to a minimum in late fall 1998 (fig. 2), the most dramatic decline in the 50-year history of the MEI (*http://www.cdc.noaa.gov/~kew/MEI/mei.html*). The MEI has remained moderately to strongly negative since late 1998 (figs. 2 and 3).

The MEI can remain negative for many months, suggesting a multiyear La Niña event (e.g., 1954–56, 1970–72; fig. 3). However, conditions can also shift quickly back to El Niño (e.g., 1972). As of April 2000, the MEI had remained negative for 21 consecutive months, the longest continuous negative period since the 1976–77 climate regime shift. The MEI does indicate, however, that La Niña conditions weakened considerably in April 2000, signaling a possible end to the 1998–2000 La Niña. A similar decline in the MEI occurred in April 1999, but was followed by a regrowth of La Niña. May is often a pivotal month in the development of climate anomalies such as El Niño; this La Niña could reintensify as it did in 1999, or return to a positive MEI and El Niño conditions as in 1972.

Surface anomalies throughout the Pacific during 1999 and early 2000 (fig. 4) remained in a pattern typical of La Niña (Murphree and Reynolds 1995). Strong clockwise wind anomalies in the northeast Pacific were associated with a very strong North Pacific High (fig. 4). These anomalies contributed to enhanced trade winds in the western tropical Pacific, and unusually robust upwelling-favorable winds along the North American west coast. Upper-level winds were affected by the unusual sea-level pressure patterns. For much of the previous several months, the North Pacific jet stream flowed over western Canada, well north of its usual path; however, a more zonal, southerly-positioned jet stream redevel-

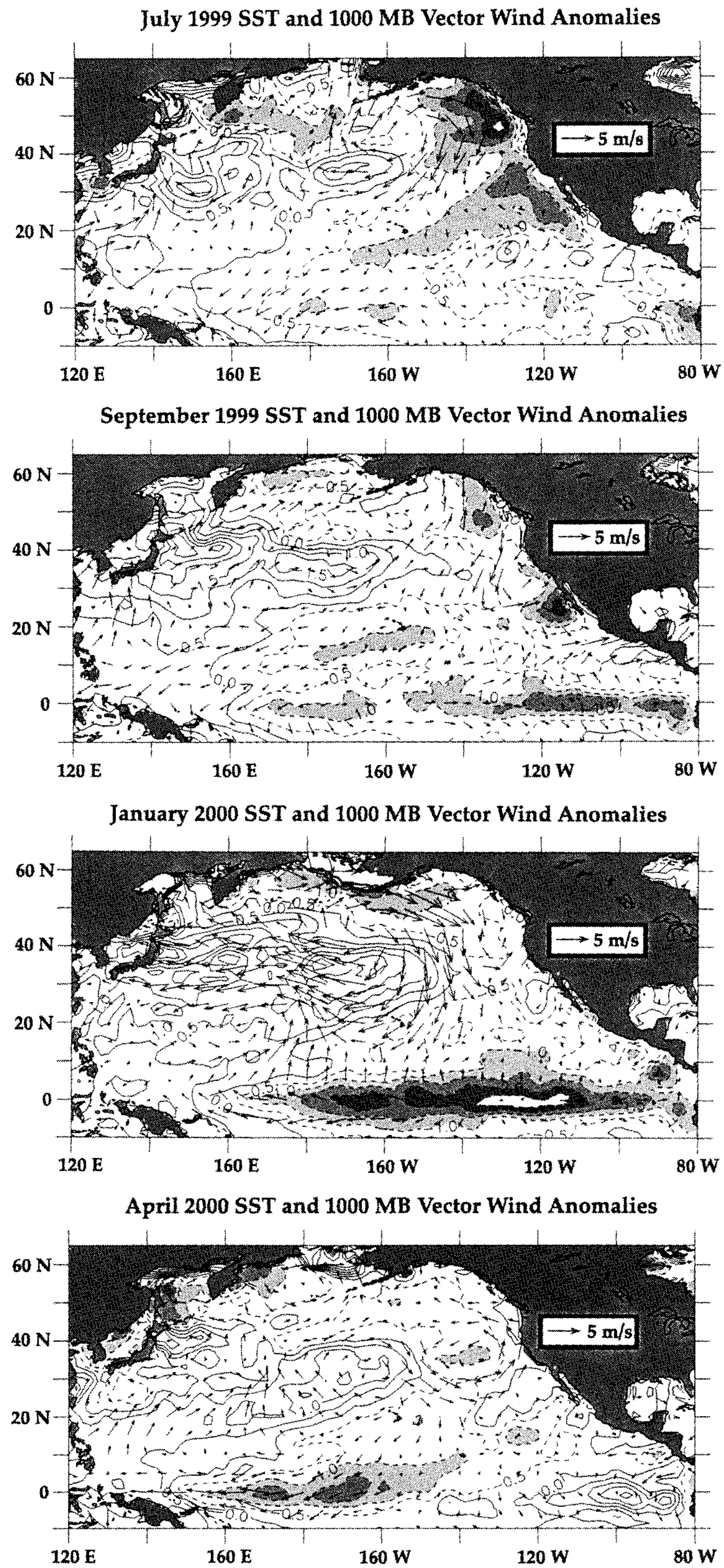

Figure 4. Anomalies in the North Pacific Ocean. Anomalies of surface wind velocity and sea-surface temperature (SST) for July 1999, September 1999, January 2000, and April 2000. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 0.5°C. Negative SST anomalies (dashed contours) less than −1.0°C are shaded. Wind climatology period is 1968–96. SST climatology period is 1950–79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center Web site (*http://www.cdc.noaa.gov*).

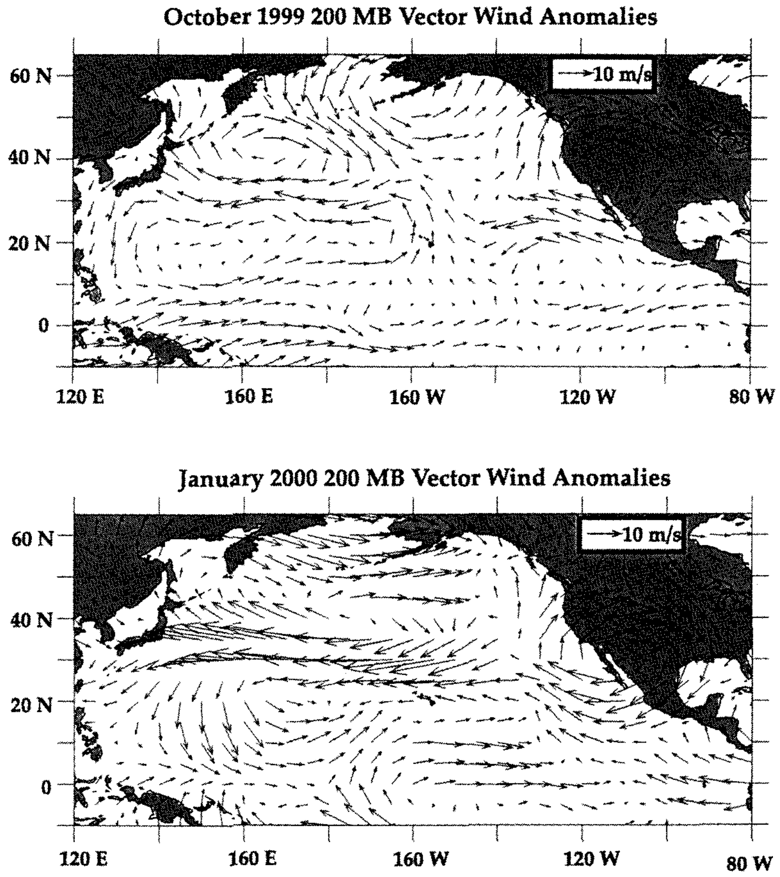

Figure 5. Anomalies of wind velocity at 200 mb for October 1999 and January 2000. Arrows indicate the direction and magnitude of the wind anomalies. Scale vector is 10 m/s. Winds at this level show position and strength of the jet stream, and general storm track. Monthly data obtained from NOAA-CIRES Climate Diagnostics Center. Wind climatology period is 1968–96.

oped in early 2000 (fig. 5). This provided a steady supply of moist, subtropical air from the southwest from mid-January through February, bringing heavy precipitation to northern and central California and producing normal annual precipitation totals in an otherwise relatively dry winter.

Since late 1998 a horseshoe-shaped region of cooler than normal sea-surface temperatures (SSTs) has stretched roughly along the axis of the North Pacific trade winds from the western equatorial Pacific to Baja California, and along the North American west coast into the Gulf of Alaska (fig. 4). Cool anomalies also spanned the equator east of the date line. These negative SST anomalies were particularly large in the CCS. The most extreme stage of this pattern was in spring–summer 1999 (fig. 4), when strong southward wind stress produced record levels of coastal upwelling for most of California (Schwing et al. 2000). Positive SST anomalies were maintained in the western tropical Pacific and from the western North Pacific to Hawaii.

The thermocline in the eastern tropical Pacific has remained unusually shallow since mid-1998, while an anomalously deep thermocline has continued in the western tropical Pacific (fig. 6). This condition typifies La Niña events. A switch toward El Niño conditions will probably occur if the associated warm subsurface anomalies move eastward along the equator, which eventually happens as La Niña wanes. Surface tropical temperature anomalies continue to display a general La Niña pattern (fig. 4). Positive SST anomalies developed in late March 2000 in the eastern equatorial Pacific (NCEP 2000b), but still were underlaid by an anomalously shallow thermocline and cooler than normal subsurface temperatures (fig. 6).

Coastal Conditions

Monthly coastal upwelling indices (Bakun 1973; Schwing et al. 1996) indicate that 1999 was a period of generally stronger than normal upwelling in the CCS (fig. 7). After an interval of weaker than normal upwelling through late spring and summer 1998 south of San Francisco, upwelling was slightly above normal in late 1998 (Hayward et al. 1999). Anomalies remained positive through 1999. Upwelling was particularly strong

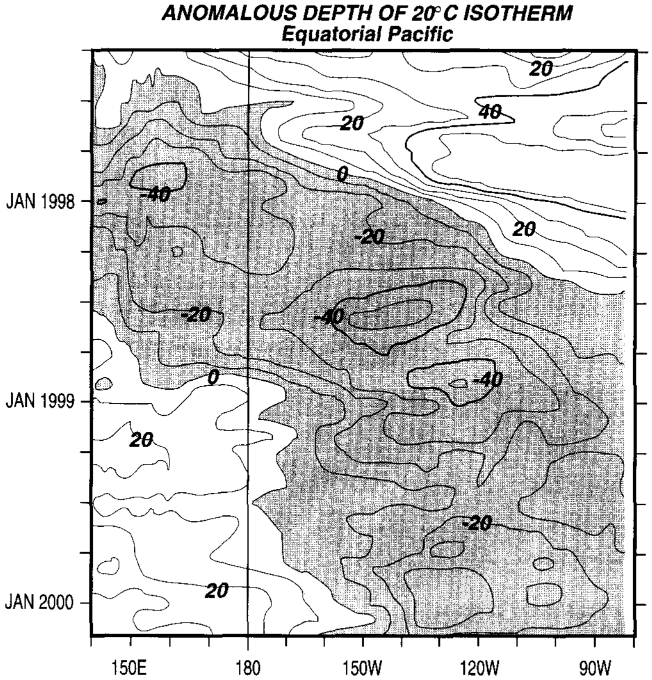

Figure 6. Anomalous depth (m) of 20°C isotherm for 5°N–5°S in the Pacific Ocean. Contour interval is 10 m. Negative anomalies (anomalously shallow thermocline) are shaded. Reference period is 1983–92. Adapted from NCEP 2000a.

along the California coast in spring and summer 1999. Upwelling anomalies off central California during the 1999 upwelling season were the greatest in the 54-year record of the upwelling index (Schwing et al. 2000). Negative upwelling anomalies throughout the CCS in early 2000 were associated with downwelling-favorable winds and a persistent northeastward upper-level flow across the region.

In the California Current region, NDBC coastal buoy winds (fig. 8) display the short-term variability associated with synoptic atmospheric events, superimposed on the annual climatological cycle of strong southward wind in summer and northward or weak southward wind in winter. Winds are typically strongest off northern California and weakest within the Southern California Bight (SCB). Wind vectors align strongly with the local coastline (table 1).

Coastal alongshore winds through the latter half of 1998 and much of 1999 were dominated by stronger than normal southward winds (i.e., more upwelling-favorable; fig. 8). A number of very robust wind events were observed coastwide during the first half of 1999. Particularly strong events occurred in late March, early May, and June–early July. The region was under the influence of northward winds in November 1999 associated with a north-south trough of low pressure that also forced the storm track well north of California (fig. 5). Winds during early 2000 were northward (fig. 8), also in association with a northward jet stream (fig. 5) and the passage of winter cyclones.

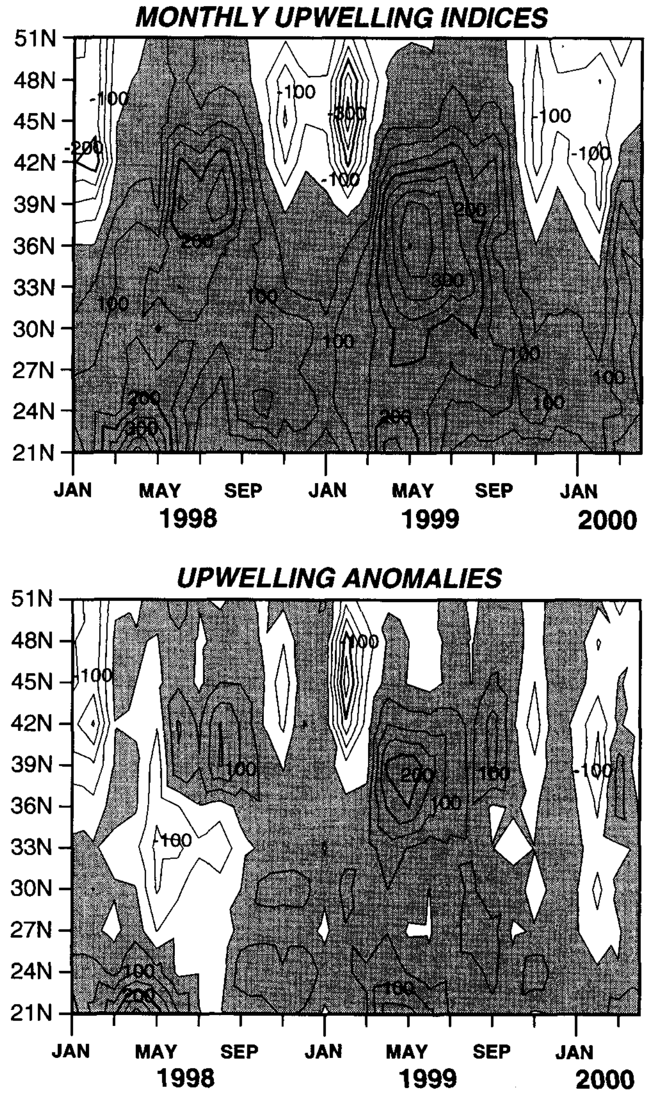

Figure 7. Monthly upwelling index and upwelling index anomaly for January 1998–April 2000. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are m^3/s per 100 km of coastline.

