THE STATE OF THE CALIFORNIA CURRENT, 2000–2001: A THIRD STRAIGHT LA NIÑA YEAR

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ABSTRACT

This report is the eighth in a series that describe recent oceanographic observations within the California Current system, from Oregon to Baja California. The emphasis here is placed on the observations conducted concurrently by the CalCOFI (California Cooperative Oceanic Fisheries Investigations), IMECOCAL (Investigaciones Mexicanas de la COrriente de CALifornia), and GLOBEC-LTOP (GLOBal Ecosystems Long-Term Observation Program) programs from April 2000 to January 2001. The large-scale oceanic and atmospheric conditions over the tropical Pacific indicated a third straight La Niña year. Coastal conditions exhibited weaker than normal upwelling off northern Baja California and southern California through 2000 and early 2001. Measurements off Oregon, southern California, and Baja California denoted oceanographic conditions near the climatological norm. Likewise, zooplankton biomass decreased from the high levels observed in 1999 to nearly normal values, while cold-water species of seabirds did not increase off southern California. A return to more normal levels of the monitored features of the CCS does not yet support the idea of a climate regime shift.

INTRODUCTION

This is the latest in a continuing series of reports that describe and outline recent observations of the physical and biological structure of the California Current system (CCS). In this report we concentrate on observations conducted from April 2000 to January 2001 along the CalCOFI (southern California) and IMECOCAL (Baja California) survey regions. We also include information from several other programs in order to put these programs into a larger regional context.

Previous reports in this series have brought into perspective the evolution of oceanographic conditions within the CCS, from the conditions prior to (Hayward et al. 1994, 1995, 1996; Schwing et al. 1997) and during El Niño 1997–98 (Lynn et al. 1998). The number and diversity of programs along the CCS have allowed the 1997–98 El Niño, one of the strongest on record, to be one of the most extensively documented by a series of regional oceanographic programs ranging from Baja California to British Columbia (Chavez et al., in press; Collins et al., in press; Huyer et al., in press; Lynn and

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TABLE 1
Locations of SST and Alongshore Wind Time Series

Buoy	Name	Position	Base period[a]	Alongshore angle (°N)[b]
46050	Stonewall Bank, Ore.	44.6°N 124.5°W	1991–99	359
46027	St. George, Calif.	41.8°N 124.4°W	1983–99	341
46022	Eel River, Calif.	40.8°N 124.5°W	1982–99	354
46042	Monterey Bay, Calif.	36.7°N 122.4°W	1987–99	328
46011	Santa Maria, Calif.	34.9°N 120.9°W	1980–99	325
46025	Catalina Ridge, Calif.	33.7°N 119.1°W	1982–99	295

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

Bograd, in press; Schwing et al., in press; Durazo and Baumgartner MS).[2] A good example of this monitoring can be seen in Castro et al. (in press), a hydrographic atlas of data collected along the west coast of North America between January 1997 and January 1999.

The demise of the 1997–98 El Niño was followed by a transition to a cold episode, as reflected by a number of environmental indices (Wolter and Timlin 1998; Schwing et al.[3]). Hayward et al. (1999) have shown how this transition period, which was characterized by a strengthening of the North Pacific High, eventually led to stronger than normal coastal upwelling and a decrease in sea level, a regime typical of La Niña. Upwelling during spring 1999 was the strongest on record (Schwing et al. 2000). Furthermore, Bograd et al. (2000) described how these conditions persisted throughout the period from spring 1999 to spring 2000. Since last year's report and at the time of this writing (May 2001), the persistent pattern of stronger than normal low-level easterlies over the central equatorial Pacific, which has been characteristic of La Niña conditions since mid-1998, has continued for 33 consecutive months. Despite small differences in their predictions, the most recent model forecasts point toward a weakening of La Niña and a return to normal conditions for summer 2001, as well as a trend to slightly positive anomalies by 2002.

Observations made between April 2000 and January 2001 are used here to describe the oceanographic conditions over the CCS, to explore the system's response to the lingering La Niña, and to contrast these observations with the long-term means. We begin by analyzing the large-scale atmospheric and oceanic conditions for the period, putting special emphasis on the northeastern Pacific; we continue our description by examining the coastal and oceanographic conditions along the CCS, roughly from 26°N to 45°N, and by examining the biological response to the oceanic conditions that force the variability in the California Current. We complete our discussion by bringing out the importance of concurrent measurements along the CCS and the need for more systematic, long-term monitoring of the biophysical coupling within the limits of the CCS.

