THE STATE OF THE CALIFORNIA CURRENT IN 1995–1996: CONTINUING DECLINES IN MACROZOOPLANKTON BIOMASS DURING A PERIOD OF NEARLY NORMAL CIRCULATION

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ABSTRACT

The large suite of environmental data collected routinely in the coastal region of California provides the basis to make timely assessments of environmental structure that can be updated continuously. Here we describe and interpret data collected during the previous 18 months. The emphasis is upon data collected on CalCOFI time-series monitoring cruises and at coastal shore stations. Spatial pattern is described, and the data are interpreted in the context of anomalies from long-term means. The pattern of circulation in the California Current was similar to the long-term mean during most of 1995. Circulation in early 1996 was anomalous in that February was marked by a strong mesoscale structure and a lack of the normal coastal countercurrent in the Southern California Bight. April 1996 was also a period of strong mesoscale structure, and the California Current was displaced farther offshore than normal. The springs of 1995 and 1996 were periods where the surface waters of the coastal region were enriched with cool, high-nutrient water, and the chlorophyll concentration and primary production were high. Indices of environmental structure based upon coastal shore station data provided contradictory signals of the forcing processes causing this biological structure. Sea-surface temperatures at coastal shore stations were warm, and the upwelling index was anomalously low during the springs of 1995 and 1996, suggesting a pattern of low nutrient inputs and primary production. However, direct measurements on the CalCOFI survey cruises showed strong upwelling-favorable wind, and that cool, high-nutrient, and high-production water was present over a large area of the coastal region. It appears that structure during the study period in the coastal waters of central and northern California was similar to that in the CalCOFI study region. In spite of strong forcing and high primary production, macrozooplankton biomass continued the long-term trend of large decline which began in the mid-1970s.

INTRODUCTION

In this report we describe and interpret recent oceanographic and related environmental data from the coastal region of California. The emphasis is upon data collected on the quarterly CalCOFI time-series monitoring cruises, but data from several sources are also considered. This report covers data for the period from April 1995 to April 1996. Data from earlier periods were covered in prior reports (Hayward et al. 1994, 1995). Our objective is to provide an up-to-date assessment of environmental structure. Atmospheric forcing processes, circulation patterns, nutrient distributions, and patterns in the distribution of phytoplankton and macrozooplankton biomass are described. We consider how these patterns differ from the long-term mean structure, and how biological structure is linked to atmospheric forcing and the circulation.

DATA SETS AND ANALYTICAL TECHNIQUES

Coastal data include measurements of temperature and salinity made at a series of shore stations (Walker et al. 1994); data from La Jolla (SIO Pier) and Pacific Grove are shown here as temperature and daily anomalies from the long-term harmonic mean (1916–93 for La Jolla and 1919–93 for Pacific Grove). Coastal sea-level data for San Diego and San Francisco are shown as monthly anomalies from the 1975–86 mean corrected for atmospheric pressure (data courtesy of G. T. Mitchum and K. Wyrtki and the IGOSS program).

Data from quarterly CalCOFI time-series survey cruises in 1994 and 1995 are shown. The CalCOFI monitoring program started in 1949; a brief history of the program is given in Hewitt 1988. The present program consists of quarterly (normally January, April, July, October) survey cruises which occupy a grid of 66 stations in the southern California region. Cruises are designated by the year and month; e.g., cruise 9501 sampled in January 1995. Station locations are designated by a line and station number; e.g., 90.60 represents station 60 on CalCOFI line 90.

The core time-series data set now collected at each station on the quarterly CalCOFI cruises includes a CTD/rosette cast with sensors for pressure, temperature, salinity, dissolved oxygen, PAR (photosynthetically active radiation), fluorescence, and transmissivity. Water samples are collected with ten-liter sample bottles at 20–24 depths in the upper 500 m for determination of salinity, dissolved oxygen, nutrients (NO_3, NO_2, PO_4, SiO_3), phytoplankton pigments (chlorophyll a and phaeophytin), and primary production (^{14}C uptake at one station per day). Oblique and surface (neuston) net tows (0.505 mm mesh) are taken at each station. Continuous near-surface measurements of temperature, salinity, and chlorophyll fluorescence are made from water pumped through the ship, and the data are logged at one-minute intervals. Doppler current profiler (ADCP) data are also recorded continuously. The ADCP data provide a measure of zooplankton biomass based upon acoustic backscatter as well as a measure of upper ocean currents. The most recent data presented here are preliminary, and some changes may be made after the final processing and quality control checks. The methods are described in more detail in the CalCOFI cruise data reports (Scripps Institution of Oceanography 1995). CalCOFI hydrographic data and information about recent activities can be accessed via the World Wide Web (*http://www-mlrg.ucsd.edu/calcofi.html*).

EVOLUTION OF STRUCTURE

Atmospheric and Oceanic Forcing

During the winter of 1994–95, the climate regime over the North Pacific differed greatly from that of the previous year. The tropical Pacific was warm (in a moderate El Niño state), and, somewhat characteristically, the winter and early spring of 1995 featured a deep, eastward-reaching Aleutian Low system with vigorous storms passing the California coast, particularly during January (figure 1) and March. Throughout this period, the westerlies were strengthened with several spates of southerly (from the south) component winds along the California

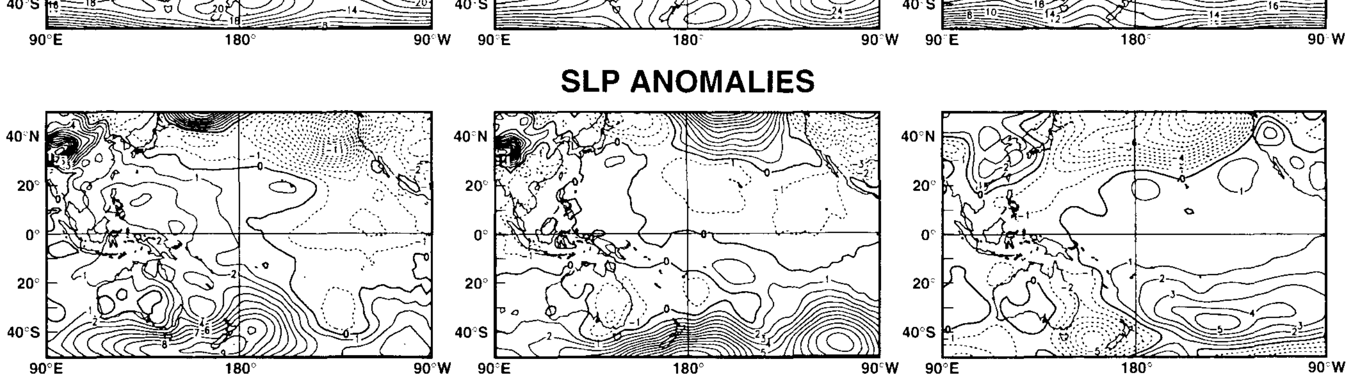

Figure 1. Sea-level pressure (SLP) and SLP anomalies over the Pacific Ocean for (*A*) January 1995, (*B*) January 1996, and (*C*) April 1996 (from the NOAA *Climate Diagnostics Bulletin*).

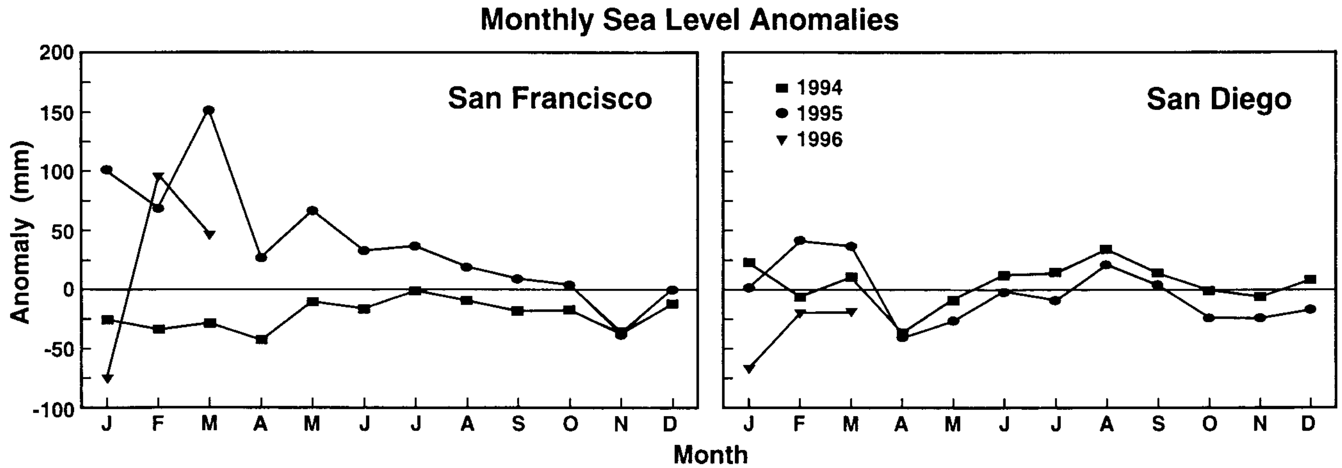

Figure 2. Monthly anomalies in sea level at San Francisco and San Diego for 1994, 1995, and 1996. The monthly anomalies are deviations from the 1975–86 period corrected for atmospheric pressure.

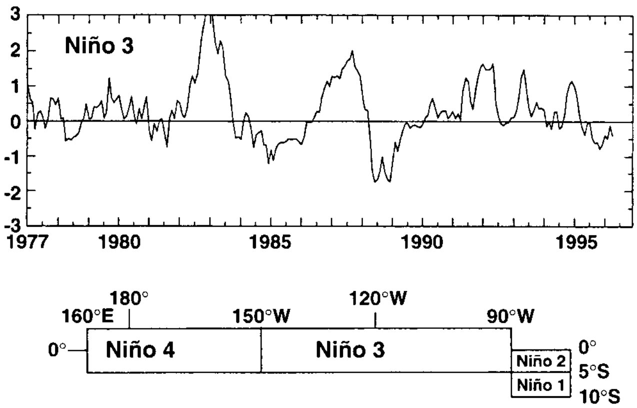

Figure 3. Tropical Pacific SST anomalies from the Niño 3 region (from the NOAA *Climate Diagnostics Bulletin*).

coast. In response, high coastal sea levels (figure 2) and a warming tendency occurred over a broad region along the California coast.

