THE STATE OF THE CALIFORNIA CURRENT IN 1994–1995: A PERIOD OF TRANSITION

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ABSTRACT

This report is a summary and preliminary analysis of recent observations of oceanographic and biological structure of the California Current region, with emphasis on atmospheric pressure and wind fields, ocean circulation pattern and hydrographic structure, and upper-ocean plankton distributions. There was a strong transition in atmospheric circulation and sea-surface temperature between the fall of 1994 and winter/spring 1995. A deep low pressure replaced high pressure over the eastern North Pacific, and this resulted in frequent and intense winter storms. During 1994, the California Current returned to a more typical circulation pattern, following El Niño conditions during 1992 and 1993. The cruise mean values of chlorophyll and primary production fit into the scatter of values observed during the prior decade, while macrozooplankton biomass continued its trend of being low both in terms of the last decade and the 45-year record. Winter and spring of 1995 were marked by an unusually strong red tide event in the coastal region of southern California, and high chlorophyll and primary production in the CalCOFI study region.

INTRODUCTION

Physical and biological structure in the California Current are variable on a broad range of space-time scales. Large interannual fluctuations, such as the changes associated with the 1992–93 El Niño event in the California Current (Hayward 1993; Hayward et al. 1994; Lynn et al. 1995), are superimposed upon the longer-term trend of increasing sea level (Roemmich 1992), warming of the upper layers, and decrease in macrozooplankton biomass (Roemmich and McGowan 1995). Regional patterns are also affected by the annual cycle and by the strong mesoscale structure of the California Current (Lynn and Simpson 1987), by storms, and by episodic events such as the dramatic red tide in southern California (described here). Understanding the causes of variability in the California Current region and wise management of its resources will require improvements in our knowledge of variability on a range of space-time scales. Management issues are further complicated by the need to make decisions based upon limited information, often before data sets can be fully analyzed. The latter problems underscore the need for a better understanding of how to interpret those data sets, such as coastal shore station data, which can be processed and distributed in a timely manner.

This is a continuation of an annual series of reports on the oceanographic state of the California Current. The emphasis here is upon the regional structure in the past two years, but some longer-term data are shown in order to place the more recent observations in a larger context. Emphasis is on the coastal shore station observations and on hydrographic data collected on CalCOFI time-series cruises and other process cruises conducted by NOAA and SIO.

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 (1916–93 for La Jolla and 1919–93 for Pacific Grove) harmonic mean. 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 station positions of the CalCOFI grid as well as the station plans for two survey cruises conducted off central California in the spring

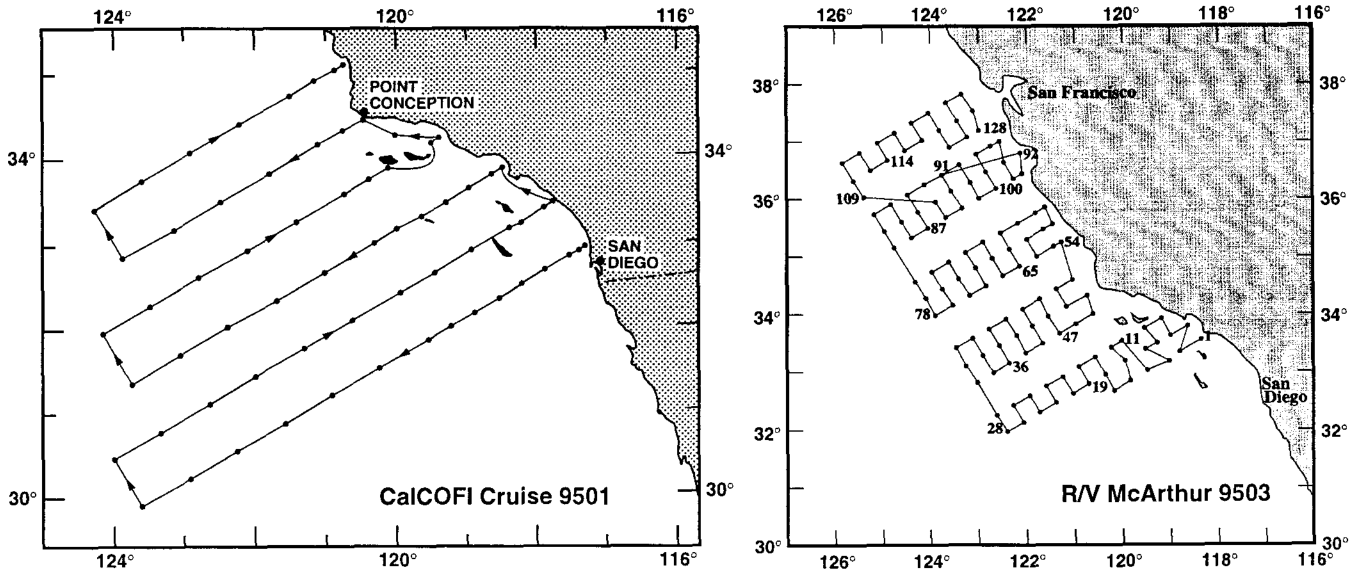

Figure 1. Current CalCOFI cruise pattern as illustrated by the cruise track for CalCOFI cruise 9501, and the cruise track for the hydrographic surveys conducted aboard R/V *McArthur* (9–27 March and 18 April–7 May 1995) as part of the hake biomass assessment program.

of 1995 are shown in figure 1. A two-ship survey using the CalCOFI station pattern was conducted 9–27 March 1995 by the Southwest Fisheries Science Center for surveying hake eggs and larvae and physical oceanography. A second survey, also with two ships, was conducted 18 April–7 May 1995 on the same basic pattern. Casts were made to 1000 m and included profiling of oxygen concentration, fluorescence, beam transmission, and, on the second survey, backscatterance. The hake egg and larval sampling (R/V *David Starr Jordan*) was conducted by a combination of bongo tows and MOCNESS tows on CalCOFI lines 87, 80, 73, 67, and, in the second survey only, 60.

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 10 l 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, chlorophyll fluorescence, and dissolved oxygen are made from water pumped through the ship, and the data are logged at one-minute intervals. Acoustic 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 1994). CalCOFI hydrographic data can be accessed via the Internet; telnet to **nemo@ucsd.edu** and login as **info**.

In addition to the above core measurements made by the CalCOFI program, a diverse group of measurements were made by cooperative research programs on recent cruises. These include pelagic seabird abundance (R. Veit, J. McGowan), bio-optical and phytoplankton measurements (G. Mitchell, M. Vernet, J. Collier, S. Bower, E. Venrick), copepod egg production (M. Mullin), phytoplankton pigment production (R. Goericke, M. Olaizola), optical particle counter (K. Osgood, D. Checkley), carbon dioxide (D. Keeling), chlorofluorocarbons (D. Min), methyl halides (B. Miller), and CO dynamics (O. Zafiriou). These observations will be discussed separately by the groups making them. Several students and volunteers have also been trained on recent cruises.

An index of monthly averaged coastal upwelling (Bakun 1973) was calculated. This index is based on six-hourly estimates of alongshore wind stress, which are derived from surface atmospheric pressure gradients using the geostrophic constraint. Time-series of the index were generated at coastal grid points every three degrees of latitude. Monthly anomalies, referenced to the mean for that calendar month for 1946–94, are contoured for the period January 1991 through April 1995.

EVOLUTION OF STRUCTURE

Sea-surface temperature (SST) at La Jolla was anomalously warm during most of 1994, and the positive

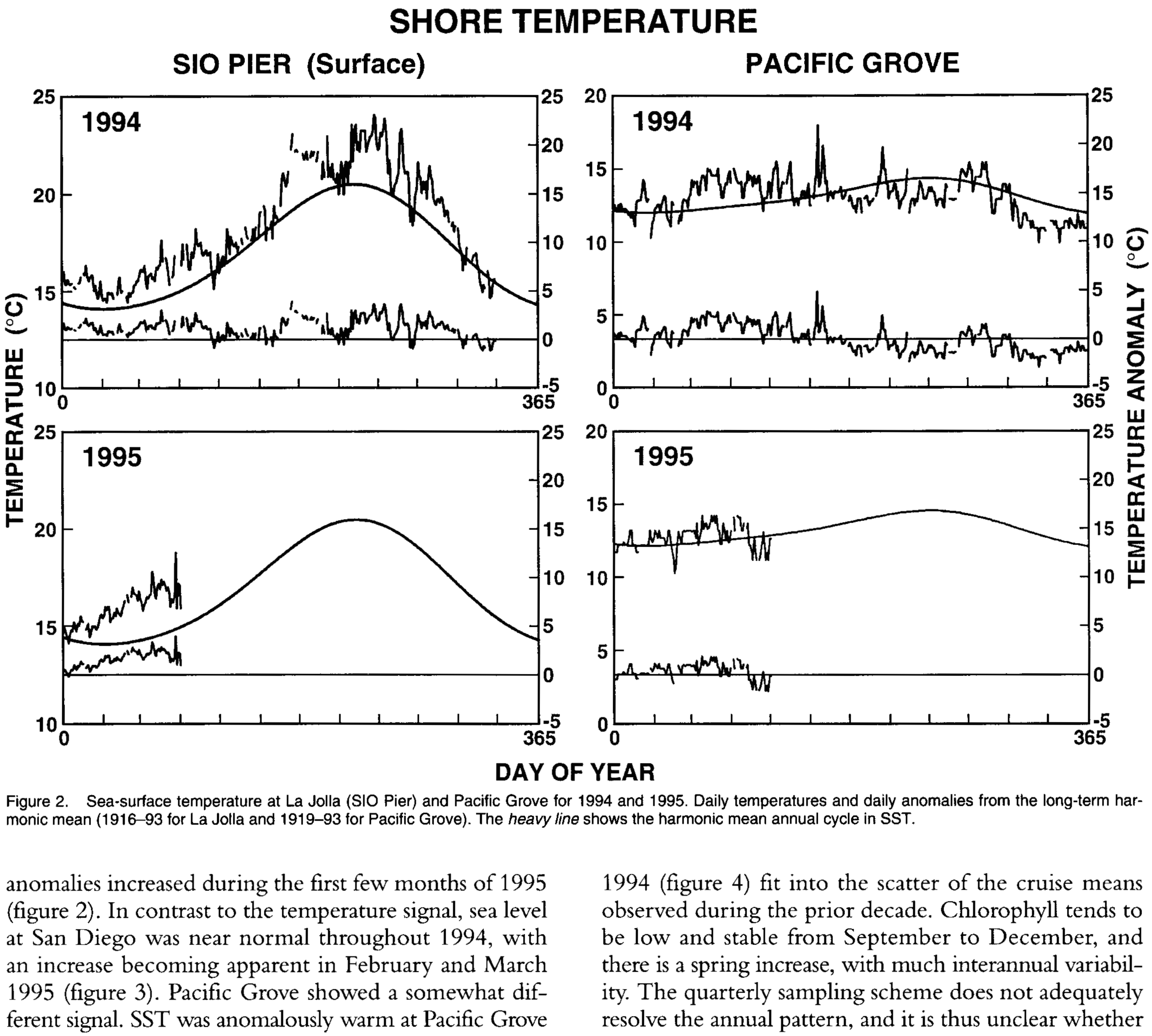

Figure 2. Sea-surface temperature at La Jolla (SIO Pier) and Pacific Grove for 1994 and 1995. Daily temperatures and daily anomalies from the long-term harmonic mean (1916–93 for La Jolla and 1919–93 for Pacific Grove). The *heavy line* shows the harmonic mean annual cycle in SST.

anomalies increased during the first few months of 1995 (figure 2). In contrast to the temperature signal, sea level at San Diego was near normal throughout 1994, with an increase becoming apparent in February and March 1995 (figure 3). Pacific Grove showed a somewhat different signal. SST was anomalously warm at Pacific Grove in the first half of 1994 and anomalously cool in the latter half of the year. Pacific Grove appeared to be fluctuating about normal conditions in early 1995. Sea level at San Francisco was anomalously low throughout 1994, but there was an abrupt increase to anomalously high values in January and February 1995. It is possible that the 1995 increase in sea level was associated with the runoff of large volumes of fresh water into San Francisco Bay, rather than being an indicator of the offshore hydrographic structure of the California Current.