DATA SETS AND METHODS

The observations presented here were obtained from fixed (buoys) and moving (ships, drifters) platforms. Time series of the daily alongshore wind component and sea-surface temperature (SST) observations for six geographical regions of the CCS are obtained from buoys operated by the NOAA National Data Buoy Center (NDBC); the location and base period of each buoy is given in table 1. Monthly upwelling indices and their anomalies, relative to the 1948–67 mean, for the western North American coast are presented. The indices estimate the intensity of large-scale, wind-induced coastal upwelling and are based on the descriptions of Schwing et al. (1996).

The CalCOFI program monitors the oceanographic conditions off southern California on quarterly surveys (normally January, April, July, and October) that occupy a grid of 66 stations (fig. 1). Routine station activity includes CTD/rosette casts to 500 m depth, with sensors for pressure, temperature, salinity, dissolved oxygen, photosynthetically active radiation, fluorescence, and transmissivity. Water samples are collected at 20–24 depths 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 underway sampling of temperature and salinity are carried out, and high-resolution measurements of upper ocean currents are made with an acoustic Doppler current profiler (ADCP). During the winter and spring cruises, the continuous underway fish egg sampler (CUFES; Checkley et al. 1997) is used. Vessel-based (CalCOFI) and colony-based (PRBO) seabird observations between spring 1999 and spring 2001 are placed in perspective by relating them to existing long-

[2]Durazo, R., and T. Baumgartner. MS. Evolution of oceanographic conditions off Baja California: 1997–1999.

[3]Schwing, F. B., T. Murphree, and P. M. Green. MS. A climate index for the northeast Pacific.

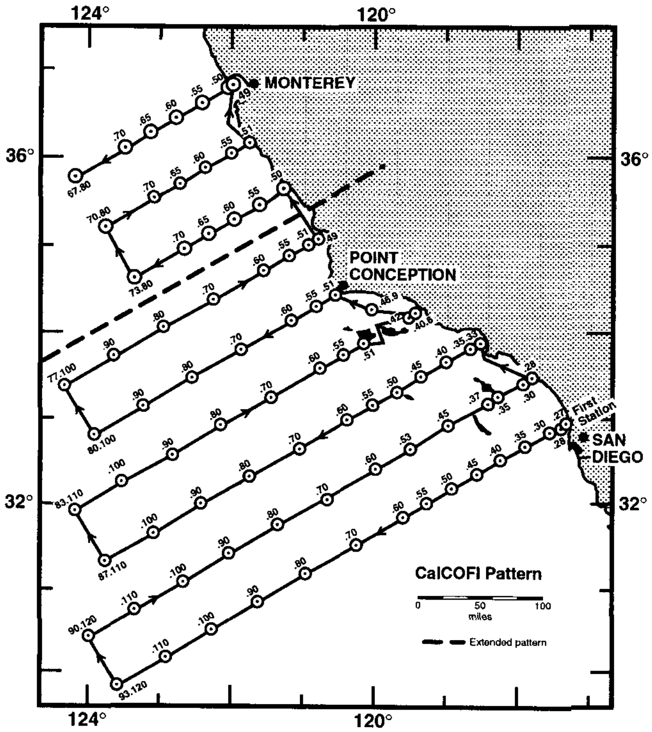

Figure 1. The standard CalCOFI sampling grid. The regular 66-station pattern occupied by CalCOFI since 1985 (lines 77, 80, 83, 87, 90, and 93) is shown by a solid line. The area of additional underway sampling north of the regular pattern is above the dashed line (lines 67, 70, and 73).