In contrast, during the winter of 1995–96 the tropical Pacific hovered in a weak La Niña state, with slightly cool surface temperatures (figure 3), and there was rather strong anomalously high pressure over the North Pacific (figure 1). However, conditions over the California Current region were changeable over winter and spring of 1996, as the atmospheric circulation wavered considerably across the basin during the winter months. Coastal sea levels (figure 2) alternated between anomalously low elevations during January 1996 to moderate-high elevations during February. These fluctuations corresponded to the accentuated high-pressure, strengthened northerly winds during January, and to lower-pressure, anomalous southerly winds during February. An exceptional feature that developed during winter and continued through spring of 1996 was the unusually warm water temperatures (figure 4) with anomalies exceeding 1°C over most of the eastern North Pacific (also see shore station temperatures at Pacific Grove and SIO Pier in figure 5). This warm regime actually took hold in fall of 1995 and strengthened during winter and spring of 1996. The causes are presumably associated with warming from the previous El Niño episode combined with regional wind and cloud conditions.

During the spring of 1995, the sea-level pressure (SLP) field retained a negative (low-pressure) anomaly feature in the eastern North Pacific. However, because the pressure tended to also be low over the western United States, the pressure gradient was relatively unaltered from its climatological normal, and northwesterly winds took hold along the California coast during April and May 1995. The spring northwesterly wind regime is shown by the vector wind plots from California coastal buoys in figure 6. Consequently, sea level dropped from its winter levels (figure 2), and coastal surface temperatures were cool.

During the spring of 1996, SLP in the region (figure 1) was near its normal levels in March and higher than average in April. The April SLP configuration was such as to weaken the wind field over the southern California coast, which evidently enhanced the warming of the coastal region with near-record warm shore temperatures.

Sea-surface temperature (SST) measured at shore stations at La Jolla and Pacific Grove started 1995 above normal, but a sharp drop in mid-April occurred at both La Jolla and Pacific Grove. SST has been near normal to below normal through the remainder of 1995 and for the first two months of 1996 at Pacific Grove (figure 5). Temperatures at La Jolla fluctuated about normal from April to September 1995. Anomalously warm water was present at La Jolla from October 1995 through March 1996.

Sea level was above normal from January to March 1995 at San Francisco, and above normal during February and March at San Diego (figure 2). Sea level was near

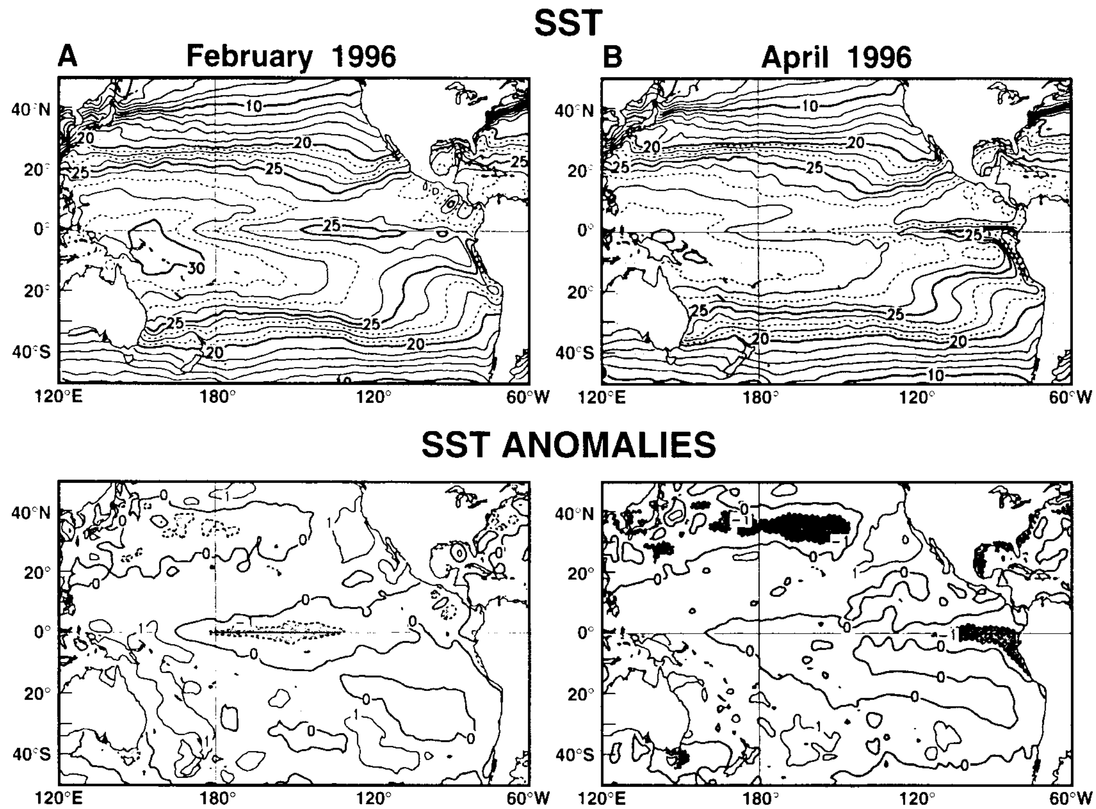

Figure 4. SST and SST anomalies over the Pacific Ocean, February 1996 and April 1996 (from the NOAA *Climate Diagnostics Bulletin*).

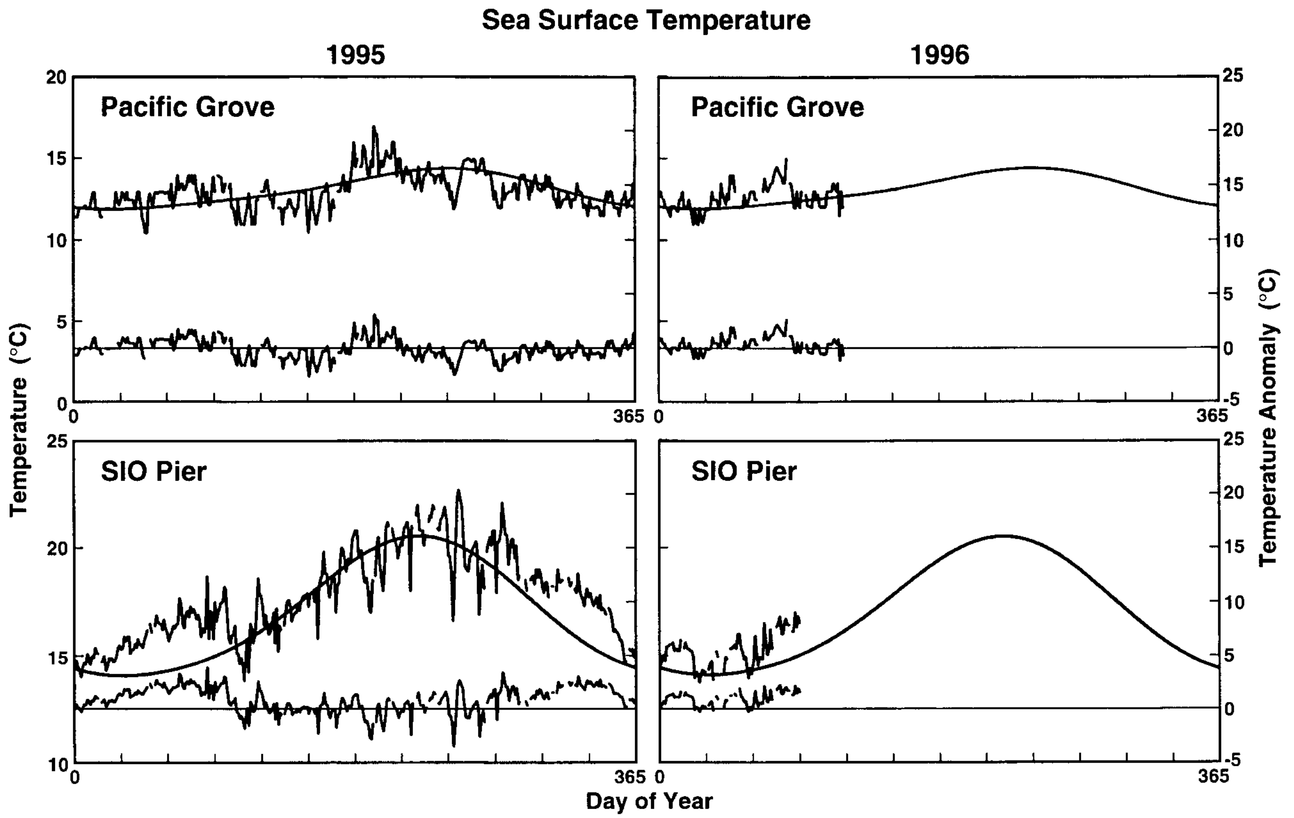

Figure 5. Sea-surface temperature at Pacific Grove and La Jolla (SIO Pier) for 1995 and 1996. Daily temperatures and daily anomalies from the long-term harmonic mean (1919–93 for Pacific Grove and 1916–93 for La Jolla). The *heavy line* shows the harmonic mean annual cycle in SST.

