1997

The State of the California Current, 1996-1997: Mixed Signals from the Tropics

Schwing, Franklin B.

http://hdl.handle.net/10945/43399

THE STATE OF THE CALIFORNIA CURRENT, 1996–1997: MIXED SIGNALS FROM THE TROPICS

FRANKLIN B. SCHWING
Pacific Fisheries Environmental Laboratory
National Marine Fisheries Service, NOAA
1352 Lighthouse Avenue
Pacific Grove, California 93950-2097

THOMAS L. HAYWARD
Marine Life Research Group
Scripps Institution of Oceanography, UCSD
9500 Gilman Drive
La Jolla, California 92093-0227

KEITH M. SAKUMA
Tiburon Laboratory
National Marine Fisheries Service, NOAA
3150 Paradise Drive
Tiburon, California 94920

TOM MURPHREE
Department of Meteorology
Naval Postgraduate School
254 Root Hall
589 Dyer Road
Monterey, California 93943-5114

AFFONSO S. MASCARENAS JR.
Instituto de Investigaciones Oceanológicas
Universidad Autónoma de Baja California
Apartado Postal 453
Ensenada, Baja California 22830
México

SERGIO I. LARIOS CASTILLO
Instituto de Investigaciones Oceanológicas
Universidad Autónoma de Baja California
Apartado Postal 453
Ensenada, Baja California 22830
México

ARNOLD W. MANTYLA
Marine Life Research Group
Scripps Institution of Oceanography, UCSD
9500 Gilman Drive
La Jolla, California 92093-0227

SHERRY L. CUMMINGS
Marine Life Research Group
Scripps Institution of Oceanography, UCSD
9500 Gilman Drive
La Jolla, California 92093-0227

FRANCISCO P. CHAVEZ
Monterey Bay Aquarium Research Institute
P.O. Box 628
7700 Sandholdt Road
Moss Landing, California 95039

KENNETH BALTZ
Pacific Fisheries Environmental Laboratory
National Marine Fisheries Service, NOAA
1352 Lighthouse Avenue
Pacific Grove, California 93950-2097

DAVID G. AINLEY
H. T. Harvey and Associates
906 Elizabeth Street
Alviso, California 95002

ABSTRACT

A large number of data sets from within the California Current region, and the large-scale fields that affect this region, are available for timely assessment of recent environmental conditions in this system. In addition to the long-running quarterly CalCOFI cruises, which featured the initial research cruise of RV *Roger Revelle*, several surveys off Baja California and central California have provided information on coastal areas adjacent to the present CalCOFI coverage. Conditions throughout the north Pacific and in the California Current are summarized and interpreted for the 1996–97 period.

Moderate to weak La Niña conditions have affected the north Pacific since late 1995. But this particular La Niña event displayed an unusual pattern of atmospheric heating in the tropical Pacific, compared to other La Niña events. This may have helped produce a different response over the north Pacific that was, in several important respects, different from a typical La Niña. The most notable differences were in the wind anomalies, which may have contributed to relatively high sea level and warm SSTs offshore of California and Mexico throughout this period. El Niño conditions began to develop in the tropics in early 1997. If this event continues to develop, significant effects on the California Current region can be expected.

Variability in coastal conditions is complex, and seems due to the combined effect of local processes and anomalies in large-scale atmospheric and ocean forcing. Coastal indices and time series show no dominant pattern of variability, and the anomalies from their long-term seasonal means were generally not remarkable. Upwelling indices and buoy time series suggest generally high upwelling in the spring and summer of 1996, and unusually high rates in early 1997. In May 1997, upwelling was dramatically reduced along the entire coast. At SIO Pier, SSTs were anomalously warm during the first half of 1996, but closer to the norm in late 1996 and early 1997. In spring 1997, SST and coastal sea-level anomalies began increasing, but it is premature to say this was related to El Niño forcing. What is certain is that warm, El Niño–like conditions have been observed in the region long before the initial development of this latest apparent El Niño. Winter sea-level heights were relatively high due to onshore winds and high freshwater discharge, and were connected with positive height anomalies extending across the entire north Pacific, a consequence of La Niña.

Oceanic circulation patterns observed in 1996–97 were similar to the long-term mean, and have featured relatively high mesoscale activity since early 1996. Salinities in the core of the California Current were noticeably lower than historical climatologies indicate. A strong coastal countercurrent was noted off southern California in August and October 1996 and April 1997, and along the Big Sur coast in June 1996. Warm, saline water that was low in chlorophyll was associated with this flow.

Despite reasonably high primary production based on chlorophyll concentrations, macrozooplankton biomass remains very low compared to historical levels in the

California Current. In recent years, there have also been reduced abundances of juvenile rockfish and seabird populations. High primary production is not clearly related to coastal time series or circulation patterns, and does not appear to be a good predictor of production at higher trophic levels in the California Current.

1. INTRODUCTION

Providing a timely summary and interpretation of basic environmental data sets that are applicable to ecological research is a high priority, particularly for the California Current system, where a number of interdisciplinary problems are being investigated. This report continues a series of annual papers in *CalCOFI Reports* (cf. Hayward et al. 1994, 1995, 1996) that describe and interpret recent atmospheric and oceanographic conditions in the California Current. Our objective is to provide an up-to-date assessment of environmental patterns and conditions. The primary period covered by this report is from April 1996 to April 1997, although some earlier data are included to compare recent structure to previous patterns and trends.

The fundamental emphasis is on results from the quarterly cruises that are part of the data-rich CalCOFI time series. Additional information obtained off central and Baja California during this period substantiates many of the features and patterns noted in the present CalCOFI sampling region, and gives a contemporary context to the historical CalCOFI data set that once extended from the Gulf of California and the southern tip of Baja California to the Oregon border and north. We also examine the large-scale atmospheric and oceanic conditions that force much of the variability in the California Current. Physical and biological patterns are related as well. We consider how these patterns differ from long-term means, and how biological structure may be linked to atmospheric forcing and ocean circulation.

Local patterns were affected by a weak La Niña in the tropics, which featured an unusual distribution of anomalies compared to typical La Niña events. Unlike conditions during the 1992–94 El Niño, no single dominant pattern was expressed throughout the California Current during the previous year.

2. DATA SETS AND METHODS

Coastal data include temperature and salinity at shore stations (Walker et al. 1994). La Jolla (SIO Pier) and Pacific Grove daily temperatures and their anomalies from the long-term harmonic mean (1916–93 for La Jolla and 1919–93 for Pacific Grove) are shown as time series. Coastal sea-level data from San Diego and San Francisco are shown as monthly anomalies from the 1975–95 mean, corrected for atmospheric pressure (data courtesy Patrick Caldwell, U. Hawaii Sea Level Center).

TABLE 1
Locations of SST and Alongshore Wind Time Series

Buoy	Position	Base period[a]	Alongshore angle (°N)[b]
46050 (Stonewall Bank, OR)	44.6°N, 124.5°W	(1991–96)	0
46027 (St. George, CA)	41.8°N, 124.4°W	(1983–96)	341
46013 (Bodega, CA)	38.2°N, 123.3°W	(1981–96)	312
46042 (Monterey Bay, CA)	36.7°N, 122.4°W	(1987–96)	328
46011 (Santa Maria, CA)	34.9°N, 120.9°W	(1980–96)	326
46025 (Catalina Ridge, CA)	33.7°N, 119.1°W	(1982–96)	294

[a]Period of harmonic mean.
[b]Angle determined from principal component analysis.

Monthly upwelling indices and their anomalies, relative to 1948–67, for the western North American coast are presented. From six representative buoys throughout the California Current region, time series of the daily alongshore wind component and SST (data courtesy NOAA National Data Buoy Center) are plotted against the harmonic mean of each record; the location and base period of each buoy is given in table 1.

Data from quarterly CalCOFI surveys in 1996 and 1997 are described. 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) cruises that occupy a grid of 66 stations off southern California. The core time series data set now collected at each station includes a CTD/rosette cast with sensors for pressure, temperature, salinity, dissolved oxygen, photosynthetically active radiation, fluorescence, and transmissivity. Water samples are collected at 20-24 depths in the upper 500 m to determine 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. Acoustic Doppler current profiler (ADCP) data are also recorded continuously, providing a measure of upper ocean currents as well as an estimate of zooplankton biomass based upon acoustic backscatter. The most recent data presented here are preliminary, and some changes may be made after the final processing and quality control checks. More details on the methods, information about recent activities, and CalCOFI hydrographic data can be accessed via the World Wide Web (*http://www-mlrg.ucsd.edu/calcofi.html*).

3. DYNAMICAL RESULTS

A. Large-Scale Oceanic and Atmospheric Climate Patterns

1995–97 La Niña. Large-scale surface anomalies are summarized from monthly fields, assembled from a variety of sources by the NOAA Climate Prediction Center (NCEP 1997a, b). Monthly anomalies (figures 1, 2) are departures from the 1979–95 base period. Much of the physical variability—wind, sea-surface temperature (SST)—of the California Current region during 1996–97 appears to have been related to climate anomalies in the tropical Pacific. La Niña conditions appeared in the tropical Pacific about September 1995 and continued

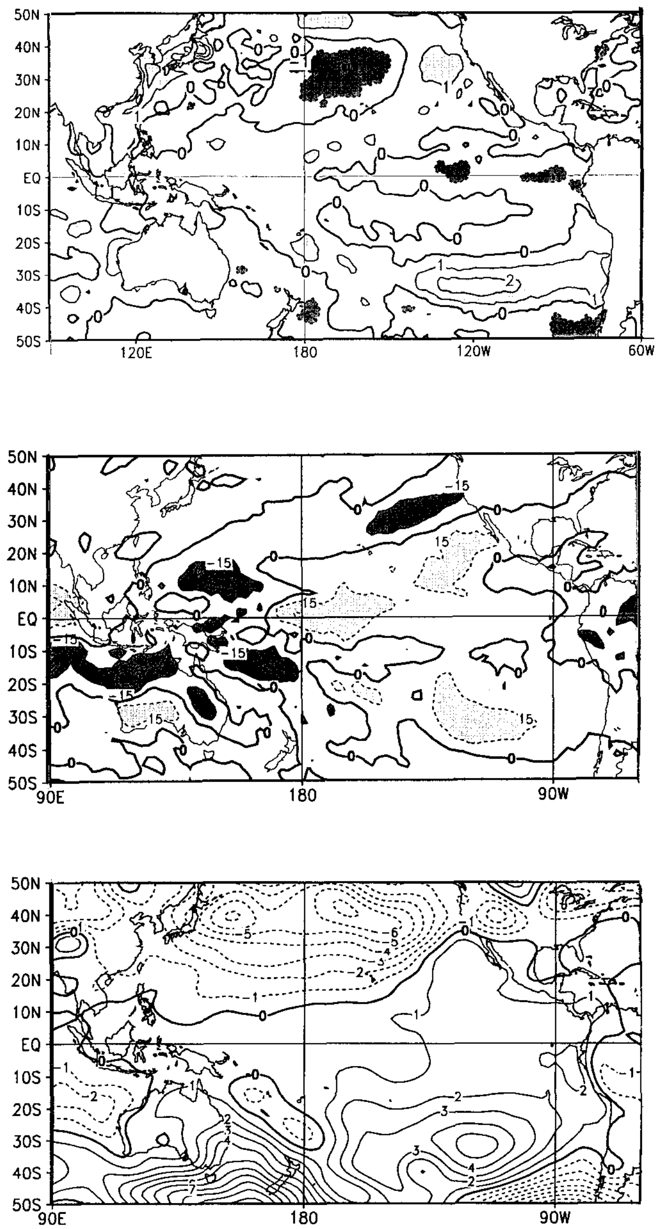

Figure 1. January 1997 Pacific Ocean anomalies of sea-surface temperature (SSTA; *top*), outgoing longwave radiation (OLRA; *center*), and sea-level pressure (SLPA; *bottom*). Anomalies are departures of monthly-averaged fields from the 1979–95 base period. Positive anomalies denote warmer than normal SST, lower than normal atmospheric heating, and higher than normal atmospheric pressure. Anomalous surface winds are approximately parallel with SLPA contours, and cyclonic (counterclockwise in Northern Hemisphere) around negative anomalies. Closer-spaced SLPA contours indicate faster anomalous winds. Adapted from NOAA National Centers for Environmental Prediction (NCEP 1997a).

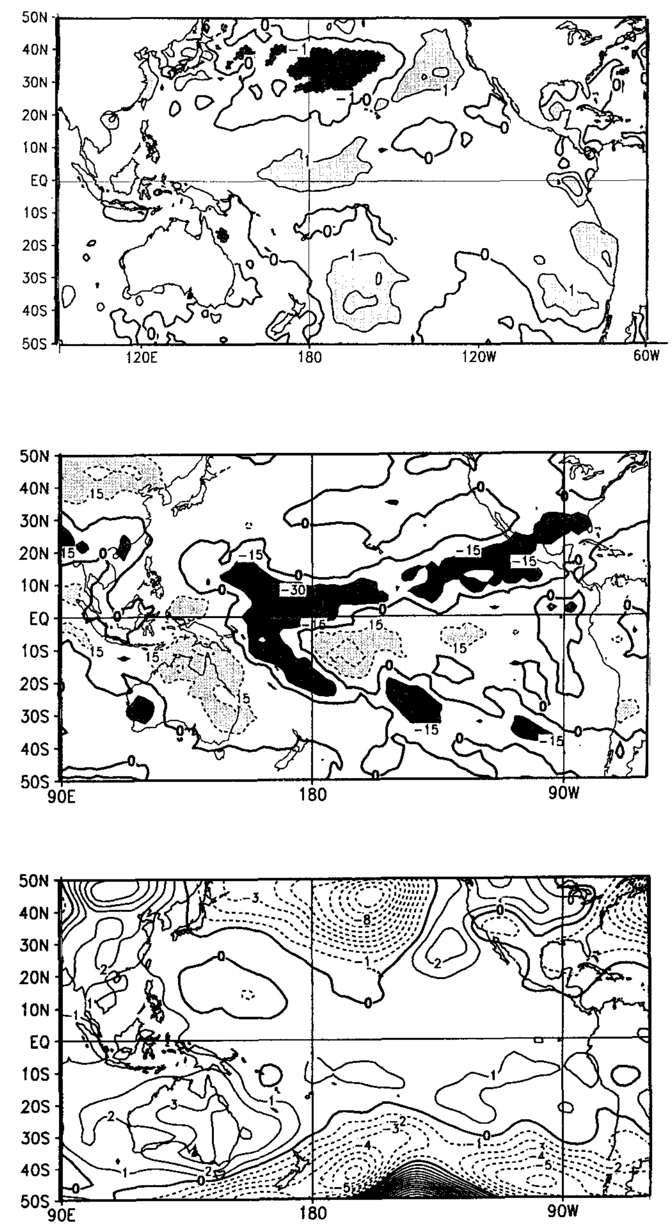

Figure 2. April 1997 Pacific Ocean anomalies of sea-surface temperature (SSTA; *top*), outgoing longwave radiation (OLRA; *center*), and sea-level pressure (SLPA; *bottom*). Anomalies are departures of monthly-averaged fields from the 1979–95 base period. Positive anomalies denote warmer than normal SST, lower than normal atmospheric heating, and higher than normal atmospheric pressure. Anomalous surface winds are approximately parallel with SLPA contours, and cyclonic (counterclockwise in Northern Hemisphere) around negative anomalies. Closer-spaced SLPA contours indicate faster anomalous winds. Adapted from NOAA National Centers for Environmental Prediction (NCEP 1997b).

through January 1997. La Niña conditions were moderate to weak until June 1996 and weak during the last eight months of this period. In February 1997, several tropical Pacific Ocean and atmospheric anomalies appeared that indicated a shift toward El Niño conditions. Throughout this period SSTs in and offshore of the California Current region were unusually warm, possibly because of La Niña conditions in the tropics that differed from those in a typical La Niña.

These tropical developments were indicated by the sea-surface temperature anomaly (SSTA) and the corresponding outgoing longwave radiation anomaly (OLRA) patterns in the tropical Pacific. Negative OLRAs indicate anomalously high tropical storm activity and high latent heating of the troposphere, or lower atmosphere (Murphree and Reynolds 1995), in essence greater than usual atmospheric heating. Anomalous atmospheric heating or cooling in the tropics may trigger a sequence of events that leads to significant disturbances of the extratropical ocean and atmosphere. In particular, OLRAs associated with El Niño and La Niña events may alter the atmospheric forcing and circulation of the mid-latitude north Pacific, including the California Current region (Murphree and Reynolds 1995). La Niña conditions, illustrated by the January 1997 fields, are indicated by positive SSTAs and negative OLRAs in the tropical western Pacific, along with negative SSTAs and positive OLRAs in the tropical central and eastern Pacific (figure 1). The transition toward El Niño conditions in early 1997 (e.g., April) is suggested by the development of positive SSTAs in the tropical central and eastern Pacific, positive OLRAs in the western Pacific, and negative OLRAs near the dateline (figure 2).