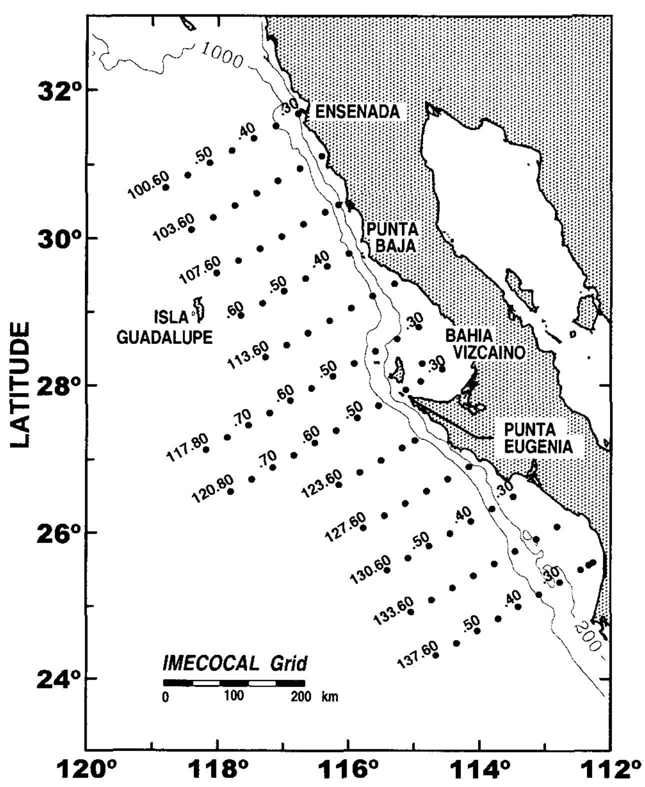

Figure 2. The standard IMECOCAL sampling grid. The regular 93-station pattern (lines 100 to 137) is shown by solid circles. The 200 and 1,000 m depth contours are included.

term data sets. Our objective was to determine whether marine bird at-sea abundance and demography reflected enhanced upwelling and elevated ocean productivity recorded since the winter of 1999 (Bograd et al. 2000; Schwing et al. 2000).

The IMECOCAL program continued sampling the southern region of the California Current, off Baja California, on a reduced CalCOFI grid of 93 stations (fig. 2). The sampling includes CTD casts to 1,000 m, bottom depth permitting, as well as water samples from the upper 200 m to determine dissolved oxygen, nutrients, chlorophyll *a*, and primary production (one ^{14}C "in situ" incubation per day). Standard (.505 mm mesh) oblique bongo tows are conducted, with one cod end dedicated to icthyoplankton and the other to macrozooplankton. Continuous underway measurements of temperature, salinity, and fluorescence are also made; the ADCP was used for continuous current profiling. Starting in January 2000, a CUFES system (Checkley et al. 1997) has been incorporated into the sampling, and preliminary results are presented below.

We also present data from the U.S. GLOBEC Northeast Pacific Program that began a series of seasonal cruises in the northern California Current in July 1997 as part of its long-term observation program (LTOP). Observations are made five times per year along the Newport hydrographic (NH) line at 44.65°N, and three times per year along a set of 4 or 5 zonal sections between 42°N and 45°N. Additional data sets presented here include hydrographic observations along CalCOFI line 67 conducted in November 2000 by the Naval Postgraduate School (NPS) and the Monterey Bay Aquarium Research Institute (MBARI), as well as tracks depicted by isobaric (400 dbar) subsurface floats deployed in November 1998 and May 1999.

LARGE-SCALE OCEANIC ATMOSPHERIC CONDITIONS

After the dramatic transition in 1998 from one of the strongest El Niño events in the century to a strong La Niña event (Hayward et al. 1999; Schwing et al., in press), 2000 and early 2001 were marked by a continuation of La Niña conditions in the tropical Pacific. As indicated by the multivariate ENSO index, or MEI (Wolter and Timlin 1998), winter 2000–2001 was the third consecutive winter in which weak to moderate La Niña conditions intensified (fig. 3). As of April 2001, the MEI had remained negative for 33 consecutive months, the longest continuous negative period since the 1976 climate regime shift. Negative MEI values historically have persisted for 20–35-month periods (cf. 1995–97 La Niña in fig. 3), suggesting that multiyear La Niña events are common (Schwing et al., in press). A number of unusual physical and biological observations

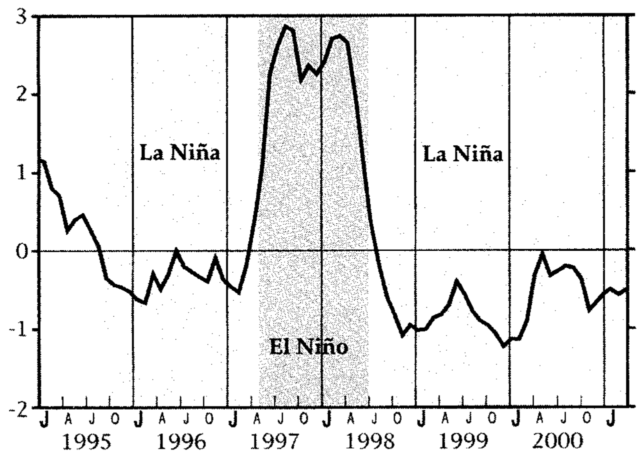

Figure 3. Monthly time series of the multivariate ENSO index, or MEI (Wolter and Timlin 1998), for January 1995–March 2001. Series highlights rapid transition from El Niño to La Niña in 1998, and extended negative phase of MEI associated with the 1998–2001 La Niña.