In less than two years, SSTs in this region dropped from the warmest on record—during the height of El Niño—to low temperatures not seen in decades. West Coast buoy SSTs began to drop in late 1998 following the mature phase of El Niño (fig. 9). A series of unseasonably strong upwelling-favorable wind events during this time (fig. 8) contributed to the dramatic cooling. SSTs continued to decline through the first half of 1999 (fig. 9). The very strong southward wind events in spring and summer 1999 led to enhanced coastal upwelling and contributed directly to this rapid cooling (Schwing et al. 2000). Coastal sea level was also well below normal during this period (Schwing et al. 2000).

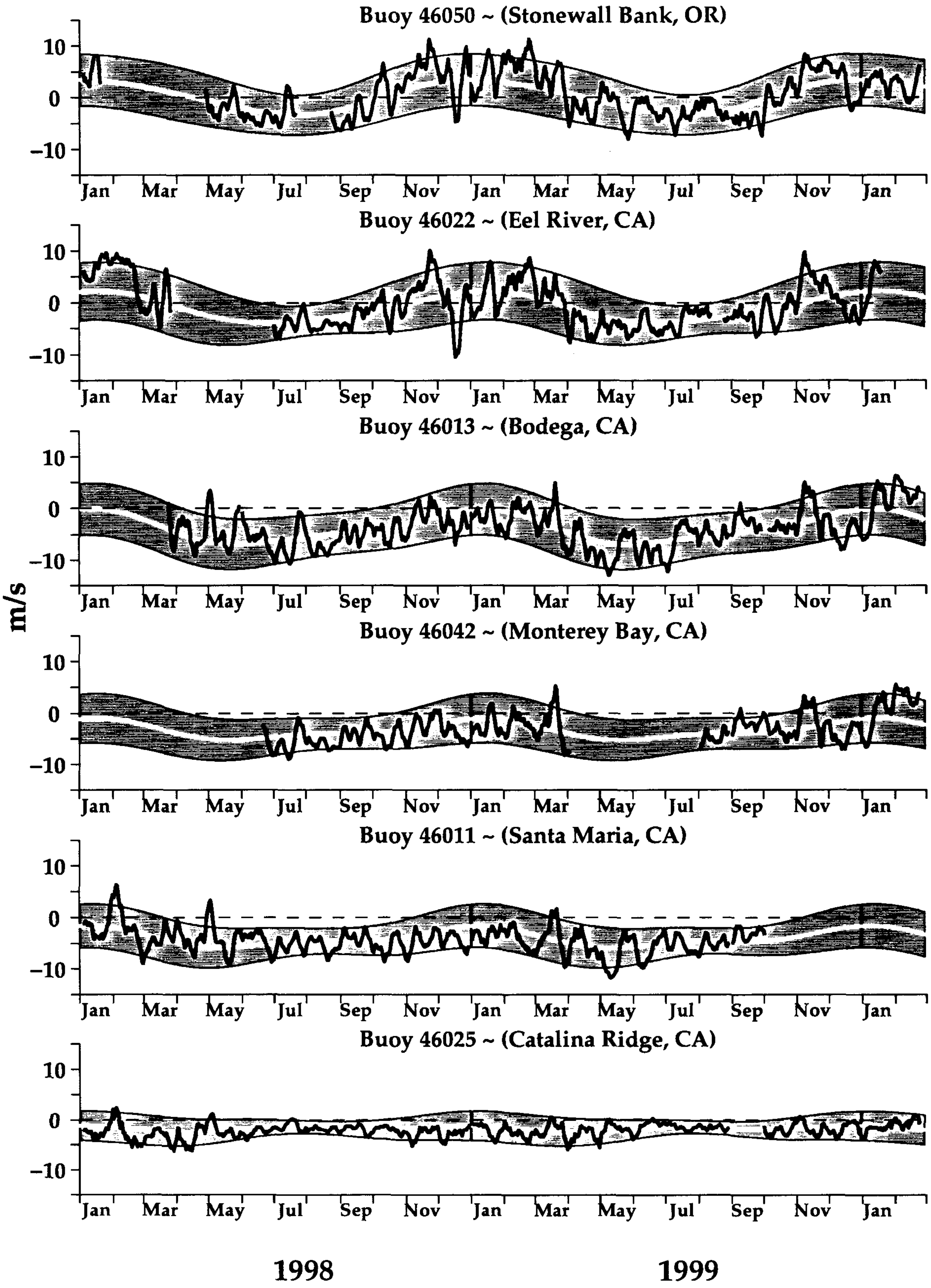

Figure 8. Time series of daily averaged alongshore winds for January 1998–February 2000 at selected NDBC coastal buoys. Bold lines indicate the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard error for each Julian day. Series have been smoothed with a 7-day running mean. The periods used for calculating the climatology at each site and the alongshore angle are shown in table 1.

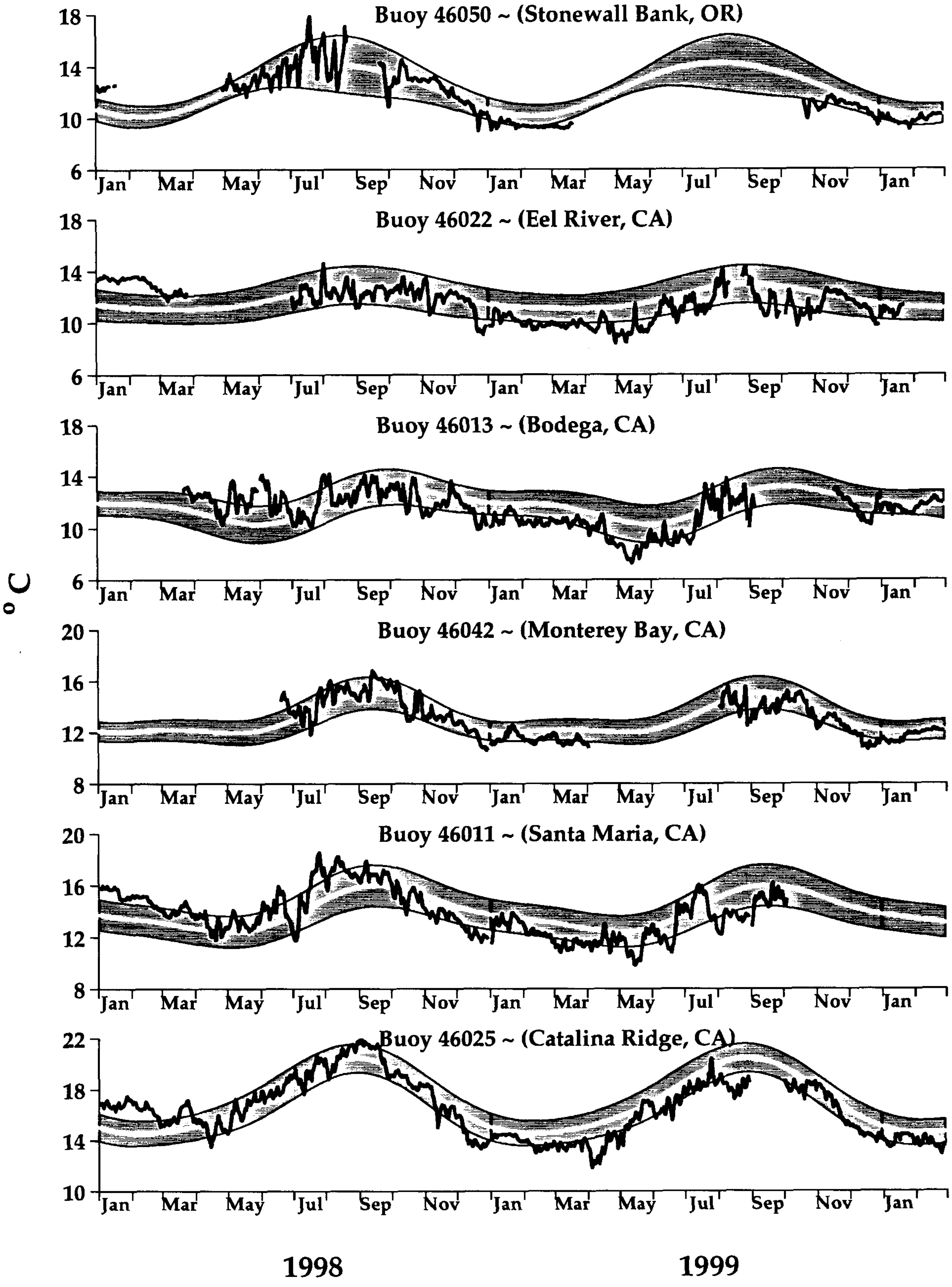

Figure 9. Time series of daily averaged SST for January 1998–February 2000 at selected NDBC coastal buoys. Bold lines show the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard error for each Julian day. The periods used for calculating the climatology at each site are shown in table 1.

TABLE 1
Locations of SST and Alongshore Wind Time Series

Buoy	Name	Position	Base period[a]	Alongshore angle (°N)[b]
46050	Stonewall Bank, Ore.	44.6°N 124.5°W	1991–99	359
46022	Eel River, Calif.	40.8°N 124.5°W	1982–99	354
46013	Bodega, Calif.	38.2°N 123.3°W	1981–99	312
46042	Monterey Bay, Calif.	36.7°N 122.4°W	1987–99	328
46011	Santa Maria, Calif.	34.9°N 120.9°W	1980–99	325
46025	Catalina Ridge, Calif.	33.7°N 119.1°W	1982–99	295

[a] Period of harmonic mean.
[b] Determined from principal-component analysis.

Surface anomalies were as much as 3°–4°C below normal during the 1999 upwelling season, with a drop at some locations of nearly 10° in less than one year (fig. 9). Bodega buoy SST, for example, was ~7.5° for several days in May 1999. With few exceptions, SST anomalies remained negative throughout the CCS from fall 1999 into early 2000. Individual southward wind events throughout this period are reflected as significant drops in the buoy SST time series. However, SST at several locations appeared to be returning to seasonal means in January–February 2000 under northward winds.

CalCOFI Survey Cruises

We summarize a portion of the data obtained on each of the five quarterly CalCOFI cruises conducted since the preparation of last year's report. Here we focus on the near-surface physical and biological parameters. The reader is encouraged to refer to the cruise data reports (e.g., Scripps Institution of Oceanography 1999) or the CalCOFI Web page (*http://www-mlrg.ucsd.edu/calcofi.html*) for a complete presentation of the data sets. A CD-ROM containing the first 50 years of CalCOFI data (1949–99), as well as software tools for navigating and extracting data segments, is also available.

The long-term seasonal mean circulation in the CalCOFI region provides a useful reference for the patterns seen in 1999–2000 (fig. 10). The southward-flowing core of the California Current is seen as the offshore region of high gradient in the 0/500 dbar dynamic height field. It is strongest in spring and summer, and tends to be closer inshore in spring. The seasonally modulated Inshore Countercurrent is the poleward-flowing near-surface feature near the coast (Lynn and Simpson 1987). The subsurface (200–300 m) California Undercurrent transports relatively warm and saline (spicy) slope waters into the region from the south, particularly in summer and autumn (Lynn and Simpson 1990). The quasi-permanent Southern California Eddy (SCE; Lynn and Simpson 1987) often occupies much of the Southern California Bight, and is evident in each season of this climatology. Numerous studies have shown a strong association between circulation patterns and ecosystem structure within the CCS (e.g., Hayward and Mantyla 1990; Haury et al. 1993; Hayward and Venrick 1998; Bograd et al., in press).

9904 (1–20 April 1999). Preliminary data from this cruise were included in last year's report (Hayward et al. 1999). This cruise marked the peak of the dramatic shift from El Niño to La Niña conditions in the southern CCS, and is included here for reference. This was also the period of unusually strong coastal upwelling along the California coast, including the region around Point Conception (Schwing et al. 2000). The 0/500 dbar dynamic height field reveals a strong California Current meandering through the offshore side of the grid, with its characteristic low-salinity core (fig. 11). The SCE is evident south of Point Conception, while another eddy appears on line 90. The strong coastal upwelling kept inshore near-surface waters anomalously cool, particularly near Point Conception, while weak poleward flow (the Inshore Countercurrent) between stations 93.30 and 93.45 transported relatively warm and saline waters into the region from the south. The most dramatic pattern observed on this cruise is that of near-surface chlorophyll-a, with elevated values extending well offshore over the entire grid (fig. 11). The mesoscale structure of the 10 m chlorophyll-a pattern closely resembles that of the near-surface dynamic height field.