During most of the September 1995–January 1997 period, compared to other La Niña events, OLRAs were moderate to strong (more than normal atmospheric heating for La Niña) in the western region, but weak to moderate (less than normal heating for La Niña) in the central and eastern Pacific (figure 1). The uneven development of atmospheric heating anomalies over the tropical Pacific during 1995–97 may have helped produce a response over the north Pacific that was, in several important respects, different from that typically observed during La Niña.

The typical north Pacific winter response to a La Niña event includes a negative sea-level atmospheric pressure anomaly (SLPA) near Hawaii and a positive SLPA over the northeast Pacific, corresponding to a weaker Aleutian Low (Murphree and Reynolds 1995). But for most of the November 1995–January 1997 period, a negative SLPA occurred over much of the northeast Pacific. This negative anomaly frequently extended northeastward from the central north Pacific toward North America.

Surface wind anomalies associated with the SLPAs were cyclonic (counterclockwise), with generally northeastward and northward anomalies over much of the California Current region and the northeast Pacific (NCEP 1997a). Such anomalies should lead to reduced coastal upwelling and higher coastal sea level along the U.S. west coast. North Pacific sea-level height anomalies tended to be anomalously low on the north side of this region of anomalous wind, but high south of it (U. Hawaii, Sea Level Center, unpubl. data). Incidentally, the northeastward wind anomalies were also responsible for bringing warm, humid, subtropical air to much of the west coast during the 1995–96 and 1996–97 winters and the 1997 spring.

The extratropical north Pacific SSTA pattern from February 1995 to June 1997 was dominated by a negative SSTA in the central north Pacific, and a positive SSTA that extended northeastward from the tropical western Pacific across the northeast Pacific. These features were supplemented at times by monthly or seasonal SSTAs along western north America produced by upwelling episodes (e.g., in October 1996). The area of positive SSTA was roughly coincident with the region of anomalously high sea level.

During April–May 1997, the northeast Pacific warmed substantially in a roughly triangular region extending between Vancouver Island, Hawaii, and Cabo San Lucas (figure 2). By early June 1997, SSTAs in this region ranged from +0.5° to more than +4.0°C. Normally during spring, the North Pacific High migrates to the northwest from its winter position west of northern Baja California, while also expanding to the west. But during spring 1997, this migration and expansion was reduced, leading to northeastward winds and wind anomalies over much of the northeast Pacific and parts of the west coast (NCEP 1997b). This situation was especially pronounced in May 1997. This wind field is associated with more open-ocean downwelling, which may have contributed to these warm ocean anomalies as well as higher than typical sea level, identical to patterns seen in the previous La Niña.

The atypical response of the extratropical north Pacific to the 1995–97 La Niña may have been dominated by the effects of unusually well-developed positive tropospheric heating anomalies in the tropical western Pacific, and by the absence of well-developed cooling anomalies in the tropical central and eastern Pacific (Murphree and Gelaro, unpubl. model results). These extratropical responses include the negative SLPA in the northeast Pacific and its associated low-level wind, sea-level anomalies, and SST anomalies.

The extratropical North Pacific anomaly patterns observed during this La Niña period suggest that sea-level anomalies were controlled by Ekman pumping (divergence in the surface Ekman transport) produced by the unusual winds. Increased open-ocean upwelling in much of the central north Pacific, but open-ocean downwelling and warmer surface waters offshore of California and Mexico are implied. While the interactions between these processes are complex, the ocean provides feedback to the atmosphere which may have helped sustain the La Niña pattern for over two years.

El Niño outlook. In late 1996 and early 1997 (November–May), eastward surface wind anomalies in the tropical western Pacific helped initiate a transition toward El Niño conditions. The early stages of an El Niño event were clearly indicated by positive SSTAs in the eastern and central equatorial Pacific in February–June 1997 (figure 2). By April, anomalies in surface pressure, wind, atmospheric heating, and ocean temperatures across much of the tropical Pacific were consistent with a shift toward El Niño conditions. Over a large area near Ecuador and Peru, SSTAs exceeded +2°C by late May, an increase in the anomaly of more than 3°C since the beginning of the year.

During early 1997, temperature anomalies at and near the thermocline propagated eastward through the equatorial Pacific (figure 3). These were associated with two equatorial Kelvin waves, whose downwelling phase is indicated by an anomalously deep mixed layer, each apparently forced by a relaxation in westward wind stress in the western equatorial Pacific (NCEP 1997b). The downwelling phase of the first wave reached South America in March 1997; the second arrived in April–May 1997. These waves would be expected to propagate poleward along the Americas as coastal Kelvin waves, with the first reaching southern California in mid-to-late April 1997 (the time of a CalCOFI cruise), and the second arriving in early June. The expected direct effects of these waves would include increased coastal sea level and northward flow, along with warmer and less saline water (Simpson 1992; Lynn et al. 1995). We stress, however, that SSTs were elevated throughout the most recent La Niña, and that the June 1997 warm anomalies off California have not been introduced by El Niño.

If El Niño conditions persist or strengthen during 1997–98, significant effects in the California Current region would be expected via atmospheric and/or oceanic teleconnection processes (Murphree and Reynolds 1995; Lau 1997). Several El Niño/Southern Oscillation forecast models run in early spring 1997 are predicting El Niño conditions for the second half of 1997 and early 1998, although other models have predicted cool to normal conditions for this period (Barnston 1997).

B. Coastal Conditions

Coastal upwelling indices. The monthly upwelling indices (Bakun 1973; Schwing et al. 1996) along the North American west coast since 1995 display the annual cycle

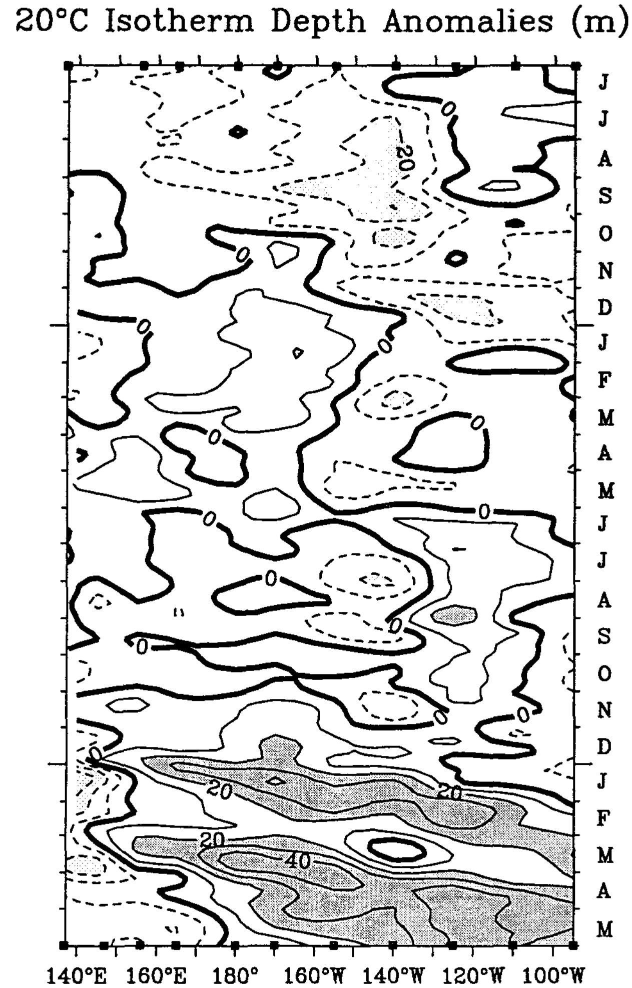

Figure 3. Depth of the 20°C isotherm between 2°N and 2°S for June 1995–May 1997. Analysis based on the five-day averages of moored time series data from the TAO (Tropical Atmosphere Ocean) array. *Shading* denotes isotherm depths more than 20 m deeper than the monthly climatology. Deeper than normal isotherms indicate the eastward propagation of the downwelling phases of two Kelvin waves across the equatorial Pacific in early 1997. Adapted from NCEP (1997b).

of increased upwelling during spring and summer, with generally higher values in 1996 than in 1995 (figure 4). Anomalies were generally positive (greater than normal upwelling) for the latter half of 1995, but reversed to slightly negative (weaker than normal upwelling) along the U.S. coast in early 1996. In May 1996, values became anomalously high at 36°N and north, but remained negative at 33°N. Weaker than normal upwelling off Baja California was suggested during the summer of 1996. Upwelling remained high along most of California during the biologically productive months of 1996. After negative anomalies in December 1996, the indices were unusually high in early 1997 south of Cape Mendocino (40°N). Winds were relatively calm in May 1997, leading to much weaker than normal upwelling along the entire west coast. The indices have been near zero off Oregon for the first six months of 1997.

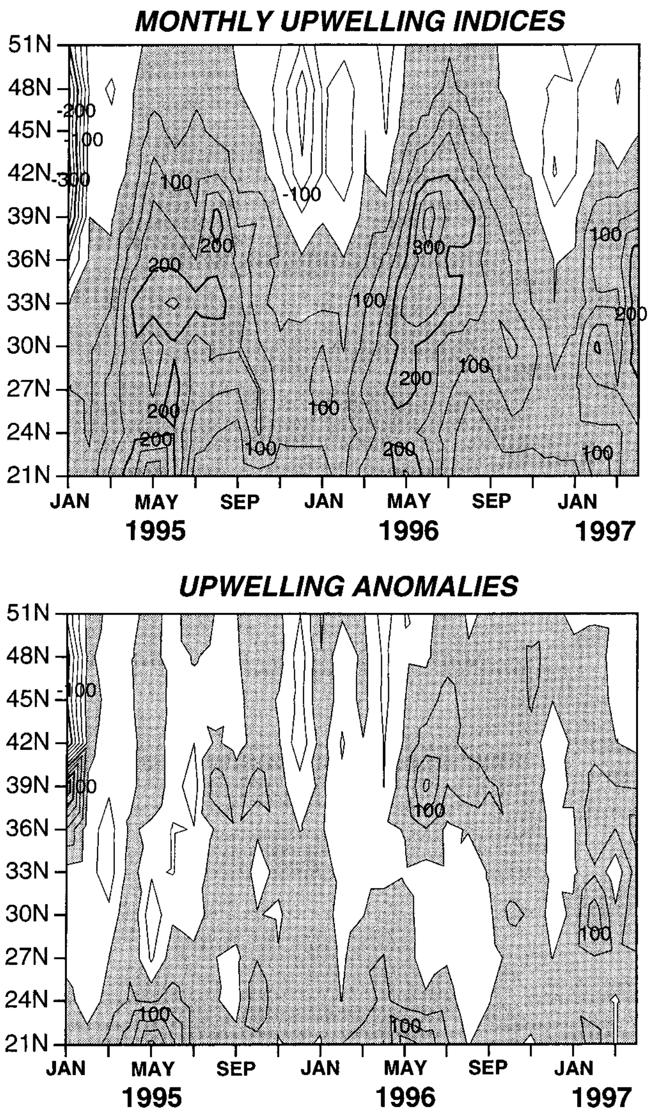

Figure 4. Monthly upwelling index and upwelling index anomaly during 1995–97. Positive values imply coastal upwelling. *Shaded areas* denote positive (upwelling-favorable) values in *upper panel*, and positive anomalies (generally greater than normal upwelling) in *lower panel*. Units are in m^3 sec^{-1} per 100 km of coastline.

Coastal upwelling indices during this period do not correlate with the large-scale atmospheric anomalies described in section 3A. Thus at times coastal conditions (e.g., SST) may show a different pattern from that in the greater north Pacific. For example, strong coastal upwelling in early 1997 appears to have mitigated the warming effects of wind-forced Ekman downwelling in the northeast Pacific (figure 1).

Coastal buoy time series. Winds measured at NDBC buoys (table 1) along the U.S. west coast (figure 5) reflect the interannual differences, as well as the annual cycle, noted in the upwelling indices. Seasonal patterns observed in 1995 and 1996 correspond well to the long-term climatology of west coast buoys (Dorman and Winant 1995). 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, particularly in summer, relative to those north of Point Conception. Winter winds in 1995 and 1996 were highly variable over short time scales, a consequence of a series of strong winter storms that crossed the coast. On average, the winter winds were poleward and stronger than normal, particularly in early 1995. Summer winds were predominantly equatorward, or upwelling favorable, with occasional wind relaxation events or reversals to poleward flow. Coastwide reversals in April and May 1996 produced poleward winds for a brief period. Overall, the winds during 1996 were more upwelling favorable than during 1995, and featured stronger than usual velocities.

At the coastal buoys SSTs reflect both the large-scale anomaly patterns seen throughout the north Pacific, and changes in local wind forcing over time (figure 6). Maximum SSTs occur in late summer along the entire coast. But the minima are delayed off much of California, due to the cooling effect of coastal upwelling. The spring transition for 1995 arrived in mid-April; in 1996 it arrived in mid-March. During 1995 and 1996, as well as in the long-term climatology, SST variance was greater in summer than winter. This is probably due to the combined effect of upwelling/downwelling events that periodically advect the strong seasonal alongshore SST front separating upwelled and offshore water past the buoys, along with interannual variability associated with El Niño, La Niña, and other large-scale climate events. Generally, SSTs were warmer than normal in early 1995, but cooler than usual off southern California from spring through fall 1995. In early 1996, SSTs were unusually warm, particularly in the northern half of the California Current. Unusually cool SSTs, related to strong upwelling-favorable wind conditions (figures 4, 5), predominated for most of the summer of 1996; SSTs gradually returned to their long-term mean in December.

Shore time series. Unlike SSTs at the nearby coastal buoy (Catalina Ridge, figure 6), which featured cooling tendencies in early spring 1996, surface temperatures measured at the SIO Pier remained anomalously warm through the first half of 1996 (figure 7). This pattern was a continuation of the warm SSTs that commenced in fall 1995, and of the warm conditions noted over a large area of the north Pacific (figure 1). Exceptions to these warm anomalies in 1996 were a sharp decline in SST in May from strong positive to near-normal anomalies, and brief periods of very cool SST in July and August. Events like these are not unusual in the historical record. Variations in SST at SIO corresponded closely to anomalies at the Catalina Ridge buoy. Shore temperatures at Pacific Grove fluctuated about the seasonal norm during

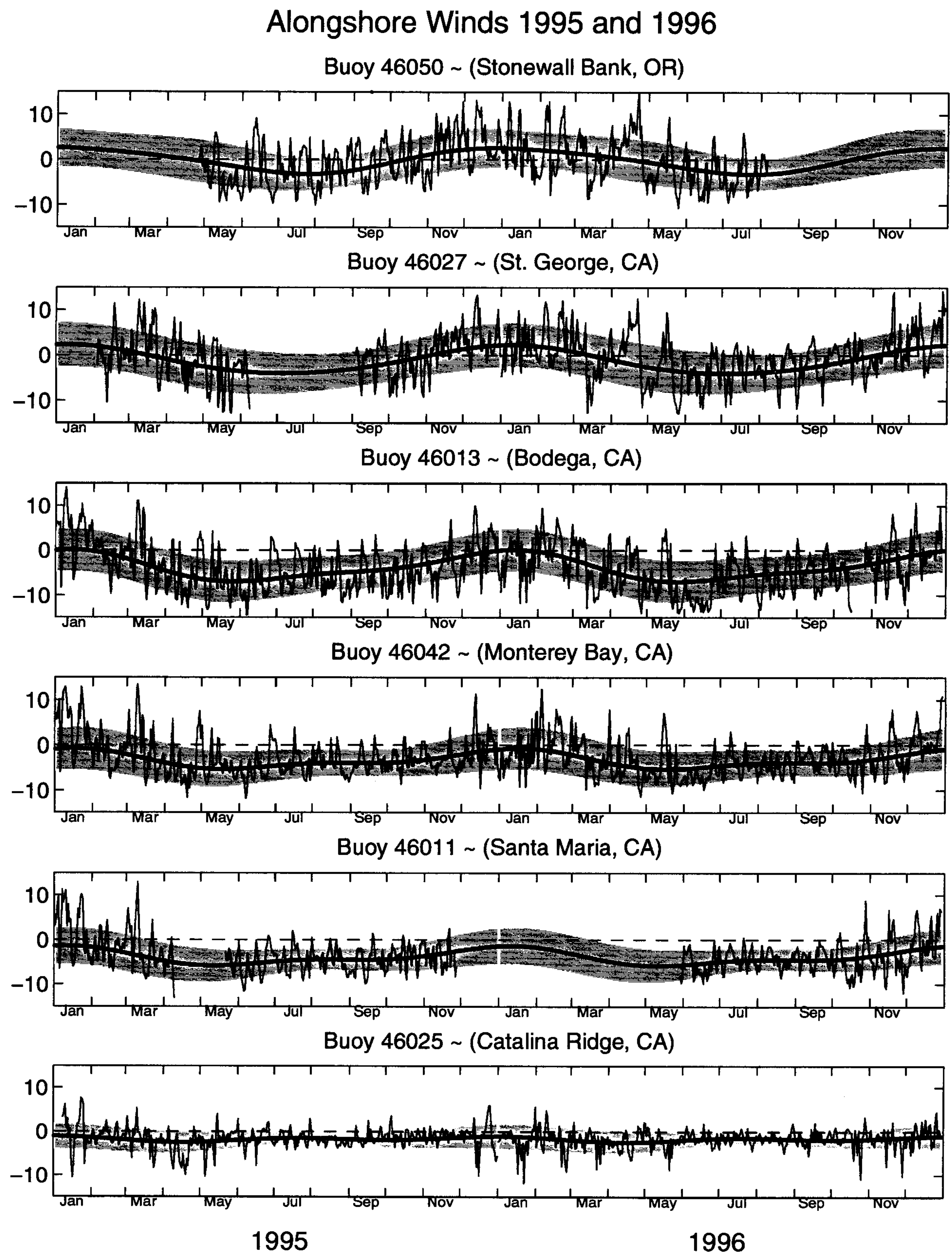

Figure 5. Time series of daily-averaged alongshore winds for 1995–96 at selected NDBC buoys. *Bold lines* indicate the harmonic mean annual cycle for each buoy. *Shaded areas* are the standard error for each Julian day. The period used for calculating the mean at each site and the alongshore angle are shown in table 1.