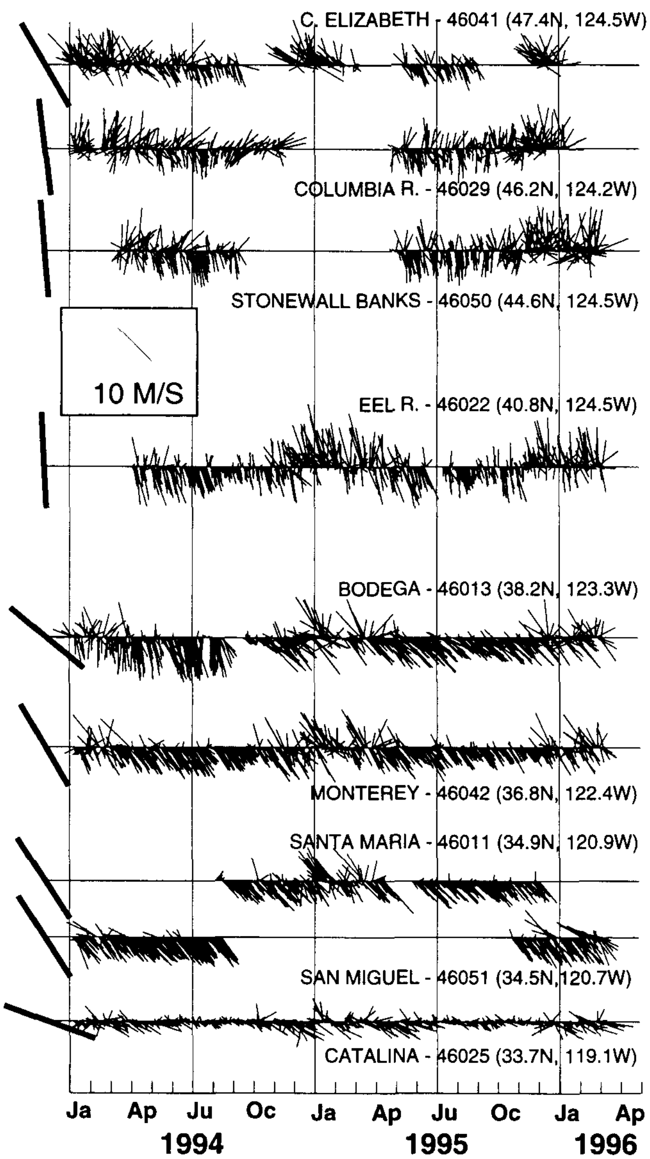

Figure 6. Vector time series of winds at selected National Data Buoy Center meteorological buoys along the U.S. west coast, January 1994–February 1996. Vectors represent daily averages of hourly observations. *Bold lines* to left of each time series denote coastline orientation at the sites.

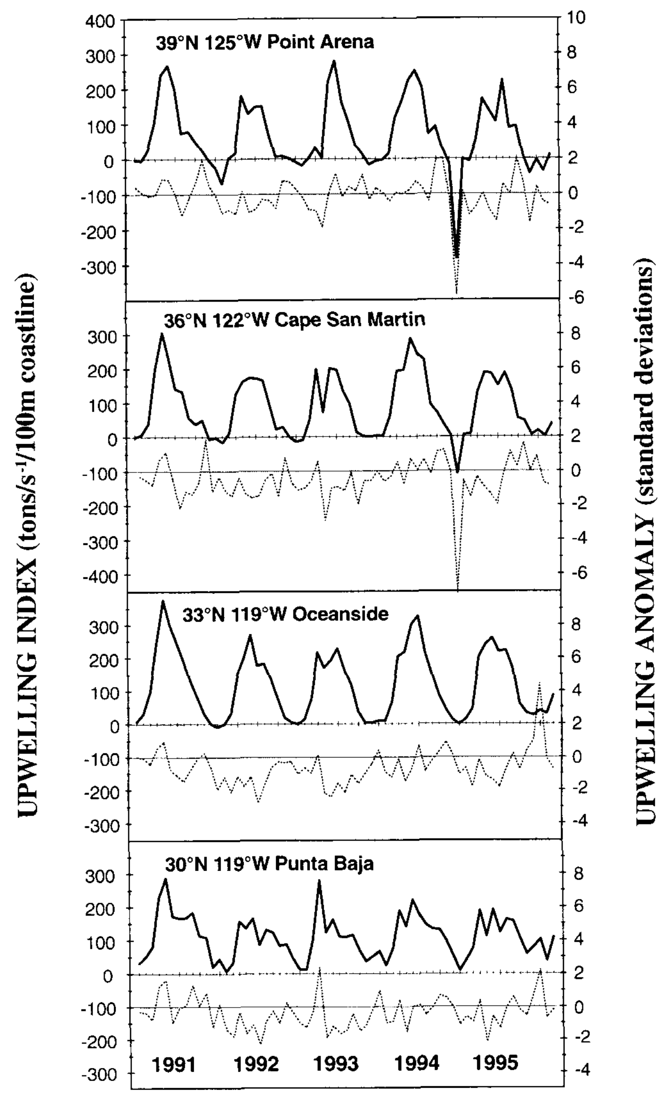

Figure 7. Time series of the monthly average upwelling index (*solid line*) and normalized anomalies (*shaded*) for January 1991 to March 1996 at four coastal locations.

normal at both stations during the remainder of 1995. San Diego and San Francisco both showed a sharp decline to anomalously low values of sea level in January 1996. Sea level increased to normal values at San Diego in February and March, and to anomalously high values at San Francisco. As in early 1995, it is likely that the high values in San Francisco Bay are due, at least in part, to freshwater runoff caused by heavy rains.

The upwelling index (Bakun 1973) measured at 36°N, 122°W (Cape San Martin) and 33°N, 119°W (Oceanside) was anomalously low from January to July 1995 except for April, which was near normal (figure 7). There were anomalously high values in the fall and winter of 1995. The index in February 1996 was anomalously low at both stations. The anomalously low values in the spring of 1995 are important because they occurred when upwelling was approaching its seasonal maximum. The high values of the anomalies in the fall and winter of 1995 occurred when upwelling is normally at the annual low.

Wind data, collected from an array of coastal buoys, provide a more direct measure of regional atmospheric forcing. Harsh environmental conditions make continuity of measurement of wind and other meteorological data from coastal buoys a chronic problem. Plotting a selected number of daily-averaged wind time series along the length of the West Coast, however, gives some indication of seasonal and interannual differences in the large-scale coastal wind field (figure 6). Winter winds are highly variable over short time scales, a result of frequent and vigorously propagating storms. The general direction of winter winds is poleward, especially north of Cape Blanco (42°N). Summer winds are predominantly equatorward, with occasional wind-relaxation events or reversals to poleward flow (Schwing et al. 1991). Wind vectors align strongly with the local coastline, particularly off central and southern California. Winds within the Southern California Bight are weak and variable throughout the year, relative to those north of Point Conception. The seasonal patterns shown here correspond well to a statistical summary of west coast buoy observations by Dorman and Winant (1995). Winds during 1995 and early 1996 appear fundamentally similar to 1994, and to the long-term climatology. Specifically, winds were upwelling favorable (equatorward) through summer 1995 along the entire coast, and there were numerous episodes of equatorward wind throughout winter 1995–96 south of Cape Blanco.

Additional Data Sets from the Coastal Region

The region off central California between Monterey Bay and Bodega Bay was surveyed three times in May–June 1995, as part of the Southwest Fisheries Science Center (SWFSC) Tiburon Laboratory's annual surveys (begun in 1983) of pelagic young-of-the-year rockfish on the RV *David Starr Jordan*. A repeat of the May–June survey was conducted in 1996. In addition, the *Jordan* conducted bongo tows, CTD and PAR casts, and ADCP profiling at CalCOFI station 63.55 for ten days in early February 1995. Preliminary analysis reveals semidiurnal vertical excursions of 25–50 m in the density field. The Tiburon Laboratory can be contacted for further information on these data sets. The SWFSC La Jolla Laboratory's pelagic egg and larval and oceanography surveys extended north to this region in early 1995 (hake) and early 1996 (sardine).

Coastal ocean conditions off central California during May–June 1995 suggest a continuation of the more typical conditions that developed in early 1994 following an extended ENSO, consistent with the results of the CalCOFI surveys off southern California (Hayward et al. 1995). ADCP currents in May–June 1995 off central California showed the meandering southward flow typical of the upper water column during this time of year, highlighted by a strong offshore flow of a cold-water plume off Bodega Bay seen to at least 200 m. The expected northward undercurrent was evident at 200 m. The geostrophic currents inferred from the dynamic topography were similar to the ADCP circulation patterns, although the ADCP data reveal a much more complex current field. Dynamic heights were very similar in magnitude and structure to those in 1994 (Sakuma et al. 1995). The upper ocean was as much as 10 dyn. cm lower than during ENSO conditions in May–June 1992 (Lynn et al. 1995) and 1993 (Sakuma et al. 1994).

Upper water column temperatures and salinities were generally near average for this area for May–June, and cooler and more saline in comparison to 1992 and 1993. Extremely low salinities (values less than 30), a result of high runoff from heavy spring rains and floods in northern California, were limited to the upper 10 m. Otherwise, near-surface temperature and salinity values and distributions imply typical coastal upwelling conditions, despite lower than normal values of upwelling index at this latitude. However, local buoy winds were southward throughout most of the survey (figure 6), consistent with coastal upwelling. Slope water temperatures and salinities at 200 m depth in 1995 were similar to the long-term means, but more saline relative to 1994, a period in which hydrographic conditions suggested a reduced countercurrent, or increased transport in the California Current. Farther offshore, isopycnal surfaces at 200–500 m were uplifted in 1994 and 1995, compared to ENSO conditions when relatively warm, fresh California Current water is displaced shoreward by anomalous poleward wind stress (Simpson 1984; Lynn et al. 1995).

Analysis of data from a program of routine deployment of satellite-tracked drifters in the California Current by the Surface Velocity Program of the Global Drifter Center at SIO provides an additional source of information about the large-scale pattern of upper ocean circulation and the paths of water parcels. The historical data taken since 1985 illustrate the pattern of southward flow and the strong mesoscale variability of the California Current (figure 8). The CalCOFI survey area was not well sampled by the drifter deployments in 1995, but southward flow in the area offshore of the CalCOFI pattern is well illustrated.