9908 (6–29 August 1999). The near-surface circulation pattern in August was similar to that observed in April (fig. 12). The California Current was vigorous, but located considerably farther offshore than in the climatological mean (fig. 10). Significant mesoscale eddy activity was again evident, with a strong cyclonic eddy in the southwest portion of the grid forcing a large meander in the California Current. The Southern California Bight was characterized by a recirculation south of the SCE, with poleward flow north of line 87. Strong coastal upwelling continued in parts of the SCB through the summer of 1999 (Schwing et al. 2000), keeping near-surface waters anomalously cool (fig. 12). The 10 m temperature near Point Conception was nearly 4°C cooler than the long-term mean. Near-surface temperatures farther south, on the other hand, were warmer than

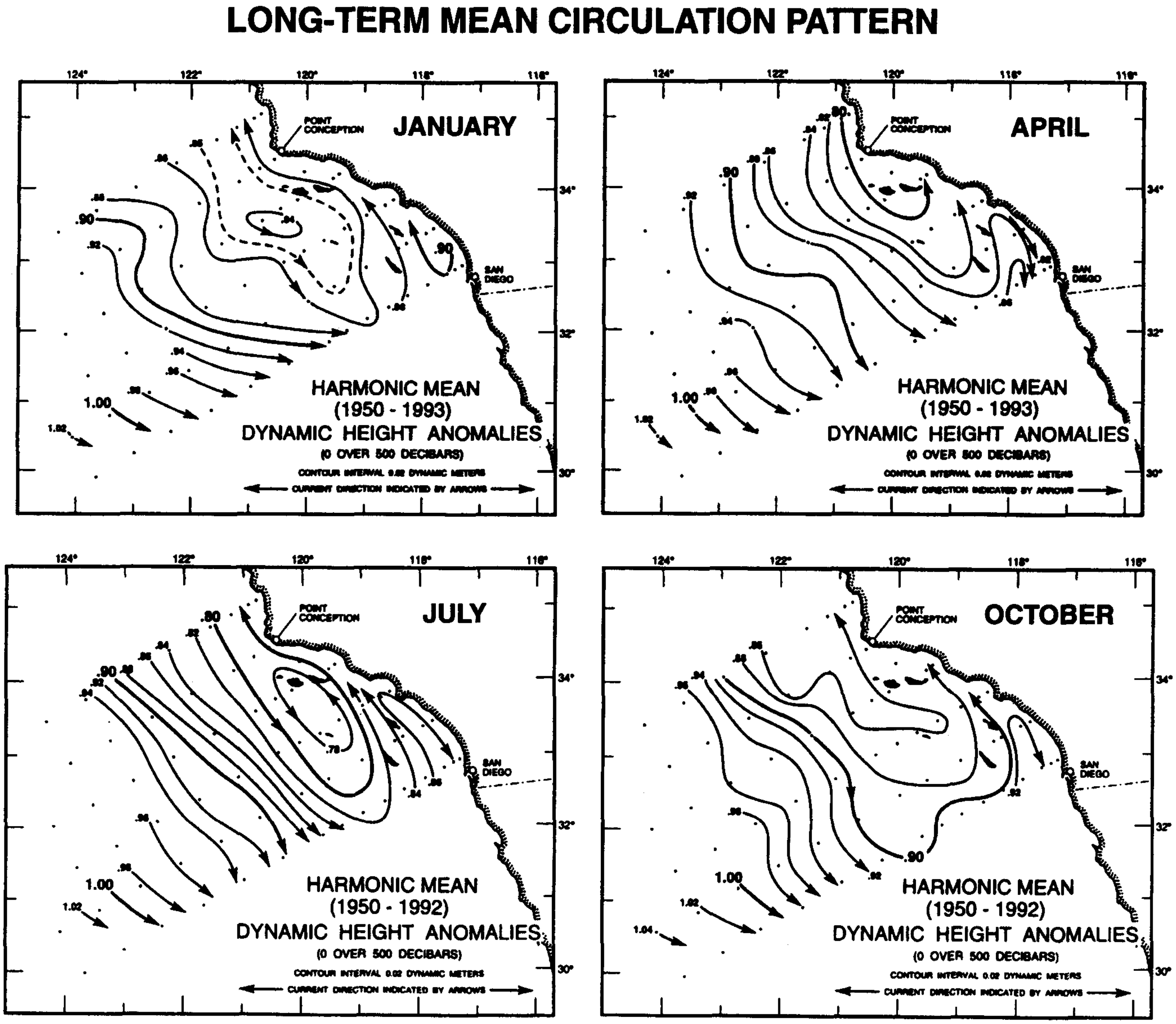

Figure 10. Long-term mean (1950–92) circulation patterns based upon 0/500 dbar dynamic height for the target months of the CalCOFI quarterly surveys.

usual. The 10 m salinity field (fig. 12) clearly shows the low-salinity core of the California Current on lines 77, 80, and 83, and has little gradient within the bight. Chlorophyll-a levels continued high (fig. 12), but with most of the productivity confined to the region of upwelled water in the inner bight.

9910 (3–21 October 1999). The California Current was again (or perhaps still) located well offshore in October, and considerably stronger than the usual October pattern (fig. 13), while flow in the SCB was weak and variable. There was an incursion of Subtropical Gyre water into the southwest corner of the grid. The 10 m temperature and salinity fields (fig. 13) resemble those from the previous cruise, with an offshore low-salinity core and cool inshore temperatures on the three northern lines (anomalies near Point Conception of about 3°C). As in the previous cruise, there appeared to be a transport of warmer water from the south into the southeast corner of the grid. The highest chlorophyll-a values were again at the Point Conception upwelling region and the Santa Barbara Channel (fig. 13), but were lower than those measured in August.

0001 (7–27 January 2000). The near-surface dynamic height field for January 2000 reveals two southward-flowing jets, one near the center of the grid and another at the southwest corner (fig. 14). This may represent two distinct branches of the California Current, as has been observed in past hydrographic surveys (Hickey 1979). The SCE was well developed at this time, with the Inshore Countercurrent composing its eastern limb and

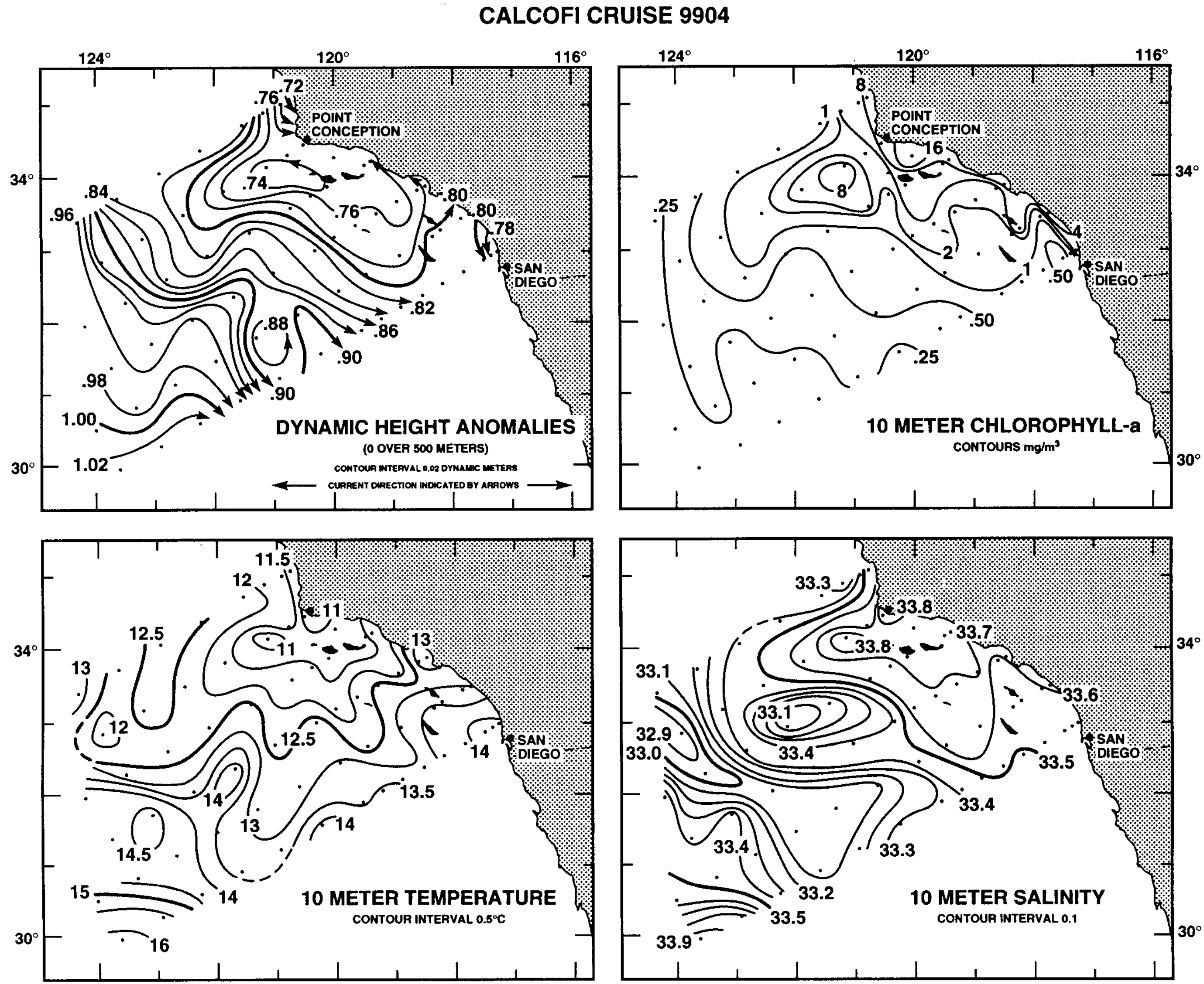

Figure 11. Spatial patterns for CalCOFI cruise 9904 (1–20 April 1999), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll-a, 10 m temperature, and 10 m salinity.

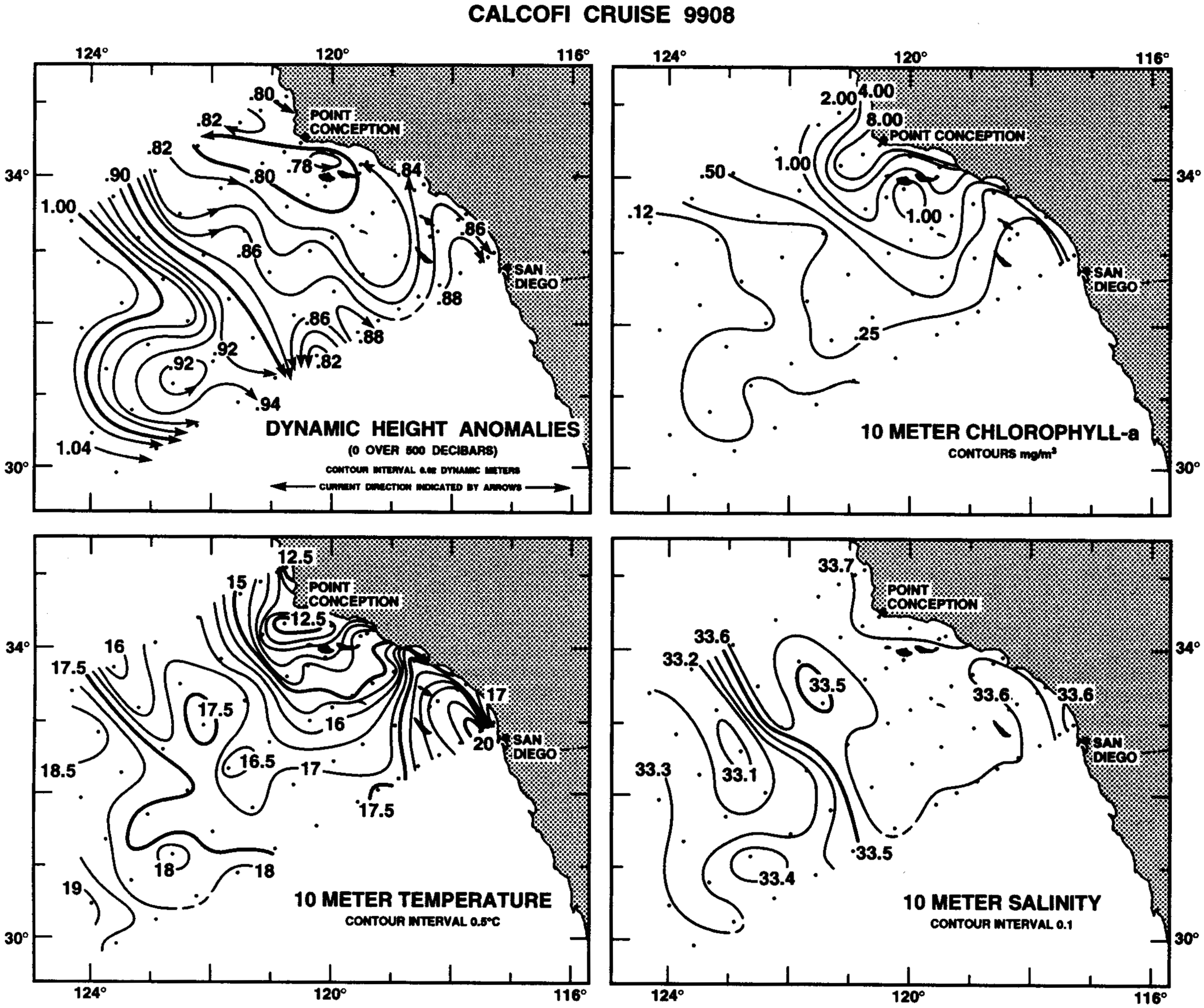

Figure 12. Spatial patterns for CalCOFI cruise 9908 (6–29 August 1999), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll-a, 10 m temperature, and 10 m salinity.