Cruise mean values of vertically integrated chlorophyll, an index of phytoplankton abundance (and also primary production; Mantyla et al. 1995), and macrozooplankton biomass from the CalCOFI survey cruises provide an index of biological structure during this period. Cruise means of integral chlorophyll for 1993 and 1994 (figure 4) fit into the scatter of the cruise means observed during the prior decade. Chlorophyll tends to be low and stable from September to December, and there is a spring increase, with much interannual variability. The quarterly sampling scheme does not adequately resolve the annual pattern, and it is thus unclear whether the between-year differences are real or due to undersampling of the annual pattern. The January and, especially, April 1995 CalCOFI cruises showed high values of chlorophyll (see below). Macrozooplankton biomass showed a continuation of the long-term pattern described by Roemmich and McGowan (1995); the 1993 and 1994 cruise mean values were quite low when compared to both the preceding decade and the 1951–84 mean for the area. Anchovy spawning biomass has declined steadily since 1983–84 in the Southern California Bight, while sardine biomass continues to increase (see Smith 1995).

Atmospheric Forcing

There was a remarkable transition in the North Pacific atmospheric circulation and sea-surface temperature be-

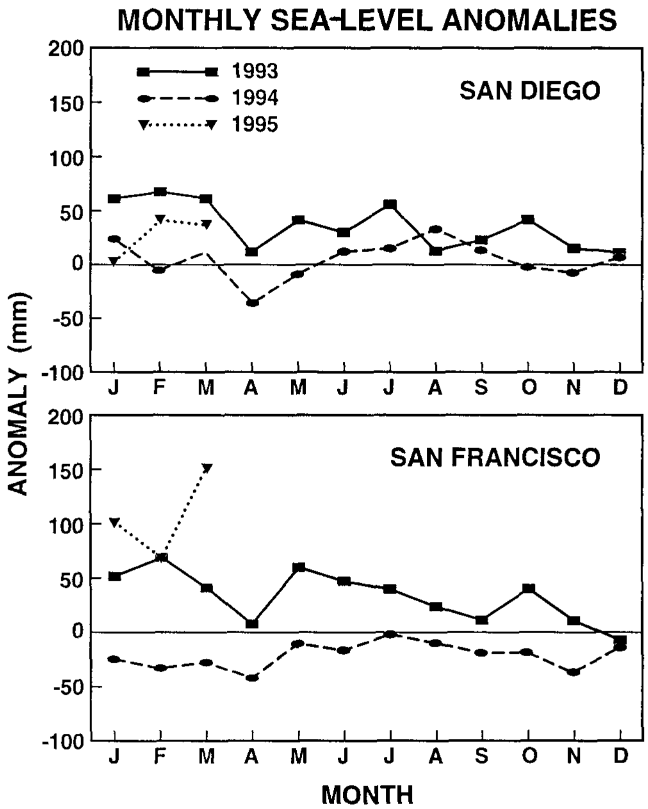

Figure 3. Monthly anomalies in sea level at San Diego and San Francisco for 1993, 1994, and 1995. The monthly anomalies are deviations from the 1975–86 period corrected for atmospheric pressure.

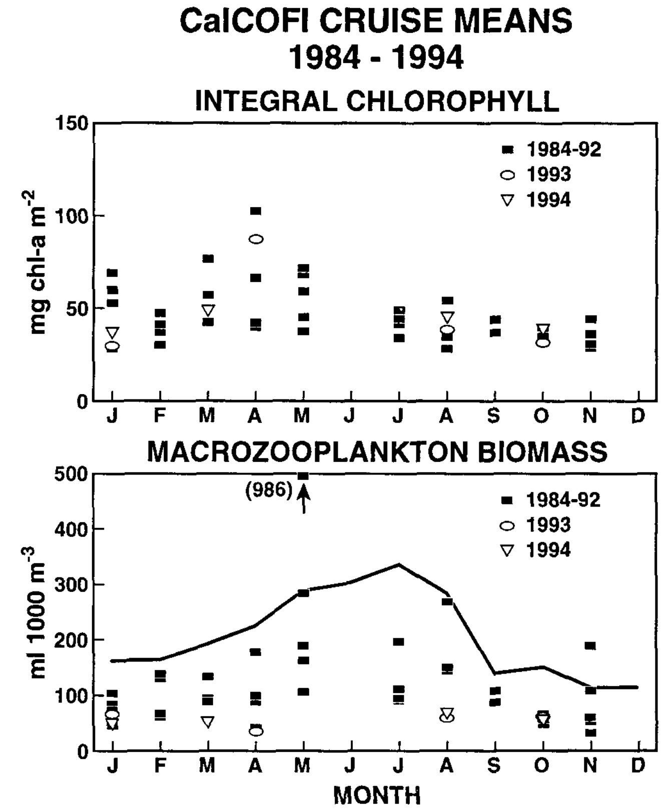

Figure 4. Cruise means of vertically integrated chlorophyll and macrozooplankton biomass plotted versus the month of each cruise. Each point represents the mean of all of the measurements made on a single cruise (normally 66). The *solid squares* show the cruises that took place from 1984 to 1992; the *open symbols* indicate data for 1993 and 1994. The monthly mean macrozooplankton biomass for the study area from 1951 to 1984 is shown as a *solid line*.

tween fall 1994 and winter/spring 1995. The fall was marked by higher-than-average atmospheric pressure and the anticyclonic (air) circulation over the eastern North Pacific, with enhanced northerly (equatorward) winds along the west coast of the United States (figure 5). Consistent with this flow pattern, fall 1994 had cooler-than-normal air temperatures over the western United States and cool SST along the west coast (figure 6). The atmospheric pattern reversed in winter, with the appearance of a deep low pressure (figure 7) and frequent storminess over the eastern North Pacific. The strong low which developed in December and prevailed during the early spring (figure 8) is a typical feature during winters with "mature" El Niño conditions such as those present during the 1994–95 winter. Offshore of northern California at about 40°N, 145°W the anomaly of the winter (December, January, February) mean sea-level pressure approached −9 mb, more than 2 standard deviations below its long-term mean. In response to the cyclonic flow around the deep low, enhanced westerly/northwesterly winds dominated the central North Pacific, and anomalous southerly/southwesterly winds occurred along the west coast of the United States. This would have promoted enhanced wind mixing and heat losses in the central North Pacific and diminished these effects along the eastern boundary. Evidence of these processes is provided by the marked cooling of the SST in the central North Pacific and a decided warming along the west coast, where the SST anomalies reversed from their cool state in the fall to positive values in March (figure 9).

The patterns in the coastal upwelling indices are consistent with the patterns in North Pacific atmospheric circulation and SST in 1994–95. The indices in fall 1994 were upwelling-favorable south of about 45°N. Anomalies, relative to 1946–94 means, were positive (greater-than-normal upwelling) along virtually the entire west coast. Anomalies in October and November 1994 were especially large, often more than 2 standard deviations above the long-term mean (figure 10). The situation changed dramatically in December. Indices were strongly downwelling north of 40°N; anomalies shifted to negative or near-zero from 27°–57°N. Anomalies were even more negative in January 1995 (< -100 $m^3/s/100$ m coastline), 2–6 standard deviations below the long-term mean over 36°–51°N, corresponding to downwelling indices of about -100 to -300 m^{-3} s^{-1} per 100 m

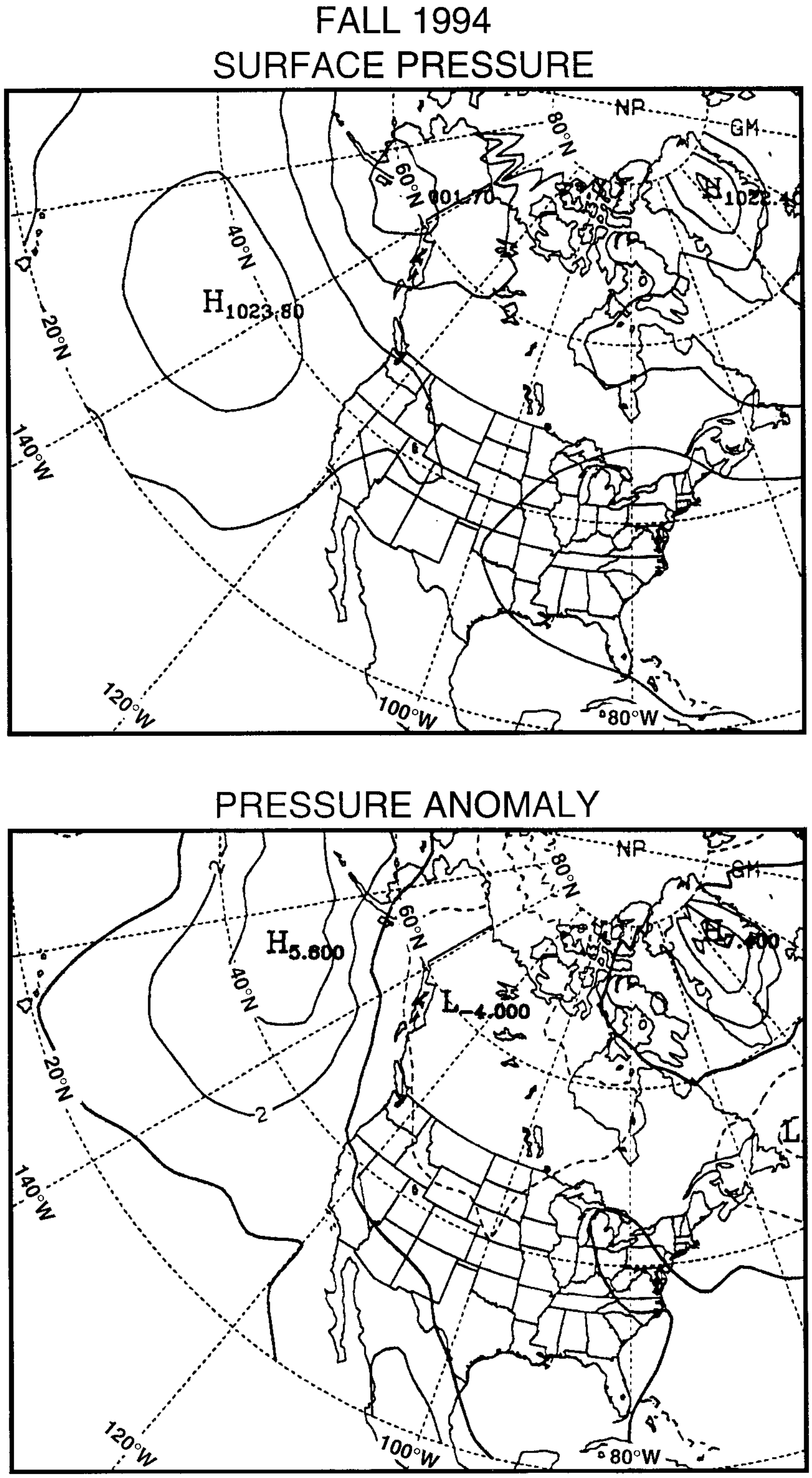

Figure 5. Surface atmospheric pressure (mb) and surface atmospheric pressure anomaly for fall (September–November) 1994.