The annual pattern of primary production in Monterey Bay has been measured as part of the monitoring program conducted by the Monterey Bay Aquarium Research Institute. A time series of primary production measured by ^{14}C uptake using methods described by Chavez et al. (1990) made from 1992 to 1995 shows a strong seasonal cycle in primary production (figure 9). As expected, values during the spring bloom in Monterey Bay are greater than in most of the CalCOFI survey area except in high-production patches. There was much variability between individual measurements, but the running means did not show strong between-year differences, even when the El Niño years of 1992 and 1993 are compared to 1994 and 1995.

Biological Structure in the CalCOFI Region

During 1995 and early 1996, the mean chlorophyll concentration on the CalCOFI survey cruises was relatively high in the context of measurements made during the last decade in April, and nearly normal in the other months (figure 10). Values in the summer, fall, and

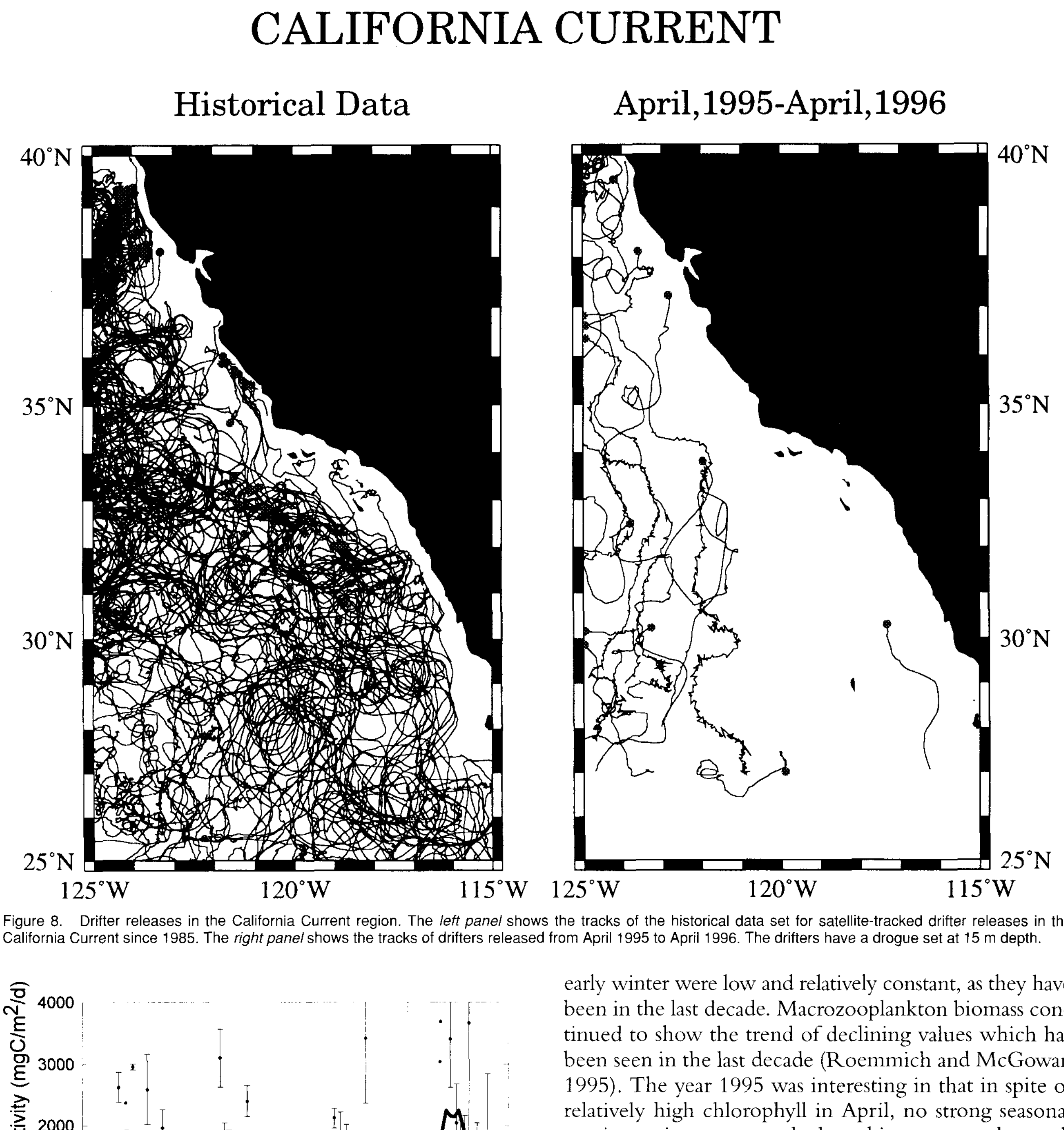

Figure 8. Drifter releases in the California Current region. The *left panel* shows the tracks of the historical data set for satellite-tracked drifter releases in the California Current since 1985. The *right panel* shows the tracks of drifters released from April 1995 to April 1996. The drifters have a drogue set at 15 m depth.

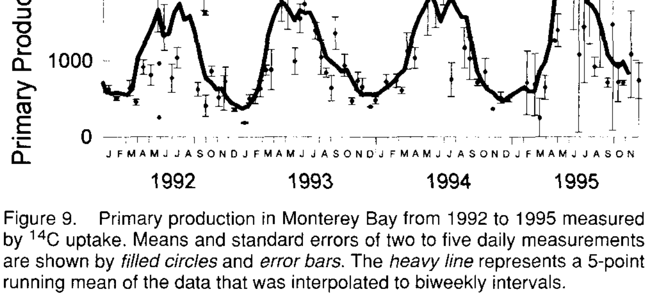

Figure 9. Primary production in Monterey Bay from 1992 to 1995 measured by ^{14}C uptake. Means and standard errors of two to five daily measurements are shown by *filled circles* and *error bars*. The *heavy line* represents a 5-point running mean of the data that was interpolated to biweekly intervals.

early winter were low and relatively constant, as they have been in the last decade. Macrozooplankton biomass continued to show the trend of declining values which has been seen in the last decade (Roemmich and McGowan 1995). The year 1995 was interesting in that in spite of relatively high chlorophyll in April, no strong seasonal maximum in macrozooplankton biomass was observed. It is not known if a seasonal maximum in macrozooplankton biomass was missed by the relatively long intervals between sampling on the quarterly cruises.

Red tide events occurred from San Diego to Monterey in the winter and spring of 1995 (Hayward et al. 1995). A moderate red tide was again evident in the vicinity of La Jolla in April 1996. The April 1996 event was evident as far south as Todos Santos Bay (G. Hemingway, pers. comm.). However, during the spring of 1996 no

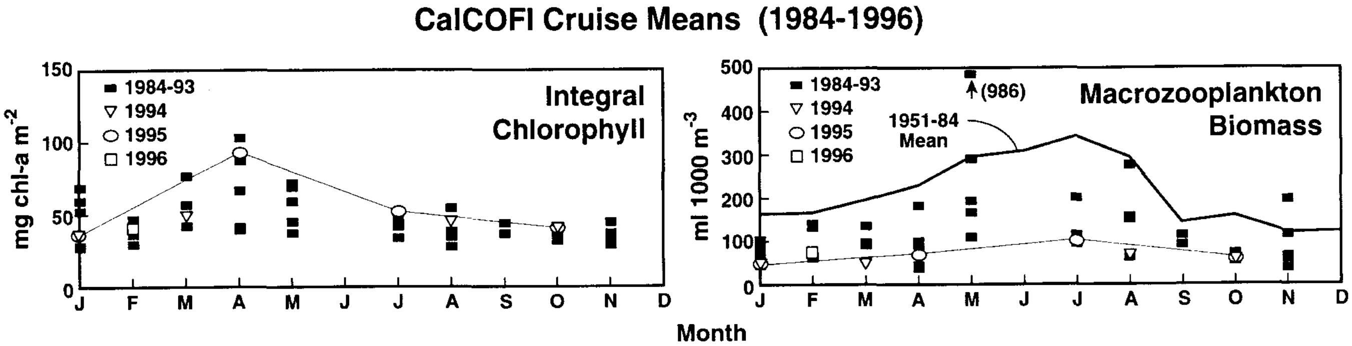

Figure 10. Cruise means of vertically integrated chlorophyll and macrozooplankton biomass plotted versus the month for CalCOFI cruises from 1984 to 1996. Each point represents the mean of all measurements on a cruise (normally 66). The *solid squares* show the cruises that took place from 1984 to 1993. The *open symbols* are cruises from 1994 to 1996; cruises in 1995 are connected with a line. The *bold line* in macrozooplankton biomass indicates the monthly means for the period from 1951 to 1984.

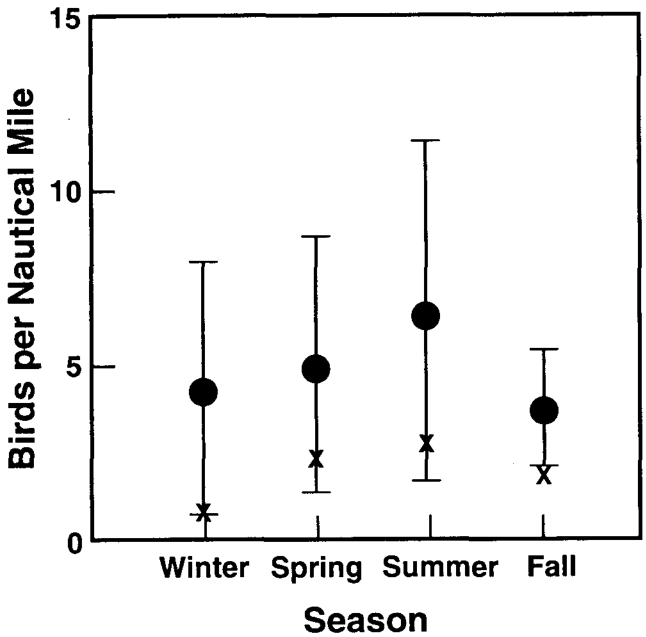

Figure 11. Mean and standard deviation (*filled circles* and *error bars*) of seabird abundance on CalCOFI cruises for the period May 1987 to April 1994. Seabird abundances from the four cruises in 1995 are marked with an *X*.

obvious red tide conditions were apparent at either Monterey or Santa Barbara (B. Prezelin, pers. comm.). In the CalCOFI region on cruise 9604, the primary red tide dinoflagellate (*Gonyaulax polyedra*) was found only in moderate, subdominant abundances (400–500 cells l^{-1}) and only at stations 93.26.7 and 93.28. In contrast, during April 1995, near the end of the red tide, this species was found in equal or greater abundances as far west as station 90.90. The 1996 red tide appears to have been relatively restricted to the immediate coastal environment.