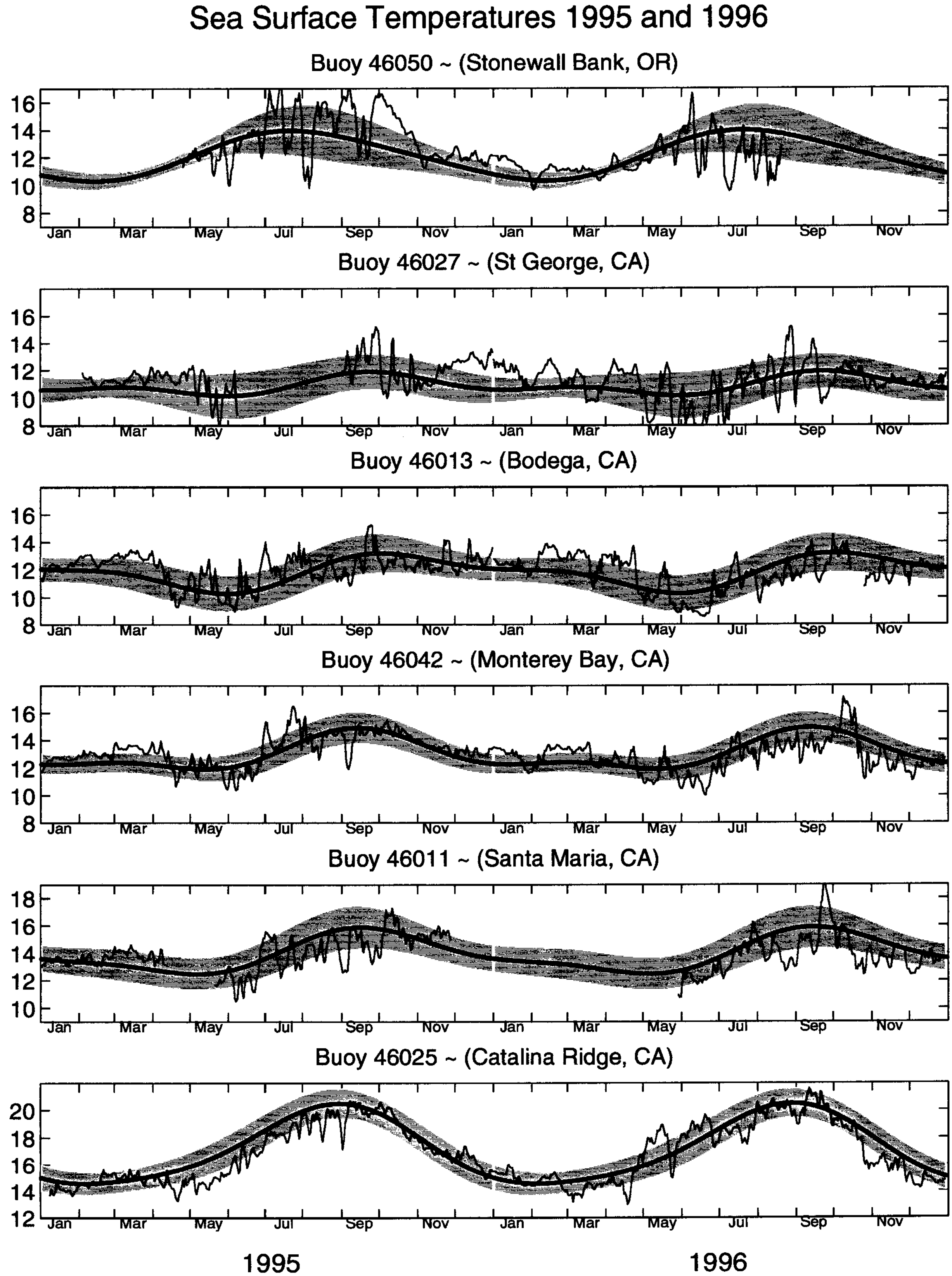

Figure 6. Time series of daily-averaged SST for 1995–96 at selected NDBC buoys. *Bold lines* indicate the harmonic mean annual cycle for each buoy. *Shaded areas* are the standard error for each Julian day. The period used for calculating the mean at each site is shown in table 1.

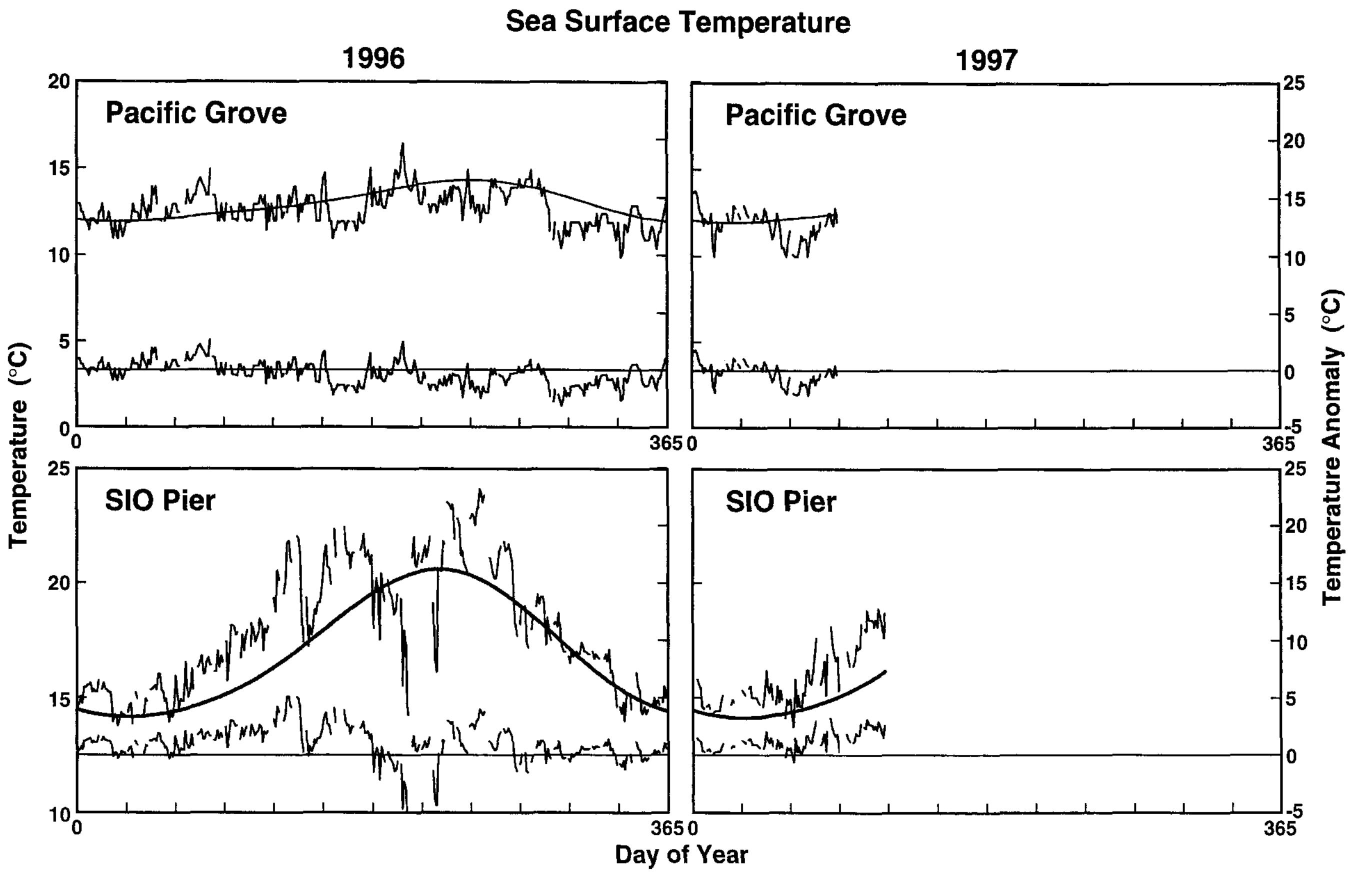

Figure 7. Sea-surface temperature at Pacific Grove and La Jolla (SIO Pier) for 1996 and 1997. Daily temperatures and anomalies from the long-term harmonic mean (1919–93 for Pacific Grove and 1916–93 for La Jolla). The *heavy line* shows the harmonic mean annual cycle in SST.

the first half of 1996, and were slightly cooler than average during the latter half, presumably in response to the stronger than normal upwelling-favorable winds (figures 4, 5), and show a marked agreement with nearby buoy SSTs (figure 6). Seasonal anomalies for the buoy and shore series are not directly comparable because they are based on very different periods.

More recent coastal SSTs are available at a few locations. At Granite Canyon, an open site on the Big Sur coast that reflects upwelling events, SST jumped from 9.5° to 13.5°C over the course of several days in early May 1997 (Jerry Norton, pers. comm.). The 1971–94 mean for May at this site is 10.36° (David Newton, SIO, pers. comm.). The relatively cool SSTs in April and early May were associated with higher than normal upwelling indices, and the sudden increase was possibly due to the initiation of weak upwelling (figure 4).

Coastal sea levels at San Diego and San Francisco (figure 8) were near or slightly below average throughout most of 1996, and consistently lower than 1995 values at San Francisco. Note that the annual climatologies have been revised recently, so the anomalies do not correspond with those described in Hayward et al. 1996. San Francisco sea level was near normal from April through October 1996. As in 1995, sea level at San Francisco was anomalously high in late winter 1996 and January 1997, presumably because of winter storm winds that favored onshore Ekman transport (figures 4, 5), along with high freshwater discharge through the Golden Gate in association with heavy rains and widespread flooding throughout northern California. San Diego sea level anomalies were slightly lower than normal in spring and relatively higher in winter during the past two years. High coastal sea levels in winter 1996–97 are consistent with a large area of positive height anomalies extending southwestward across the entire north Pacific (U. Hawaii Sea Level Center, unpubl. data) discussed in section 3A.

C. Conditions during the CalCOFI Surveys

In contrast to the relatively well-defined large-scale anomalies in the north Pacific associated with the 1992–94 La Niña, but perhaps in agreement with fairly typical seasonal values in the coastal time series discussed in section 3B, the quarterly CalCOFI surveys displayed no strong pattern. The circulation of the California Current appeared to feature relatively high mesoscale activity since early 1996. Over this same period, salinities in the core of the current were clearly lower than

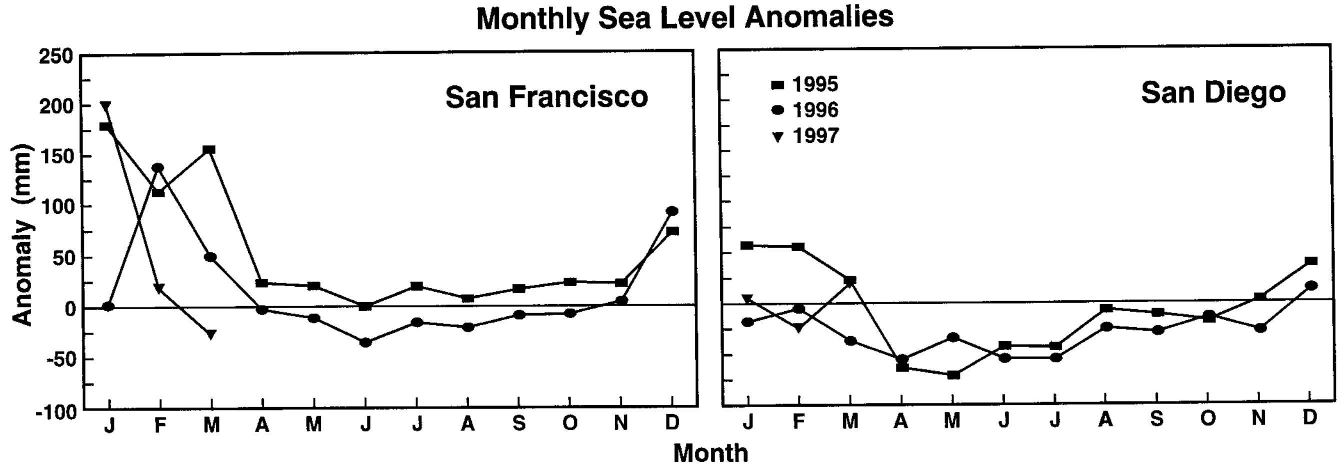

Figure 8. Monthly sea-level anomalies at San Francisco and San Diego for 1995, 1996, and 1997. The monthly anomalies are deviations from the period 1975–95, corrected for atmospheric pressure.

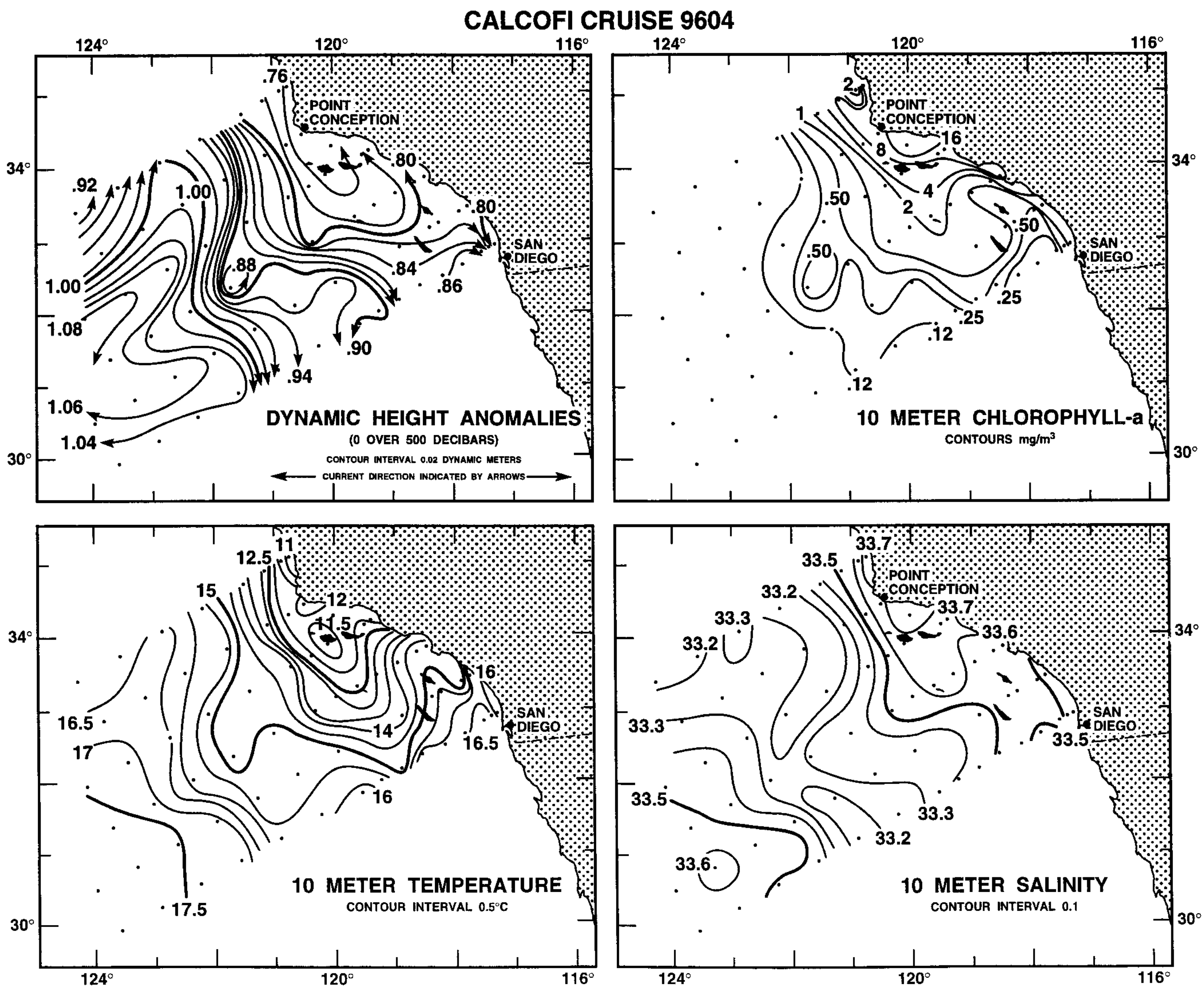

Figure 9. Spatial patterns for CalCOFI cruise 9604 (15 April–3 May 1996), including upper-ocean geostrophic flow estimated from 0 over 500-db dynamic height anomalies, 10-m chlorophyll, 10-m temperature, and 10-m salinity.