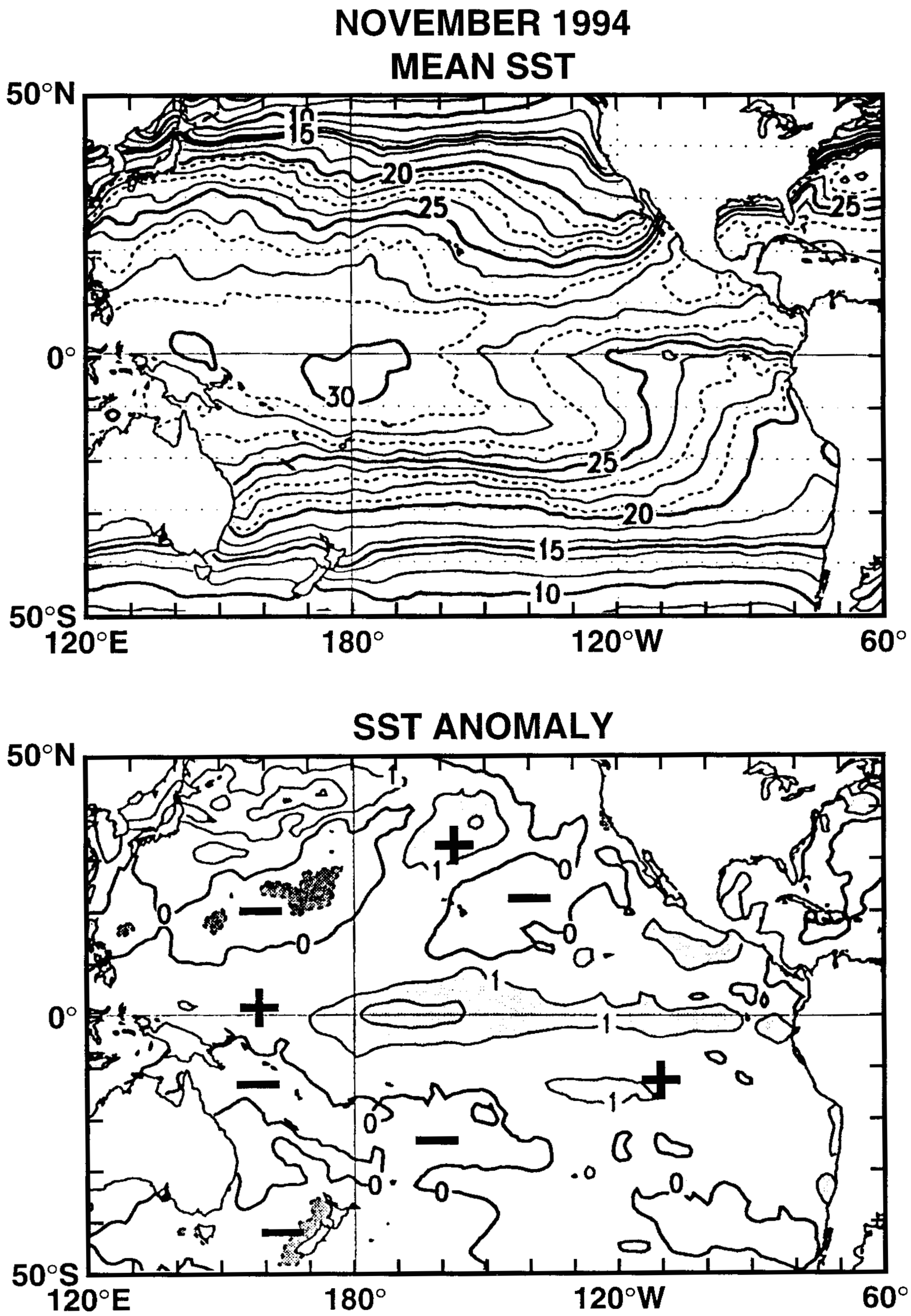

Figure 6. Mean and anomalous SST (°C) for November 1994.

coastline. Anomalies relaxed in February, but remained negative south of 40°N. The region of positive (upwelling) values coincided with this area of negative anomaly; i.e., weaker-than-usual downwelling north of 40°N, weaker-than-normal upwelling south of 40°N. While the sign of the index remained positive in March south of 40°N, negative anomalies (reduced upwelling) returned to virtually the entire California Current region. Thus the signature of upwelling conditions changed from positive anomalies and very strong upwelling in the fall of 1994, to very negative anomalies and strong downwelling in early 1995. This transition is presumably a reflection of the latest El Niño. It agrees with similar transitions in late 1991 and 1992, which also are associated with El Niño events, although the upwelling anomalies in early 1995 were significantly more negative than their 1992 and 1993 equivalents.

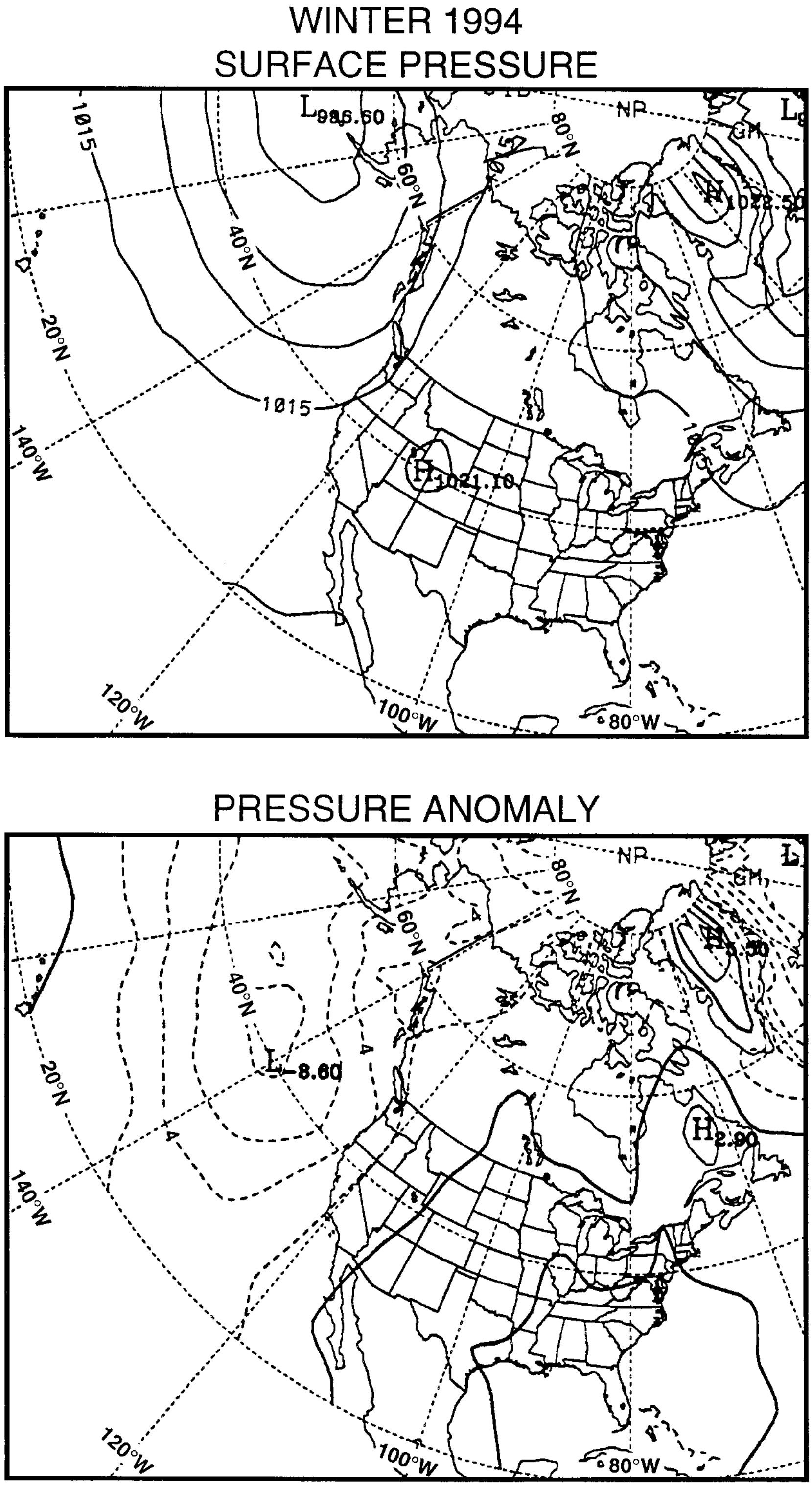

Figure 7. Surface atmospheric pressure (mb) and surface atmospheric pressure anomaly for winter 1995 (December 1994, January and February 1995).

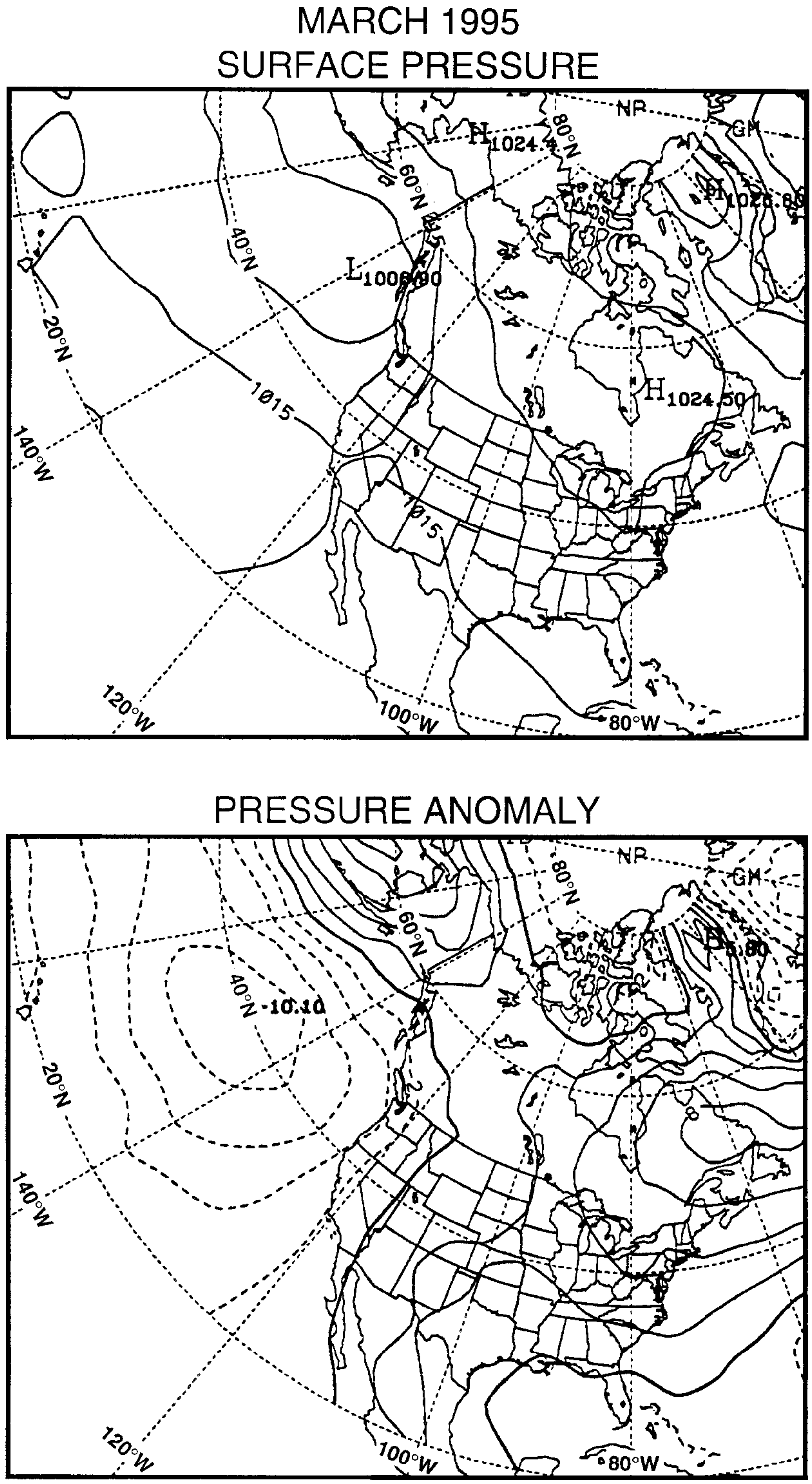

Figure 8. Surface atmospheric pressure (mb) and surface atmospheric pressure anomaly for March 1995.