Abundance of oceanic birds in the CalCOFI study region has declined steadily since 1988 (Veit et al., in press). This general decline continued through 1995 (figure 11). Bird abundance increased slightly on the spring and summer cruises of 1995. Seabirds can respond to changing environmental conditions on at least two temporal scales. They can respond to short-term (less than one year) fluctuations through population redistribution, and to longer-term changes through population growth or mortality. The short time scale suggests that the slightly elevated numbers of birds observed in spring and summer of 1995 represent redistribution. Perhaps birds were able to exploit some improved aspect of the environment associated with the elevated primary production in the spring of 1995. Highly mobile predators such as sooty shearwaters could have easily moved to the CalCOFI region from farther north in California, for example. Thus the small increases in 1995 would represent short-term redistribution embedded in a longer-term population decline that has been discussed by Veit et al. (in press).

Spatial Pattern on the CalCOFI Time-Series Cruises

The following section narrates the spatial patterns observed on the five most recent CalCOFI cruises. The circulation patterns on individual cruises are compared to the long-term mean circulation patterns (Lynn et al. 1982), which are shown in Hayward et al. 1994.

9504. Preliminary data from cruise 9504 were presented in Hayward et al. 1995. The dynamic height field (figure 12) from the final data is quite similar to the circulation pattern inferred from the 100 m temperature field (shown in Hayward et al. 1994). This again illustrates the value of this index for inferring the circulation in the California Current region. The circulation pattern was typical of the long-term mean pattern, with a strong cyclonic eddy in the offshore region of southern California superimposed upon it. The cyclonic eddy is also evident in the SST pattern determined from satellite remote sensing (figure 13). Near-surface chlorophyll was quite high in the coastal region throughout the pattern, and this is reflected in the high value of the cruise

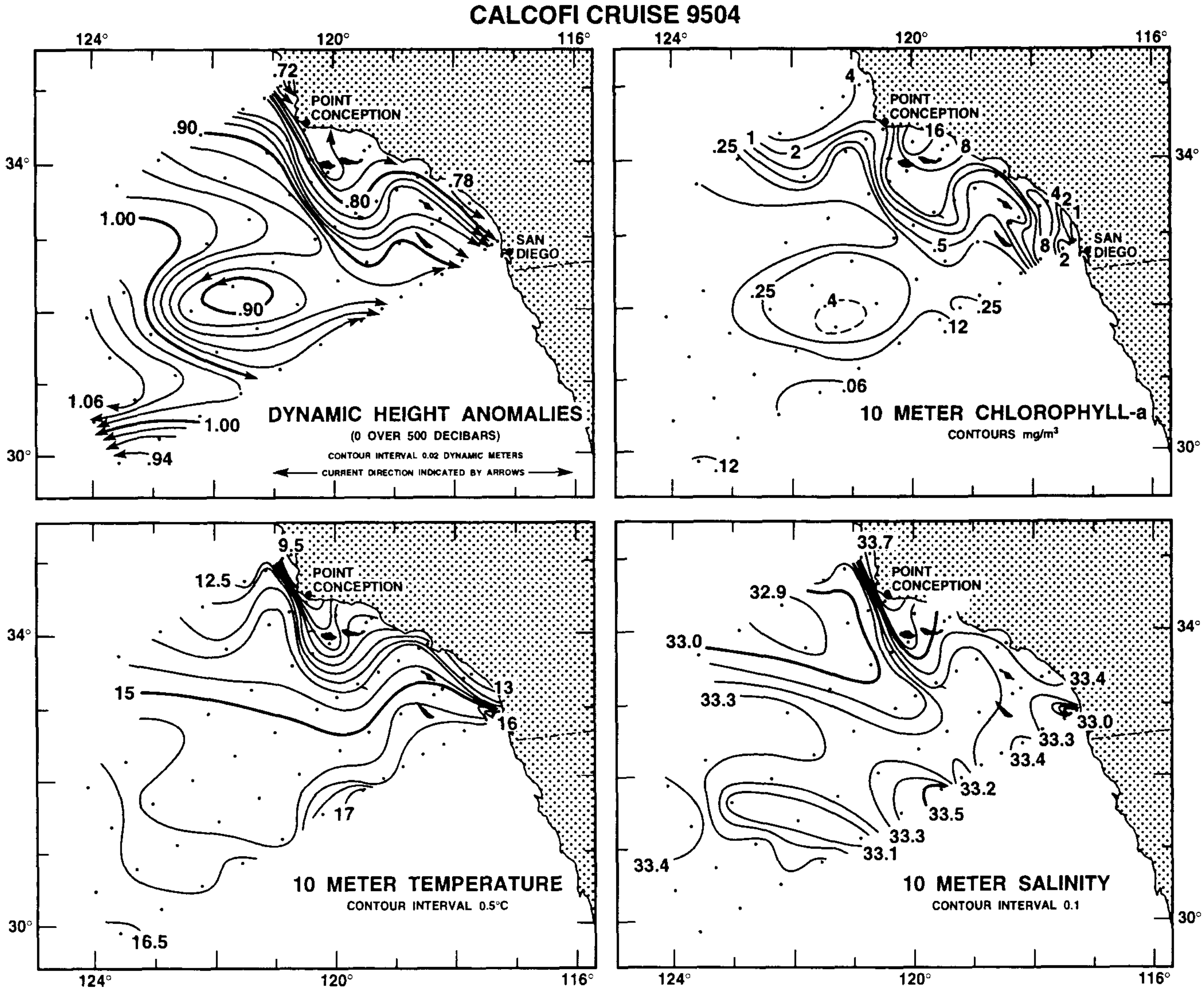

Figure 12. Spatial patterns for CalCOFI cruise 9504 (April 6–22, 1995), including upper ocean flow fields derived from 0 over 500 m dynamic height anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

mean integral chlorophyll (figure 10). Some of the enrichment was associated with the strong red tide event which affected the coast of California from the U.S.–Mexico border to at least Monterey. However, the enrichment extended much farther offshore than the coastal region where the red tide was evident, and the bloom in the waters offshore of the red tide was dominated by diatoms (Hayward et al. 1995). In spite of the elevated chlorophyll on this cruise, the cruise mean macrozooplankton biomass was low. Strong winds blowing from the north and exceptionally high seas were experienced during this cruise. This was not reflected in the upwelling index, which was anomalously low during most of the spring but near normal in April (figure 7).

9507. The circulation in July 1995 was remarkably similar to the long-term mean pattern. There was strong southward flow of the California Current offshore of the Channel Islands and a well-developed eddy south of the Channel Islands (figure 14). There was northward flow offshore of Catalina and San Clemente Islands and southward flow along the coast in the Southern California Bight. All of these features are in the harmonic mean dynamic height field. Mesoscale structure was weak on this cruise. As expected from the pycnocline topography, chlorophyll was elevated at the inshore edge of the California Current, where the pycnocline slopes sharply upward, and in the coastal waters of the Southern California Bight.

9510. In October 1995 the dynamic height field was quite similar to the long-term mean pattern. There was a strong southward-flowing California Current in the offshore waters and a well-developed coastal counter-