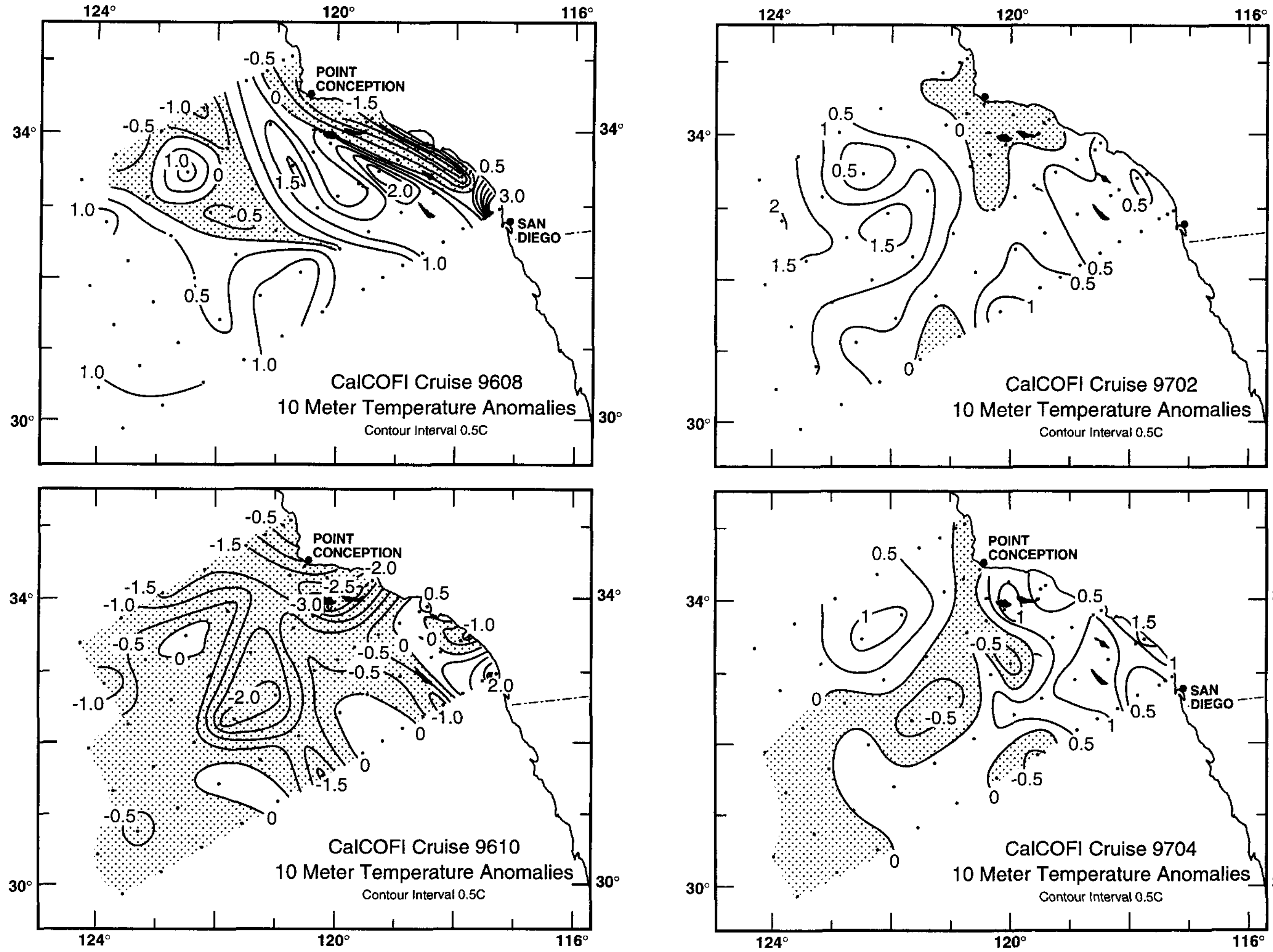

Figure 10. Anomalies in SST (°C) for CalCOFI cruises 9608, 9610, 9702, and 9704.

normal, but temperature anomalies in the region varied with each cruise. Episodes of strong coastal countercurrent coincided with warm and saline water, and low chlorophyll near the coast.

Conditions prior to April 1996. The CalCOFI cruises of 1995 and early 1996 were described in Hayward et al. 1996. The region's circulation during 1995 was fairly typical of the long-term mean. But by February 1996 the pattern shifted so that strong mesoscale eddy activity complicated the typical southward flow of the California Current and the northward coastal countercurrent. The region featured generally warm SST anomalies during this period. Chlorophyll concentrations were high, particularly in coastal waters, but macrozooplankton continued a decade-long trend of low biomass (Roemmich and McGowan 1995).

9604 (15 April–3 May 1996). Preliminary data from this cruise were also included in last year's report (Hayward et al. 1996). Dynamic height anomalies (figure 9) support the conclusion that the core of the California Current, as defined by the southward velocity maximum and corresponding salinity minimum, was anomalously far offshore, and that the region had developed a strong mesoscale eddy field around the meandering southward jet. The core of the current in this area was unusually warm and fresh (cf. Lynn et al. 1982), a pattern seen in subsequent cruises as well (figure 10). Chlorophyll levels were high, especially in the coastal area north of the Channel Islands, where relatively cool, saline surface conditions suggested recent strong upwelling.

9608 (7–24 August 1996). The California Current continued to be farther offshore than normal in the southern part of this survey (figure 11). The flow field featured strong meanders and weaker than normal southward flow off the Southern California Bight. Dynamic heights in the bight were higher than typical, and there appeared to be a stronger than usual coastal countercurrent. Most of the region was anomalously warm, but the spatial pattern included cool anomalies near the coast and near the core of the current. Salinities were higher than normal throughout the region, compared to the summer climatology of Lynn et al. (1982). Chlorophyll concen-

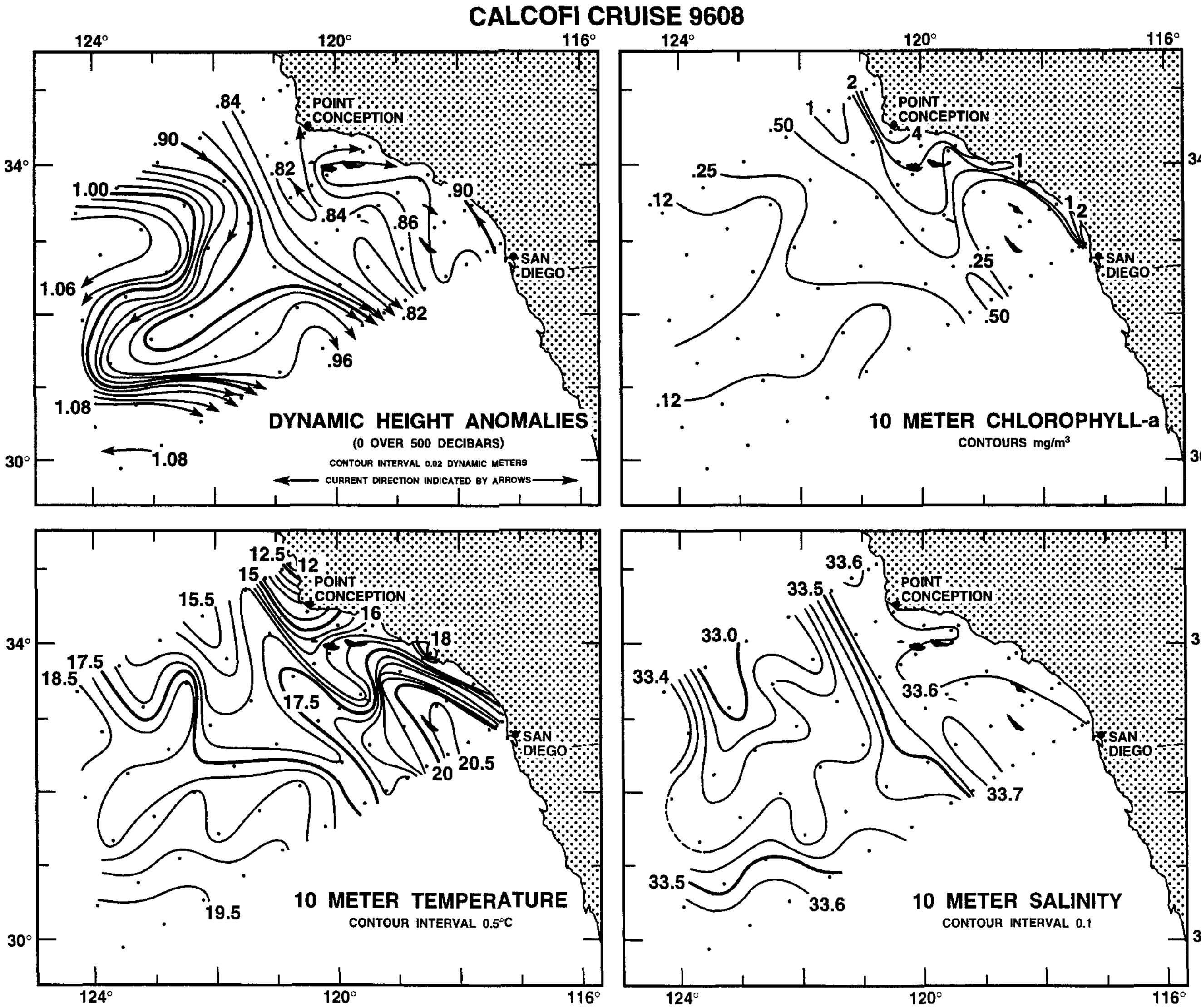

Figure 11. Spatial patterns for CalCOFI cruise 9608 (7–24 August 1996), including upper-ocean geostrophic flow estimated from 0 over 500-db dynamic height anomalies, 10-m chlorophyll, 10-m temperature, and 10-m salinity.

trations were low in the bight, where surface water was warm and saline, but elevated in the cool, saline coastal waters near Point Conception and the Channel Islands. Concentrations were similar to those during the 9408 cruise and a little lower than during the 9507 cruise.

9610 (10 October–2 November 1996). This CalCOFI survey marked the inaugural research cruise of the new SIO research vessel *Roger Revelle*, and included an expanded sampling program with much more effort by cooperative programs. The circulation pattern was fairly typical of fall, but again featured a strong mesoscale eddy field (figure 12). A strong cross-shelf temperature front located off Los Angeles coincided with a very sharp inshore meander of the California Current, which fed into a strong coastal countercurrent. The result was an intense cyclonic circulation around the Channel Islands. As in the previous survey, very warm (>2°C, figure 10) and saline anomalies were noted near San Diego. Most of the region, however, featured relatively large negative SST anomalies and lower than normal salinities. Near the Channel Islands, SSTs up to 3°C below normal were observed, and a large portion of the area had anomalies cooler than −1°C. Figure 13 presents NOAA polar orbiter images of gray-scaled radiometric SST (channel 4) for the 9610 cruise. The California Current jet and the offshore eddies found in the survey are clearly evident in the satellite image.

In terms of chlorophyll, this was one of the most anomalous cruises in the past decade. Fall is normally a time of low chlorophyll, but concentrations were quite high throughout this cruise. The pattern was much more similar to that in April 1996 and 1997, the seasonal peak

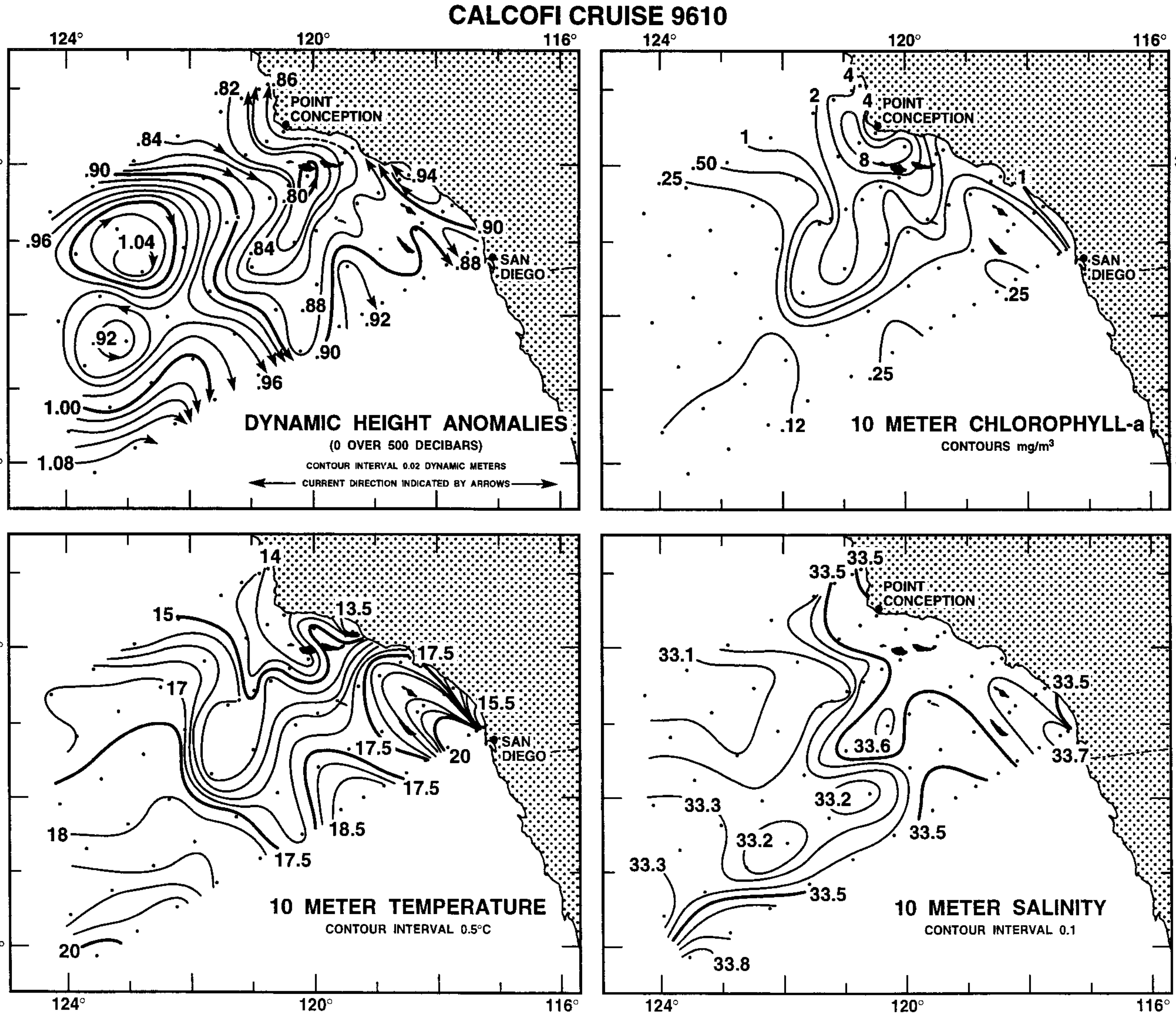

Figure 12. Spatial patterns for CalCOFI cruise 9610 (10 October–2 November 1996), including upper-ocean geostrophic flow estimated from 0 over 500-db dynamic height anomalies, 10-m chlorophyll, 10-m temperature, and 10-m salinity.

in chlorophyll. Chlorophyll values were particularly high in the coastal region near Point Conception. Compared to the previous year's cruise (9510), when 10-m values did not exceed 4 mg m^{-3}, during this cruise there was a large area of chlorophyll concentrations greater than 4 mg m^{-3}, with the highest concentrations being more than 12 mg m^{-3}. Buoy records were highly variable in time and space during October (figures 5, 6), further complicating the interpretation of this pattern.