along the West Coast are highly suggestive of a regime shift in the north Pacific in 1998 or 1999 (Schwing and Moore 2000; Schwing et al. 2000).

Atmospheric anomalies throughout the Pacific Ocean during 2000 and early 2001 (fig. 4) continued a pattern typical of La Niña that developed in late 1998 (Hayward et al. 1999; Bograd et al. 2000; Schwing et al., in press). Generally clockwise wind anomalies in the northeast Pacific were associated with a strong, persistent North Pacific High. These contributed to unusually robust upwelling-favorable winds along much of the North American west coast. An unusually deep Aleutian Low in winter 2000–2001 was linked to anomalous cyclonic winds over the Gulf of Alaska and the persistence of a storm track well north of its typical winter path through the Pacific Northwest.

Since late 1998, a region of cooler than normal sea-surface temperatures (SSTs) has stretched roughly along

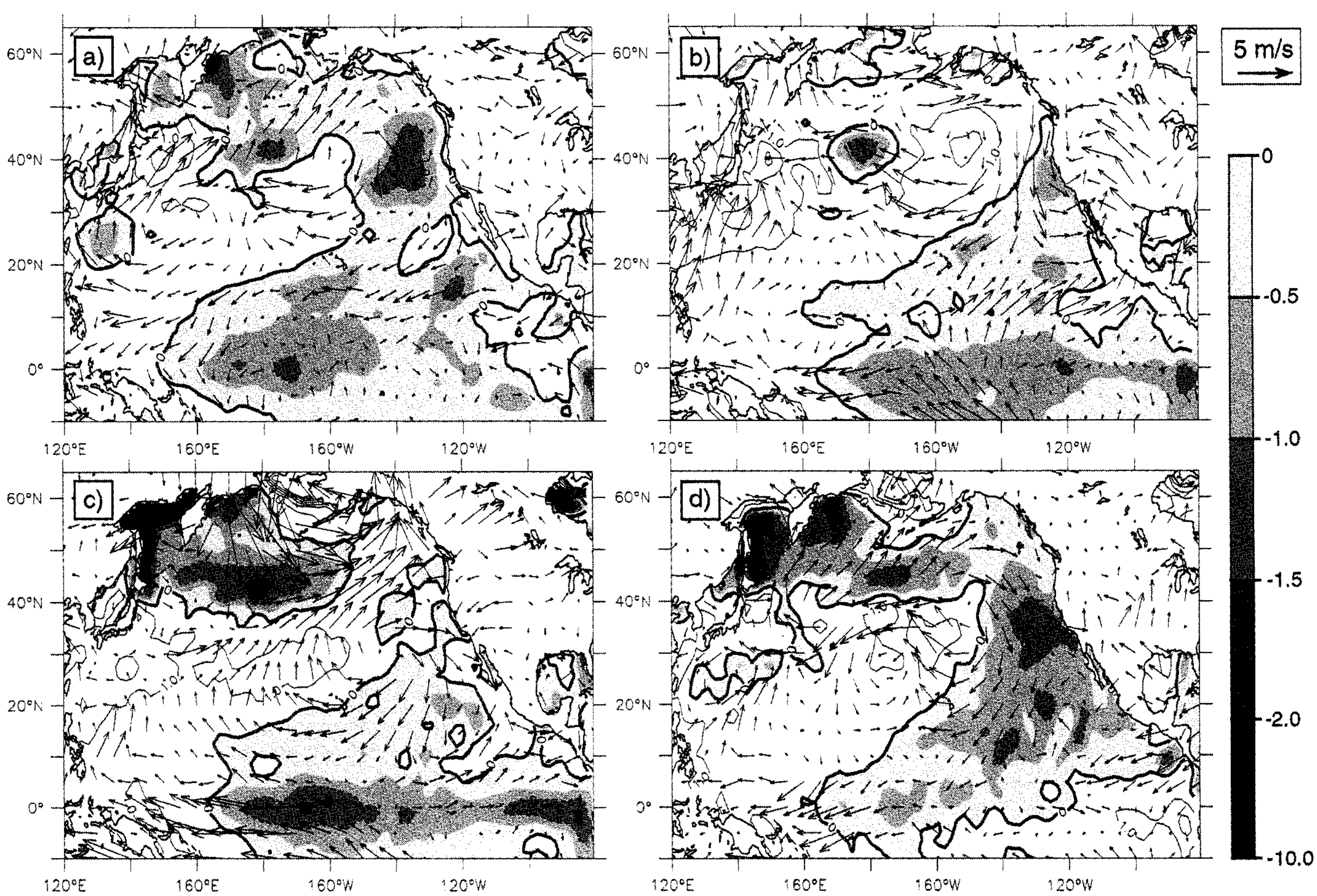

Figure 4. Anomalies of surface wind velocity and sea-surface temperature (SST) in the north Pacific Ocean: *a*, July 2000 wind and May–July 2000 SST; *b*, October 2000 wind and October–November 2000 SST; *c*, January 2001 wind and December 2000–January 2001 SST; and *d*, April 2001 wind and SST. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative SST anomalies are shaded. Wind climatology period is 1968–96. SST climatology period is 1950–79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