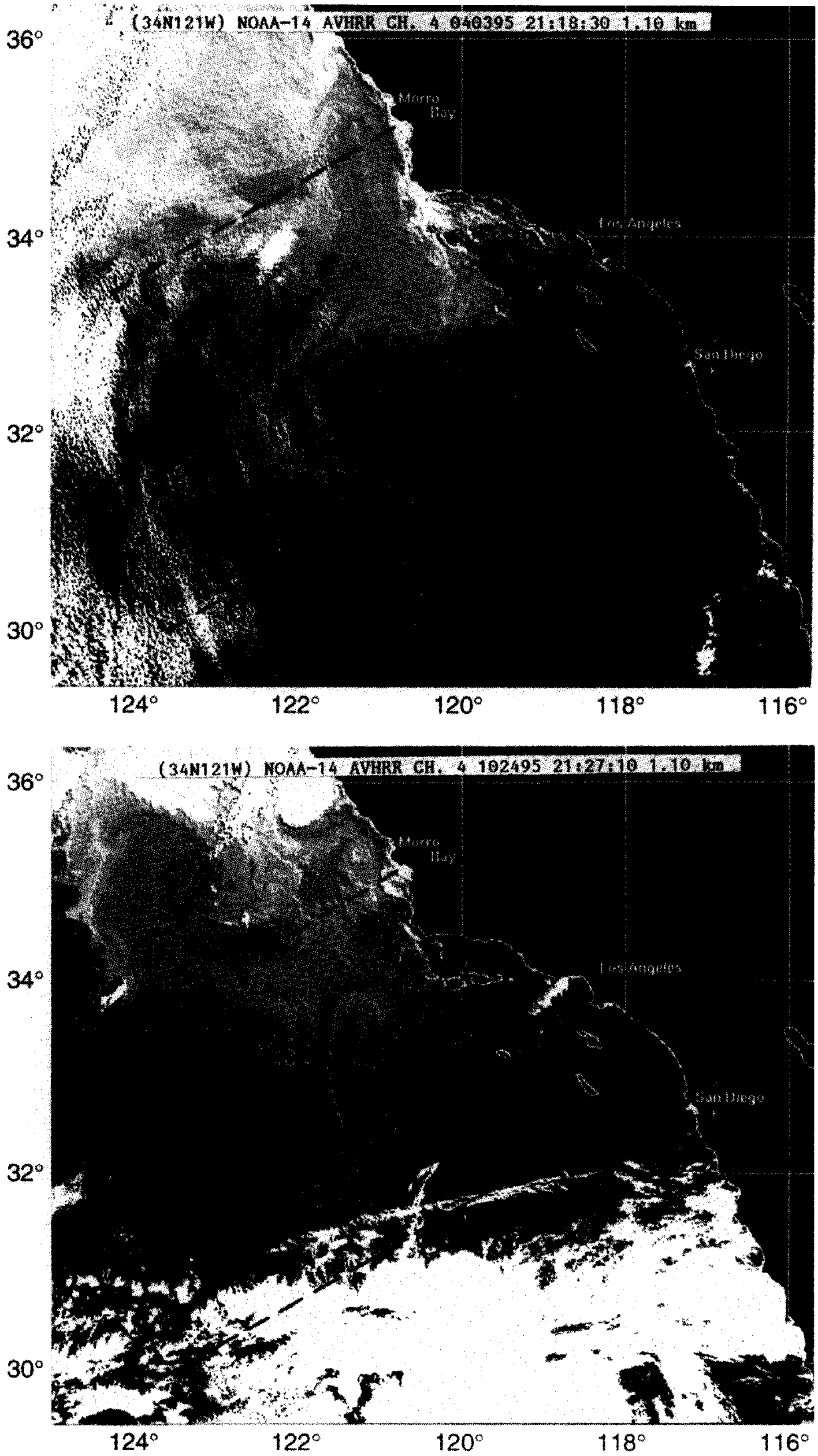

Figure 13. Radiometric temperature from NOAA-14 AVHRR channel 4 for April 3, 1995, 2118 UTC (*upper panel*) and October 24, 1995, 2127 UTC (*lower panel*). Data provided by CoastWatch, West Coast Node.

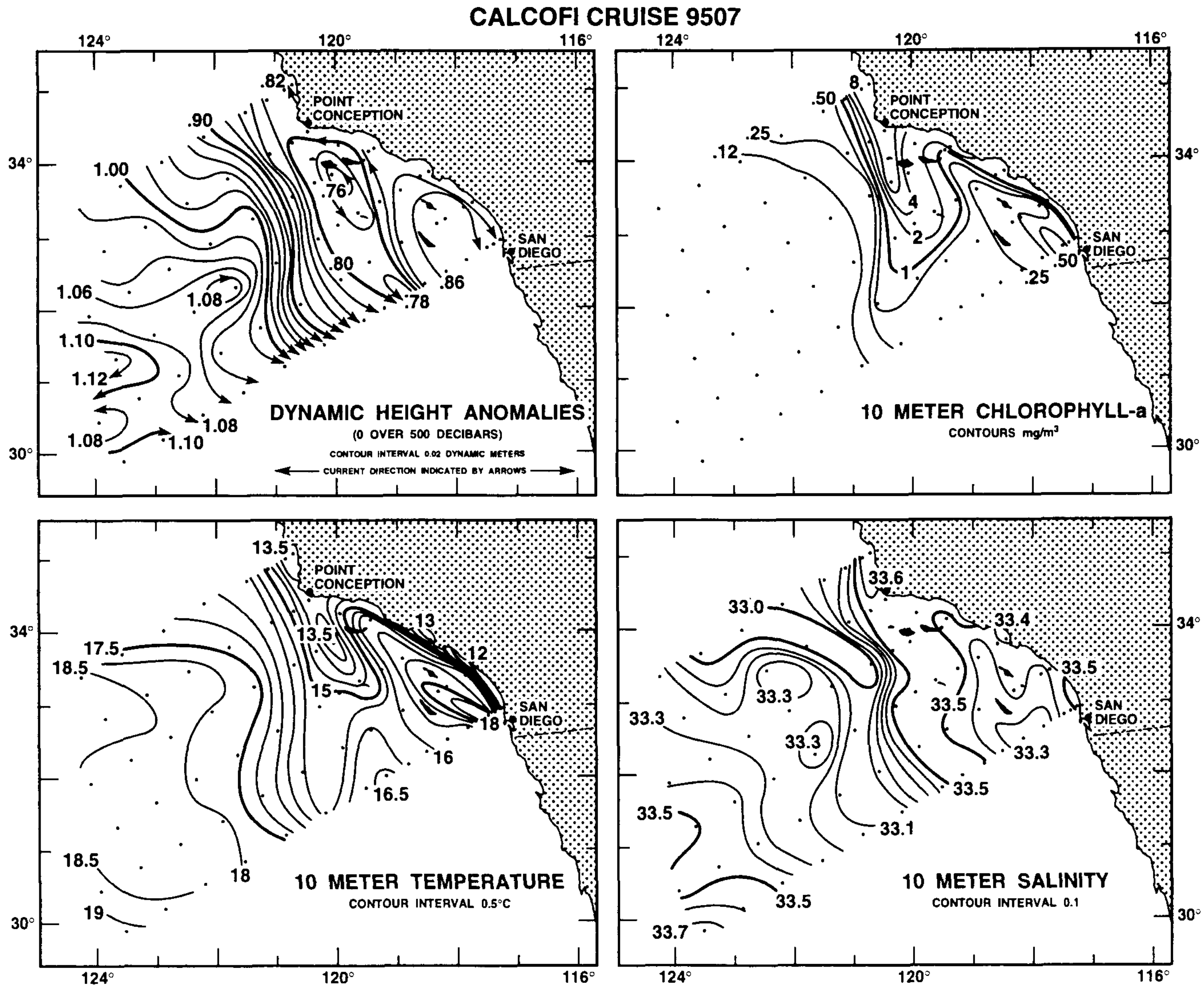

Figure 14. Spatial patterns for CalCOFI cruise 9507 (July 6–23, 1995), including upper ocean flow fields derived from 0 over 500 m dynamic height anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

current (figure 15). Additional aspects of mesoscale structure are evident in the remotely sensed SST pattern (figure 13). Chlorophyll was relatively low throughout the grid, as is typical of the seasonal pattern. The highest values of chlorophyll were found at the inshore edge of the California Current.

9602. Oceanographic structure had changed by February 1996. In contrast to the preceding year, the circulation pattern (figure 16) differed in several aspects from the long-term mean pattern (figure 17). The normal pattern, in which a low-salinity core of the California Current is evident in the 10 m distributions, was not apparent. A strong mesoscale eddy field nearly masked the large-scale flow. The normal coastal countercurrent was absent in the Southern California Bight, but the typical pattern of a well-developed Southern California Eddy was present. A notable aspect of the circulation was the strong mesoscale eddy field and the strong onshore-flowing jet located in the offshore part of the survey pattern between lines 87 and 90. The absence of the coastal countercurrent and southward flow in the Southern California Bight is consistent with the anomalously low sea level at La Jolla during the winter of 1995–96.

9604. Cruise 9604 was completed on May 3 as this report was being prepared. Preliminary data from this cruise again show an anomalous circulation pattern and very strong physical forcing of biological structure. The flow field inferred from the 100 m temperature distribution shows that the core of the California Current was located anomalously far offshore. As in February, there is a strong mesoscale eddy field. There was strong onshore and offshore flow in the region offshore of southern California.