9702 (29 January–15 February 1997). Although dynamic height anomalies are not yet available for the 1997 cruises, the circulation patterns can be inferred from temperatures at 100 m. Strong mesoscale structure characterized this winter survey (figure 14), a continuation of the pattern seen in 1996. The normally strong seasonal coastal countercurrent was weak to nonexistent, especially in the Southern California Bight. Chlorophyll was relatively low, as is typical of winter, with higher values in the coastal region in the northern part of the grid. The high chlorophyll concentrations of October 1996 had generally declined. However, the area where 10-m chlorophyll was greater than 2 mg m^{-3} was greater than at this time in 1995 and 1996. Throughout the area, SSTs were anomalously warm (+0.5° to 1.5°) except for the coastal region near the Channel Islands and Point Conception, which was slightly cooler than the norm (figure 10). A strong alongshore salinity front transected the survey. Seaward of this feature, the core of the California Current was 0.2–0.4 ppt fresher than historical means (Lynn et al. 1982). Although near-surface salinity was high north of Point Conception, nearshore waters were unusually fresh from Point

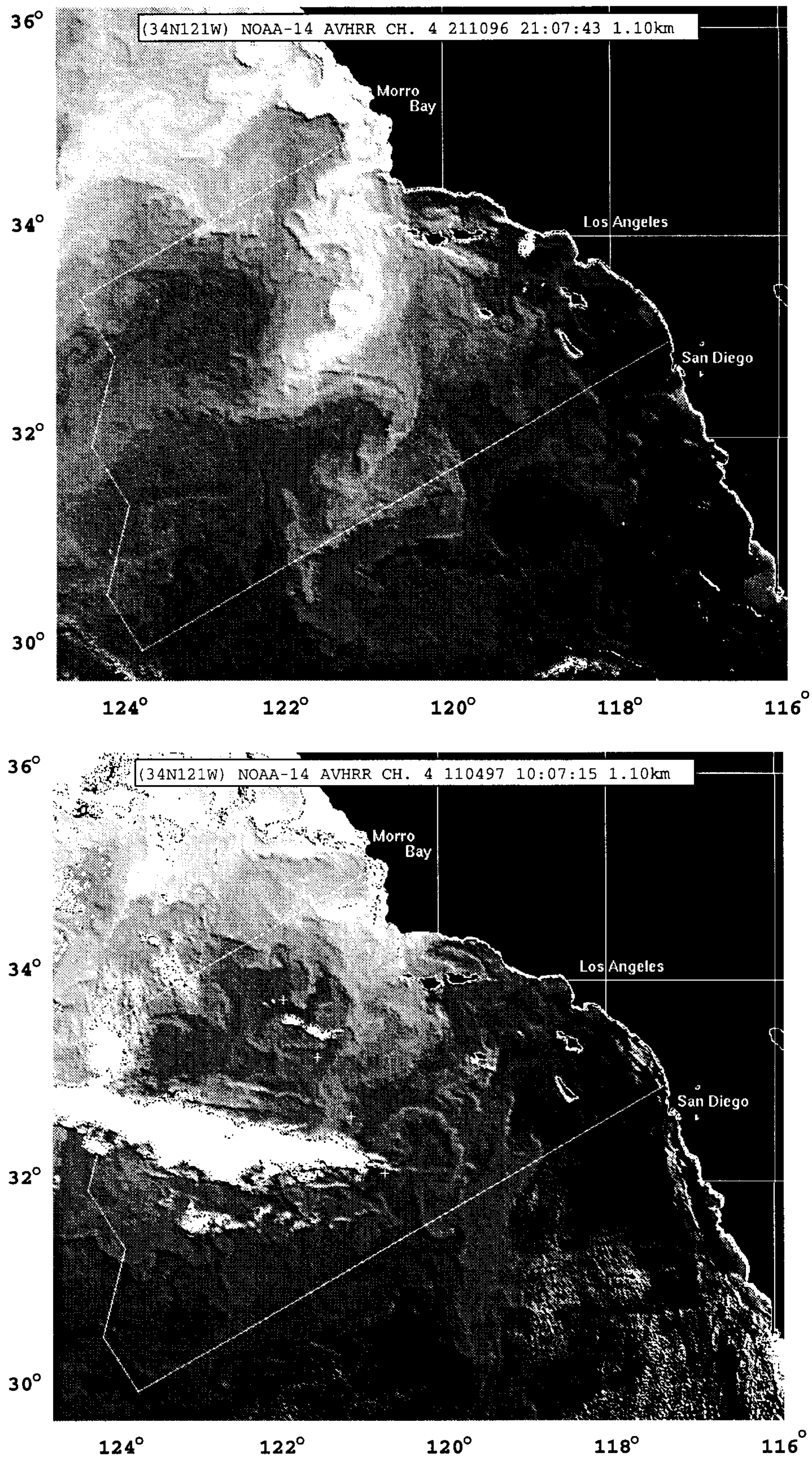

Figure 13. AVHRR channel 4 radiometric temperature from NOAA-14 polar orbiter satellite for 2107 UTC 21 October 1996 (*top*) and 1007 UTC 11 April 1997 (*bottom*). *Dashed lines* show extent of CalCOFI survey. *Grey levels* represent relative temperature differences (lighter shades denote cooler SST) and are not quantitative. Data provided by CoastWatch West Coast Node.

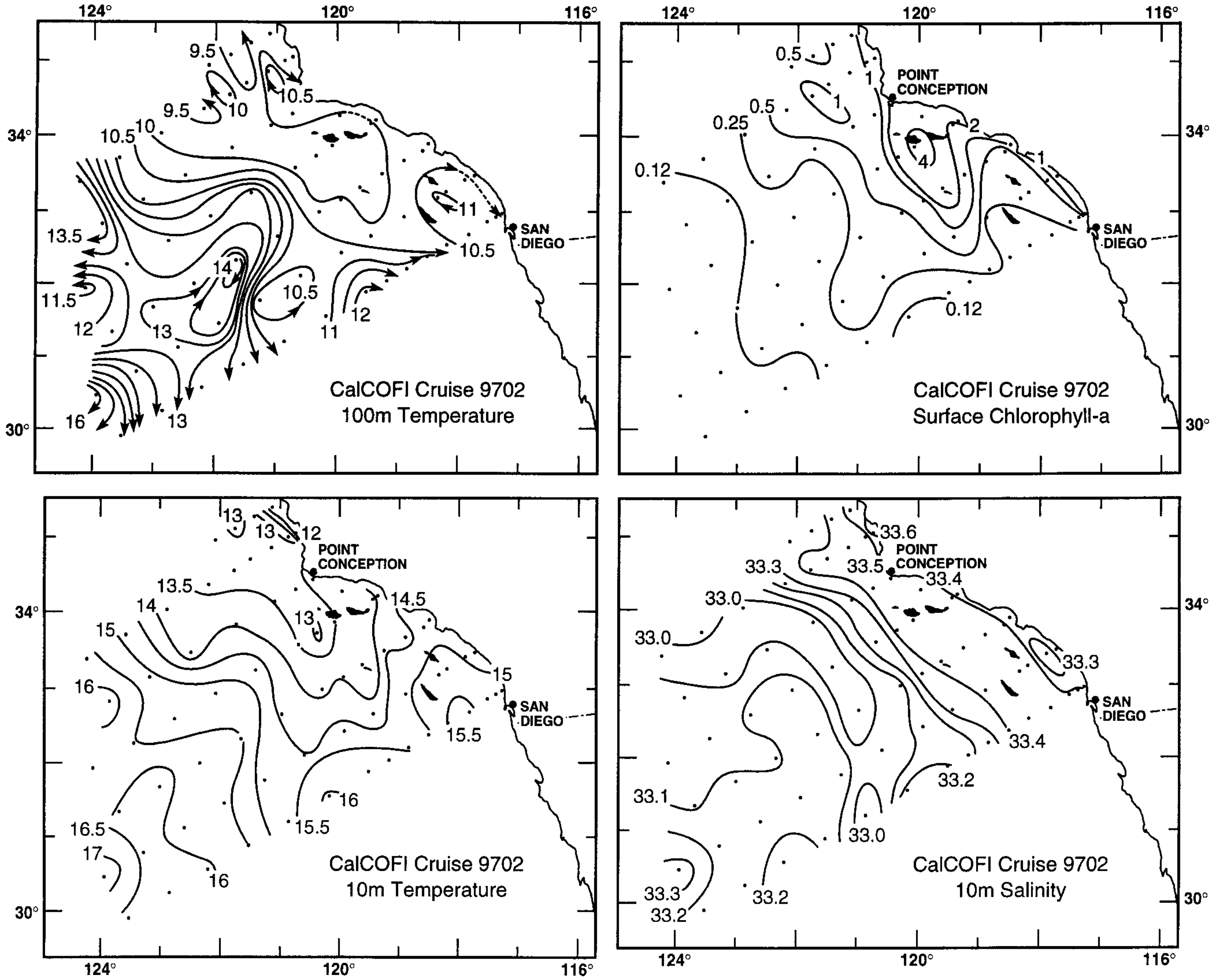

Figure 14. Spatial patterns for CalCOFI cruise 9702 (29 January–15 February 1997), including upper-ocean geostrophic flow estimated from the 100-m temperature, 10-m chlorophyll, 10-m temperature, and 10-m salinity.

Conception to San Diego, consistent with the reduced countercurrent.

9704 (2–20 April 1997). The data shown here are preliminary. The circulation pattern in April, inferred from the 100-m temperatures (figure 15), was anomalous in several respects. Poleward flow in the Southern California Bight was confirmed by ADCP data, which showed a northward coastal flow that appeared to be continuous around Point Conception (T. Chereskin, SIO, pers. comm.). The main flow of the California Current was strongly perturbed by mesoscale eddies and by a very sharp and unusual meander that brought the relatively warm (figure 10), low-salinity core of the current close to Point Conception. On the other hand, the main flow of the California Current was unusually far offshore in the southern part of the sample grid. Anomalously warm and saline water was seen in the Southern California Bight region. This is consistent with the anomalously strong coastal countercurrent bringing in warmer and more saline water from the south, a relationship inferred in August and October 1996 as well. Unlike the October cruise, the circulation and thermal gradients observed during this cruise correspond less well to a midcruise AVHRR image (figure 13). The chlorophyll distribution during 9704 continued to be strongly influenced by the circulation pattern. Chlorophyll levels were again highest in the coastal region near the Channel Islands and Point Conception. The enriched area near Point Conception was compressed near the coast due to the inshore sweep of the California Current, but extended farther offshore and south of the Channel Islands because of the offshore meander of the current in that region. The 9704 pattern in the southern California region is not markedly different from the 9604 pattern.

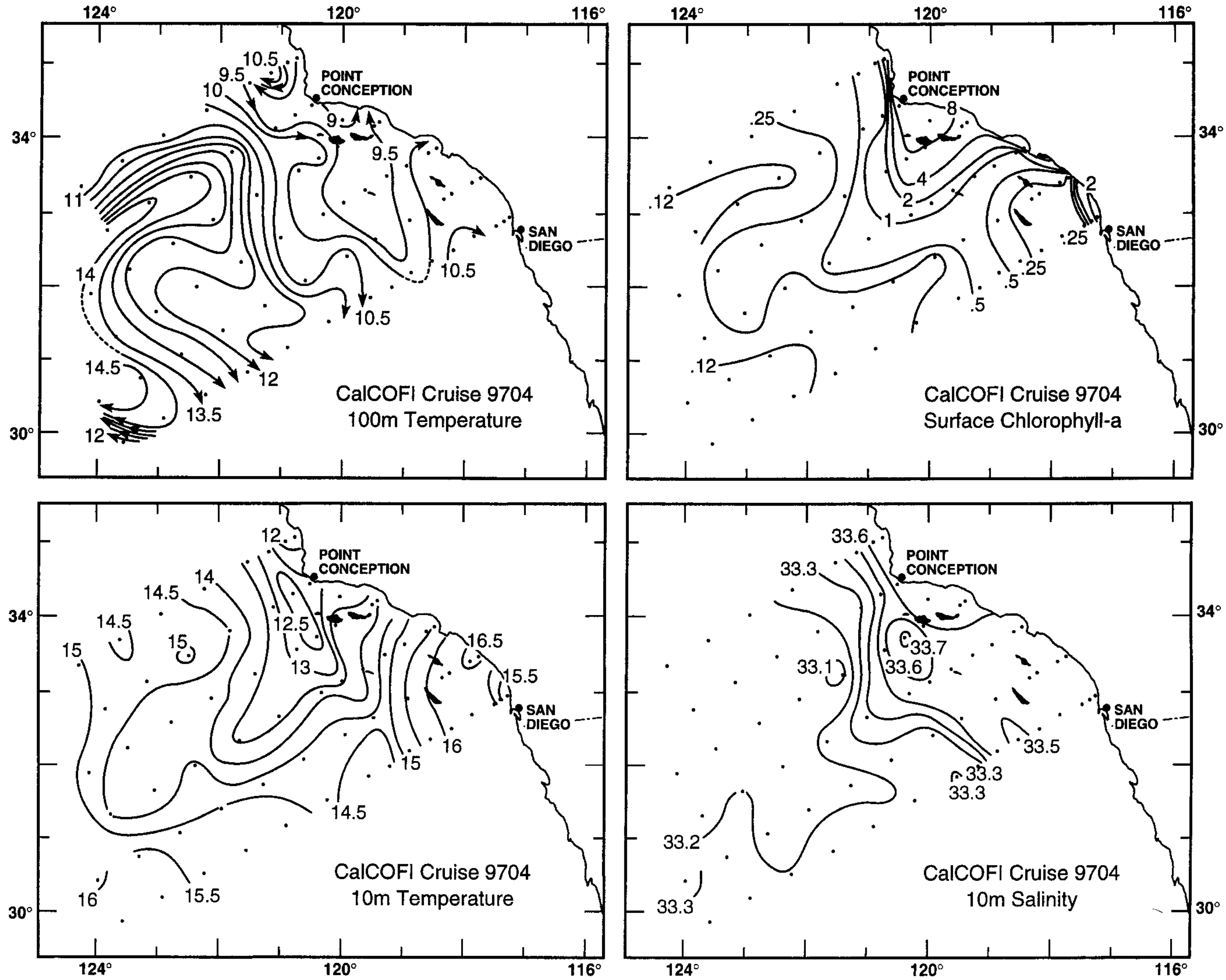

Figure 15. Spatial patterns for CalCOFI cruise 9704 (2–20 April 1997), including upper-ocean flow field estimated from the 100-m temperature, 10-m chlorophyll, 10-m temperature, and 10-m salinity.

In addition to the quarterly CalCOFI cruises, several other notable oceanographic surveys were made in coastal waters south and north of the present CalCOFI region. Although these surveys were generally smaller in scale and confined closer to the coast, they do provide information about the spatial variability of patterns in the California Current.

D. Baja California Coastal Conditions

As part of a cooperative program to study the circulation variability on the Baja California continental shelf/slope between Tijuana and San Quintín, the Estación de Investigación Oceanográfica de Ensenada of the Mexican navy (EIOE/SM) and the Instituto de Investigaciones Oceanológicas of the Universidad Autónoma de Baja California (IIO/UABC) initiated a series of oceanographic cruises in 1995. To date, three cruises have been made; preliminary results from the October 1995 and June 1996 cruises are presented here. The coastal surveys off Baja California indicate that the circulation pattern was similar to the long-term mean.