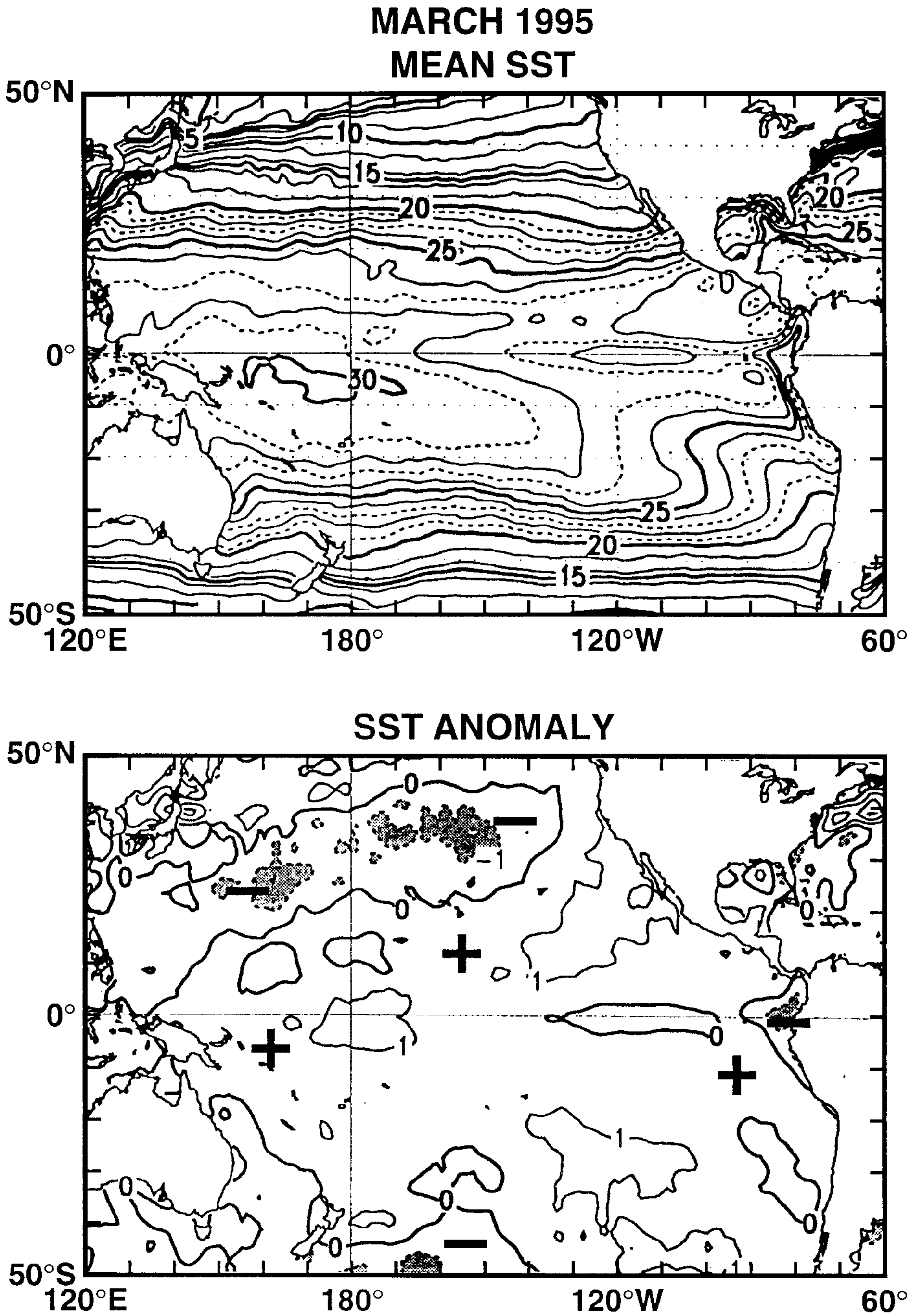

Figure 9. Mean and anomalous SST (°C) for March 1995.

The 1995 Southern California Red Tide

The southern California coastal region was affected by a strong red tide event in spring 1995. Although no systematic study of this event was organized, a series of ad hoc observations including measurements from small boats and the SIO Pier, counts of phytoplankton samples collected on CalCOFI cruises, and observations from private planes and ships of opportunity allow a preliminary description of this phenomenon and its relation to the local weather. Discoloration of the coastal waters of southern California caused by massive accumulations of phytoplankton has been relatively common. Red tides have been recorded in the southern California region since 1901 (Torrey 1902), and they are usually created by the dinoflagellate species *Gonyaulax polyedra*, *Porocentrum micans*, *Gymnodinium sanguinium*, and—as "yellow tides"—*G. flavum*.

During the first four months of 1995, an exceptional

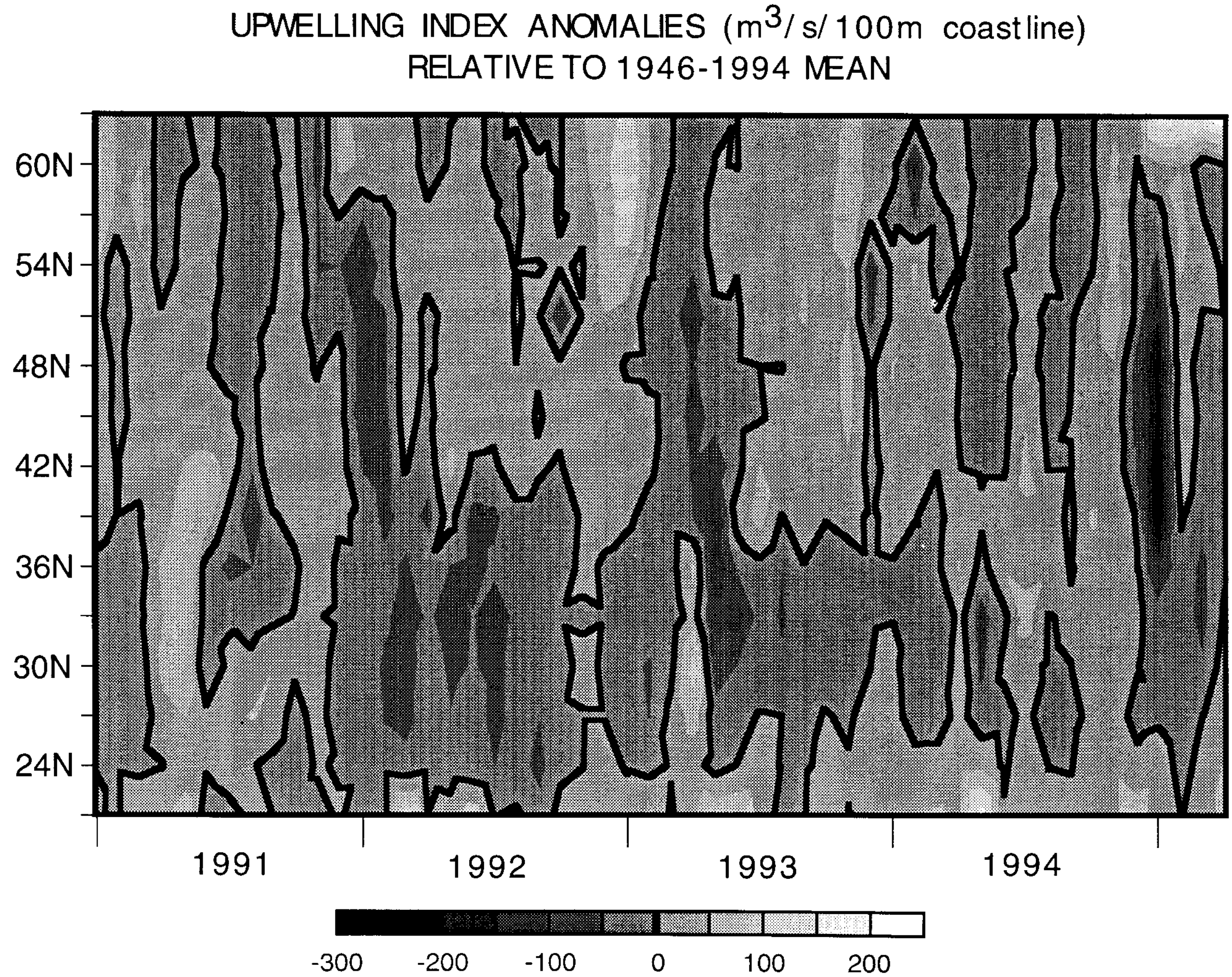

Figure 10. Contour plot of anomalies of monthly averaged coastal upwelling indices for January 1991 through April 1995 for 22°N to 60°N. Anomalies are referenced to the 1946–94 period. Positive values denote stronger-than-average upwelling, or weaker-than-normal downwelling. *Lighter shading* denotes higher (more upwelling) values. *Bold contours* denote zero anomaly (value equal to long-term monthly mean).

bloom of *Gonyaulax polyedra* Stein was recorded from Santa Barbara to San Diego, and as far offshore as San Clemente Island. This bloom reached concentrations of more than 2 million cells l^{-1}, with associated values of chlorophyll of 519 µg chl a l^{-1} at La Jolla. These were not the highest values recorded for this region; Holmes et al. (1967) measured similar chlorophyll values during a *Gymnodinium* bloom during May 1964. Not since the records of Torrey (1902), however, has a bloom been so dense or so widespread. While apparently nontoxic, this bloom was unusual in its timing, duration, and spatial extent.

January, February, and March 1995 were unusually wet in southern California, with some record warm temperatures during February. Approximately 17 inches of rain were recorded in San Diego, with about 10 inches falling in January alone (figure 11). Normal rainfall from July 1 to May 1 is about 9.7 inches. Extensive flooding occurred in northern California, while landslides, flooding, and great coastal runoff were recorded in many communities along the Southern California Bight.

Cell counts of samples taken from the SIO Pier on January 3, 1995, showed nearly 60,000 cells l^{-1} of *Gonyaulax polyedra*. This sample preceded the first major San Diego rainstorm by one day, indicating that there was a substantial population of *G. polyedra* in the water column before the heavy rains and runoff. Mixed-layer samples taken during the first 1995 CalCOFI cruise (9501) showed up to 80,000 cells l^{-1} in coastal waters of the Southern California Bight, with *G. polyedra* dominant in every coastal station (figure 12). The highest cell concentrations were associated with anomalously fresh water (salinity of 32.8) located between lines 90 and 87. Consistent with this, CTD/Rosette casts on CalCOFI cruise 9501 showed low surface salinity at a few coastal stations, and high nutrient concentrations in the low-salinity surface water.