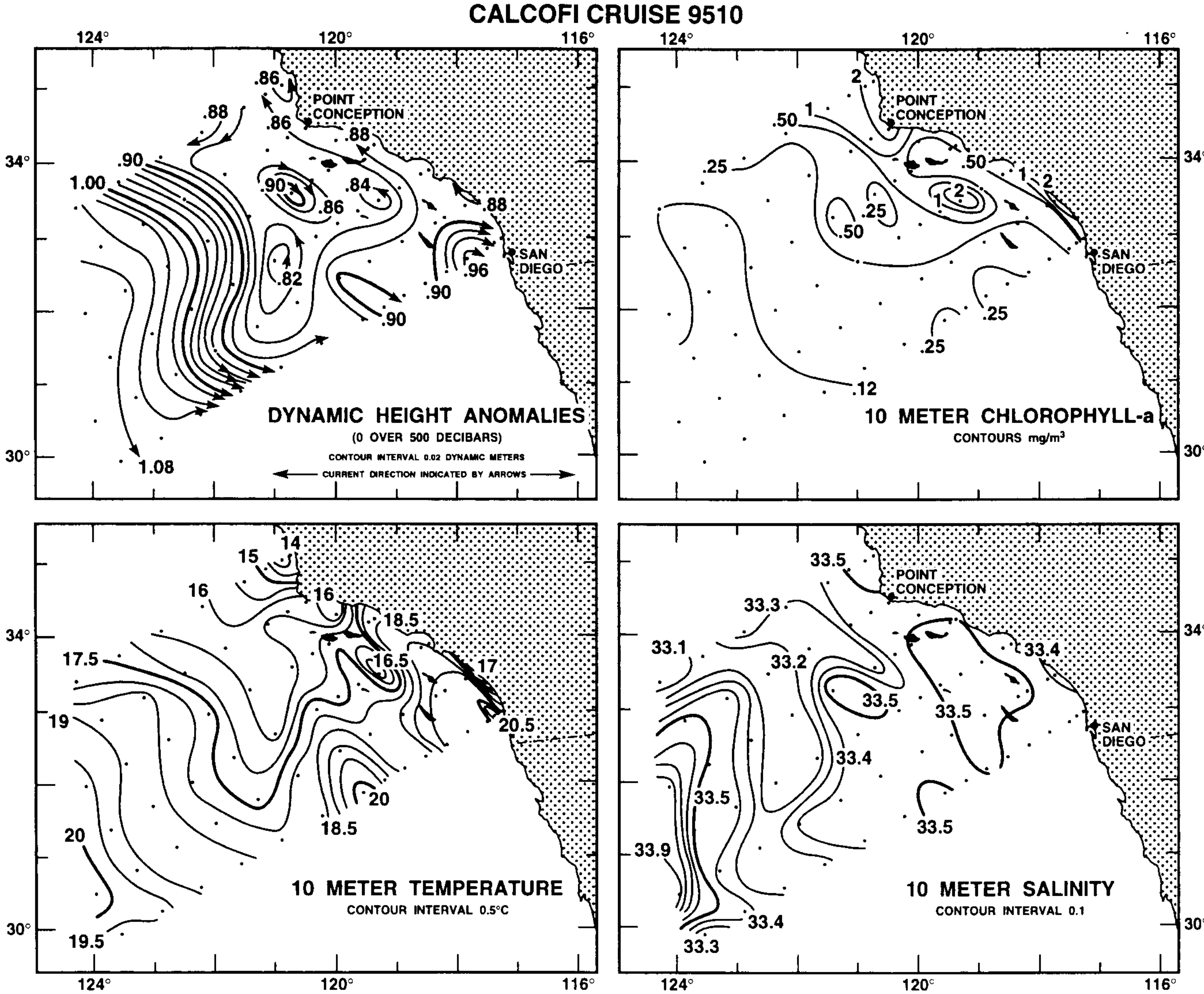

Figure 15. Spatial patterns for CalCOFI cruise 9510 (October 6–28, 1995), including upper ocean flow fields derived from 0 over 500 m dynamic height anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

The area inshore of the inner edge of the low-salinity jet of the California Current was enriched in both southern and central California. Chlorophyll values were quite high (figure 18) in the surface waters near Point Conception and in the Santa Barbara Channel. The Santa Barbara Channel bloom was dominated by diatoms.

An interesting pattern of sea-surface temperature anomalies emerged on this cruise. The surface waters inshore of the California Current were anomalously cool over most of the pattern (figure 19). The exception was the two stations closest to San Diego at the inshore end of line 93. The offshore waters were anomalously warm. The boundary between the anomalously warm and anomalously cool waters coincided with the inshore edge of the California Current. This was also the boundary of the area with high chlorophyll. This pattern is in contrast to the pattern in February 1996, when the surface waters were anomalously warm over most of the pattern.

DISCUSSION

A large suite of environmental data is now being routinely collected in the coastal region of California. These data provide the basis for timely assessments of the California Current ecosystem. Data are collected at various frequencies, and they differ in the length of time it takes before they become widely available. Only a subset of the data that have been collected is included in this report.

A goal for coastal oceanographers is to interpret these data in a way which improves our understanding of the current state of the ecosystem. Prediction is a longer-

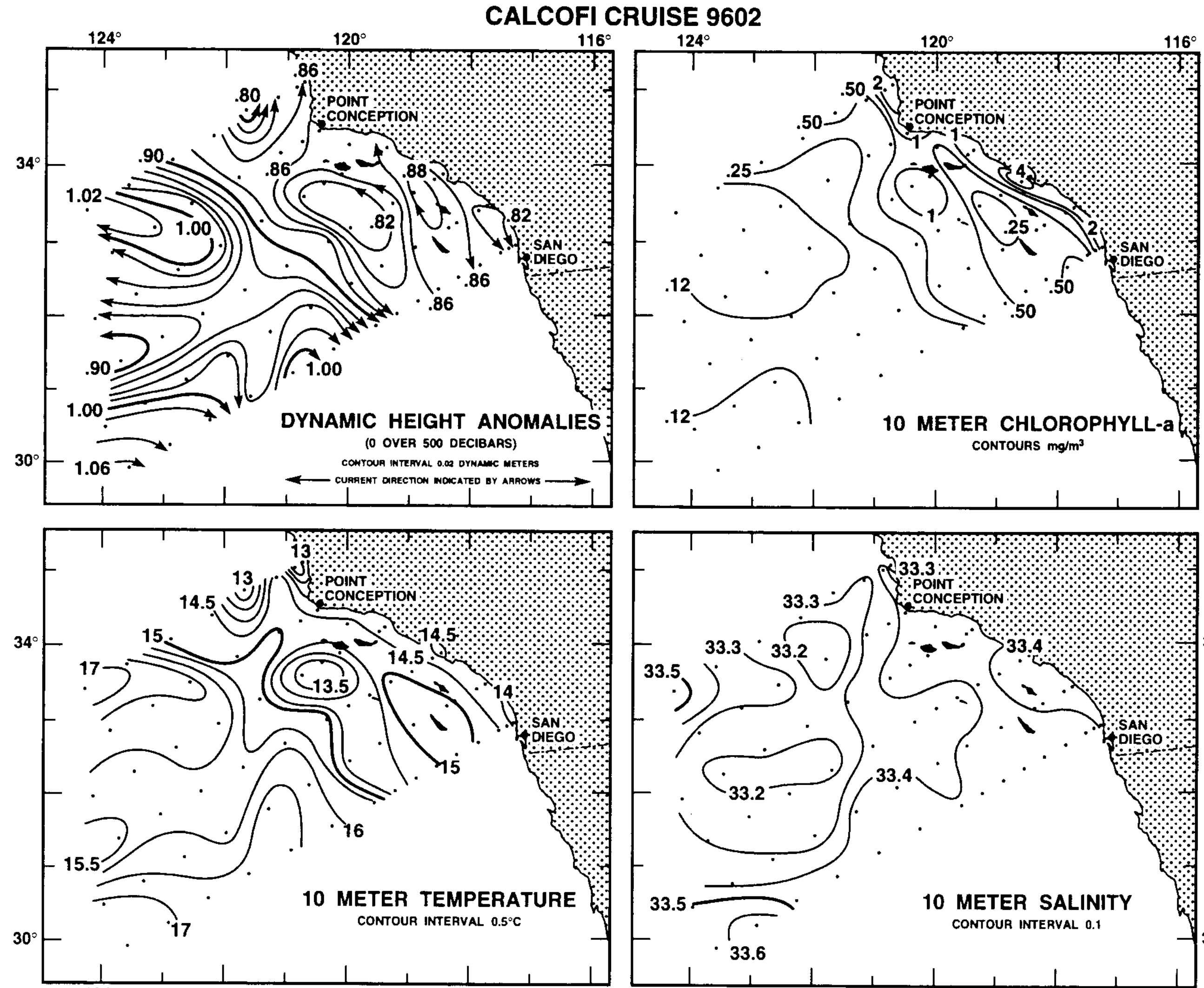

Figure 16. Spatial patterns for CalCOFI cruise 9602 (January 29–February 16, 1996), including upper ocean flow fields derived from 0 over 500 m dynamic height anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

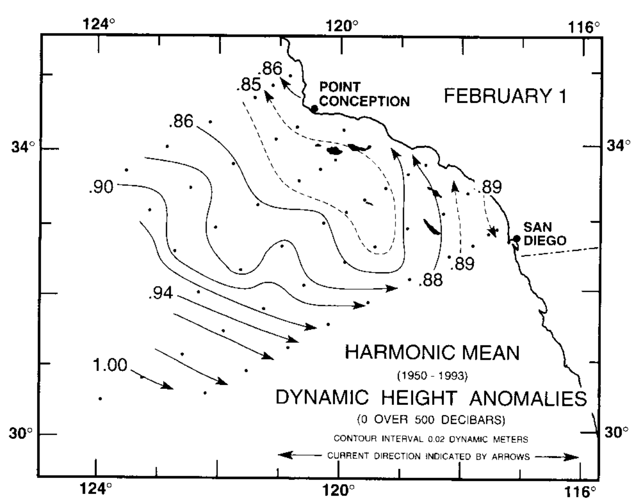

Figure 17. Long-term mean upper ocean flow field for February 1. This plot shows the harmonic mean for 1950 to 1992 of the 0 over 500 m dynamic height field.

term goal. Achievement of both goals will require advances in modeling and in our understanding of how marine populations are linked to environmental structure. It is likely that modeling and predictive ability will improve more rapidly for physical structure, and that successful prediction of biological structure will follow. Interpretation of these data sets requires an understanding of the relation between those aspects of structure which are commonly measured and for which efficient data distribution systems exist and those aspects of ecosystem structure which we wish to assess. Prediction will also require an improved understanding of the linkages between physical and biological structure.