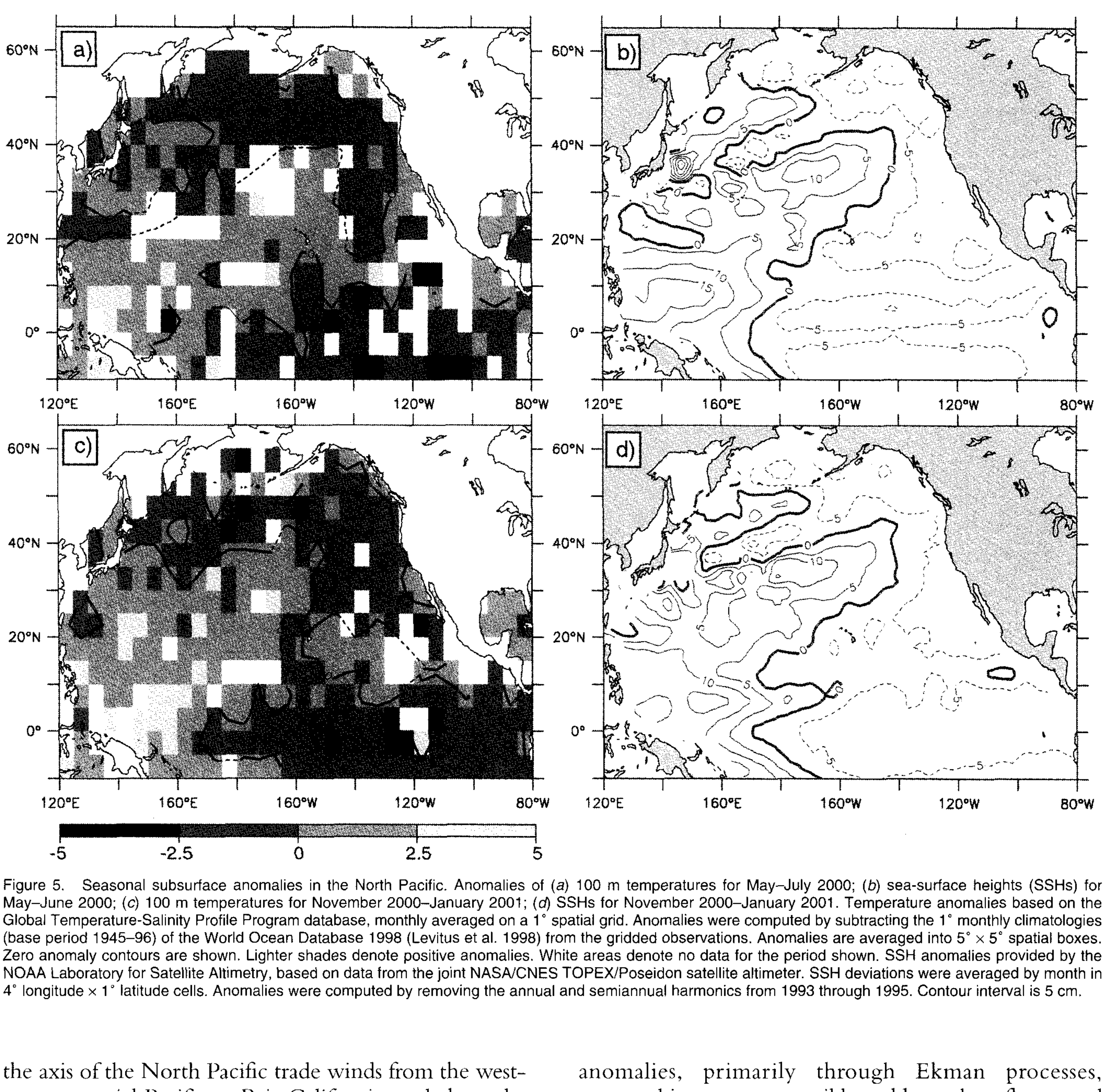

Figure 5. Seasonal subsurface anomalies in the North Pacific. Anomalies of (*a*) 100 m temperatures for May–July 2000; (*b*) sea-surface heights (SSHs) for May–June 2000; (*c*) 100 m temperatures for November 2000–January 2001; (*d*) SSHs for November 2000–January 2001. Temperature anomalies based on the Global Temperature-Salinity Profile Program database, monthly averaged on a 1° spatial grid. Anomalies were computed by subtracting the 1° monthly climatologies (base period 1945–96) of the World Ocean Database 1998 (Levitus et al. 1998) from the gridded observations. Anomalies are averaged into 5° × 5° spatial boxes. Zero anomaly contours are shown. Lighter shades denote positive anomalies. White areas denote no data for the period shown. SSH anomalies provided by the NOAA Laboratory for Satellite Altimetry, based on data from the joint NASA/CNES TOPEX/Poseidon satellite altimeter. SSH deviations were averaged by month in 4° longitude × 1° latitude cells. Anomalies were computed by removing the annual and semiannual harmonics from 1993 through 1995. Contour interval is 5 cm.