The surface waters off Scripps Pier were freshened

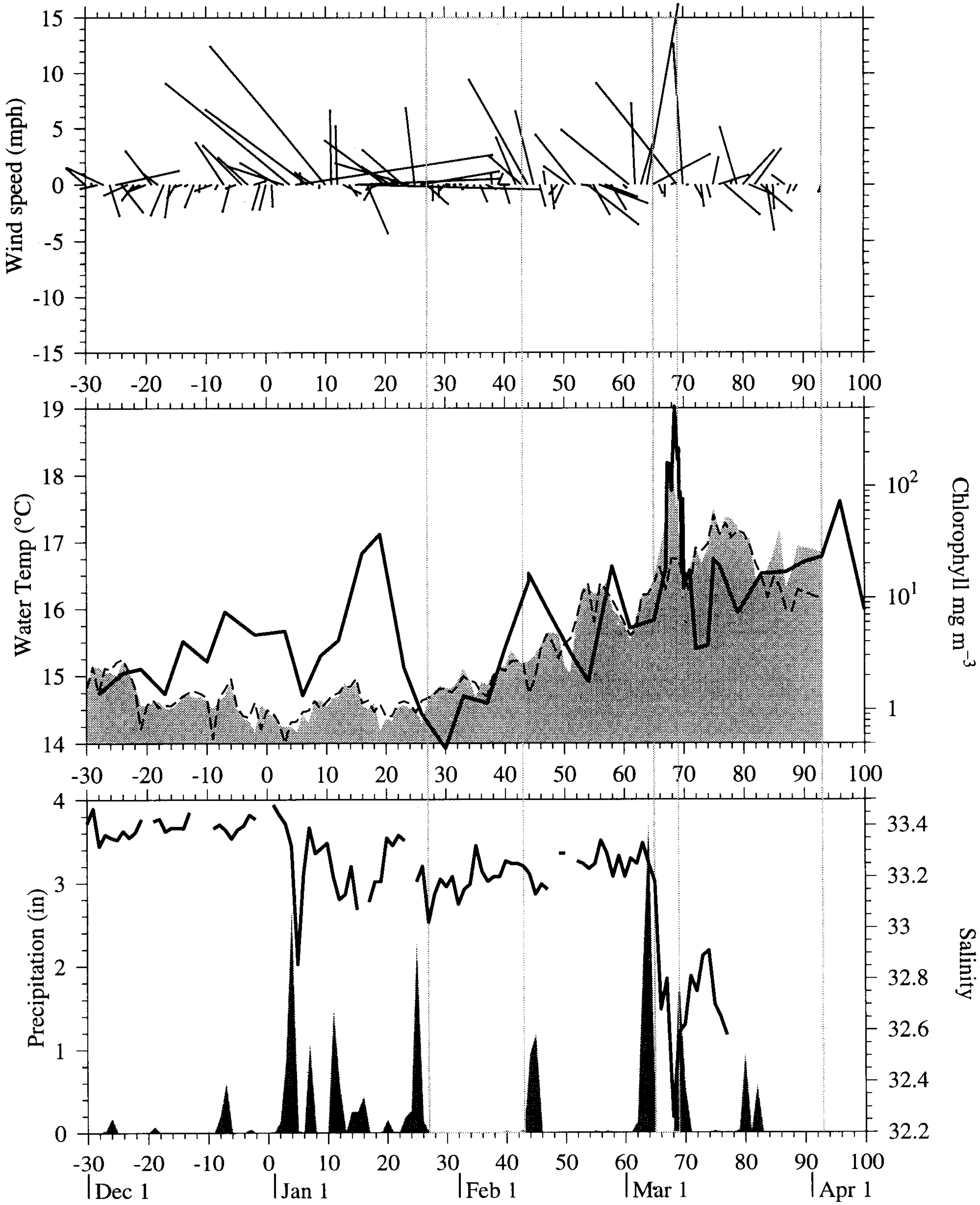

Figure 11. *Upper panel*, time series of wind speed and direction measured at the SIO Pier. Vector points in the direction toward which the wind was blowing. *Middle panel*, surface (*shaded area*) and bottom (*dashed line*) water temperatures measured at the SIO Pier. Temperatures are uncalibrated, but the trends are believed to be accurate. Chlorophyll concentration (*heavy solid line*) measured from surface samples taken at the SIO Pier. *Bottom panel*, precipitation (*shaded curve*) measured in San Diego, and surface salinity (*heavy line*) at SIO Pier. *Vertical gray lines* bracket the period of initial red patch observation and red tide growth (January 27 to February 12), peak red tide density and bioluminescence (March 6 to March 10), and peak *Noctiluca* concentrations (April 3).

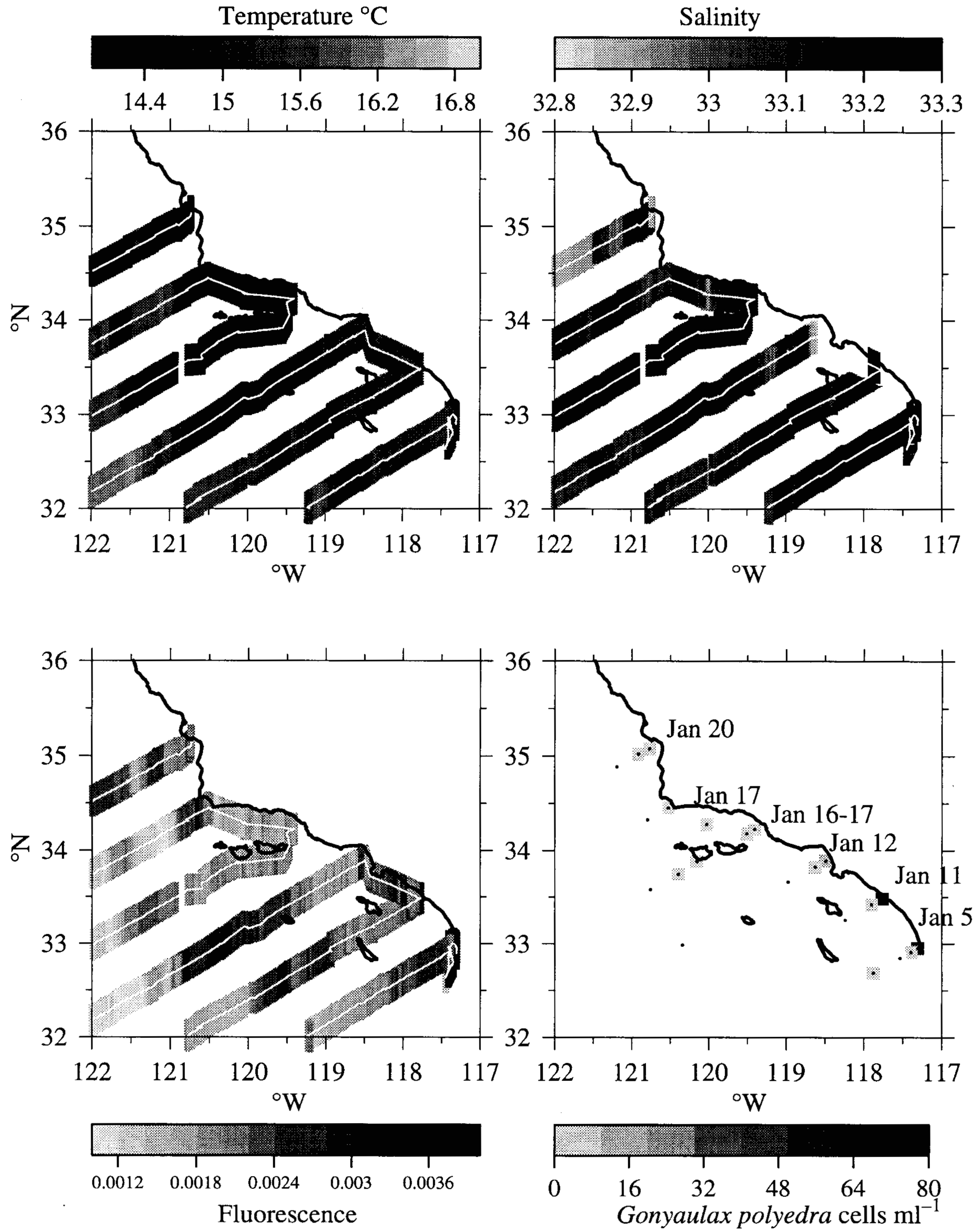

Figure 12. Temperature, salinity, fluorescence, and *Gonyaulax polyedra* cell concentration on CalCOFI cruise 9501. Data are from the continuous underway data logging system. *White line* gives the ship track. The salinity was below 30 (minimum value of about 22.5) in the area along the coast between the second and third lines (about 32.5° to 33°N) where no data are apparent. Dates on the *G. polyedra* panel indicate when the station was occupied.

dramatically after a major storm on January 4. By the middle of January chlorophyll values had climbed to nearly 40 $\mu g\ l^{-1}$, but they declined sharply during the latter part of the month. Around February 1, visible patches of red water were evident off the SIO Pier and in the waters off Point Loma. On February 7, red patches were observed off San Clemente Island. A calm, sunny period during the first two weeks of February led to warming of the surface waters and steadily increasing chlorophyll values at La Jolla. The phytoplankton community was dominated by *Gonyaulax polyedra*, which created almost a monoculture in coastal waters. By the first week of March, coastal waters were dark brown, with obvious stripes and patches created by the interaction of physical flows and dinoflagellate swimming behavior (e.g., Kamykowski 1974, 1981). Nocturnal bioluminescence was quite spectacular: the crests of breaking waves glowed with a strong blue light. The bioluminescence and chlorophyll peaked at SIO on March 10. Strong winds beginning on the night of March 10 temporarily dissipated the bloom.

The phytoplankton bloom recovered after the March 10 storm, but never to the levels recorded the previous week. About this time, high numbers of the heterotrophic dinoflagellate *Noctiluca miliaris* were recorded in the plankton, and the cells were filled with *Gonyaulax polyedra*. By the first week of April, the *Noctiluca* had reached such high concentrations that they created bright orange stripes in convergence zones along the coast. Observations from a small plane showed that these stripes were less than 100 m wide in their cross-shelf dimension, and as much as 40 km long, stretching from Point Loma to Solana Beach. The surface waters were a dense orange color, created by massive accumulations of floating *Noctiluca*. A storm during the weekend of April 8 effectively dissipated both the *Noctiluca* and *Gonyaulax* blooms.

The occurrence of such a dense *Gonyaulax polyedra* bloom in the winter months in the coastal waters of southern California had never previously been observed. Previous records show this dinoflagellate species to form red tides only during May–September (Torrey 1902; Allen 1938, 1946; Clendenning 1958; Holmes et al. 1967). The unusual timing of the formation of *G. polyedra* red tide is probably related to the unusual oceanographic conditions prevailing in the region during the winter of 1994–95 (see previous section).

Although there were substantial numbers of *Gonyaulax polyedra* present in the coastal waters before the high rainfall of January 1995, it is likely that the nutrients contained in the runoff contributed to the exceptionally high blooms seen during the following several weeks. In particular, the peak biomass and bioluminescence during the first week of March followed a very heavy rain and strong heating of the surface waters. The strong stratification that developed probably isolated the nutrients in the freshwater runoff to the surface layer, creating a well-lit, nutrient-rich stratum. Growth rates estimated from changes in chlorophyll concentration at the SIO Pier were very roughly 0.1 day^{-1}, a reasonable value for this dinoflagellate (e.g., Thomas and Gibson 1990). Peak growth rates may have been higher, but were still probably much lower than the maximal growth rate possible at that temperature (about 1.4 day^{-1} for diatoms at 14°C; Eppley 1972).

The decline of the *Gonyaulax polyedra* bloom was related both to grazing by *Noctiluca miliaris* and to storms. The highest concentrations of *Noctiluca* were found offshore of the maximum *Gonyaulax* numbers, in relatively clear waters (Secchi depths of 12–14 m versus 1–4 m in the *Gonyaulax* bloom). The clarity of the water probably resulted as grazing *Noctiluca* eliminated *Gonyaulax* from the water column. Both the *Gonyaulax* and *Noctiluca* blooms disappeared suddenly after a storm on April 8, which mixed the populations downward and washed them out to sea.

Pattern on CalCOFI Survey Cruises

9401. As suggested by the preliminary data shown previously (Hayward et al. 1994), the circulation pattern in January 1994 consisted of a meandering southward-flowing jet of low-salinity water (figure 13). The flow field was perturbed by a series of several strong mesoscale eddies. This flow field was anomalous with respect to the long-term January pattern derived from the harmonic mean dynamic height field in that the typical, well-developed inshore countercurrent was absent. This was in marked contrast to January of 1992 and 1993, when the coastal countercurrent was exceptionally strong and broad due to El Niño conditions (Hayward 1993; Hayward et al. 1994; Lynn et al. 1995). (The long-term harmonic mean dynamic height field for the period of time corresponding to each CalCOFI cruise is shown in Hayward et al. 1994.) Surface chlorophyll was generally low throughout the grid, except for a band of relatively high values (>1 $\mu g\ l^{-1}$) along the coast. Vertical sections along line 90 (shown in Scripps Institution of Oceanography 1994) show that shoaling of the pycnocline and nutricline at the inshore edge of the high-velocity southward flow features is associated with regions of elevated chlorophyll.