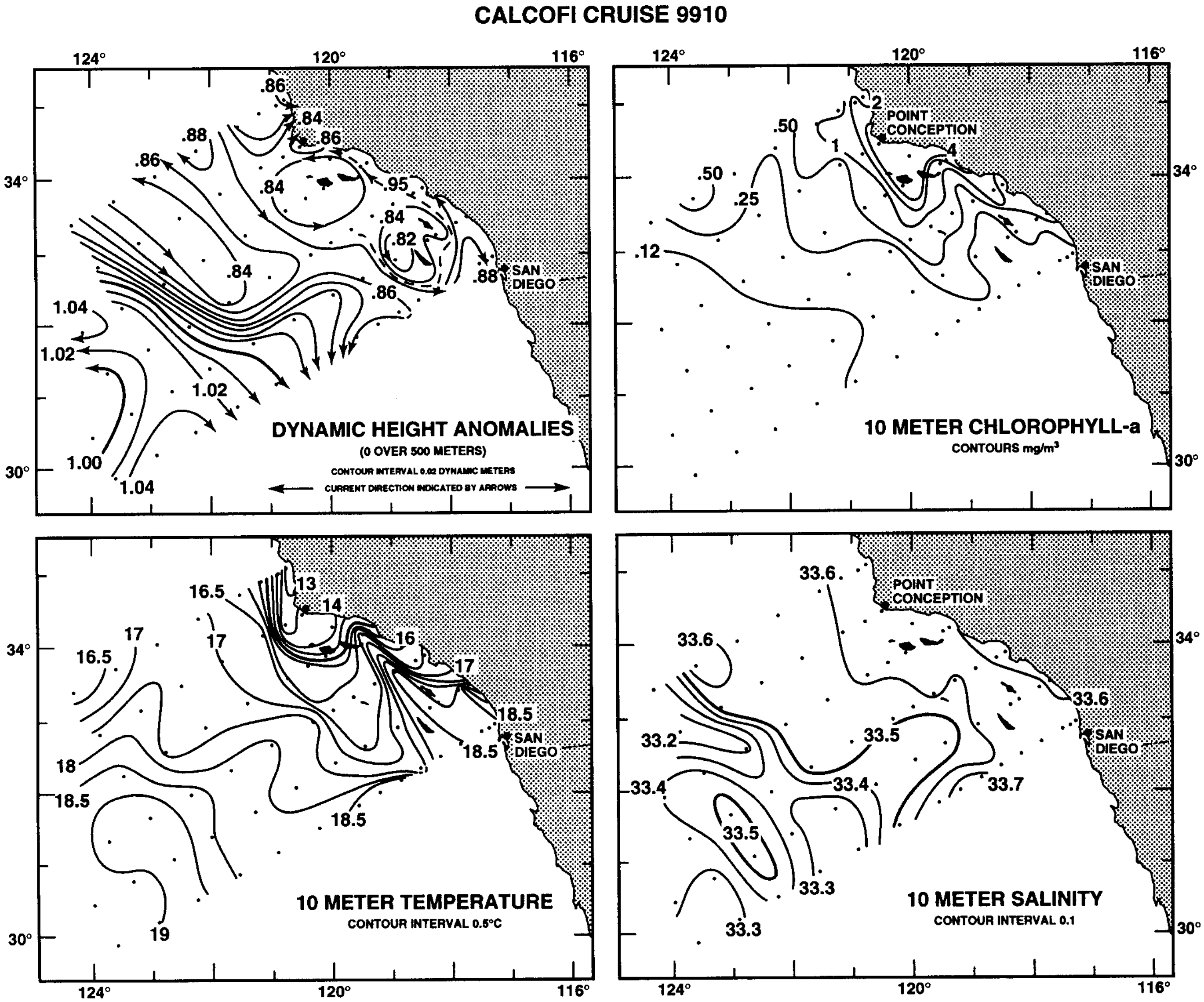

Figure 13. Spatial patterns for CalCOFI cruise 9910 (3–21 October 1999), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll-a, 10 m temperature, and 10 m salinity.

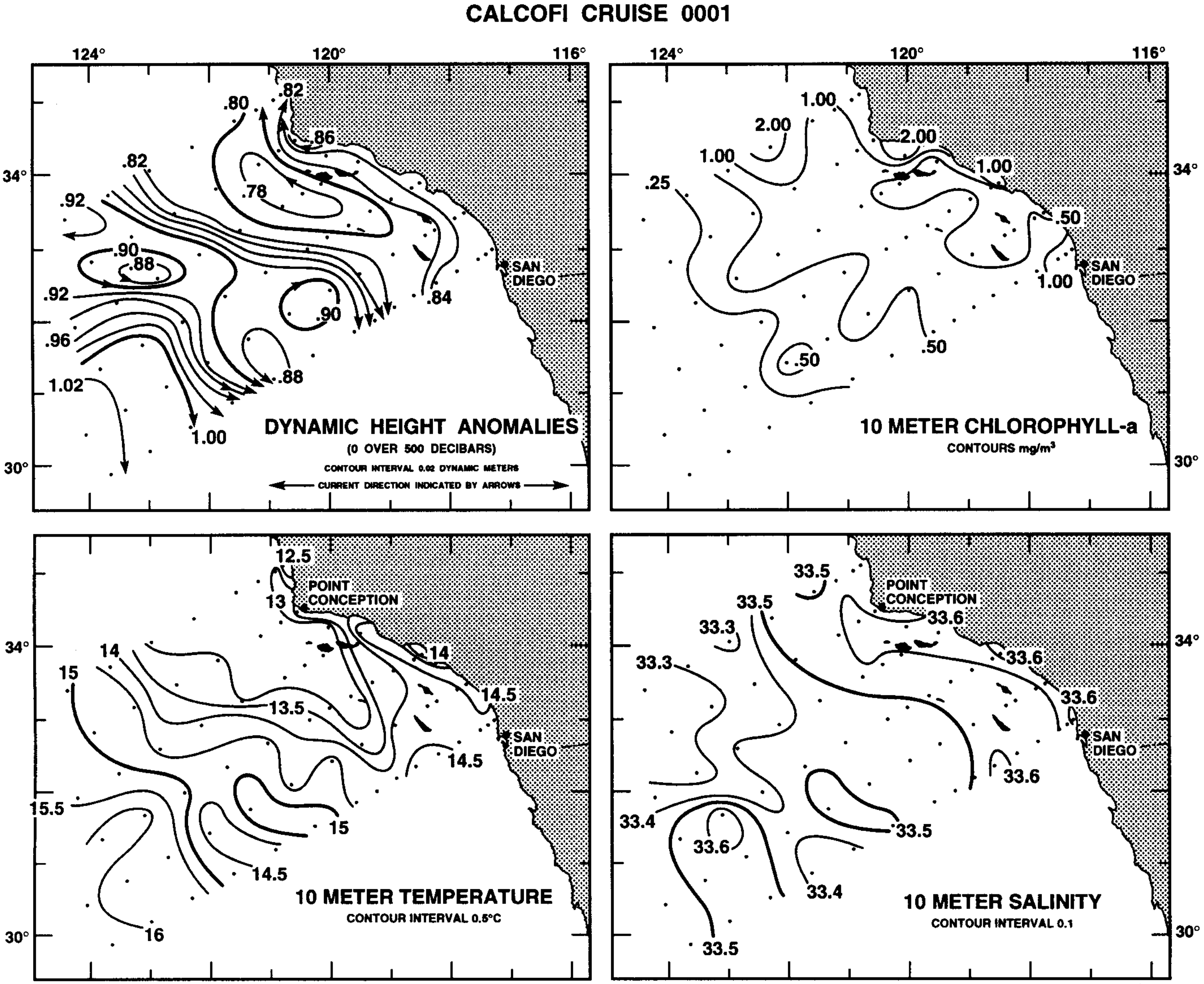

Figure 14. Spatial patterns for CalCOFI cruise 0001 (7–27 January 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll-a, 10 m temperature, and 10 m salinity.

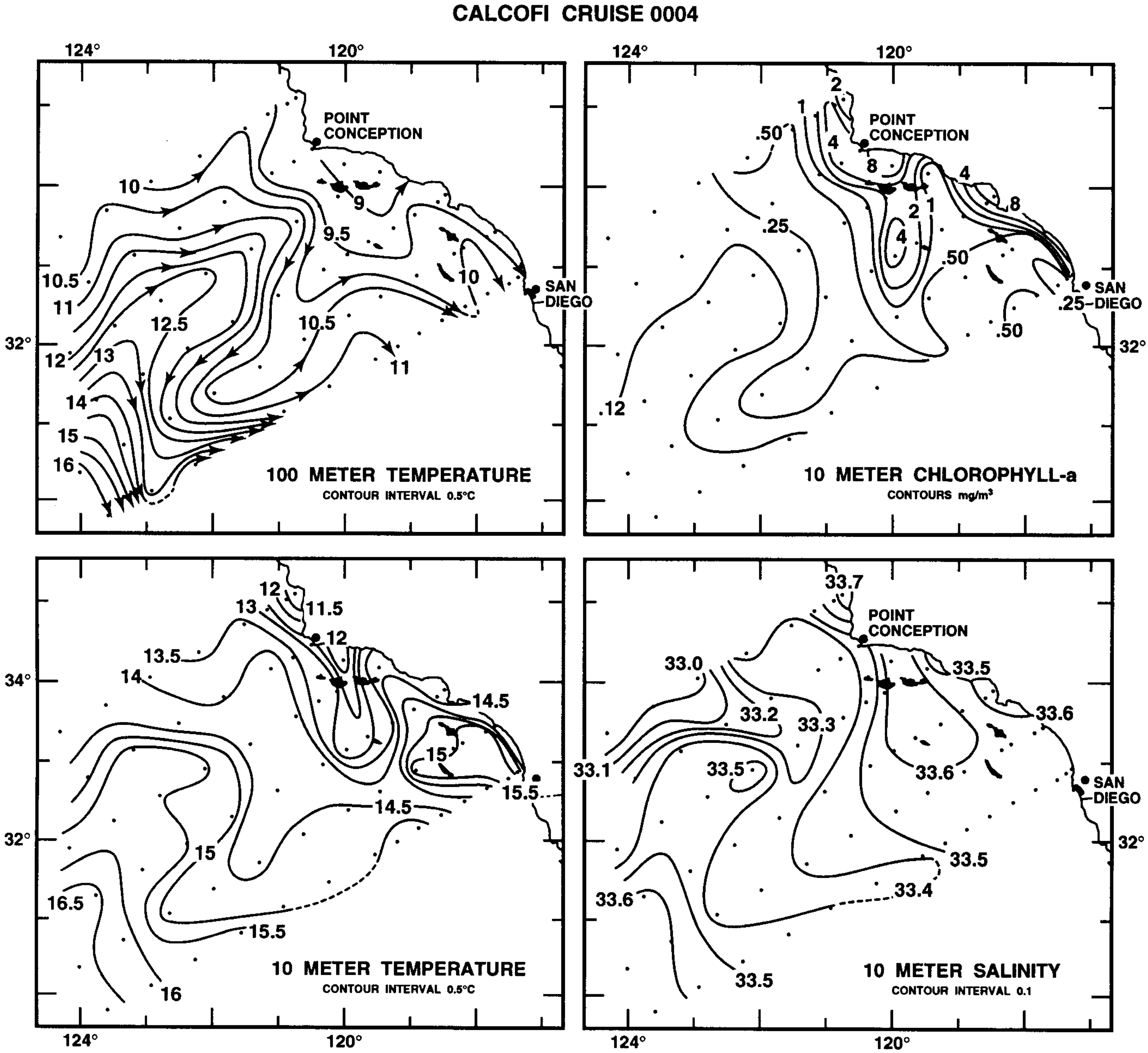

Figure 15. Spatial patterns for CalCOFI cruise 0004 (4–28 April 2000), including 100 m temperature (proxy for upper ocean geostrophic flow), 10 m chlorophyll-a, 10 m temperature, and 10 m salinity.

transporting relatively warm, saline water poleward along the extent of the coast (fig. 14). There was again considerable eddy activity throughout the region. Near-surface temperatures and salinities were very near their climatological means, except for a pool of relatively cool water just south of Point Conception. Chlorophyll-a was low at this time (fig. 14), but its mesoscale pattern again appeared to be correlated with the flow field.

0004 (6–29 April 2000). We include preliminary data from the April 2000 cruise, which had just returned as this report was being compiled (fig. 15). This cruise surveyed farther north than usual, to Cape Mendocino, using the CUFES system to track sardine and anchovy eggs. The 100 m temperature field, a reliable proxy for near-surface flow (A. Mantyla, pers. comm.), reveals unusual dynamics on the CalCOFI grid. There was a great deal of zonal (inshore/offshore) flow, which may reflect the early stages of large eddy development. The California Current can be recognized from the low-salinity core meandering through the center of the grid. The inshore region was composed of strong southward-flowing currents from Point Conception to San Diego, which brought relatively cool water into the near-coastal region from the north. The tilting of isopycnals near the coast, evident by the cool, saline waters, yielded a surface oxygen saturation of 144% at station 90.28 (A.

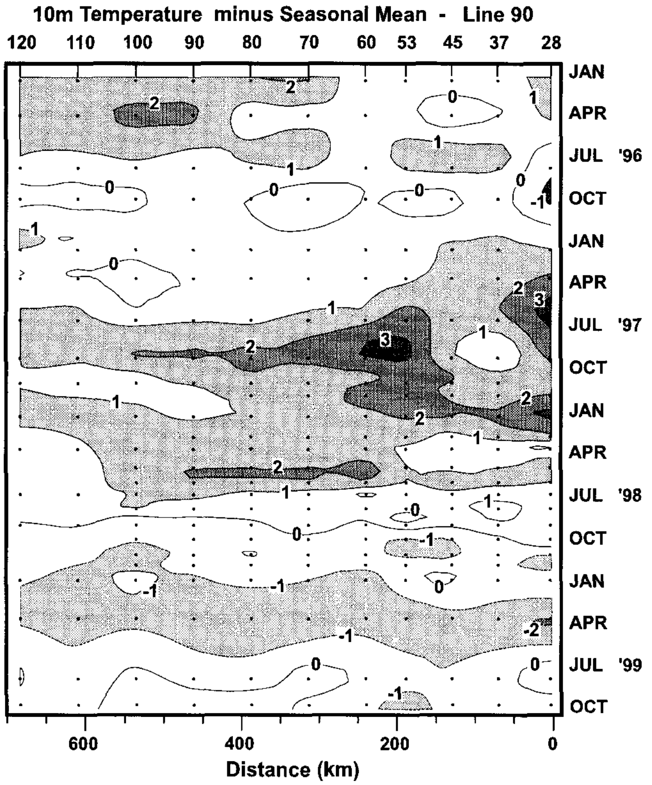

Figure 16. Ten-meter temperature anomalies from January 1996 through October 1999 for line 90 stations. Anomalies are based upon the 1950–98 harmonic means.