the axis of the North Pacific trade winds from the western equatorial Pacific to Baja California, and along the North American west coast (cf. Hayward et al. 1999; Bograd et al. 2000). Cool anomalies also were common north of 40°N, and spanned the equator east of the date line. Positive SST anomalies were maintained south of 40°N from the western North Pacific to north of Hawaii. This basic SST anomaly pattern, which is seen commonly during La Niña events (Schwing et al., in press), was evident throughout 2000 and early 2001 (fig. 4). In summer 2000 and again in spring 2001, an SST anomaly minimum developed west of the California Current system (CCS). It is thought that these anomalously cool SSTs were created and maintained by regional wind anomalies, primarily through Ekman processes, geostrophic transport, sensible and latent heat fluxes, and vertical mixing (Schwing et al., in press).

The SST anomalies during the past year were a general reflection of the upper water column, as defined by anomalies of temperature at 100 m depth and sea-surface heights from the TOPEX/Poseidon satellite altimeter (fig. 5). Particular key features are the arc of cool anomalies along the West Coast and eastern tropical Pacific; extremely warm anomalies in the western tropical Pacific; and warm anomalies extending across the North Pacific from east Asia to north of Hawaii. These temperature and height anomaly patterns have been present since late 1998 (Schwing et al., in press), supporting the idea that