9403. The flow field on cruise 9403 was similar to the long-term mean pattern for March, with southward flow extending inshore to the coast and the normal seasonal absence of the Southern California Eddy (figure 14). These observations again show that pattern in the 100 m temperature field based upon preliminary data (shown in Hayward et al. 1994) was a good predictor of the dynamic height field. An eddy dipole was present in the

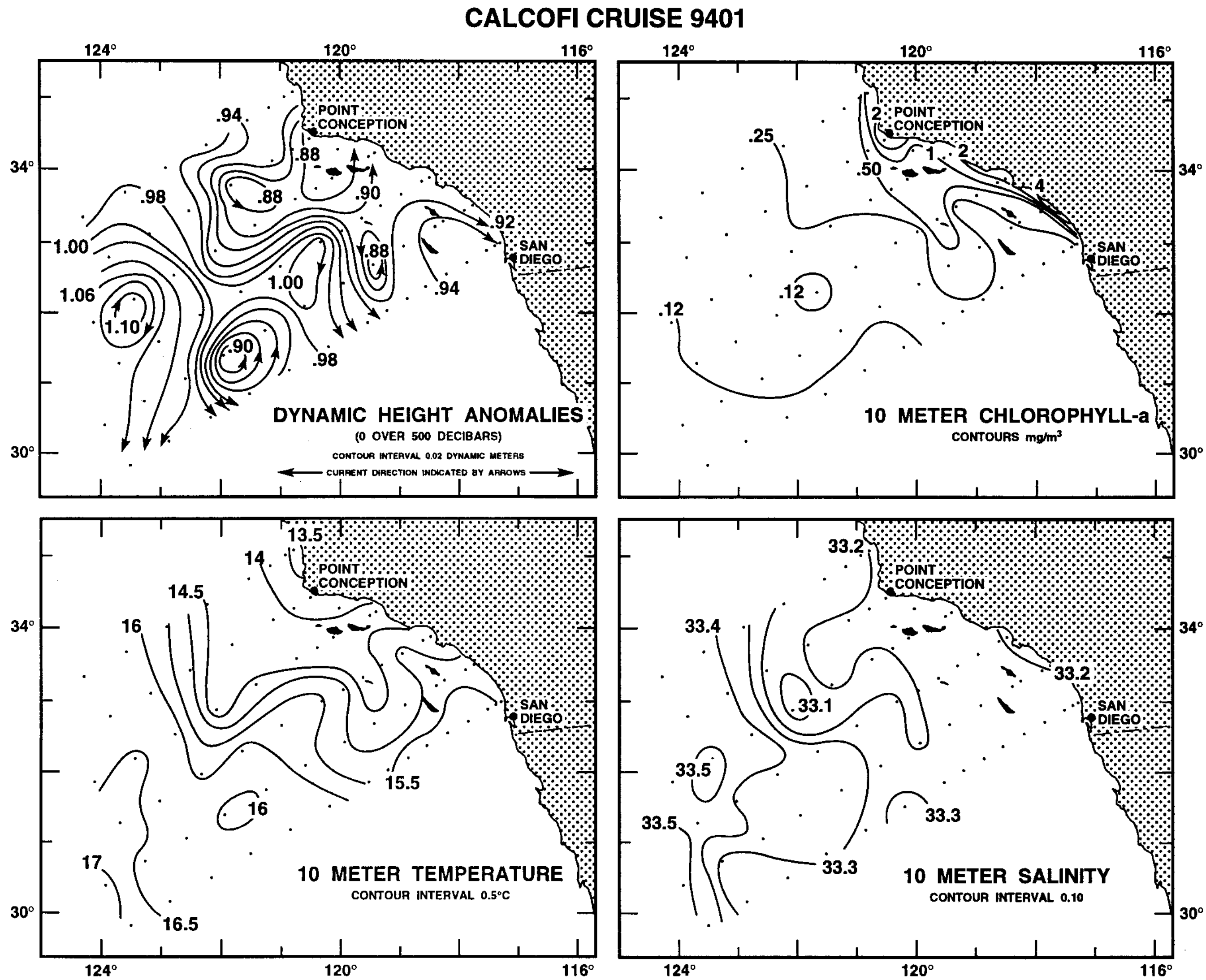

Figure 13. Spatial patterns for CalCOFI cruise 9401, 20 January–7 February 1994, including upper ocean flow field derived from 0 over 500 m dynamic anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

offshore part of the pattern. Chlorophyll increased to relatively high values (>4 μg l^{-1}) in the central coastal region, especially the Santa Barbara Channel. Vertical sections along line 90 show the sharp rise of the pycnocline and nutricline in the coastal region which is expected from the flow field, and that chlorophyll is elevated in the region where the nutricline has shoaled (figure 15).

9408. The circulation pattern in August 1994 continued to be typical of the long-term mean: the Southern California Eddy and a coastal countercurrent were well developed throughout the sample grid (figure 16). Broad southward flow of the low-salinity core of the California Current was evident offshore of the Southern California Eddy. No well-developed eddies were present in the sample grid. There was a sharp offshore bend to the California Current and associated east-west front between lines 90 and 93. Ten-meter chlorophyll was generally low throughout the grid, with the exception of the coastal region near Point Conception, where higher values were seen especially at inshore stations.

9410. The October 1994 current structure was also quite similar to the long-term mean pattern for October, with a broad coastal countercurrent extending along the shore to north of Point Conception, and southward flow of the low-salinity core of the California Current offshore (figure 17). Mesoscale structure had intensified from the weak structure of August, and several mesoscale eddies were now apparent within the sample grid. The sharp offshore bend of the California Current evident during the previous August was absent, indicating that it was not a persistent feature; this was in contrast to a sharp bend in the California Current in the same region, which persisted for at least six months during

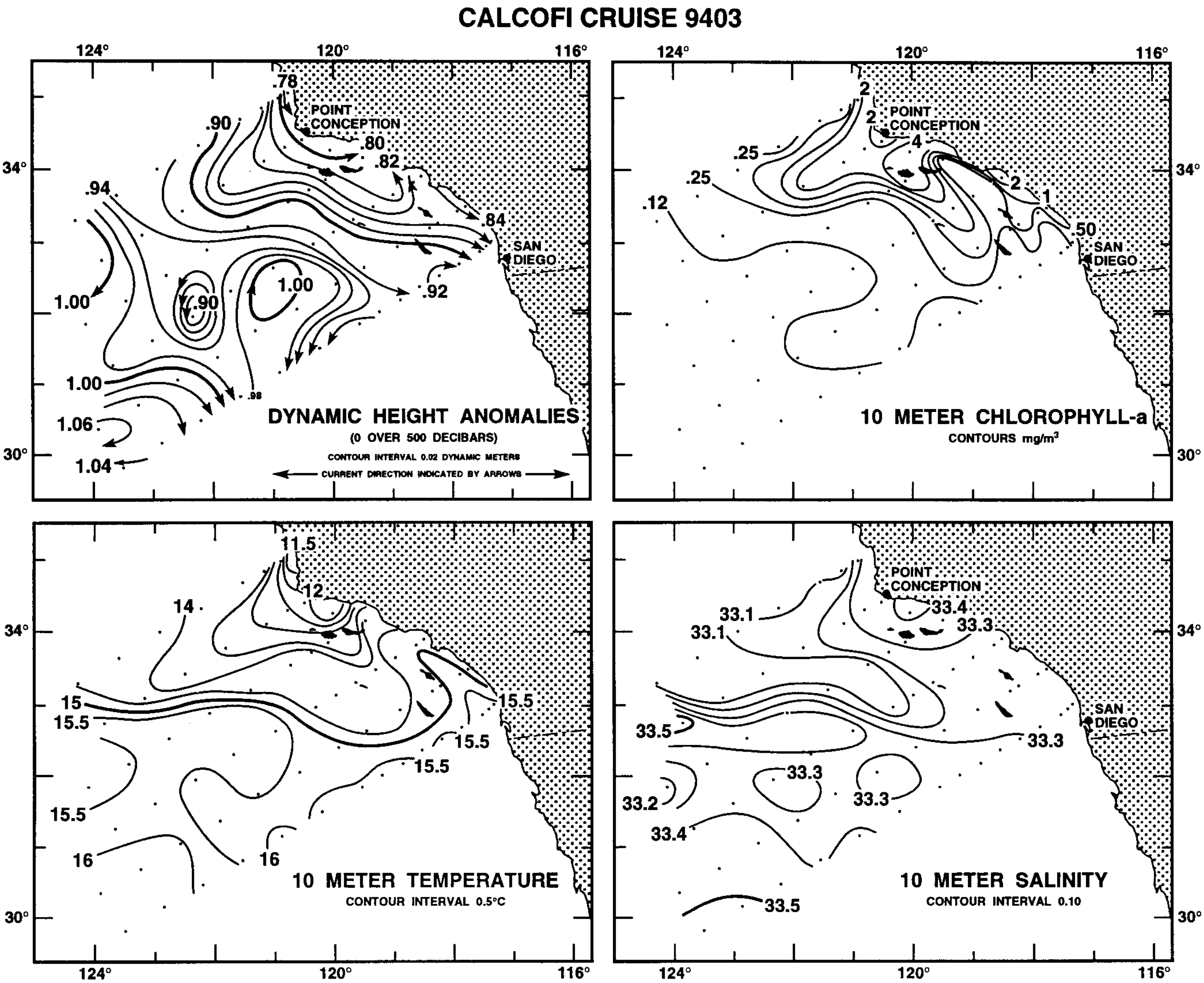

Figure 14. Spatial patterns for CalCOFI cruise 9403, 22 March–8 April 1994, including upper ocean flow field derived from 0 over 500 m dynamic anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

1993–94 (Hayward et al. 1994). Ten-meter chlorophyll continued to be low, except for the coastal region near Point Conception.

9501. The January 1995 dynamic height field indicated a confused circulation pattern with generally southerly flow in the offshore region of the California Current perturbed by a series of several strong mesoscale eddies (figure 18). There was strong onshore flow between lines 77 and 80. A coastal countercurrent was evident in southern California, and there was strong southward flow along the coast at Point Conception. The overall pattern was anomalous with respect to the long-term mean in that the northward flow along the coast did not extend around Point Conception. The January cruise sampled during a period of strong winter storms which also brought extremely heavy precipitation to California and much of the west coast. Some of the most inshore stations showed low surface salinity, high nutrient and high surface chlorophyll concentrations, presumably due to runoff and the developing red tide event. Chlorophyll exceeded 10 $\mu g\ l^{-1}$ at station 90.28. Ten-meter chlorophyll values were greater than in January of 1992 or 1993, with a pool with values of greater than 1 $\mu g\ l^{-1}$ offshore of southern California. Elevated values of chlorophyll were present in the coastal region near Point Conception as on several prior cruises.

9504. The April 1995 cruise sampled during what was perhaps the roughest weather observed at sea during a CalCOFI cruise in the last decade. In contrast to the large-scale patterns in atmospheric forcing, there were strong northerly winds and strong coastal upwelling for the duration of the cruise. This was also a cruise with some of the highest values of chlorophyll (and presumably primary production; e.g., Mantyla et al. 1995)