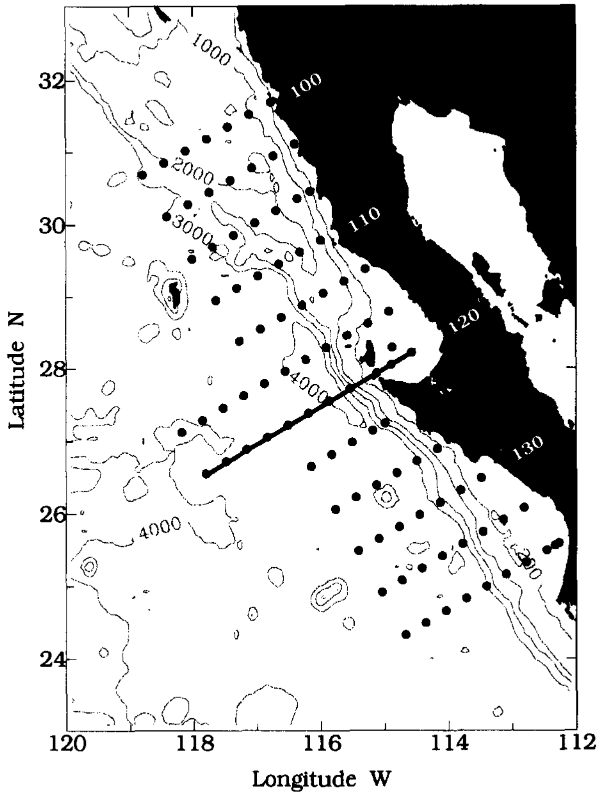

Figure 17. IMECOCAL station map. Lines 100 and 103 were extended offshore to station 60, and lines 133 and 137 were added to the grid. Depth contours in meters. Solid line indicates line 120, which is analyzed in detail.

Mantyla, pers. comm.). This is much higher than is normally observed in the SCB. Chlorophyll-a values were correspondingly high all along the coast, and within the tongue of cool water extending south from Point Conception. There appears to be a close relation between the chlorophyll-a pattern and the flow field, with the shallowest (deepest) chlorophyll-a maximum in the cyclonic (anticyclonic) loops (not shown). The dynamics of mesoscale physical-biological coupling is an important area of research, and one for which CalCOFI continues to be an ideal platform.

A tremendous transition in the physical environment of the CalCOFI region has taken place over the past few years. The 10-meter temperature anomaly time series at stations along line 90 summarizes the strong pattern of nonseasonal temperature variations over the period from January 1996 through October 1999 (fig. 16). The pattern of warm offshore and cool inshore temperatures that prevailed at the beginning of 1996 evolved into a near-neutral pattern by midyear. Strong surface warming started in mid-1997. Because atmospheric teleconnections between the tropics and temperate zone are weak in summer months, the warming has been ascribed to regional wind anomalies rather than to the developing equatorial Pacific El Niño (Lynn et al. 1998). Strub and James (2000) have shown, however, that a direct effect of the equatorial El Niño progressed poleward along the continental margins in May–July 1997 as transient events of sea-surface height anomalies and geostrophic transport. The warming spread to offshore waters by September 1997.

The effects of the large-scale atmospheric conditions and ocean dynamics of the equatorial El Niño on the surface waters were clearly evident in the fall and winter months of 1997–98. The greatest warming occurred in the coastal area, where there was also variation probably associated with local upwelling events. High SST anomalies began to lessen after July 1998 while La Niña conditions began to develop in the equatorial Pacific. Below-seasonal temperature developed in fall across the entire line. Cool conditions that developed in late 1998 and into 1999 have been attributed to strong coastal upwelling (Schwing et al. 2000). Although the central and northern California coast experienced sustained strong upwelling and seasonally low SST through much of 1999, this was not the case for much of southern California. Near-surface temperatures were very close to their long-term seasonal means by August 1999, at least over the southern portion of the CalCOFI grid.

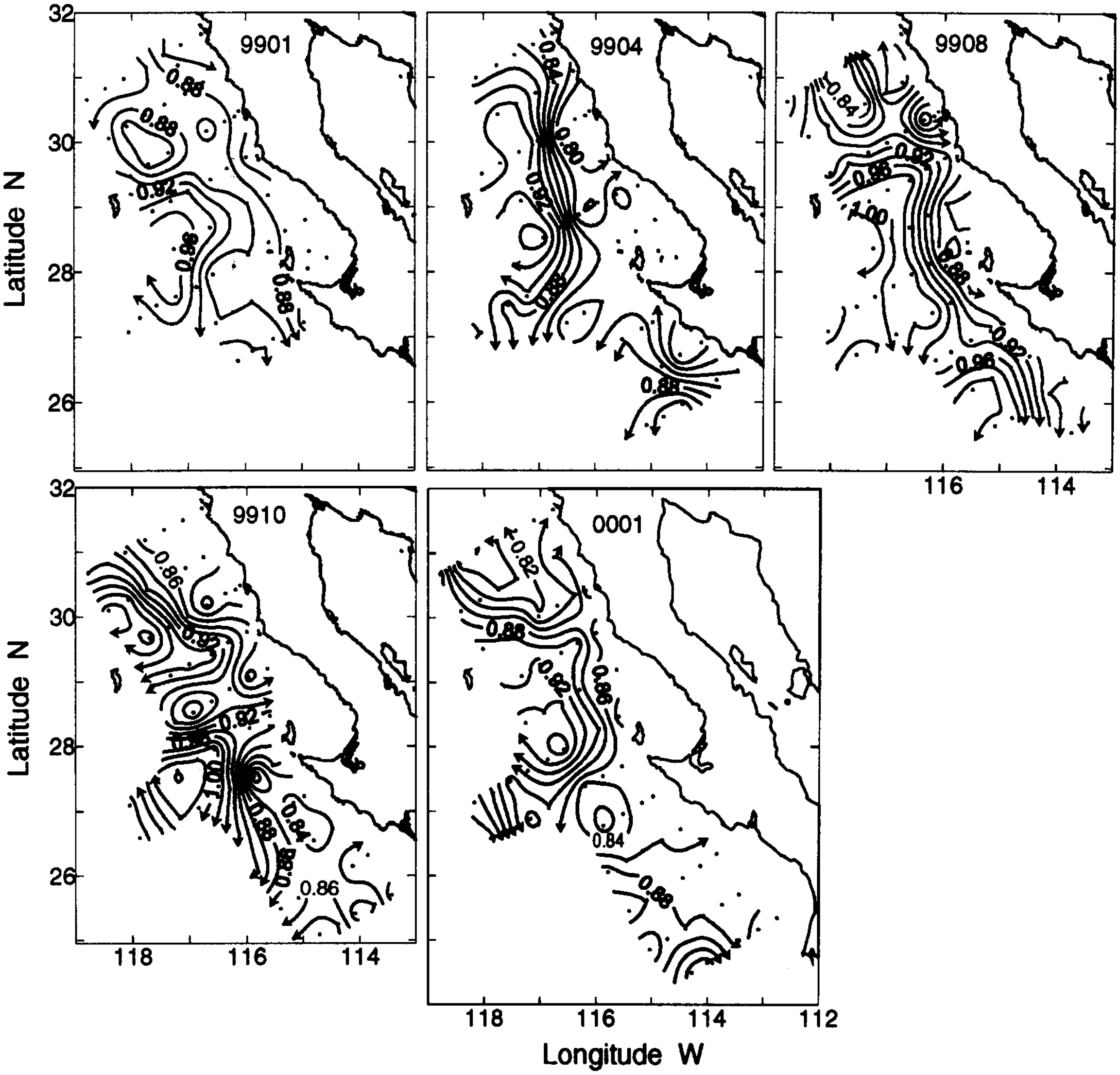

Figure 18. Dynamic heights (10/500 dbar) for the five IMECOCAL cruises from January 1999 to January 2000. Note that cruises 9910 and 0001 have more stations to the south of the sampling region.

IMECOCAL Survey Cruises

The IMECOCAL program continued sampling the southern California Current system in waters off Baja California. The sampling program carried out since 1997 was modified in order to accommodate more stations and to fully cover the station grid on each cruise. Vertical CTD casts were shortened to 1000 m, with the exception of the six deepest stations, which were sampled to 10–50 m above the bottom for purposes of conductivity calibration. Reducing the maximum depth of CTD casts made it possible to include stations 55 and 60 where needed, and to add lines 133 and 137 to the south of the grid (fig. 17).

From January 1999 to January 2000, five quarterly cruises were conducted: 9901, 9904, 9908, 9910, and 0001. Cruise 9908 was made on the B.O. *El Puma*, the rest on the B.O. *Francisco de Ulloa*. The methodology used was the same as during previous cruises (Lynn et al. 1998; Hayward et al. 1999) and follows standard CalCOFI procedures. The CUFES system has been used since April 1999, but the results are not presented here.

Dynamic height contours (10/500 db) for the five cruises depict the state of the CCS off Baja California (fig. 18). During 9901, the southward flow was restricted to distances 50–100 km from the coast, while offshore the flow was characterized by a diffuse meandering around two mesoscale eddies (a cyclonic eddy at ~30°N and an anticyclonic eddy at 28°N). April 1999 (9904) dynamic heights show the southward flow moving from the coast near 31°N and flowing around an anticyclonic eddy centered at 28°N. Part of the southward flow returned to the coast as part of a coastal cyclonic

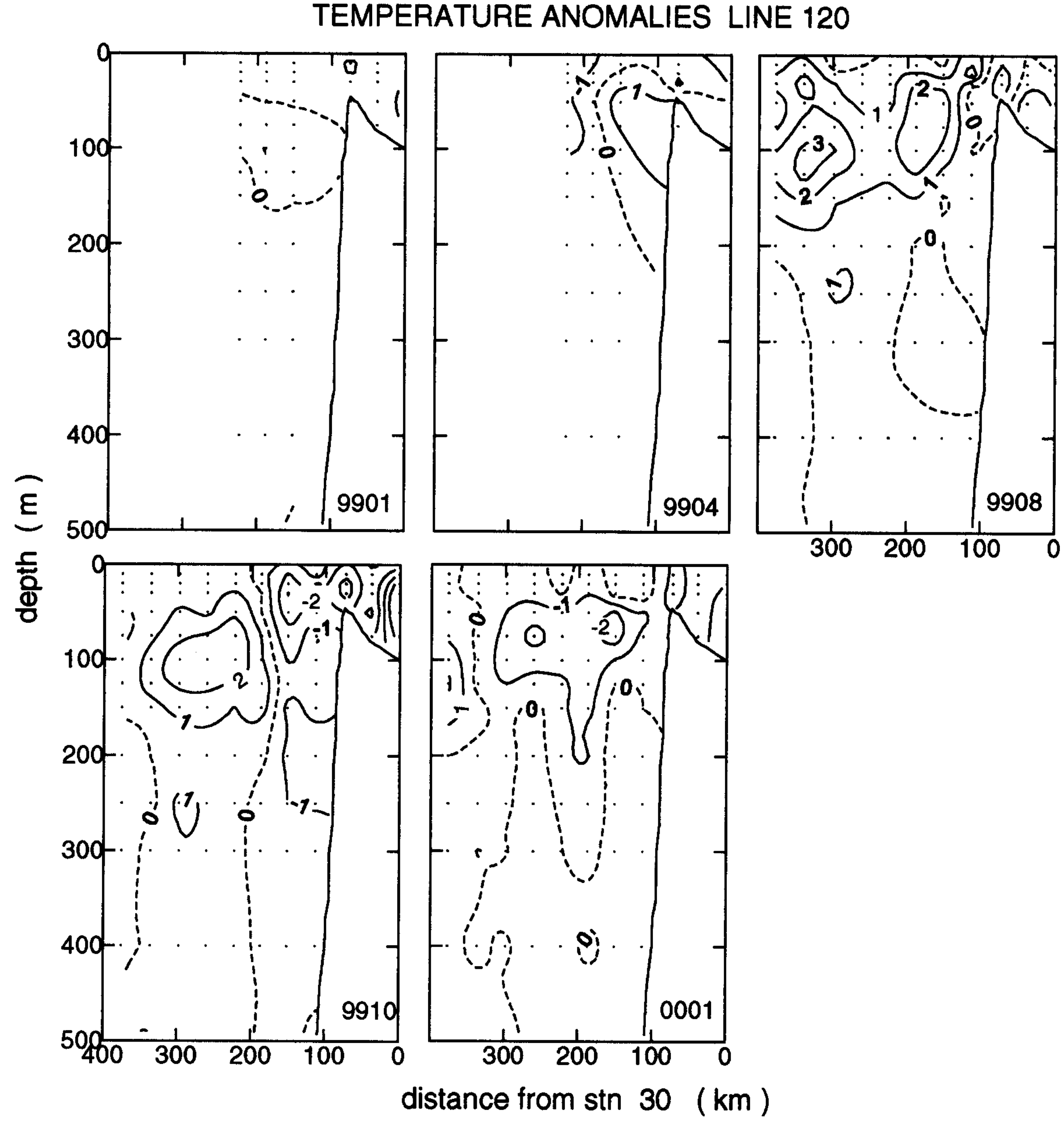

Figure 19. Temperature anomalies °(C) for line 120. Numbers in the lower right denote year and month.

eddy. South of Punta Eugenia (PE), the dynamic height field indicates northward flow which appears to merge offshore with the equatorward current. Cruise 9908 clearly depicts the southern limit of the Southern California Eddy, where the currents flow east and impinge over the coast at 30°N to separate into two branches, one flowing north and another south. The southern branch continues a more or less straight path parallel to the coast. West of the southern branch, the quasi-permanent anticyclonic eddy is discernible. October dynamic heights (9910) depict a diffuse southward current, flowing equatorward around several small-scale (20–40 km) to mesoscale (~100 km) eddies, the most conspicuous being the clockwise gyre off PE. South of PE, diffuse northward currents are also evident from the dynamic height field. The circulation charted on the January 2000 cruise, which extended as far south as line 137, greatly resembles the circulation observed on cruise 9908, with the southern limb of the SCE impinging on the coast and a southward current flowing around the large-scale, quasi-permanent eddy southeast of Isla Guadalupe.