The data which are most rapidly available are those on atmospheric forcing (winds and atmospheric pressure patterns) and temperature, salinity, and sea-level data from coastal shore stations. These are the data which can

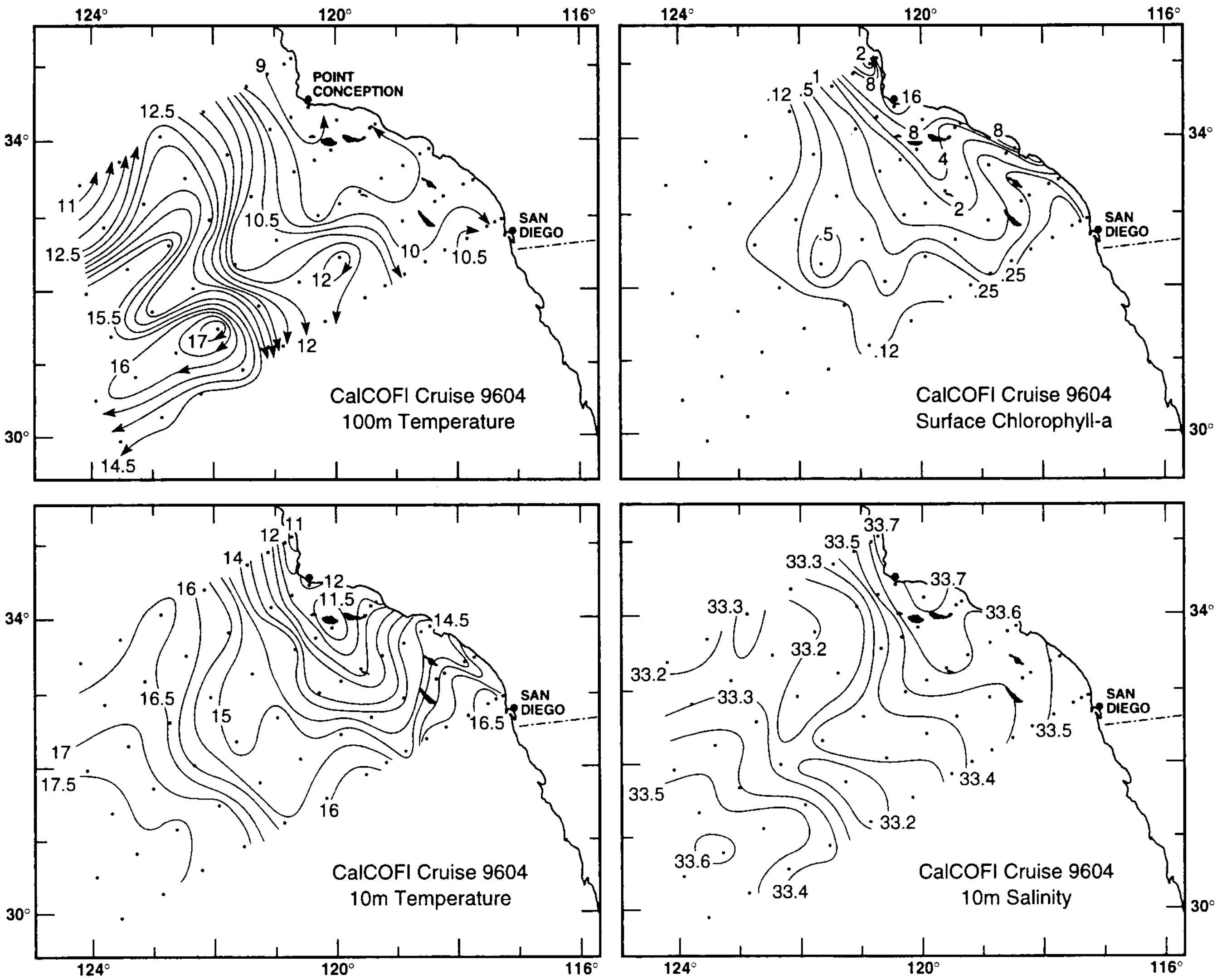

Figure 18. Spatial patterns for CalCOFI cruise 9604 (April 15–May 3, 1996), including upper ocean flow field estimated from the 100 m temperature, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

be used for the most timely assessments of ecosystem structure. During 1995 and early 1996 the upwelling index was anomalously low, especially during the spring, when strong upwelling is initiated. The buoy wind data, however, showed strong upwelling-favorable winds during the spring of 1995, and shipboard data indicated that there were strong upwelling-favorable winds at least during the period of the April 1996 CalCOFI cruise. The anomalously low values of the upwelling index imply that there would have been less upwelling than normal, which may lead to predictions of warmer than normal water in the near-coastal region, and lower nutrient and phytoplankton concentrations. The strong observed upwelling-favorable winds are consistent with the cool, high-nutrient and high-chlorophyll waters that were observed in the coastal region in the springs of 1995 and 1996. During the period considered here, the wind data provided a more useful indicator of ecosystem structure than did the upwelling index.

Elevated sea level in early 1995 (figure 2) is consistent with an enhanced coastal countercurrent, and the near normal sea level later in the year is consistent with a normal circulation pattern. Increased sea level in early 1996 would also be consistent with an enhanced coastal countercurrent. The circulation during the four cruises in 1995 was typical of the long-term mean; February 1996 was anomalous in that the normal coastal countercurrent in the Southern California Bight was absent.

Anomalously warm water was present at La Jolla (figure 5) from October 1995 through March 1996. The anomalously warm water at La Jolla and Pacific Grove during the winter and springs of 1995 and 1996 is consistent with the elevated sea level. The sharp drop in temperature in the spring of each year is consistent with

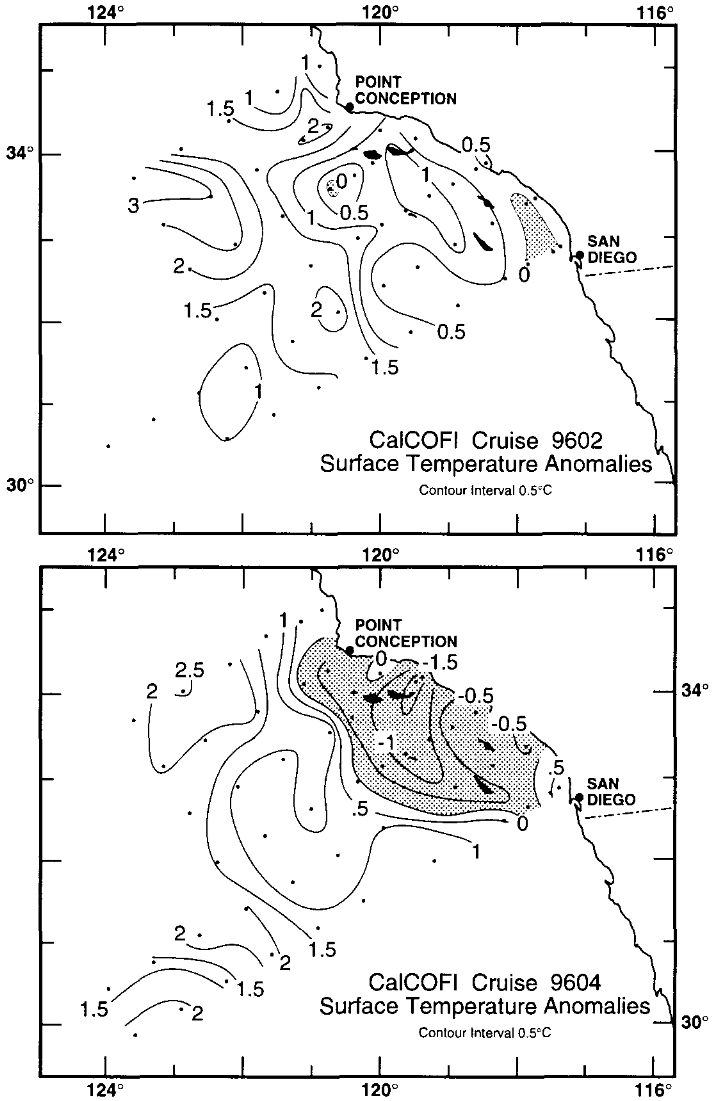

Figure 19. Anomalies in SST (°C) for CalCOFI cruises 9602 and 9604.

the strong winds observed at the coastal buoys. There was a relatively sharp drop in coastal sea-surface temperature and sea level at about the same time as the coastal winds changed from winter conditions with episodic storms and winds from the south to relatively strong winds consistently blowing equatorward along the coast. These changes all occurred about April 1995, and all were coincident with the elevated nutrient and chlorophyll concentrations in the coastal regime of the CalCOFI area during April 1995.

The data from central and northern California suggest that environmental structure to the north was responding in much the same way as in the CalCOFI region. Patterns in wind, coastal temperature, and sea level, as well as anomalies of the upwelling index were generally similar in both regions, and the coastal surveys off central California indicated that the circulation pattern was similar to the long-term mean. This is consistent with the observations that the low-frequency variability in physical and biological structure tends to be spatially coherent in the California Current (Chelton et al. 1982; Roemmich and McGowan 1995).

How are the indices of biological structure measured on the CalCOFI cruises (chlorophyll, primary production, macrozooplankton biomass, bird abundance) related to environmental structure? Spatial pattern and the annual pattern in chlorophyll is generally related to physical structure in the manner expected if phytoplankton abundance is strongly influenced by the nutrient distribution. Chlorophyll concentration is high where there are nutrients in the euphotic zone. Nutrients are generally present in the euphotic zone where they are expected based upon the physical structure. The correlation between spatial pattern in the chlorophyll concentration and physical structure is thus consistent with a relatively uncomplicated link between physical structure and phytoplankton abundance through the nutrient distribution and the relatively short response time of the phytoplankton to nutrient inputs. However, the relation between the available physical proxy variables—such as coastal temperature, sea level, wind, or the upwelling index—and the nutrient distribution is not well established, especially on an interannual time scale.

A more complex pattern of linkages between environmental structure and biological structure emerges when a longer-term view is taken and higher trophic levels are considered. Chlorophyll was relatively high during the spring of 1995 and 1996 in the context of measurements made during spring of the last twelve years. This is consistent with the nutrient distribution observed on these cruises. However, the pattern in higher trophic levels does not appear to be consistent with this. The much longer time series for macrozooplankton biomass shows a large decrease which started in the mid-1970s (Roemmich and McGowan 1995). This decrease continued over the period considered here, and 1995 and 1996 are low even in the context of the preceding twelve years.

The bird data considered here cover the past eight years. These data show an increase in the birds whose range is associated with the offshore waters of the CalCOFI survey area, and a decrease in the seabirds in the inner coastal waters of the CalCOFI survey. The mean abundance of the birds in the inner waters is much greater than the mean abundance of those found farther offshore.

The long-term trends in macrozooplankton biomass and seabird abundance thus appear to be inconsistent with bottom-up forcing. The reasons for this are unclear. It may be that macrozooplankton biomass actually is increasing, but is affected by a long time lag, or that a seasonal increase is missed by the long gaps between the spring and summer CalCOFI survey cruises. It may also be that macrozooplankton biomass and seabird abundance are not tightly coupled to phytoplankton abundance or primary production on this time scale. Ambiguity in the processes that link physical and biological structure makes it difficult to predict patterns in upper trophic levels or to model the consequences of global change in the physical environment.

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