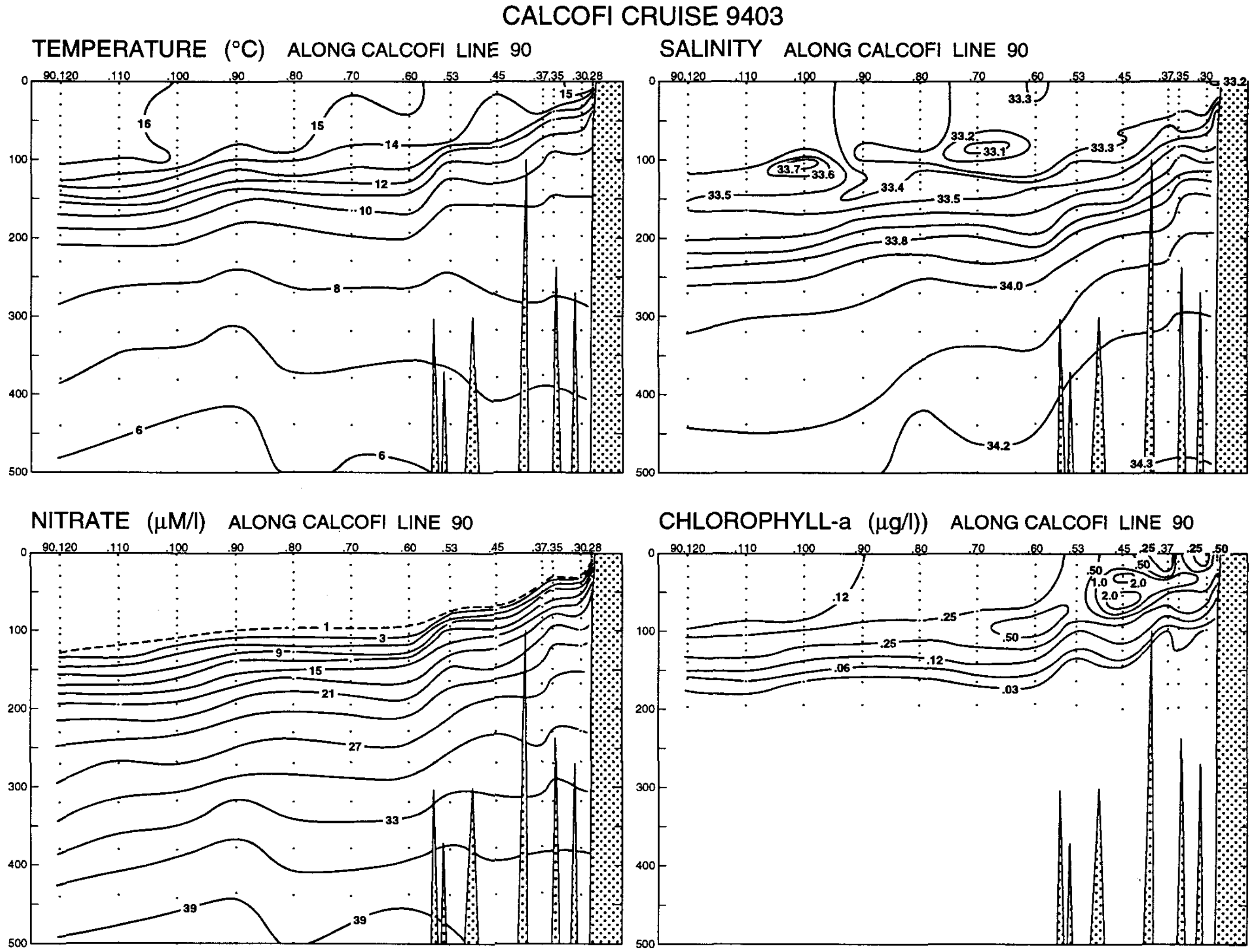

Figure 15. Vertical sections of temperature, salinity, nitrate, and chlorophyll along line 90 for cruise 9403.

during the past decade. The hydrographic data are preliminary. The current field inferred from the 100 m temperature shows generally southward flow with a strong eddy in the outer part of line 87 (figure 19). This looks very much like the long-term mean pattern of dynamic height. The coastal countercurrent appeared to be absent. In spite of the large positive SST anomalies at La Jolla, the circulation pattern is not consistent with El Niño conditions being present in the California Current. Ten-meter chlorophyll was very high throughout the coastal region. Values of greater than 20 $\mu g\ l^{-1}$ were observed in the Santa Barbara Channel, and the area with values greater than 4 $\mu g\ l^{-1}$ was quite extensive. This area was much more extensive than the area affected by the southern California red tide event. Examination of the phytoplankton samples showed that phytoplankton in the high chlorophyll regions was dominated by diatom species characteristic of the spring bloom, although red tide species were still present at some inshore stations in the Southern California Bight. Chlorophyll was much higher than in cruise 9304, probably due to sampling later in the year and a stronger bloom.

Central California Observations

The region off central California between Monterey Bay and Bodega Bay was surveyed once in March 1994 and three times in May–June 1994, as part of the SWFSC Tiburon Laboratory's annual surveys of pelagic young-of-the-year rockfish (data provided by William Lenarz and Stephen Ralston). At this time, the CTD data are available for interpretation; ADCP and biological data are currently being processed. The Tiburon Laboratory can supply further information on these data sets. In addition, the hake surveys in early 1995 extended north to this region.

The hydrographic and dynamic nature off central California during early 1994 suggests a return to more typical conditions following the 1992–93 El Niño period,

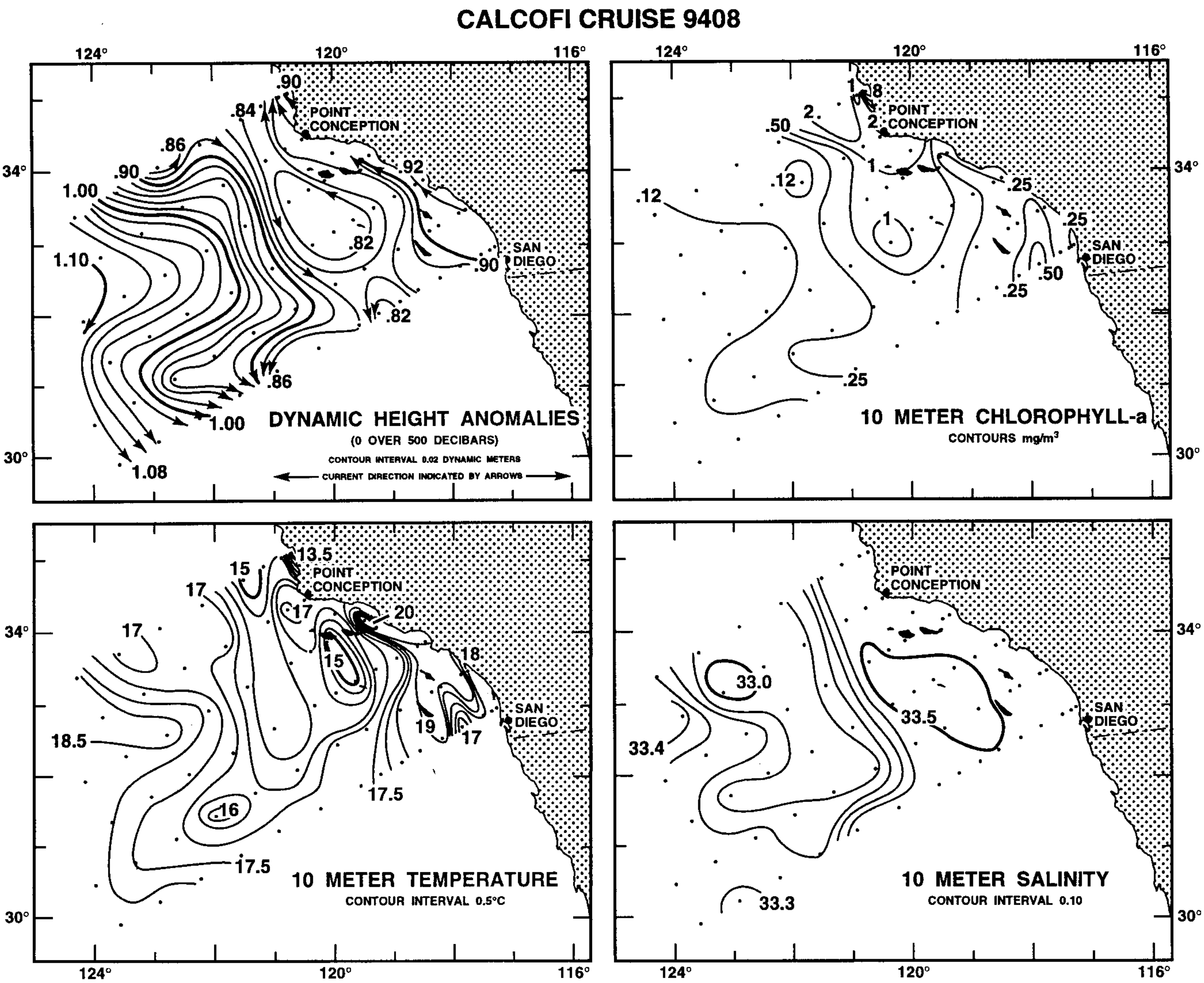

Figure 16. Spatial patterns for CalCOFI cruise 9408, 5–20 August 1994, including upper ocean flow field derived from 0 over 500 m dynamic anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

consistent with the results of the CalCOFI surveys off southern California. The circulation in early March 1994, inferred from near-surface dynamic heights relative to 500 db, was generally southward and meandering, in stark contrast to the poleward flow noted at this time of year in 1992 (Lynn et al. 1995). The dynamic thickness of the upper ocean in 1994 was 5–10 dyn. cm lower than in early 1992 (Lynn et al. 1995) and 1993 (Sakuma et al. 1994), due to the post–El Niño return of more dense (cooler, more saline) water. The 1994 thickness values were more similar to early 1991, although the upper ocean was slightly warmer and fresher in 1994, suggesting a residual El Niño water type.

The dynamic topography in May–June 1994 off central California showed a continuation of the meandering southward flow typical of this time of year. Again the upper ocean was as much as 10 dyn. cm lower than during May–June 1992 (Lynn et al. 1995) and 1993 (Sakuma et al. 1994). Dynamic heights were very similar in magnitude and structure to 1991. Upper water-column temperatures and salinities were near typical values for this area, and cooler and more saline in comparison to 1992 and 1993. Slope water at 200 m depth in 1992 was cooler and fresher relative to 1992 and 1993, as well as relative to the long-term means. A possible explanation for this is a reduced undercurrent, or increased transport in the California Current. Alternatively, the California Current may have been displaced more onshore than normal at mid-depths.

Preliminary analysis of the CTD data collected during the hake egg and larvae surveys of March and April 1995 that were conducted off southern and central California (figure 1) were consistent with the circulation patterns observed on the CalCOFI cruises made

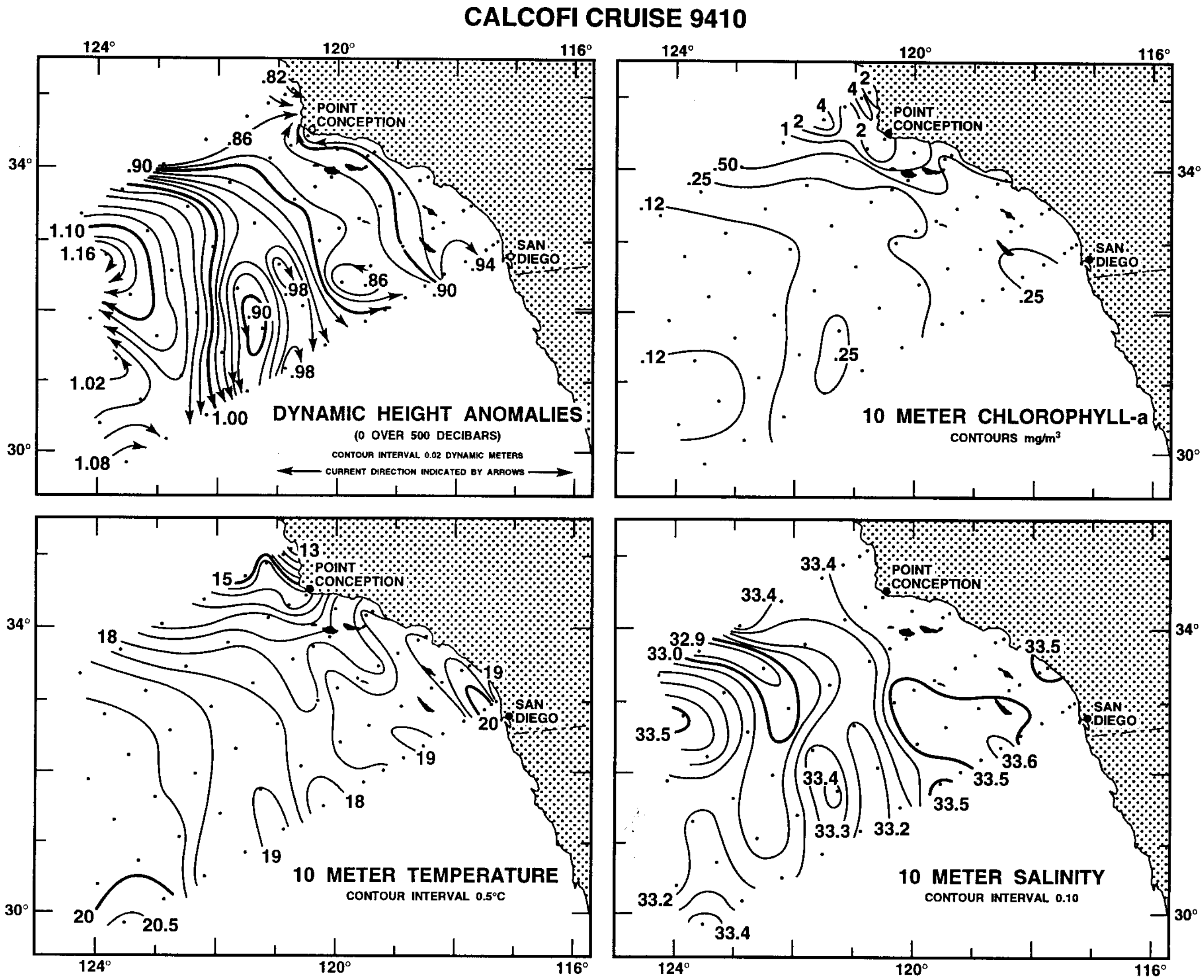

Figure 17. Spatial patterns for CalCOFI cruise 9410, 30 September–16 October 1994, including upper ocean flow field derived from 0 over 500 m dynamic anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

during the same period. The countercurrent was weak or absent, and the general southward flow was perturbed by a strong mesoscale eddy field.