Figures 19 and 20 show vertical distributions of temperature and salinity anomalies for line 120 (off PE) for each cruise. The anomalies are based on climatological means for the period 1950–78 (Lynn et al. 1982), and

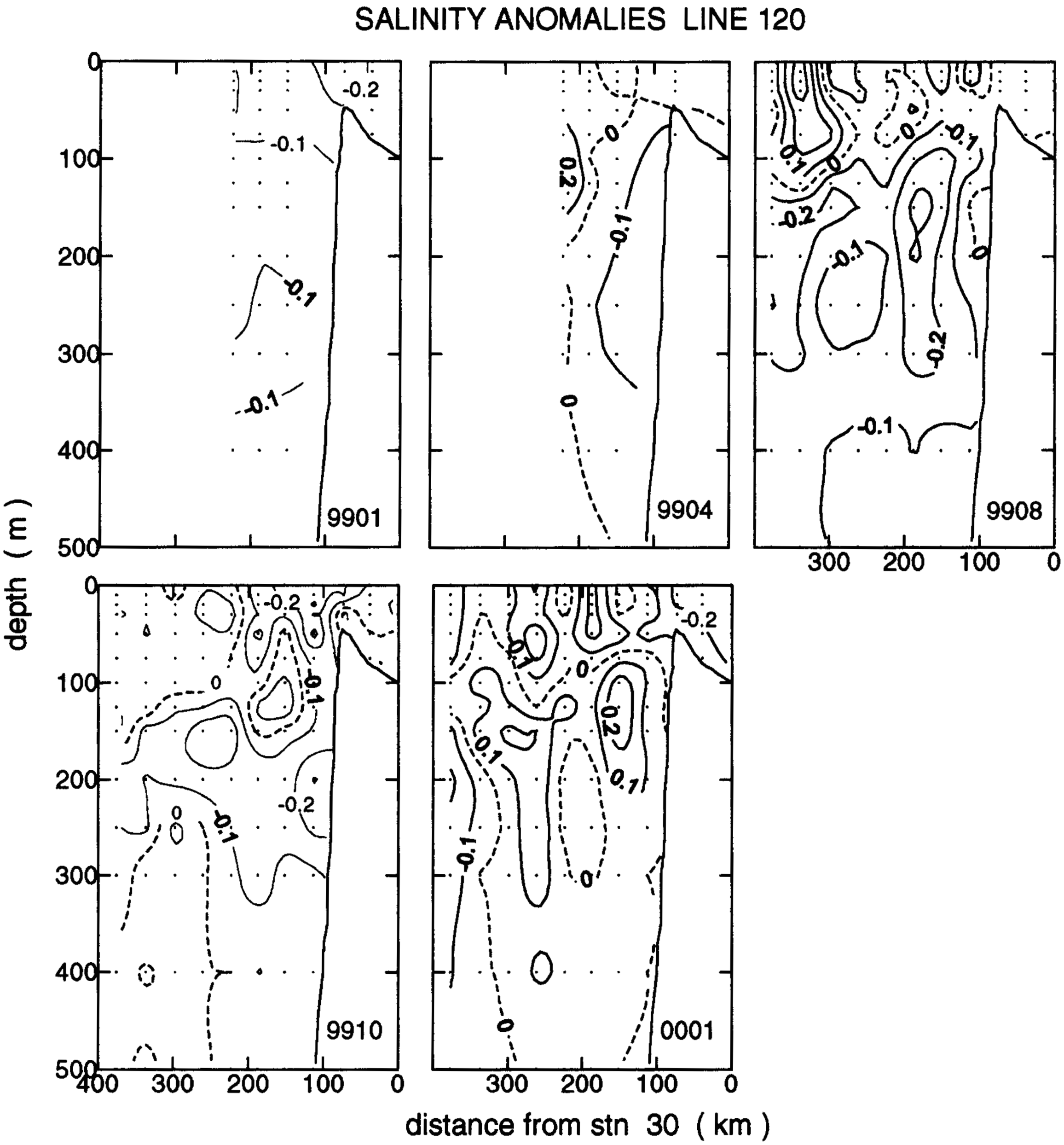

Figure 20. Salinity anomalies for line 120. Numbers in lower right denote year and month.

may differ from anomalies calculated for CalCOFI, which are based on a longer reference period. After relatively high temperature and salinity anomalies (~8°C and 0.8) during 1997–98 (Lynn et al. 1998; Hayward et al. 1999), anomalies during the latest five cruises were relatively small. Cruise 9901 showed normal temperatures and slightly lower than normal salinities (−0.1) throughout the water column. Cruise 9904 showed warmer and fresher than normal waters (1°C and −0.1) over the shelf break, but slightly cooler and saltier than normal (−1°C and 0.2) offshore. As suggested by the dynamic height field (fig. 18), positive (negative) temperature (salinity) anomalies near the coast were associated with a poleward flow south of Punta Eugenia. West and north of PE the flow was southward.

By August 1999 (9908), temperature and salinity anomalies indicate warmer (2°−3°C) and saltier (0.1−0.3) than normal conditions in the upper 100–120 m. Below 150 m, temperatures were within the climatological mean values, but fresher waters (~−0.2) were present. In close relation to the cyclonic-anticyclonic eddy pair observed west of PE, temperature anomalies near the coast (150 km) were negative throughout the water column, with maximum values at 40–50 m. Offshore water temperature anomalies were positive, with the peak (2°) at a depth of about 100 m. Salinities were

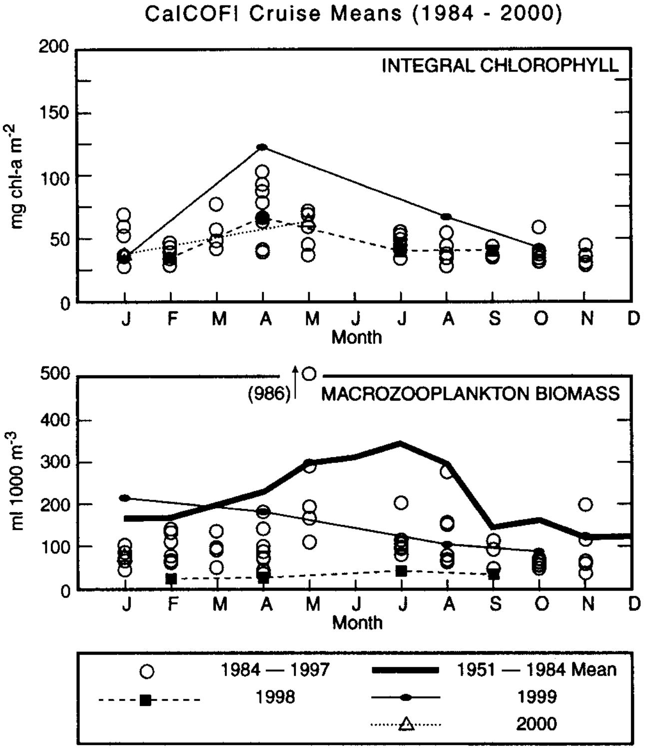

Figure 21. Cruise means of vertically-integrated chlorophyll and macrozooplankton biomass plotted versus the month of CalCOFI cruises from 1984 to April 2000. Each point represents the mean of all measurements on a cruise (usually 66). The open circles show the cruises that took place from 1984 to 1997. The solid symbols are cruises from 1998 and 1999; cruises from individual years are connected with lines. The bold line in macrozooplankton biomass indicates the monthly means for 1951–84.

fresher, with maximum values nearshore at the surface and at 250 m over the shelf break.

Finally, cruise 0001 showed cooler and fresher waters in the upper 100–150 m, with maximum anomalies near the center of the section corresponding to the core of the California Current (fig. 18). Below 150 m, normal temperatures and higher than normal salinities were observed. Relatively low spiciness was observed at the center of the section throughout most of the water column, with higher values near the coast and offshore.

BIOLOGICAL PATTERNS

Chlorophyll and Macrozooplankton

Cruise-mean values of vertically-integrated chlorophyll-a and macrozooplankton biomass for 1999–2000 are given in the context of the historical CalCOFI time series (fig. 21). The dramatic transition in the physical environment between El Niño (1997–98) and La Niña (1998–2000) periods is apparent in the biological patterns as well. After the lowest macrozooplankton biomass in the long-term (1951 to present) CalCOFI database through 1998 (Lynn et al. 1998), macrozooplankton rebounded greatly in January and April 1999, to values near the 1951–84 long-term mean. This rebound continued in the latter half of 1999 and into January 2000, although these values are below the long-term mean. The ecosystem in the CalCOFI region is undoubtedly still responding to residual effects of the recent El Niño and La Niña events, and may continue to do so for years. It is presently unclear whether the trend of declining macrozooplankton biomass in the region (Roemmich and McGowan 1995) has been affected by these events.

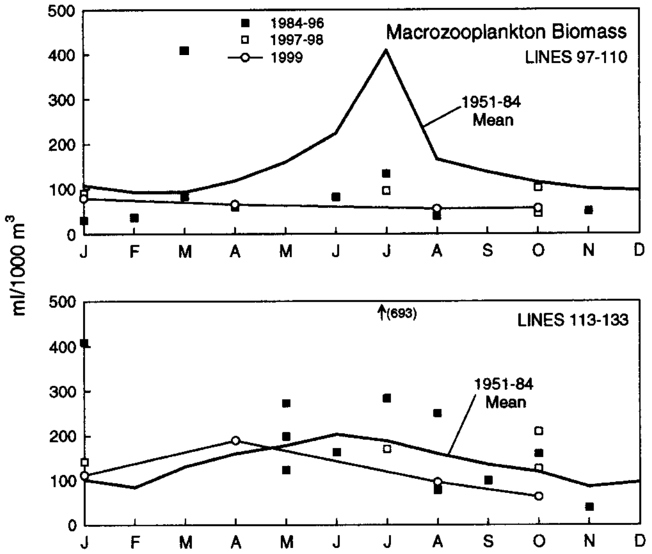

Figure 22. Macrozooplankton biomass for northern (*upper panel*) and central (*lower panel*) Baja California. Biomass from 1984 to 1998 (squares) and 1999 (open circles) is shown.

Chlorophyll-a production also rebounded after the El Niño period (fig. 21). The April and August 1999 means were the highest spring and summer values recorded. In fact, the April 1999 value of 123 mg chl a m^{-2} is the highest since regular measurements began on CalCOFI cruises in 1984, and occurred during the period of vigorous coastal upwelling (Schwing et al. 2000) and a very shallow nitricline (not shown). The values measured in January and April 2000, however, are not particularly high relative to the past 16 years. The effects of the 1997–98 El Niño on primary production in the CCS are further discussed in the following section.

Zooplankton was also sampled by Centro Interdisciplinario de Ciencias Marinas (CICIMAR) over the period 1983–91. Figure 22 puts the historical observations of CalCOFI and CICIMAR in perspective, as well as recent observations carried out by the IMECOCAL program. The data have been divided spatially into two regions, one north of 30°N, and including volumes sampled along lines 97 to 110, and a central region comprising lines 113 to 133. The northern region appears to have a secular decline similar to that observed for southern California (Roemmich and McGowan 1995),

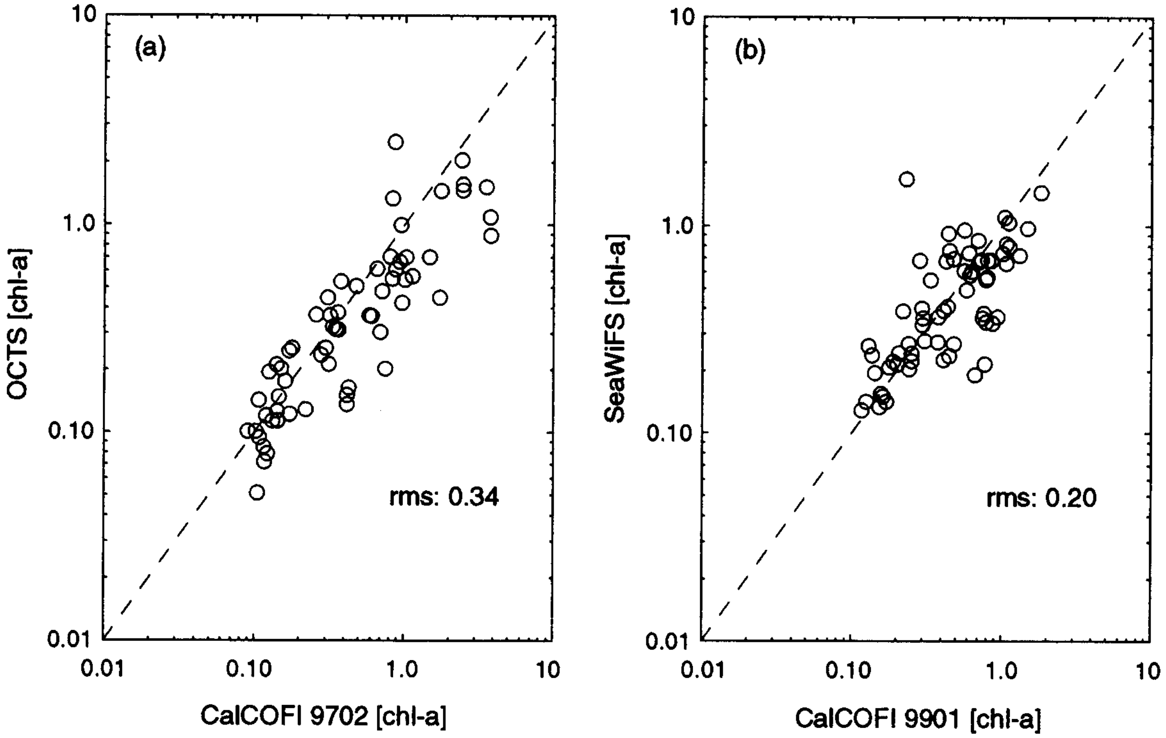

Figure 23. Comparison of in situ and satellite chlorophyll-a values, for coverage that overlaps within one week. *a*, CalCOFI cruise 9702 data (lines 77 to 93; 0–30 m station mean) versus weekly averaged OCTS data (version 4, level-3). *b*, CalCOFI cruise 9901 data (lines 77 to 93; 0–30 m station mean) versus weekly-averaged SeaWiFS data (version 2, level-3). Depth bins of 0–30 m were used to encompass at least one attenuation length.

because the 1951–84 macrozooplankton volume mean is higher than recent observations. The 1999 volumes are, however, comparable to values observed after 1984. For central Baja California, zooplankton biomass in 1984–98 is scattered around the historical mean. The region thus appears to be less rich in zooplankton than northern regions of the CCS, with means rarely exceeding 300 ml/1000 m^3. The low volumes observed during August and October of 1999 were unexpected. These were lower than the historical mean, and lower than observations during the 1997–98 El Niño.