Cruise 1095 (23 October–2 November 1995). The lowest 0/500-db dynamic height anomalies during cruise 1095 (94 dyn. cm) are found near the coast (figure 16). The horizontal pattern of this field suggests an anticyclonic gyre off Punta Colnett and Cabo San Quintín (ca. 30.5°N) associated with a density anomaly of 23.75 kg/m^3 and a salinity of 33.35 ppt. There is a tendency for weak disorganized flow toward the south. According to Lynn and Simpson (1987), the strongest equatorward surface flow off Baja California typically appears in spring and summer, whereas the poleward surface coastal countercurrent and undercurrent both peak in fall and winter. The 200/500-db picture for October 1995 indeed

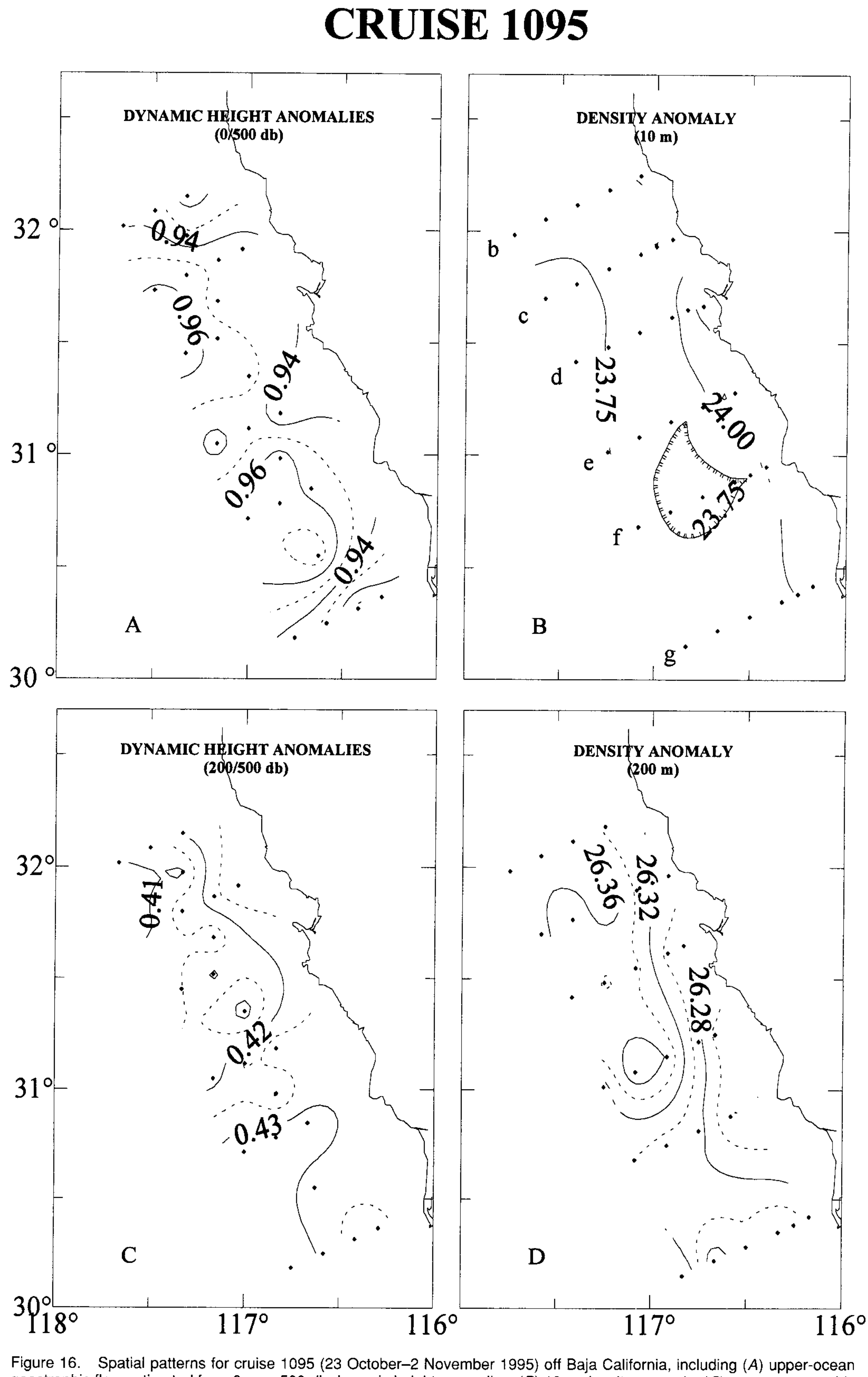

Figure 16. Spatial patterns for cruise 1095 (23 October–2 November 1995) off Baja California, including (*A*) upper-ocean geostrophic flow estimated from 0 over 500-db dynamic height anomalies, (*B*) 10-m density anomaly, (*C*) ocean geostrophic flow estimated from 200 over 500-db dynamic height anomalies, and (*D*) 200-m density anomaly.

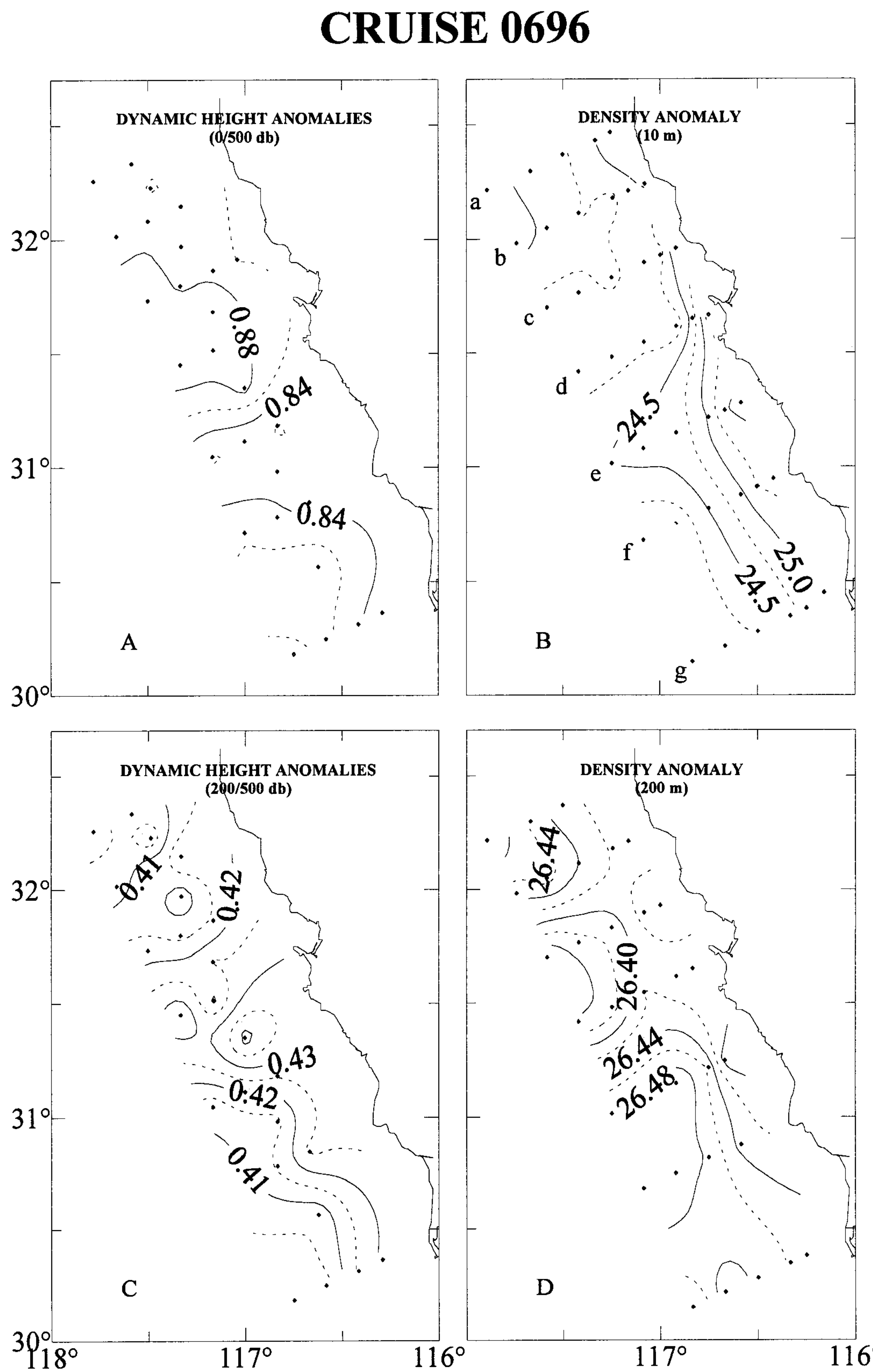

Figure 17. Spatial patterns for cruise 0696 (11–22 June 1996) off Baja California, including (*A*) upper-ocean geostrophic flow estimated from 0 over 500-db dynamic height anomalies, (*B*) 10-m density anomaly, (*C*) ocean geostrophic flow estimated from 200 over 500-db dynamic height anomalies, and (*D*) 200-m density anomaly.

shows a more organized pattern than the surface field, in spite of the weaker subsurface velocities. Dynamic heights are similar to those during CalCOFI Cruise 9510 (Hayward et al. 1996), and are comparable to the long-term mean pattern, with the same anticyclonic gyre and meandering trend. Vertical sections of geostrophic velocity show cores of northward velocity in the upper layer, particularly in the northern portion of the survey where the maximum value was about 10 cm sec^{-1}. Southward currents of 20 cm sec^{-1} were observed along line E (off Punta Cabras, ca. 31.2°N). The undercurrent could be observed in all lines, with geostrophic velocities reaching 10 cm sec^{-1}.

Cruise 0696 (11–22 June 1996). A southward flow was observed during cruise 0696 (figure 17), still disorganized but less so than during the 1095 cruise. The cross-shelf gradient was also larger (4 dyn. cm), indicating a stronger flow than in October. The apparent anticyclonic gyre during the 1095 cruise was not resolved with the June survey. The uplifting of isotherms and isohalines toward the coast in the upper 100 m was seen more clearly on the lines south of Ensenada (31.8°N). This area of upwelling can be contrasted with conditions in the northern portion of the survey in the 10-m isopycnal field. The 200/500-db dynamic height anomalies for this cruise show a pattern similar to those during the 1095 cruise. The range of values is the same, but the June field is a little more organized. Differences in the two cruises are better seen in the density fields, particularly north of 31°N. Differences in stratification are the result of higher salinities; temperatures did not change much. Vertical sections of geostrophic velocity show a better-developed undercurrent in the southern lines, reaching 10 cm sec^{-1} over the slope. A nearshore southward flow in the upper layer, with a maximum of 25 cm sec^{-1} in lines B and C, decreased to 10 cm sec^{-1} in the southern lines. While a salinity minimum indicative of the core of the California Current was not observed in the June cruise, a subsurface salinity maximum of 34.4 ppt was noted in lines E–G, the result of the better-organized countercurrent flow. This was not seen in October.

E. Central California Conditions

March–April 1996. An ADCP and CTD survey of the coastal current regime from San Diego to Point Sur was made by RV *David Starr Jordan* from 19 October to 7 November 1995 and repeated from 22 March to 7 April 1996 (data courtesy Ron Lynn, NOAA NMFS, La Jolla, and Terri Chereskin, SIO). The survey was designed to cross the basins and channels of the Southern California Bight and examine a series of better-resolved lines along the central California coast than is provided by the CalCOFI station grid. The area of coverage and the

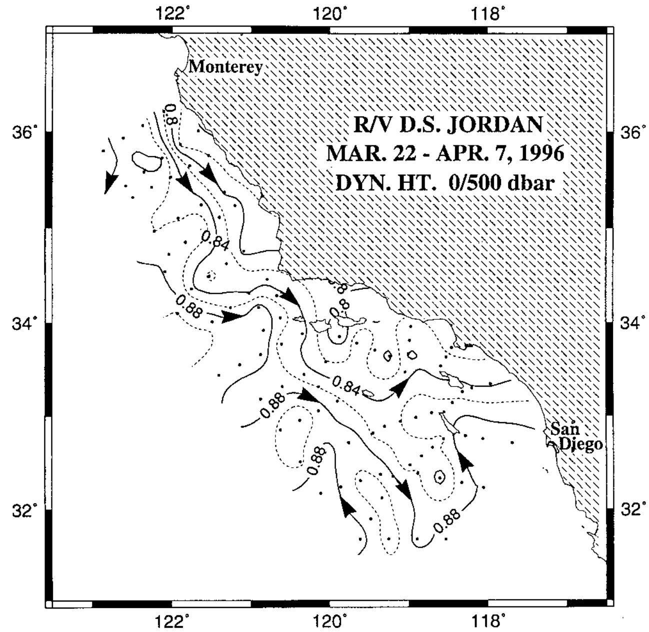

Figure 18. Upper-ocean geostrophic flow off southern and central California estimated from 0 over 500-db dynamic height anomalies for 22 March–7 April 1996.

geostrophic flow pattern for March–April are shown in figure 18. The field shows a flow meandering southward through a region of high mesoscale activity, similar in pattern and magnitude to the April–May 1996 CalCOFI cruise and the long-term mean (Lynn et al. 1982). One temporal difference was the stronger coastal countercurrent noted near the Channel Islands during 9604, which was absent when this survey occupied the same area earlier.

May–June 1996. The region between Monterey Bay and Bodega Bay was surveyed three times from 18 May to 19 June 1996, as part of the SWFSC Tiburon Laboratory's annual surveys of pelagic young-of-the-year rockfish on RV *David Starr Jordan*, begun in 1983 (data courtesy Stephen Ralston, Tiburon Groundfish Analysis Task). Researchers conducted midwater trawls, CTD casts, and ADCP profiling during the survey. The May–June survey was repeated in 1997. The Tiburon Laboratory also surveyed in the Gulf of the Farallones in June and September 1996, as part of a program to monitor how dredge spoil disposal affects marine organisms.

Conditions off central California during May–June 1996 were cooler and more saline than average (Lynn et al. 1982), and suggest the greatest coastal upwelling rates since 1991. Upper-layer temperatures were 9°–10°C, 2°–4° cooler than during the same period in 1992. Near-surface salinities exceeded 34.0 ppt in upwelling centers. Wind and CTD observations indicate that upwelling also increased over the course of the survey's three sweeps. As in May–June 1995 and March–April 1996, high levels of winter precipitation led to considerable freshwater

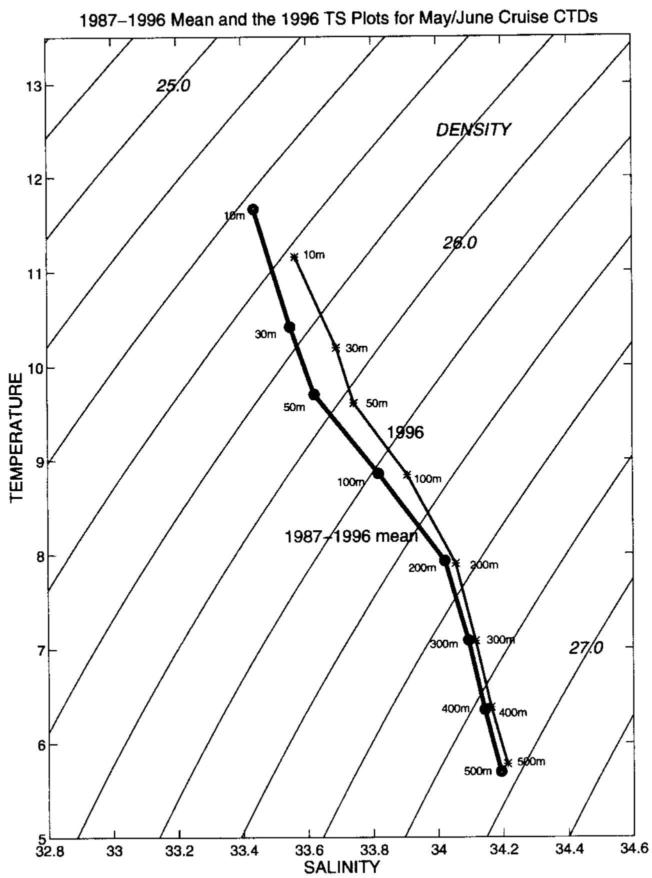

Figure 19. Relationship of mean CTD temperature and salinity from May–June 1996 survey off central California. *Asterisks* connected by *thin line* are 1996 mean values at 10, 30, 50, 100, 200, 300, 400, and 500 m. *Solid dots* connected by *bold line* are mean of all CTD casts from 1987–96 cruises. Position of 1996 values to the right of long-term means shows that water in 1996 was relatively warm and saline on density surfaces.

input from the San Francisco Bay system; salinities of 32.5–33.0 ppt were found confined to the upper 10 m seaward of the Golden Gate. Water below the mixed layer was warmer and more saline in 1996 than in the past several years (figure 19), which suggests that the region contained a lower percentage of subarctic water. Midlevel water during the 1992–94 El Niño was cooler and fresher than average, which is attributed to an onshore displacement of the core of the California Current during the event.

No unusual circulation features were evident off central California; geostrophic currents were very similar to those in previous years. The strongest feature in the geostrophic flow was an upwelling jet off Point Reyes that meandered generally southward during all three sweeps, although the magnitude of the current was much weaker than in 1995. A second relatively strong flow was an anticyclonic circulation associated with a recurring warm surface feature west of Monterey Bay (Rosenfeld et al. 1994). The 0/500-db dynamic heights continued to be depressed by 10 dyn. cm and more relative to those during the recent El Niño and were typically 2–5 dyn. cm lower than in 1995. Although the 200/500-db heights were very similar to those in the previous year, the dynamic signature of the undercurrent off Monterey Bay in 1996 was noticeably stronger.