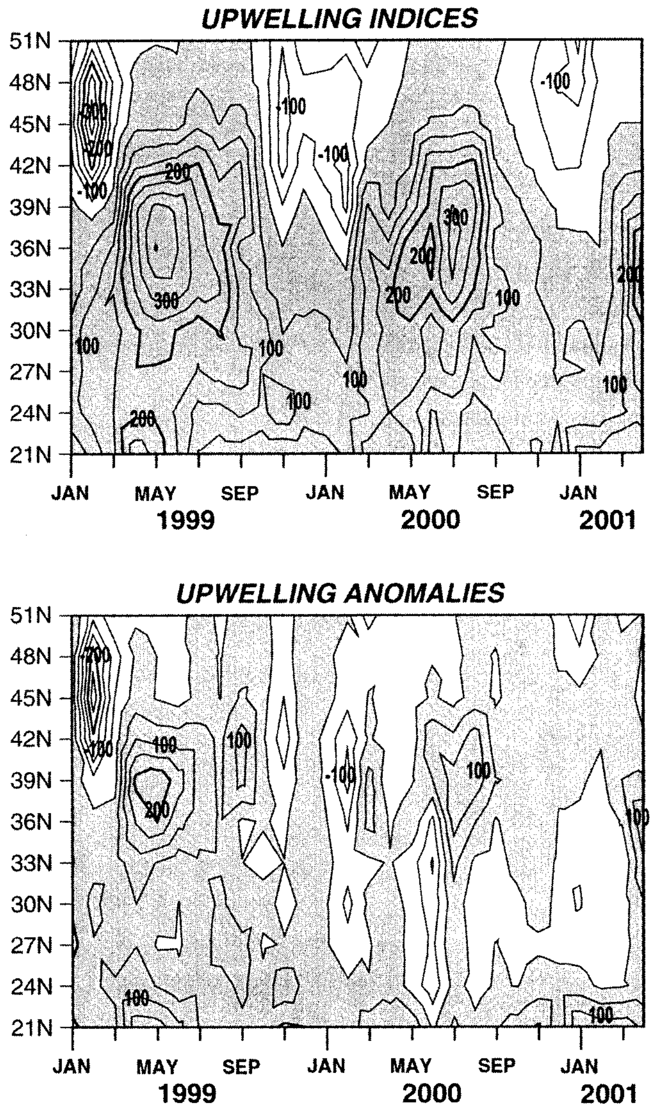

Figure 6. Monthly upwelling indices and upwelling anomalies for January 1999–April 2001. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m^3/s per 100 km of coastline.

a regime shift occurred about that time. Although SSTs were unseasonably cool in the southern CCS, subsurface temperature anomalies were positive. This may indicate an anomalously deep thermocline, possibly due to weaker than normal upwelling (fig. 6), or it may reflect downwelling associated with coastal wave activity (Clarke and Van Gorder 1994; Meyers et al. 1998). The ocean anomalies in figures 4 and 5 indicate an excess amount of heat stored in the upper ocean in the western tropical Pacific. This is conducive to the future development of El Niño, provided the proper atmospheric conditions develop (McPhaden 1999).

At the time of this writing (May 2001), mature cold episode (La Niña) conditions continued in the tropical Pacific (NCEP 2001). Across the central and eastern equatorial Pacific, SSTs remained 0.5°–1.0°C below average, and the thermocline was unusually shallow. Equatorial Pacific thermocline temperatures were up to 2°–4°C above (below) normal east (west) of 160°W. A gradual expansion of positive equatorial subsurface temperature anomalies into the central Pacific has continued for the past several months. This evolution characterizes the mature phase of La Niña events. The general impression from climate model forecasts is a continued gradual weakening of tropical Pacific La Niña conditions, with near-normal or slightly warmer than normal (weak El Niño) conditions evolving during the second half of 2001. However, the models are not in complete agreement on this; some predict that La Niña will continue into late 2001.

COASTAL CONDITIONS

Monthly coastal upwelling indices (Bakun 1973; Schwing et al. 1996) indicate generally stronger than normal upwelling in the CCS since the onset of La Niña in late 1998 (fig. 6). Following record upwelling anomalies off central California during the 1999 upwelling season (Schwing et al. 2000), upwelling was again unusually strong during the 2000 season from Point Conception to the Columbia River and off southern Baja California. Negative anomalies (weaker than normal upwelling) prevailed through 2000 and early 2001 off northern Baja California and southern California. Anomalously strong downwelling off the Pacific Northwest characterized the past three winters. In April 2001, stronger than normal upwelling extended throughout the CCS.

Winds measured by NDBC coastal buoys in the CCS (fig. 7) display the short-term variability associated with synoptic atmospheric events, superimposed on the annual climatological cycle of strong southward winds in summer and northward or weak southward winds in winter. Wind vectors align strongly with the local coastline (table 1). Coastal winds during 2000 displayed the typical pattern of stronger magnitudes and higher synoptic to annual variability off northern California, and weaker and less variable winds within the Southern California Bight (fig. 7). Alongshore winds were near their long-term norm, punctuated by a number of stronger than normal southward (more upwelling-favorable) wind events during the upwelling season, and occasional relaxation episodes of downwelling or weak upwelling.