Ship vs. Satellite-Derived Chlorophyll Patterns

Following an extended absence, the reintroduction of ocean color sensors to space in the mid- to late 1990s provided an invaluable opportunity for evaluating the biological effects of the 1997–99 El Niño/La Niña events in the California Current system. DiGiacomo (1999) used OCTS (1996–97) and SeaWiFS (1997–98) chlorophyll-a data, complemented by other satellite and field measurements, to describe how a combination of atmospheric and oceanic forcing led to large reductions in CCS phytoplankton biomass during the 1997–98 El Niño relative to the preceding year. Because the accuracy of ocean color data is always of concern, particularly in coastal zones, OCTS/SeaWiFS data were compared to CalCOFI cruise data from October 1996 through April 1999 to examine their overall correspondence, as well as to identify relevant trends (figs. 23–25).

Generally speaking, satellite-derived chlorophyll-a values were comparable to data from ship stations (e.g., fig. 23). For the CalCOFI time series in question, rms errors ranged from 0.20 to 1.16, with most values under 0.5. The largest rms errors were observed during early periods of strong upwelling (e.g., April 1997, 1999), associated with higher chlorophyll-a values. The good overall correspondence between ship and satellite-derived chlorophyll-a values can also be seen in both the relative trends and mean absolute values for inshore (fig. 24) and offshore (fig. 25) waters over this same time period. Where differences exist in these values, it is usually a case of the satellite data underestimating the ship data. Kahru and Mitchell (1999) indicated that the SeaWiFS OC2-v2 algorithm could underestimate intermediate chlorophyll-a values (1 to 10 mg m^{-3}); this seems to be the case with the OCTS algorithm as well. This also appears to explain why the chlorophyll-a differences are more pronounced inshore (fig. 24) than offshore (fig. 25), where chlorophyll-a values are generally less than 1 mg m^{-3}.

Interannual comparisons of chlorophyll-a, temperature, and nitrate data from corresponding seasonal cruises (e.g., 9610 vs. 9709) revealed a number of important trends. CalCOFI cruises 9709 and 9802, during the peak

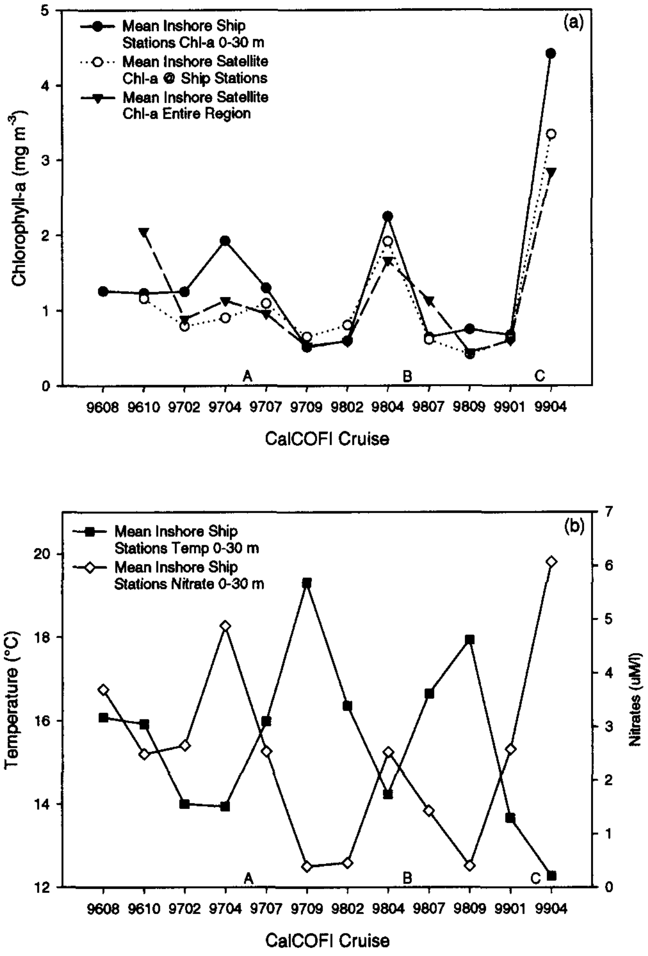

Figure 24. *a*, Comparison of mean inshore and in situ chlorophyll-a values, for coverage that overlaps within two weeks. Satellite data were extracted at corresponding CalCOFI stations and for the entire region that encompassed those stations. The "inshore" designation refers to CalCOFI stations (on lines 77 to 93) that are less than about 130 km offshore. Weekly averaged OCTS data (version 4, level-3) used for CalCOFI cruises 9610 to 9707; weekly averaged SeaWiFS data (version 2, level-3) used for CalCOFI cruises 9709 to 9904. *b*, Mean inshore temperature and nitrate from CalCOFI station data (0–30 m mean). At bottom of each graph, **A** indicates the approximate start of the 1997–98 El Niño; **B** indicates its approximate end; **C** indicates the approximate start of La Niña.

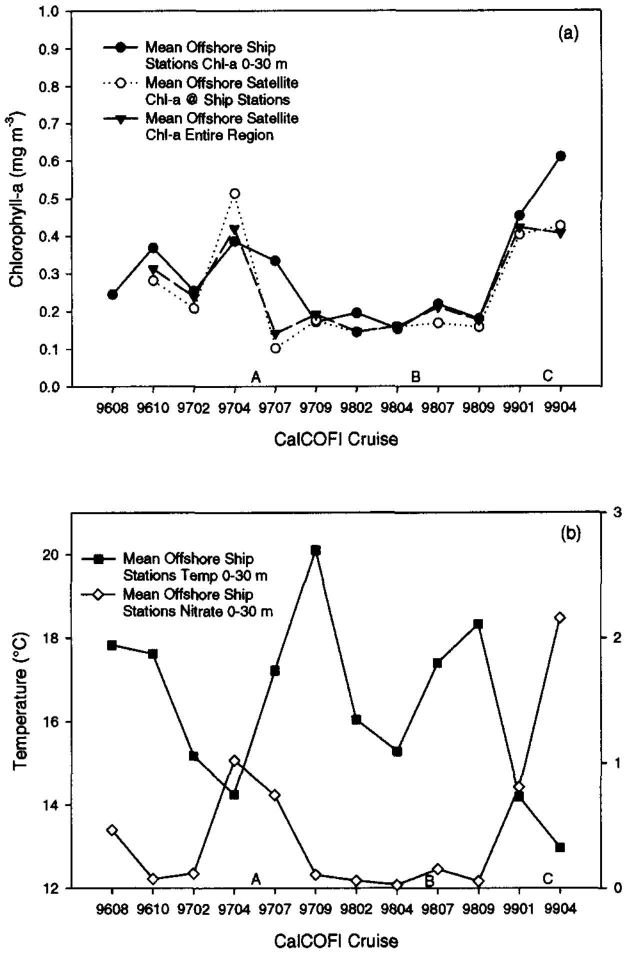

Figure 25. *a*, Comparison of mean offshore and in situ chlorophyll-a values, for coverage that overlaps within two weeks. Satellite data were extracted at corresponding CalCOFI stations and for the entire region that encompassed those stations. The "offshore" designation refers to CalCOFI stations (on lines 77 to 93) that are more than approximately 130 km offshore. Weekly averaged OCTS data (version 4, level-3) used for CalCOFI cruises 9610 to 9707; weekly averaged SeaWiFS data (version 2, level-3) used for CalCOFI cruises 9709 to 9904. *b*, Mean offshore temperature and nitrate from CalCOFI station data (0–30 m mean). At bottom of each graph, **A** indicates the approximate start of the 1997–98 El Niño; **B** indicates its approximate end; **C** indicates the approximate start of La Niña.

of El Niño, had lower mean chlorophyll-a and nitrates and higher mean temperature than the 9610 and 9702 cruises, both inshore (fig. 24) and offshore (fig. 25). Conversely, during cruise 9904, when La Niña conditions prevailed, mean chlorophyll-a and nitrate values were higher, and the mean temperature was lower relative to the two preceding spring cruises (9804 and 9704; figs. 24 and 25). Also of interest in the April 1997–99 series is the reduction observed in mean offshore chlorophyll-a (and nitrate) values during April 1998, presumably at least partly because of reduced coastal upwelling.

Avifauna

CalCOFI cruises have provided the opportunity for systematic surveys of the distribution and abundance of seabirds in relation to oceanographic conditions off southern California. Data collected between 1987 and 1998 have revealed that seabird populations fluctuate in response to interannual and longer-term variability in the properties of the California Current (Veit et al. 1996; Lynn et al. 1998; Hayward et al. 1999; Hyrenbach and Veit 1999). However, surveys during 1999–2000 have failed to detect avifaunal changes in concordance with the notion of a transition into a regime of enhanced upwelling and production in the California Current. A preliminary analysis of the available data suggests, on the other hand, that the changes in seabird abundance and community composition observed during 1998–99 were transient fluctuations apparently in response to La Niña.

Seabird communities responded to the onset of La Niña conditions during the fall of 1998 with a concomitant increase of cold-water taxa and a decline in the importance of warm-water species: subtropical seabirds prevalent during the preceding El Niño event (1997–98) were replaced by immigrating subarctic species such as the black-legged kittiwake (*Rissa brevirostris*) and the sooty shearwater (*Puffinus griseus*; Hayward et al. 1999). Additional surveys during 1999–2000 revealed that the changes in avifauna observed during the fall of 1998 persisted into the fall of 1999. During the spring and fall of 1999, the cold-water taxa (e.g., black-legged kittiwake and sooty shearwater) continued to be numerically dominant. Conversely, the southern and central Pacific species that had dominated the community in 1998 declined in 1999. Cool ocean temperatures during the fall of 1999 inhibited the immigration of southern species (e.g., black-vented shearwater, *P. opisthomelas*) and central Pacific species (Cook's petrel, *Pterodroma cookii*) into the CalCOFI grid (fig. 26a). Conversely, these conditions attracted subarctic seabirds that regularly do not occur during fall. For instance, it is noteworthy that the black-legged kittiwake, which was not sighted in the CalCOFI grid during the fall of 1997 and 1998, was observed off southern California in October 1999.

Additional surveys during the spring of 2000 revealed that the shift in community composition observed during the previous year was a transient fluctuation in response to a prolonged cold-water period (fig. 26b). After seventeen months (October 1999–February 2000) of negative temperature anomalies and enhanced upwelling, conditions reversed in the early spring of 2000. The intensity of the upwelling-favorable winds dropped to "normal" levels during March, and anomalous warm-water temperatures became apparent along the coast in April (El Niño Coastwatch Advisories, September 1998–April 2000). Seabirds responded rapidly to the changes in oceanographic conditions, and by April 2000, the avifauna included a mixture of the warm- and cold-water assemblages prevalent during the preceding El Niño (1997–98) and La Niña (1998–99) episodes.

In addition to documenting interannual variability, the CalCOFI program is particularly suited to detect changes in the physical forcing and ecosystem structure indicative of long-term shifts in ocean climate (McGowan 1990; Roemmich 1992; Roemmich and McGowan 1995). Similarly, the time series of seabird observations collected since 1987 provides a baseline for interpreting unusually large avifaunal fluctuations. Additionally, the response of seabird communities to ocean warming off southern California makes it possible to predict the probable consequences of the hypothesized transition into a cold-water regime. Thus the onset of a prolonged period of cool ocean temperatures in the fall of 1998 would likely be followed by increased numbers of sooty shearwater and overall seabird abundance after a lag of three CalCOFI cruises (Veit et al. 1996). Specifically, we would expect the response of the avifauna to be particularly strong during the boreal summer (July), when far-ranging shearwaters migrate into the California Current from the Southern Hemisphere (Briggs et al. 1987; Tyler et al. 1993). In spite of the prolonged period of cold-water conditions, surveys during the summer of 1999 revealed that overall bird abundance and sooty shearwater numbers remained below the levels recorded off southern California during the late 1970s (1975–77; Tyler et al. 1993) and the late 1980s (1988–90; Veit et al. 1996; fig. 27).