Farther south, off Big Sur, ocean conditions have been less well studied. This region was surveyed during 3–6 June 1996 as part of a multidisciplinary effort to describe the benthic fish habitat and ocean circulation near the Big Creek Ecological Reserve (Rago et al. 1997; Yoklavich et al. 1997; data courtesy Mary Yoklavich, NOAA NMFS PFEL). In a response to upwelling-favorable winds (figure 5), strong offshore jets with maximum speeds of nearly 40 cm sec^{-1}, extending to 100 m and greater, were observed in association with Point Sur and Lopez Point. Water on the southern side of these jets featured the lowest temperatures and highest salinities in the survey. Unlike the traditional view of a southward flowing California Current during this time of year, a coherent 10-to-20-km-wide poleward coastal current (10–15 cm sec^{-1}) was noted along the entire Big Sur coast from the surface to 200 m. This coastal flow coincided with a region of warm, saline water in the upper 50 m, implying a more southerly source. In the seaward portion of the survey, cool and less saline water consistent with the character of California Current water flowed south. These water types were separated by northward-moving water that appeared to have been recently upwelled. A similar region of coherent poleward coastal flow was noted in the summers of 1981 and 1984 (Chelton et al. 1988) and in October 1995 (Rago and Collins 1995). The results from this survey suggest an intriguing conceptual model of circulation, with a persistent poleward coastal flow and a series of recirculating cyclonic cells that move water and material offshore and return to the coast. Future surveys of this area will, we hope, test this model.

January 1997. During the late fall and early winter of 1996–97, an unusually large number of strong storms passed over the northeast Pacific. These storms produced strong poleward (downwelling-favorable) surface winds, along with heavy rain and snowfall that caused flooding from Washington south to central California. In California, the heaviest flooding occurred in December and January. A cruise was conducted by the Naval Postgraduate School during 22–29 January 1997 to assess the effects of flood waters leaving San Francisco Bay (data courtesy Curt Collins, Naval Postgraduate School, Monterey, CA). Observations showed a distinct cold, fresh plume extending from the Golden Gate and flowing into the northern portion of the Gulf of the Farallones. ADCP measurements indicated that the plume, which was confined to the upper 10 m of the water column, was advected northward along the coast at about 25 cm sec^{-1}. The minimum surface salinity

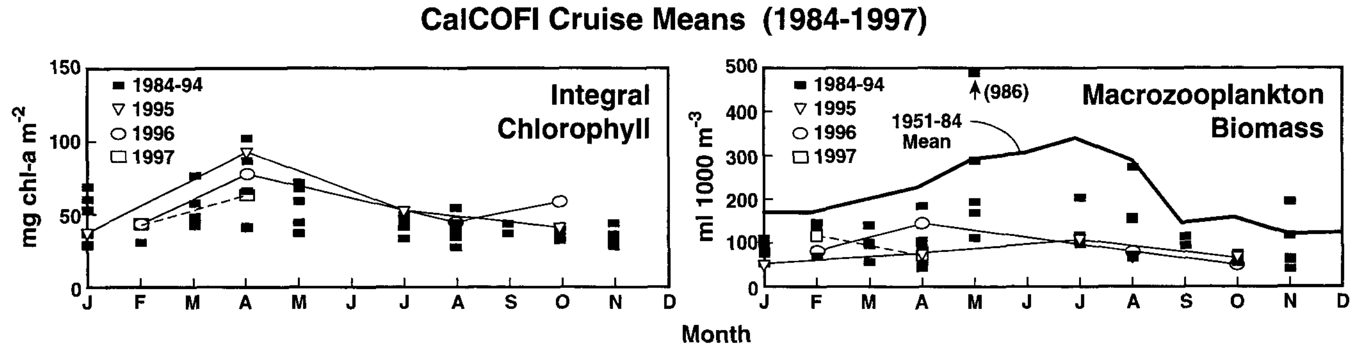

Figure 20. Cruise means of vertically integrated chlorophyll and macrozooplankton biomass plotted versus the month of CalCOFI cruises from 1984 to 1997. Each point represents the mean of all measurements on a cruise (normally 66). The *solid squares* show the cruises that took place from 1984 to 1994. The *open symbols* are cruises from 1995 to 1997; cruises from individual years are connected with lines. The *bold line* in macrozooplankton biomass indicates the monthly means for 1951–84.

observed at Point Reyes was 29 ppt. Anomalously high sea levels, reflected in San Francisco sea level (figure 8), characterized the region during this time (U. Hawaii Sea Level Center, unpubl. data).

4. BIOLOGICAL RESULTS

A. Biological Structure of the CalCOFI Region

The integral chlorophyll cruise means show that 9610 was anomalously high for fall (figure 20). This was probably the main surprise of the cruises. The first two cruises of 1997 continue the trend since 1995 of being within the range of, if not high relative to, integrated measurements made since 1984. Macrozooplankton biomass cruise means through 9704 continued the recent trend of being low both in the context of values prior to the mid-1970s (Roemmich and McGowan 1995) and relative to the past decade. This decline is continuing despite the fact that chlorophyll, and implicitly primary production (Mantyla et al. 1995), has been relatively high in the past few years compared to levels of the past decade.

Extensive red tide events were observed from San Diego to Monterey in early 1995 (Hayward et al. 1995) and from La Jolla south to Todos Santos Bay in April 1996 (G. Hemingway, pers. comm.). A dense red tide of *Lingulodinium polyedrum* (=*Gonyaulax polyedra*) was visible in the nearshore waters of the Southern California Bight from mid-March to mid-April 1997. This bloom began in December 1996, when elevated concentrations of this and other dinoflagellate species were observed near the coast. The densest cell concentrations were slow in developing, and did not appear to be correlated with rain or freshwater runoff. Indeed, the relatively strong winds that occurred during its development (figure 4) made this red tide all the more surprising, since red tide dinoflagellates are known to be sensitive to turbulence (Thomas and Gibson 1990). It is possible that dinoflagellates were exploiting recently upwelled nutrients, although diatoms tend to dominate in upwelling assemblages. The bloom eventually dissipated in late April, although recurrences of red water were seen until late May. The cause of the bloom's decline is not known, although it did not appear to be related to meteorological forcing or grazing by other protists (e.g., *Noctiluca scintillans*). The bloom was quite patchy along the coast, and was recorded from the Mexican border to north of Los Angeles. The bioluminescence was spectacular, and chlorophyll concentrations reached nearly 100 mg m^{-3} in the dense red water.

B. Biological Conditions off Central California

Primary production. The annual pattern of primary production in Monterey Bay has been measured as part of the Monterey Bay Aquarium Research Institute's monitoring program. Time series of integrated chlorophyll and primary production for 1994–96, measured by ^{14}C uptake with methods described in Chavez et al. 1990, show a strong seasonality (figure 21).

The seasonal cycle in Monterey Bay during 1996 was similar in amplitude and phase to previous years. The 1994–96 period was relatively normal with respect to coastal upwelling and primary production. Anomalously high chlorophyll levels were observed in winter 1995–96. Primary production during this time was also higher compared to seasonal means but, because of lower seasonal light levels, was not as evident as the chlorophyll signal. Maximum values occurred in spring and summer 1996 following the initial spring bloom, although levels dropped off during the time of maximum upwelling (figure 4). Chlorophyll concentrations and primary production fell to their winter minima in late 1996 (figure 21).

Early measurements in 1997 suggest that this year should also be highly productive. A March 1997 cruise found levels of nutrients and phytoplankton in the Monterey Bay area elevated as far as 250 km from shore. By June 1997, conditions had changed significantly, with

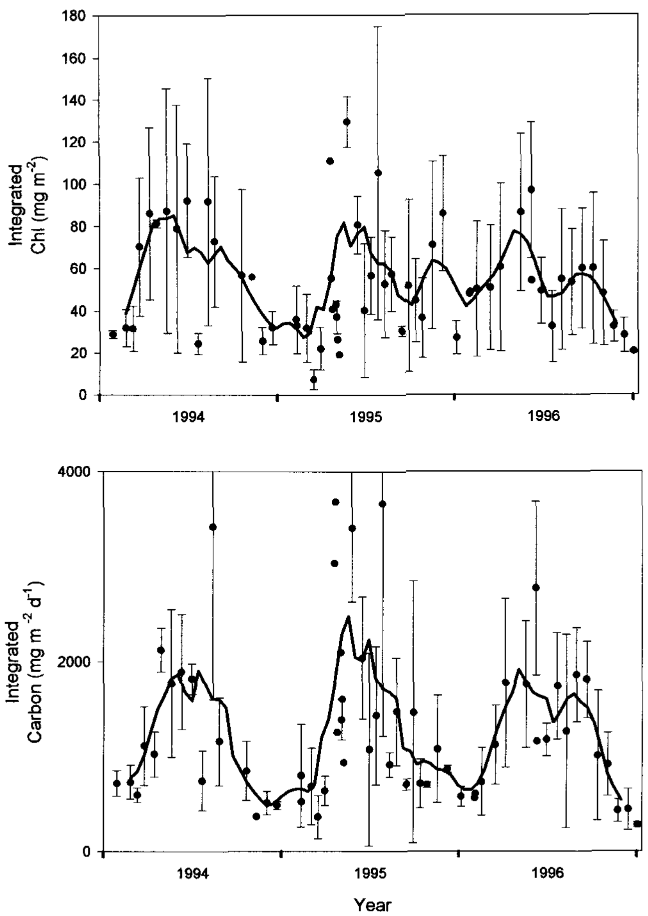

Figure 21. Integrated chlorophyll (*top*) and primary production (*bottom*) in Monterey Bay from 1994 to 1996 measured by ^{14}C uptake. Means and standard errors of two to five daily measurements are shown by *filled circles* and *error bars*. The *heavy line* represents a five-point running mean of the data interpolated to biweekly intervals.

the area of enhanced production having retreated to within 50 km of the coast. These differences can most likely be attributed to dramatically reduced coastal upwelling, which brought very warm water closer to the coast, possibly combined with the initial signature of the 1997 El Niño off central California.

Juvenile rockfish. Annual abundance indices of pelagic young-of-the-year rockfish (*Sebastes* spp.) off central California were estimated from trawls collected during the Tiburon Laboratory surveys described in section 3E (see Adams 1995 for methods). Indices were very low in 1996, continuing a trend of declining catch rates since 1994 (figure 22). The catch rate of *S. jordani* (the most common species collected) was slightly higher in 1996 than in 1995, but abundances of many rockfish species were the lowest observed in the 11 years of the surveys. In the past, poor recruitment (e.g., 1986 and 1992) has been associated with El Niño conditions. Such conditions occurred in the region in 1994 in association with the continuing El Niño, and the area experienced El Niño–like conditions in 1995 and 1996 (figure 1), despite the presence of La Niña in the tropics. While northerly distributed species (e.g., *S. entomelas*, *S. flavidus*, and *S. pinniger*; figure 22, dotted lines), were quite abundant in 1991 (a year with colder than average temperatures and strong southerly transport via the California Current; Sakuma et al. 1995), their numbers have been substantially reduced since the 1992 El Niño. In contrast, relatively high abundances of southerly distributed species (e.g., *S. goodei*, *S. jordani*, and *S. saxicola*; figure 22, solid lines) were observed in the relatively warm 1993. Even so, catches of these southerly species have been substantially lower since 1994. The numbers of invertebrates and other fish species in the 1996 trawls were also relatively low.

Seabirds. Since 1994, several avifauna species have been observed off California that have not previously been reported here, even though search effort by ornithologists has remained largely constant for the past 10–15 years (see Ainley 1976 and Briggs et al. 1987).

The dark-rumped petrel (*Pterodroma phaeopygia*) breeds in the Galápagos Islands and is common and widespread at sea in the eastern tropical Pacific (ETP; Spear et al. 1995), rarely moving as far north as the subtropical waters west of the California Current (Pyle et al. 1993). Yet at least one dark-rumped petrel has been seen annually since 1994 in the pelagic waters just off the shelf break of central and southern California. During 1996, when five individuals were observed in the California Current, two other species also found normally in the ETP—the Parkinson's petrel (*Procellaria parkinsoni*) and the swallow-tailed gull (*Larus furcatus*), another Galápagos breeder—were sighted off central California. The only previous (unconfirmed) sighting of swallow-tailed gull was made in Monterey Bay 20 years ago (S. Terrill, H. T. Harvey & Assoc., Alviso CA, pers. comm.).

Seabirds in the ETP move their locations at sea in concert with shifts in the boundaries of current systems and water types, especially as forced by El Niño or La Niña (Ribic et al. 1992). Movements within the California Current in response to shifts in oceanographic climate are also well known (Ainley 1976). The warm temperatures of the California Current and temperate eastern Pacific during the past several months (figure 1) may be partly responsible for these changes in avifauna.

5. DISCUSSION

Many factors operating on a variety of time and space scales affect the California Current system. A wide range of atmospheric forces appears to produce a complex set of physical responses and even more complicated biological responses. Thus it is difficult to develop a single model that can describe the system's dynamics under all conditions. It can also be difficult to clearly identify

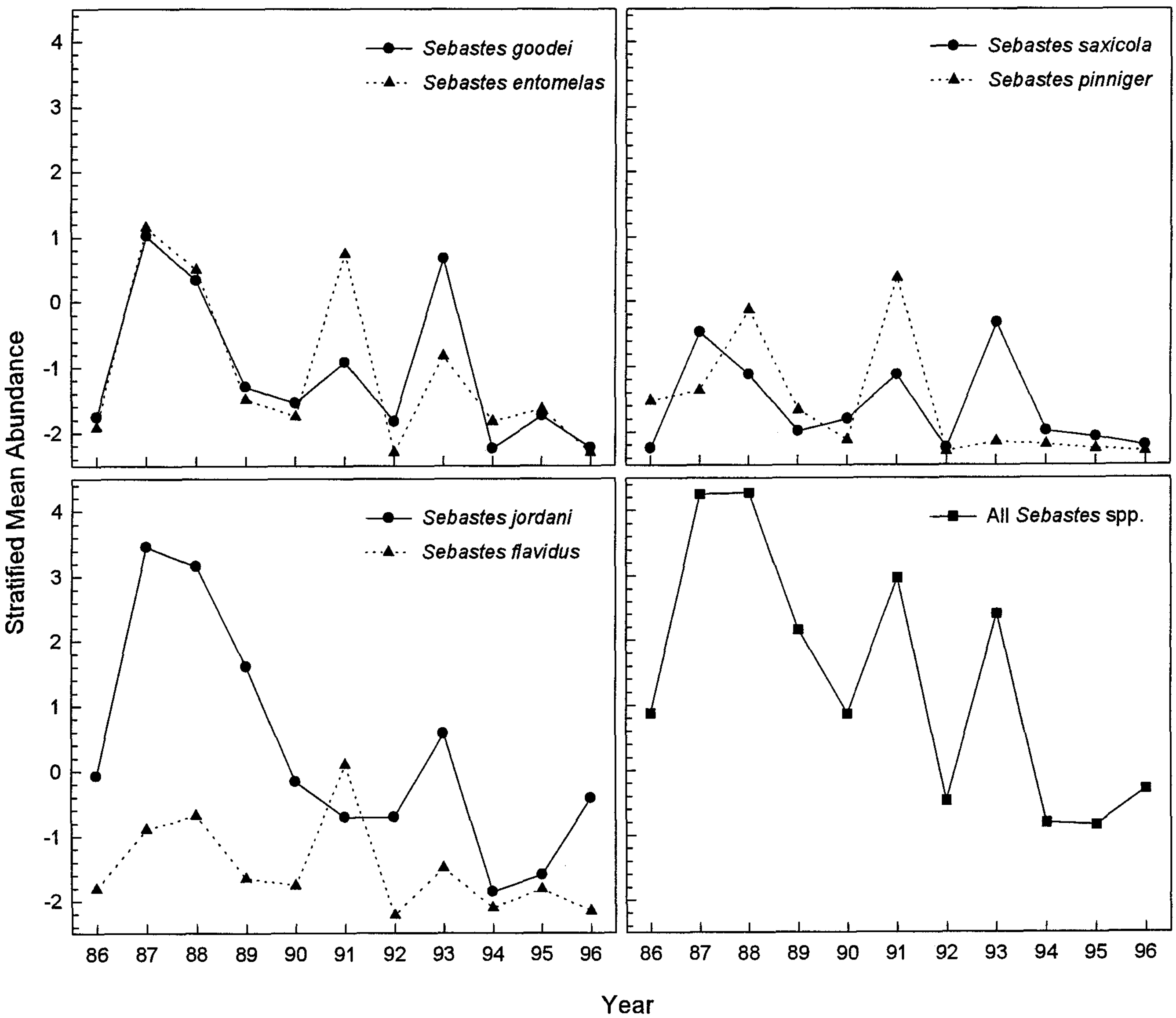

Figure 22. Annual abundance estimates of pelagic young-of-the-year rockfish, *Sebastes* spp., off central California for 1986–96, including individual estimates for three southerly distributed species (*solid lines with circles*) and three northerly distributed species (*dotted lines with triangles*). Abundances were adjusted according to Adams (1995) to account for interannual differences in size structure, and log-transformed by $\log_e(x + 0.1)$, where x is the length-adjusted catch.

the major signals within the system. This is partly due to a relative scarcity of data. Despite the large number of surveys in the CalCOFI time series, the number of observations is still quite small, given the complexity of the system being sampled. This makes it difficult, in a system with strong spatial and temporal variability, to calculate meaningful averages. This difficulty, in turn, makes it hard to identify anomalous conditions, since their calculation is based on the averages. These problems are increased when researchers use different data sets, since each set tends to have its own reference periods and sampling methods. Despite these difficulties, we have taken the liberty of speculating on some of the more intriguing results presented here, in part to stimulate the reader to develop better ways of defining environmental variability and its relation to ecosystem elements.