DISCUSSION

The circulation pattern in the California Current during January 1994 was anomalous in the absence of a coastal countercurrent. By March, however, the circulation had returned to a pattern typical of the long-term mean, and this condition persisted into early 1995. The 1994–95 period followed El Niño conditions in the California Current during 1992–93, which were characterized by an anomalously strong and broad coastal countercurrent during winter months and a deeper than normal pycnocline and nutricline. Spatial pattern in dynamic height during most of 1994 and early 1995 was similar to the long-term harmonic mean, with a mesoscale eddy field superimposed upon it. In contrast to 1992–93 (Hayward et al. 1994), during 1994 the major features in the mesoscale structure, such as eddies and sharp meanders of the California Current, did not persist in a clearly recognizable pattern between cruises. The main mesoscale pattern of 1994–95 was a waxing and waning in the number and intensity of mesoscale eddies. Mesoscale structure declined to a low level in August 1994, when no strong eddies were apparent within the CalCOFI grid, and it then increased in the fall of 1994 and early 1995.

Winter and spring of 1995 was a period of transition in the atmospheric circulation pattern. The storms and reduced upwelling of early 1995 were associated with the formation of a strong and persistent atmospheric low off the U.S. west coast. Under this winter regime winds along the California coast were anomalously southerly,

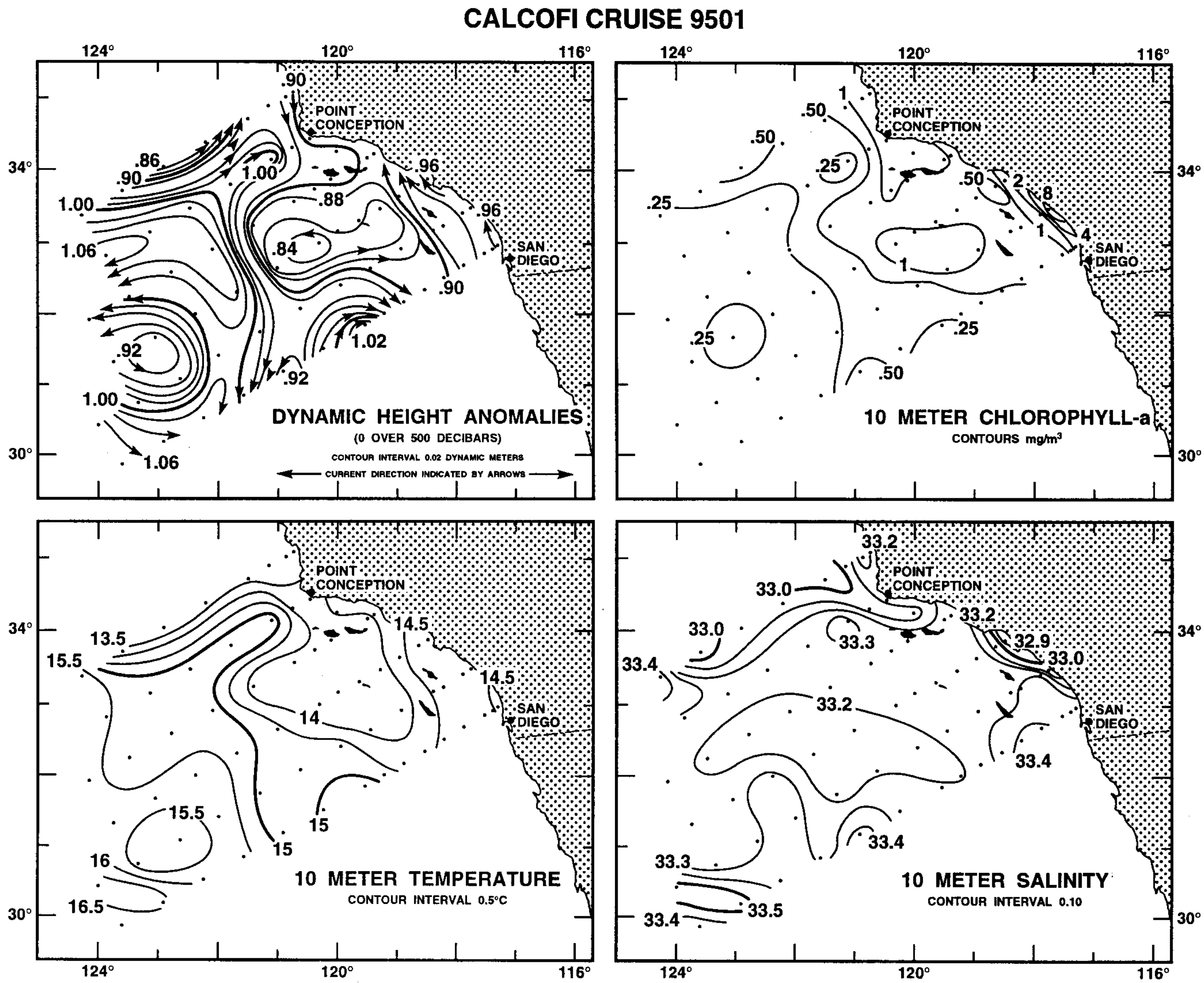

Figure 18. Spatial patterns for CalCOFI cruise 9501, 4–21 January 1995, including upper ocean flow field derived from 0 over 500 m dynamic anomalies, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

leading to reduced upwelling and warmer SSTs. But also note that the April 1995 CalCOFI cruise sampled during a period of strong upwelling and that there was an extensive phytoplankton bloom dominated by spring bloom species. Some combination of weather and oceanographic conditions during winter and early spring resulted in development of the extensive red tide in southern California. The causal factors may have included several strong storms and high runoff alternating with several days of calm and unusually warm weather in southern California and the strong slope of the pycnocline and nutricline associated with the southward flow of the California Current. Determination of what initiated the red tide will be an interesting area for further research.

The circulation pattern of the California Current during 1994 and early 1995 was not related to the coastal shore-station data in the expected manner. Predictions of a continuation or intensification of El Niño conditions in the California Current (e.g., enhanced poleward flow and a deepening of the thermocline and nutricline) based upon either the anomalously warm water at La Jolla during the second half of 1994 and early 1995 or the abrupt increase in sea level in January–March 1995 at San Francisco would have been incorrect. This shows that further research and modeling effort will be needed in order to predict the physical and biological structure of the California Current from the real-time data that are available.

Biological pattern during the study period showed a continuation of the long-term trends seen over the past few years. Chlorophyll and primary production in the CalCOFI region were typical of values observed during the prior decade. Macrozooplankton biomass continued

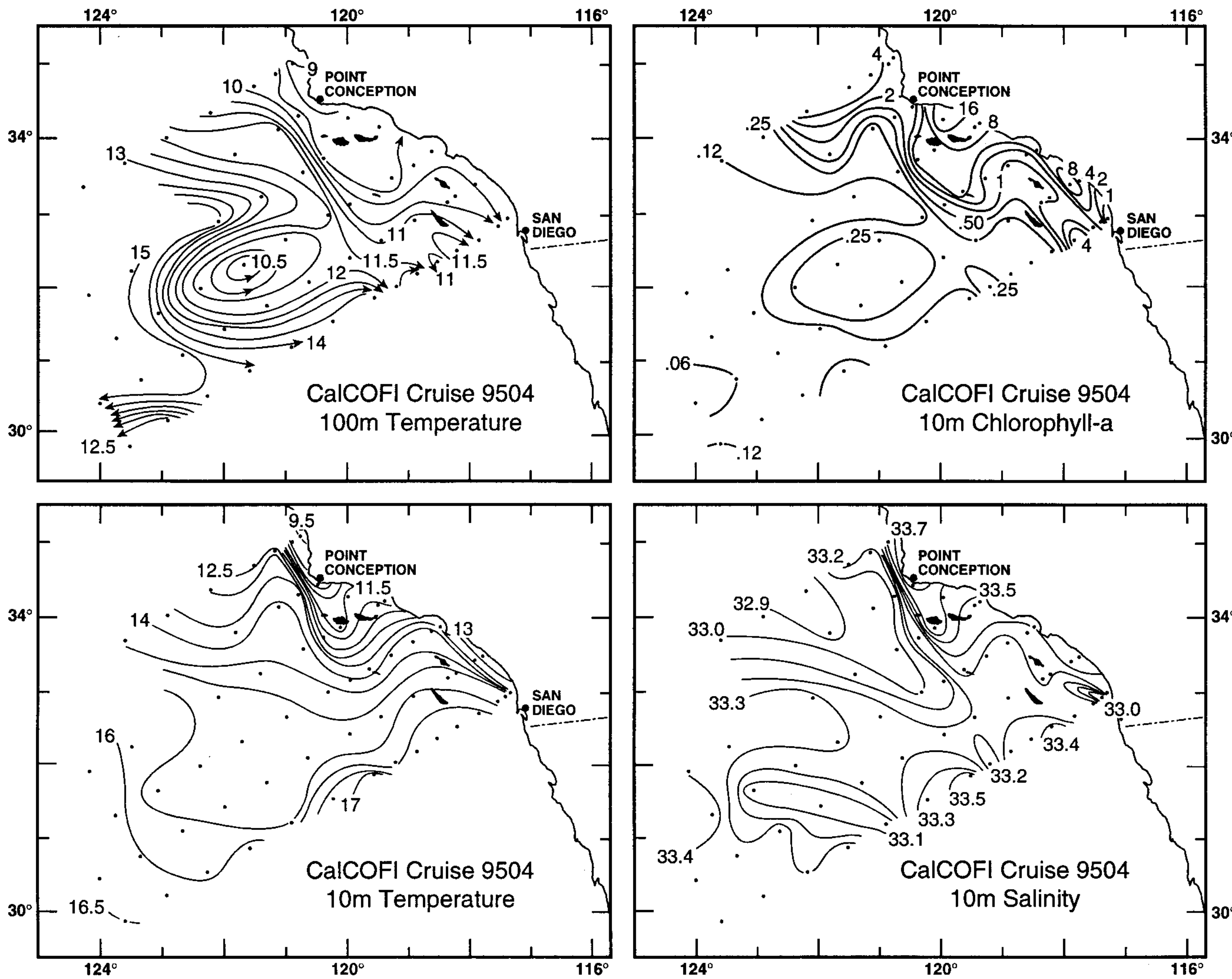

Figure 19. Spatial patterns for CalCOFI cruise 9504, 6–22 April 1995, including upper ocean flow field derived from the 100 m temperature field, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

the long-term trend of anomalously low values, with the last two years low even in the context of the prior ten years. The winter 1995 red tide in southern California was notable because of its spatial extent (at least San Diego to Santa Barbara), its unusual timing, its density (greater than 500 μg chl a l^{-1}; 2×10^6 cells l^{-1}), its striking nocturnal bioluminescence, and its obvious discoloration of the coastal waters. Although the published reports have been inadequate, this was the first reported *Gonyaulax polyedra* red tide since 1966, and was the densest reported since 1958. Biweekly chlorophyll samples from the SIO Pier have a mean of 1.574 μg chl a l^{-1}, and a standard deviation of 2.159 μg chl a l^{-1} (1984–92). The peak value of 519 μg chl a l^{-1} recorded during the 1995 red tide was 240 standard deviations above the mean, underscoring the unusual nature of this event. It was geographically the largest red tide recorded in the last 95 years, and one of the densest and most persistent on record.

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