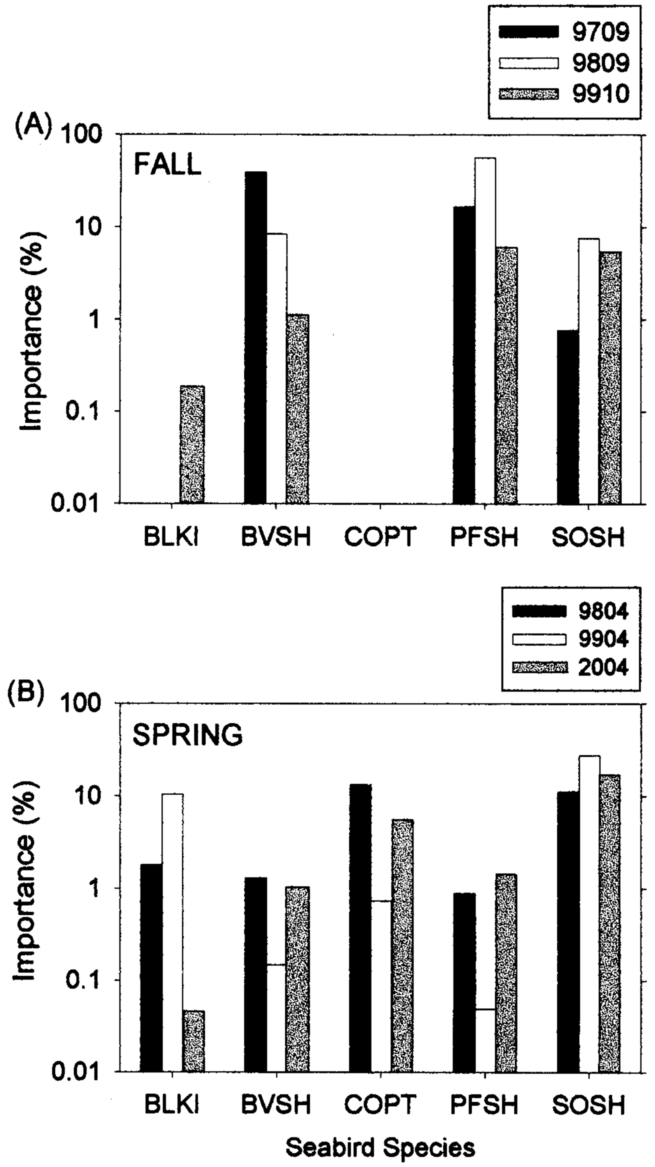

Figure 26. Relative fall (*A*) and spring (*B*) abundance of the five indicator seabirds with an affinity for different water temperatures and biogeographic domains. Importance was computed by dividing the number of individuals of a given species by the total number of seabirds sighted during each cruise. Subtropical/warm-water taxa are BVSH (black-vented shearwater); PFSH (pink-footed shearwater); and COPT (Cook's petrel). Subarctic/cold-water taxa are SOSH (sooty shearwater) and BLKI (black-legged kittiwake).

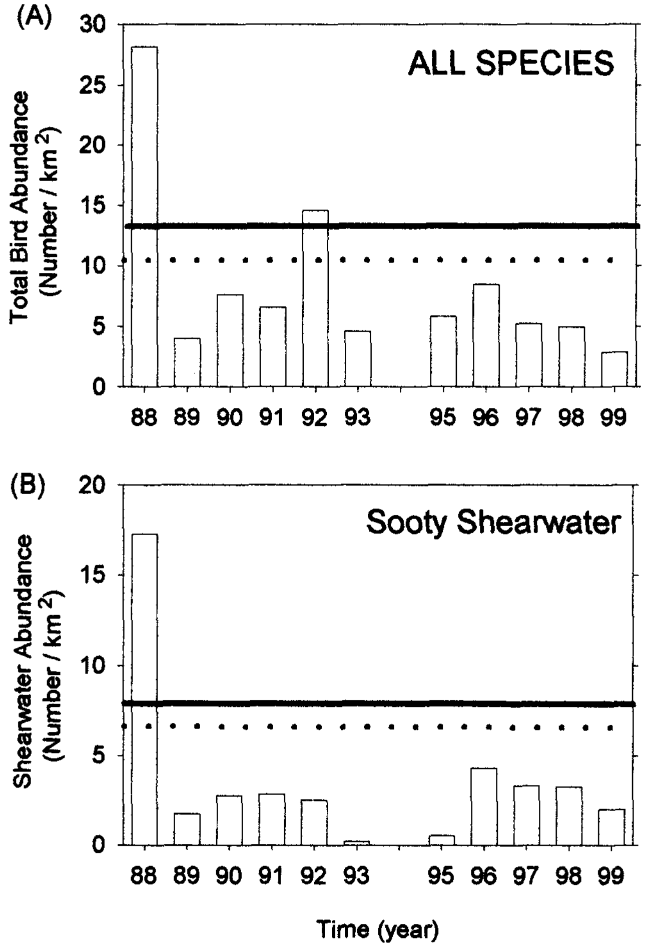

Figure 27. Changes in (*A*) overall bird abundance (all species combined) and (*B*) the density of the once numerically dominant sooty shearwater during summer CalCOFI cruises. The solid line shows the mean abundance during the early part of the CalCOFI time series (1988–90); the dotted line depicts average summer densities off southern California during the late 1970s (1975–77) from Tyler et al. 1993. No data are available for 1994.

Seabird communities off southern California have undergone persistent changes during the last decade (Veit et al. 1996; Hyrenbach and Veit 1999). Veit et al. reported a 40% decline in overall seabird abundance between the late 1980s (1987–88) and the early 1990s (1993–94), largely due to a 91% decline in the abundance of the dominant cold-water species—the far-ranging sooty shearwater. Continued surveys in recent years have revealed consistently low shearwater densities within the CalCOFI region, during periods of normal circulation (Hayward et al. 1996), El Niño (Lynn et al. 1998), and La Niña (Hayward et al. 1999). Although sooty shearwaters have increased slightly during the late 1990s, they remain well below the historical densities observed in the late 1980s. Overall, they have declined by 71% between the beginning (1987–90) and the end (1995–98) of the CalCOFI time series (Hyrenbach and Veit 1999).

Surveys in recent years have also revealed the continued presence of warm-water taxa (e.g., Cook's petrels, pink-footed and black-vented shearwaters) off our coast, despite the prolonged period of cool ocean temperatures. These observations suggest that the increase of warm-water species recorded off southern California since 1987 represents a permanent shift in the range of subtropical and southern taxa (Fields et al. 1993; Veit et al. 1996). These increases have been particularly striking for several far-ranging *Pterodroma* and *Procellaria* petrels (Cook's, Parkinson's, and dark-rumped), which have been regularly sighted in the California Current during the 1990s (Pyle et al. 1993; Schwing et al. 1997; Hyrenbach and Veit 1999).

Seabird populations are ideal indicators of changes in ocean productivity and ecosystem structure because they are sensitive to fluctuations in pelagic food webs (Sydeman and Ainley 1994; Ainley et al. 1995). The Point Reyes Bird Observatory Marine Science Program has monitored the diet and the reproductive performance of seabird populations breeding at the Farallon Islands (central California) since the early 1970s. Surveys in 1999 revealed a concomitant increase in the reproductive performance of three of the four regularly monitored pelagic species, apparently in response to the cool-water conditions since the fall of 1998. Moreover, in 1999, three species had positive anomalies over their long-term mean productivity levels. These results contrast with data from the previous year, when only the Cassin's auklet (*Ptychoramphus aleuticus*) showed a positive anomaly in productivity (fig. 28).

It is likely that seabirds' response to environmental variability is not a linear function. Moreover, it is conceivable that different processes which seem to affect the environment in a similar way (e.g., cool conditions as a result of La Niña or a regime shift) may elicit distinct ecosystem responses of varying lag and magnitude. This is particularly pertinent when dealing with a regime shift, which, by definition, entails a change in the dynamics and the mechanisms regulating a complicated system. Thus, additional surveys will be necessary to determine whether the avifauna within the CalCOFI region changed in response to a possible transition into a new oceanographic regime during 1999–2000. This uncertainty underscores the value of long-term time series to interpret changes in large-scale marine ecosystems (McGowan 1990).

DISCUSSION

Perhaps the most striking result to come out of the recent CalCOFI observations is the speed at which the physical environment varied, and at which the ecosystem apparently responded to that variation. In a period of less than one year, for instance, macrozooplankton in the CalCOFI region went from the lowest (through

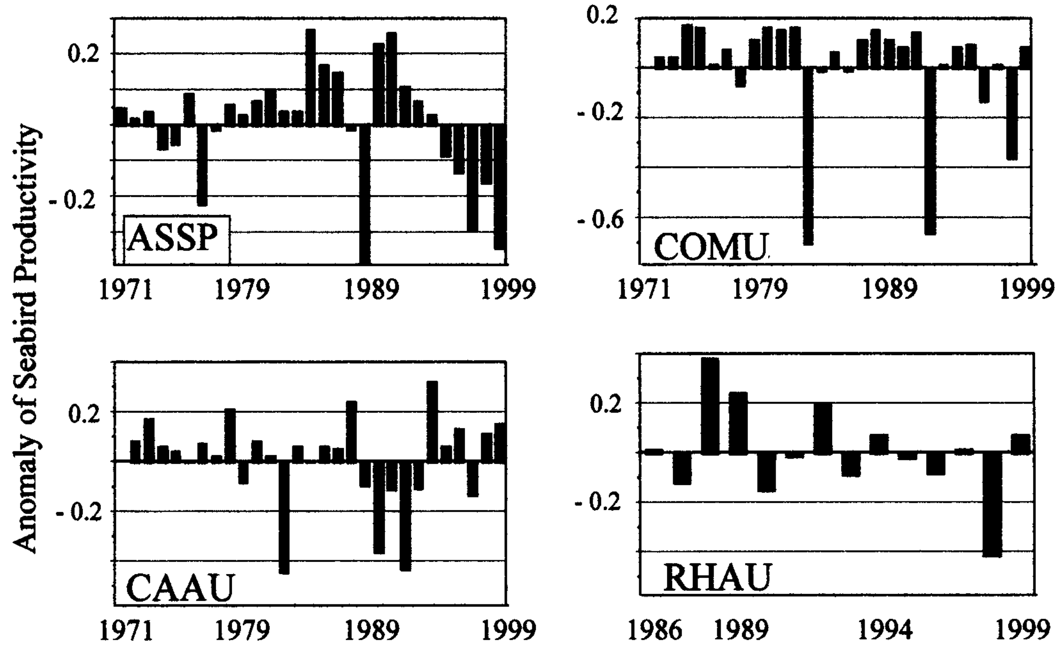

Figure 28. Interannual variability in the productivity of pelagic seabirds (ASSP: ashy storm petrel; COMU: common murre; CAAU: Cassin's auklet; RHAU: rhinoceros auklet) breeding at the Farallon Islands, central California.

1998) to the highest (winter and spring 1999) abundances observed over nearly the past two decades (fig. 21). What processes determine zooplankton biomass in the California Current? Has the trend of declining zooplankton biomass (Roemmich and McGowan 1995) been stalled or reversed, and if so, what will the effects be on higher trophic levels? These are critical questions for CalCOFI to address, even though the answers are not readily forthcoming.

Large-scale changes in zooplankton abundance and fish stocks in the North Pacific have been linked to decadal-scale climate shifts ("regime shifts"), the most notable of which occurred around 1977 (Francis and Hare 1994; Miller et al. 1994; Trenberth and Hurrell 1994; Mantua et al. 1997). Mantua et al., for example, defined a Pacific Decadal Oscillation (PDO), a measure of the leading North Pacific SST pattern, which has reversed polarity three times in the past century (1925, 1947, and 1977). They found a remarkable correlation between the PDO and the abundances of many populations of Pacific salmon, with northern (Alaska) stocks varying out of phase with southern (Oregon, California) stocks. A similar out-of-phase relationship has been found for zooplankton populations in the North Pacific (Chelton et al. 1982; Brodeur and Ware 1992; Roemmich and McGowan 1995).

Recent studies (e.g., Gargett 1997; Parrish et al., in press) have taken a mechanistic approach to understanding the relation between large-scale climate variability and fish stocks. Gargett (1997) took as a starting point three of the principal observations to come out of the correlative studies: (1) there is a link between the size of North Pacific salmon stocks and the strength of the Aleutian low-pressure system in the Subarctic Gyre; (2) northern and southern stocks vary out of phase; and (3) the major ocean influence on salmon survival occurs in early life stages, i.e., within coastal waters. Her proposed mechanism for explaining these observations is coastal water-column stability: northern and southern phytoplankton populations occupy opposite ends of an "optimal stability window," with northern (southern) populations, which are more limited by light (nutrients), experiencing amplified (reduced) growth as water-column stability increases. Gargett further proposed that coastal water-column stability, in turn, varies in phase along the entire eastern Pacific coastal margin, and depends directly on the strength of the wintertime Aleutian low. It is reasonable to assume, as Gargett (1997) did, that fluctuations in primary production directly affect production at higher trophic levels. The findings of Parrish et al. (in press) also indicate that regime shifts in coastal ecosystems are triggered by rapid shifts in large-scale extratropical atmospheric forcing.

Might we be in a transitional period to a new regime? Minobe (1999) has identified synchronized phase reversals between pentadecadal (30–80 year) and bidecadal (10–30 year) variations in the strength of the winter- and springtime Aleutian low as likely candidates for forcing the observed North Pacific regime shifts over the past century. If this synchronization were to continue, Minobe (1999) predicts a new regime shift to occur as early as 1999–2000, and most likely within the next several years. The present state of the California Current, in fact, is similar to that observed in the years prior to the 1977 regime shift, as well as to conditions following the strong El Niño events of 1957–58 and 1982–83 (Schwing et al. 2000).

In the event of a regime shift, we might expect a prolonged period during which the Aleutian low (subtropical high) is relatively weak (strong), and transports in the California Current are anomalously high. According to Gargett's (1997) hypothesis, this situation would lead to increased coastal upwelling, decreased coastal water-column stability, and higher productivity off California. A higher California Current transport, in fact, may be sufficient to increase zooplankton biomass in the CCS (Chelton et al. 1982), and may partly explain the higher zooplankton abundance seen on recent CalCOFI cruises. Decreased stratification may also provide a deeper source for upwelled waters and enhanced nutrient input into the euphotic zone (Roemmich and McGowan 1995), thus contributing to heightened productivity in the region.

We must consider short-term climate fluctuations such as El Niño and La Niña within the context of lower-frequency variability, which may include natural variability on decadal time scales (including regime shifts) or anthropogenically forced global warming. Indeed, resonance of variability on different time scales may be a necessary trigger for climate shifts (Minobe 1999). Furthermore, Parrish et al. (in press) point out that the climate does not necessarily oscillate between two extremes (regimes), but may enter a new state that differs from any recent previous regime. North Pacific climate and coastal ecosystems are complicated, nonlinear systems, and may vary in unpredictable ways.

Whither the California Current? At the risk of disappointing eager readers, the question asked in the title of this paper must go unanswered for now. Over the next year CalCOFI surveys will provide a comprehensive suite of physical and biological data from the CCS, and may take us closer to an answer. It should be recognized, however, that the unusual nature of the recent observations could not have been fully appreciated without reference to the historical CalCOFI time series. There is an obvious need for continuing the CalCOFI monitoring, as well as for augmenting the program with process-oriented field studies and continued modeling efforts (e.g., Miller et al. 2000) in order to more fully understand, and eventually predict, the relation between environmental variability and ecosystem structure.

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