Many variations in coastal parameters may be well explained by fluctuations in local atmospheric and oceanic conditions. But local factors clearly do not tell the whole story. Both large-scale and local dynamical processes contribute to variations in SST, sea level, currents, and other fields in the California Current region. For example, coastal upwelling, geostrophic adjustments in the coastal countercurrent and California Current, changes in wind forcing over the central north Pacific, and equatorial El Niño and La Niña processes can all force large changes in coastal sea level and currents. However, since these processes operate at different space and time scales, it can be difficult to disentangle their coastal effects.

La Niña conditions in the tropical Pacific from late 1995 through early 1997 seem to have significantly affected the extratropical north Pacific (figure 1). Several tropical features of this La Niña event differed from those of a typical La Niña. These differences appear to have contributed to the formation of extratropical anomalies that were uncharacteristic for La Niña, most notably a large area of unusually warm SST that extended across much of the northeast Pacific. Again we emphasize that the warm SSTs off our coast at this time (June 1997) continue a pattern established and maintained by this unusual La Niña, and do not yet reflect an extratropical signal of the developing El Niño. The anomalous extratropical atmospheric processes helped produce unusually warm waters in the California Current region, although this coastal effect has been reduced somewhat since mid-1996 by higher than normal coastal upwelling along much of California.

Many of the observations in the California Current region during late 1996 and early 1997 were fairly close to the seasonal norms. This may have been partly because La Niña conditions in the tropical Pacific were weak or absent during this period. But significant anomalies may be expected in the region during 1997 and 1998, if the emerging El Niño event is maintained or strengthened. Since late 1996, two Kelvin waves have developed and propagated eastward across the equatorial Pacific, in association with the emergence of El Niño (figure 3). The downwelling phase of the first wave reached the west coast of South America in March 1997, and may have continued traveling poleward along the west coast of the Americas, arriving off southern California sometime in April. This may have contributed to the increase in sea-level anomalies at San Diego in March and the strong coastal countercurrent observed in the bight during April 1997. However, coastal Kelvin waves can be created by more local processes (e.g., extratropical coastal storms), so a careful analysis of the source of such anomalies is needed.

The circulation of the California Current appeared to switch in early 1996 to a pattern of relatively high mesoscale activity that has continued through the most recent cruises. Mesoscale features in the current were not geographically fixed during the 1996–97 cruises, although a strong onshore meander toward Point Conception was noted in three surveys (9608, 9610, 9704). But it is difficult to compare this mesoscale activity to the region's long-term circulation, and to know if this activity represents a shift to a new state. Over this same period, salinities in the core of the current were clearly lower than in the climatologies for the region. There were also periods (August, October 1996, April 1997) in which a strong coastal countercurrent was associated with warm, saline water near the coast that was also low in chlorophyll. The countercurrent appears to have been an important mechanism for bringing more subtropical water into the Southern California Bight.

The high chlorophyll levels in the bight during October 1996 were not clearly related to the shore station data or to the general pattern of circulation. Coastal sea level and temperature were near seasonal norms at that time. Buoy winds in the bight showed no strong wind events, although the conditions at the Santa Maria buoy suggested a period of elevated upwelling north of Point Conception in October (figures 5, 6), in agreement with the upwelling index (figure 4). The circulation pattern was typical of the long-term mean, with a strong superimposed mesoscale eddy field. The mesoscale field has often been this strong before, but without elevated levels of chlorophyll. The spatial pattern of chlorophyll was strongly related to the circulation pattern and presumably the nutrient distribution, with the nutricline probably shallower than normal in the northern part of the grid. Much of the area of high chlorophyll is often found well offshore of the wind-driven coastal upwelling region, and in association with isopycnal shoaling along the inner edge of the California Current as it meanders into the CalCOFI region.

Although chlorophyll estimates are good indicators of primary production (Mantyla et al. 1995), chlorophyll is not a good predictor of higher trophic production in the California Current ecosystem. Despite the relatively high levels of phytoplankton production on some cruises, particularly during October 1996, the biomass at higher trophic levels appears to have been low compared to historical observations. Macrozooplankton biomass remains depressed in comparison to recent historical levels. The abundance of juvenile rockfish off central California has been at a low for the past decade. It also appears that decreases in plankton-feeding seabird species reported recently by Ainley et al. (1995) and Veit et al. (1997) continued during 1995–97 (Spear and Ainley, unpubl. data). Decreases are consistent with the decline in zooplankton reported by Roemmich and McGowan (1995) and with the aforementioned decreases in juvenile rockfish. The issue of why zooplankton, fish, and bird populations have been reduced for the past several years remains a pressing question in this system.

As part of the California Department of Fish and Game's Central California Marine Sport Fish Project-Refugia Study, scientists have been monitoring rockfish populations to determine the feasibility of marine reserves as a management tool (data courtesy David

VenTresca, CDFG, Monterey, CA). A statistically significant relationship exists between the monthly upwelling index at 36°N and the subsequent recruitment of young-of-the-year blue rockfish (*Sebastes mystinus*) in the Monterey Bay area (D. VenTresca, CDFG, Monterey, CA, pers. comm.). Recruitment in Monterey Bay was below normal in 1995, and very poor in 1996. The March 1997 upwelling index (figure 4) indicates that the 1997 recruitment of young-of-the-year blue rockfish will be the highest since the exceptionally strong 1988 year class. In addition, recruitment of this fish in 1997 has been unusually early, possibly in conjunction with the rather early transition to strong upwelling-favorable conditions. Whether this early recruitment is eventually reflected in other higher trophic level components, or ultimately leads to a strong year class for rockfish in general remains to be seen.

An encouraging note from the 1996–97 period was the large number of projects that examined the oceanography of various regions of the California Current. It is critical that projects such as those off Baja California and central California (described in previous sections) be linked with the CalCOFI program to produce a result that is greater than the sum of its parts. Independent ocean data sets from different areas of the California Current allow a better assessment of individual environmental features and the processes that produce them.

The growing number of observations of the California Current include a wide variety of data types and sources. Researchers need to develop innovative ways to analyze and interpret the historical environmental data from CalCOFI and the greater north Pacific region. One technological advance that has helped and will continue to help is the increasing use of telecommunications and the World Wide Web to make data more readily and widely available. As mentioned in section 2, the CalCOFI data are accessible on the Web, as are a growing number of other databases and products relevant to the California Current.

We suggest a few ideas to encourage closer links between the area's numerous field research programs. First, efforts should be made to standardize sampling methods for basic physical and biological measurements, and to attempt to include sampling of these basic variables on all cruises. This may require the help of experts from new disciplines on existing field research teams. If possible, cruise plans should include opportunities for adding outside researchers to take samples that are part of the standard set of critical measurements (e.g., chlorophyll on fisheries surveys). Second, the Internet should be used as an electronic bulletin board to post detailed cruise plans so that independent but concurrent cruises can be coordinated. Third, the California Current is highly variable, and the most important results are often unexpected. Chief scientists should communicate with scientists of recently completed surveys regarding any unusual or anomalous findings, and cruise plans should consider "adaptive sampling" strategies to further investigate these features. Finally, we encourage someone to step forward to attempt a more complete assessment and "model" of the California Current that incorporates various data sets such as those described here. This will require not only keen scientific insight but also the ability to bring together a diverse group of researchers from a wide variety of academic, government, and private institutions.

It is important for physical and biological oceanographers to continue working together; to join with scientists in other disciplines to better understand long-term (i.e., interannual to decadal) variability in the environmental and biological components of the California Current region; and to better describe how climate shifts may affect the region and its living resources.

ACKNOWLEDGMENTS

We thank the large number of scientists, technicians, and support staff who contributed to the collection and analysis of the data presented here, and particularly the individuals and groups that provided the data sets for this publication. We appreciate the comments and scientific input of Mary Yoklavich, David VenTresca, Paul Smith, Ron Lynn, Peter Franks, Curt Collins, and many unnamed individuals. Holly Price, Jerry Norton, and George Boehlert reviewed the manuscript and suggested many valuable improvements for the final version.

LITERATURE CITED

Adams, P. B. 1995. Progress in rockfish recruitment studies. NMFS, SWFSC, Admin. Rep., Tiburon, T-95-01, 51 pp.

Ainley, D. G. 1976. The occurrence of seabirds in the coastal region of California. West. Birds 7:33–68.

Ainley, D. G., R. R. Veit, S. G. Allen, L. B. Spear, and P. Pyle. 1995. Variations in seabird numbers in the California Current, 1986–1994. Calif. Coop. Oceanic Fish. Invest. Rep. 36:72–77.

Bakun, A. 1973. Coastal upwelling indices, west coast of North America, 1946–71. U.S. Dep. Commer., NOAA Tech. Rep., NMFS SSRF-671, 103 pp.

Barnston, A., ed. 1997. Experimental long-lead forecast bulletin 6, March 1997. Climate Prediction Center, National Centers for Environmental Prediction, National Weather Service, Washington, D.C.

Briggs, K. T., W. B. Tyler, D. B. Lewis, and D. R. Carlson. 1987. Bird communities at sea off California: 1975–1983. Studies Avian. Biol. No. 11.

Chavez, F. P., K. R. Buck, and R. T. Barber. 1990. Phytoplankton taxa in relation to primary production in the equatorial Pacific. Deep-Sea Res. 37:1733–1752.

Chelton, D. B., A. W. Bratkovich, R. L. Bernstein, and P. M. Kosro. 1988. Poleward flow off central California during spring and summer of 1981 and 1984. J. Geophys. Res. 93:10,604–10,620.

Dorman, C. E., and C. D. Winant. 1995. Buoy observations of the atmosphere along the west coast of the United States, 1981–1990. J. Geophys. Res. 100:16,029–16,044.

Hayward, T. L., A. W. Mantyla, R. L. Lynn, P. E. Smith, and T. K. Chereskin. 1994. The state of the California Current in 1993–1994. Calif. Coop. Oceanic Fish. Invest. Rep. 35:19–35.

Hayward, T. L., D. R. Cayan, P. J. S. Franks, R. J. Lynn, A. W. Mantyla, J. A. McGowan, P. E. Smith, F. B. Schwing, and E. L. Venrick. 1995. The state of the California Current in 1994–1995: a period of transition. Calif. Coop. Oceanic Fish. Invest. Rep. 36:19–39.

Hayward, T. L., S. L. Cummings, D. R. Cayan, F. P. Chavez, R. J. Lynn, A. W. Mantyla, P. P. Niiler, F. B. Schwing, R. R. Veit, and E. L. Venrick. 1996. The state of the California Current in 1995–1996: continuing declines in macrozooplankton biomass during a period of nearly normal circulation. Calif. Coop. Oceanic Fish. Invest. Rep. 37:22–37.

Hewitt, R. P. 1988. Historical review of the oceanographic approach to fishery research. Calif. Coop. Oceanic Fish. Invest. Rep. 29:27–41.

Lau, N.-C. 1997. Interactions between global SST anomalies and the midlatitude atmospheric circulation. Bull. Am. Met. Soc. 76:21–33.

Lynn, R. J., K. A. Bliss, and L. E. Eber. 1982. Vertical and horizontal distributions of seasonal mean temperatures, salinity, sigma-t, stability, dynamic height, oxygen and oxygen saturation in the California Current, 1950–1978. Calif. Coop. Oceanic Fish. Invest. Atlas 30.

Lynn, R. J., F. B. Schwing, and T. L. Hayward. 1995. The effect of the 1991–93 ENSO on the California Current system. Calif. Coop. Oceanic Fish. Invest. Rep. 36:57–71.

Lynn, R. J., and J. J. Simpson. 1987. The California Current system: the seasonal variability of its physical characteristics. J. Geophys. Res. 92:12,947–12,966.

Mantyla, A. W., E. L. Venrick, and T. L. Hayward. 1995. Primary production and chlorophyll relationships, derived from ten years of CalCOFI measurements. Calif. Coop. Oceanic Fish. Invest. Rep. 36:159–166.

Murphree, T., and C. Reynolds. 1995. El Niño and La Niña effects on the northeast Pacific: the 1991–1993 and 1988–1989 events. Calif. Coop. Oceanic Fish. Invest. Rep. 36:45–56.

NCEP. National Centers for Environmental Prediction. 1997a. Climate diagnostics bulletin, January 1997. Climate Prediction Center, NOAA/NWS/NCEP. No. 97/1. 75 pp.

———. 1997b. Climate diagnostics bulletin, April 1997. Climate Prediction Center, NOAA/NWS/NCEP. No. 97/4. 77 pp.

Pyle, P., L. B. Spear, and D. G. Ainley. 1993. Observations of dark-rumped petrels off Oregon and California. West. Birds 24:110–112.

Rago, T. A., and C. A. Collins. 1995. Hydrographic data along the California coast from Pt. Lobos to Cape San Martin 22–25 October 1995. Naval Postgraduate School Tech. Rep. NPS-OC-95-005, Monterey, CA. 87 pp.

Rago, T. A., C. A. Collins, and J. Steger. 1997. Hydrographic data along the California coast from Pigeon Point to Cape San Martin though July 1996. Naval Postgraduate School Tech. Rep. NPS-OC-97-002, Monterey, CA. 154 pp.

Ribic, C. A., D. G. Ainley, and L. B. Spear. 1992. Effects of El Niño and La Niña on seabird assemblages in the equatorial Pacific. Mar. Ecol. Prog. Ser. 80:109–124.

Roemmich, D., and J. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. Science 267:1324–1326.

Rosenfeld, L. R., F. B. Schwing, N. Garfield, and D. E. Tracy. 1994. Bifurcated flow from an upwelling center: a cold water source for Monterey Bay. Continental Shelf Res. 14:931–964.

Sakuma, K. M., F. B. Schwing, H. A. Parker, and S. Ralston. 1995. The physical oceanography off the central California coast during February and May–June, 1991: a summary of CTD data from larval and pelagic juvenile rockfish surveys. U.S. Dep. Commer., NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-220, 156 pp.

Schwing, F. B., M. O'Farrell, J. M. Steger, and K. Baltz. 1996. Coastal upwelling indices, west coast of North America, 1946–95. U.S. Dep. Commer., NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-231, 207 pp.

Simpson, J. J. 1992. Response of the southern California Current system to the mid-latitude north Pacific coastal warming events of 1982–1983 and 1940–1941. Fish. Oceanogr. 1:57–79.

Spear, L. B., D. G. Ainley, N. Nur, and S. N. G. Howell. 1995. Population size and factors affecting at-sea distribution of four endangered procellariids in the tropical Pacific. Condor 97:613–638.

Thomas, W. H., and C. H. Gibson. 1990. Quantified small-scale turbulence inhibits a red-tide dinoflagellate, *Gonyaulax polyedra* Stein. Deep-Sea Res. 37:1583–1593.

Veit, R. R., J. A. McGowan, D. G. Ainley, T. R. Wahl, and P. Pyle. 1997. Apex marine predator declines ninety percent in association with changing oceanic climate. Global Change Biol. 3:23–28.

Walker, P. W., D. M. Newton, and A. W. Mantyla. 1994. Surface water temperatures, salinities and densities at shore stations. United States west coast. SIO Ref. 94-9.

Yoklavich, M., R. Starr, J. Steger, H. G. Greene, F. Schwing, and C. Malzone. 1997. Mapping benthic habitats and ocean currents near the Big Creek Ecological Reserve. Final report to NOAA/NOS/Monterey Bay National Marine Sanctuary. 53 pp.