Coastal SSTs cooled (warmed) in response to local upwelling (downwelling) wind events, particularly in the northern CCS (fig. 8). Strong downwelling episodes occurred in November 1999 and January–February 2000 over most of the CCS. Although these winds resulted in some ocean warming, SSTs remained near or below their seasonal norms. Significant upwelling events were noted off northern California and Oregon in late March,

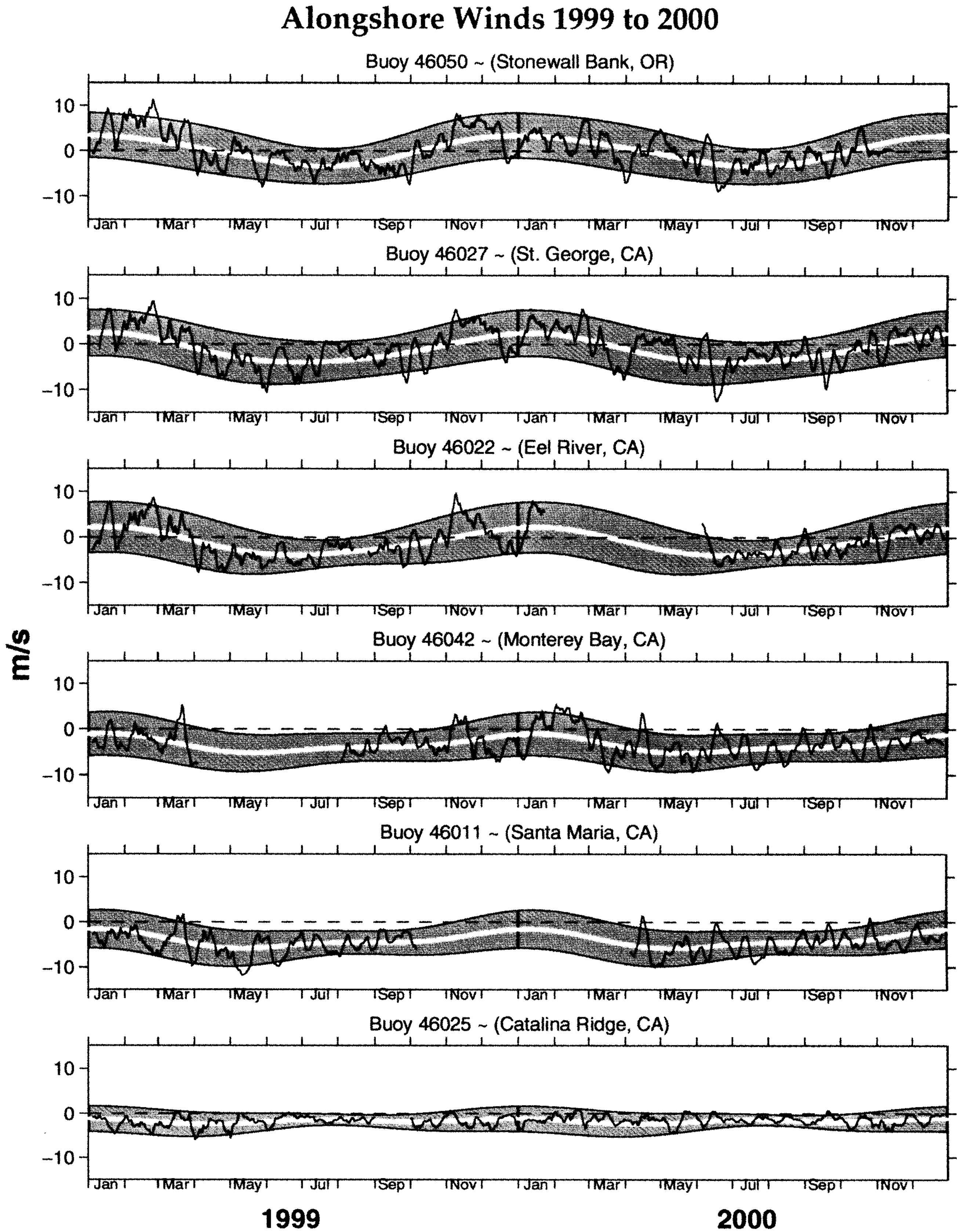

Figure 7. Time series of daily-averaged alongshore winds for January 1999–December 2000 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard error for each Julian day. Series have been smoothed with a 7-day running mean. The periods used for calculating the climatology at each site and the alongshore angle are shown in table 1.

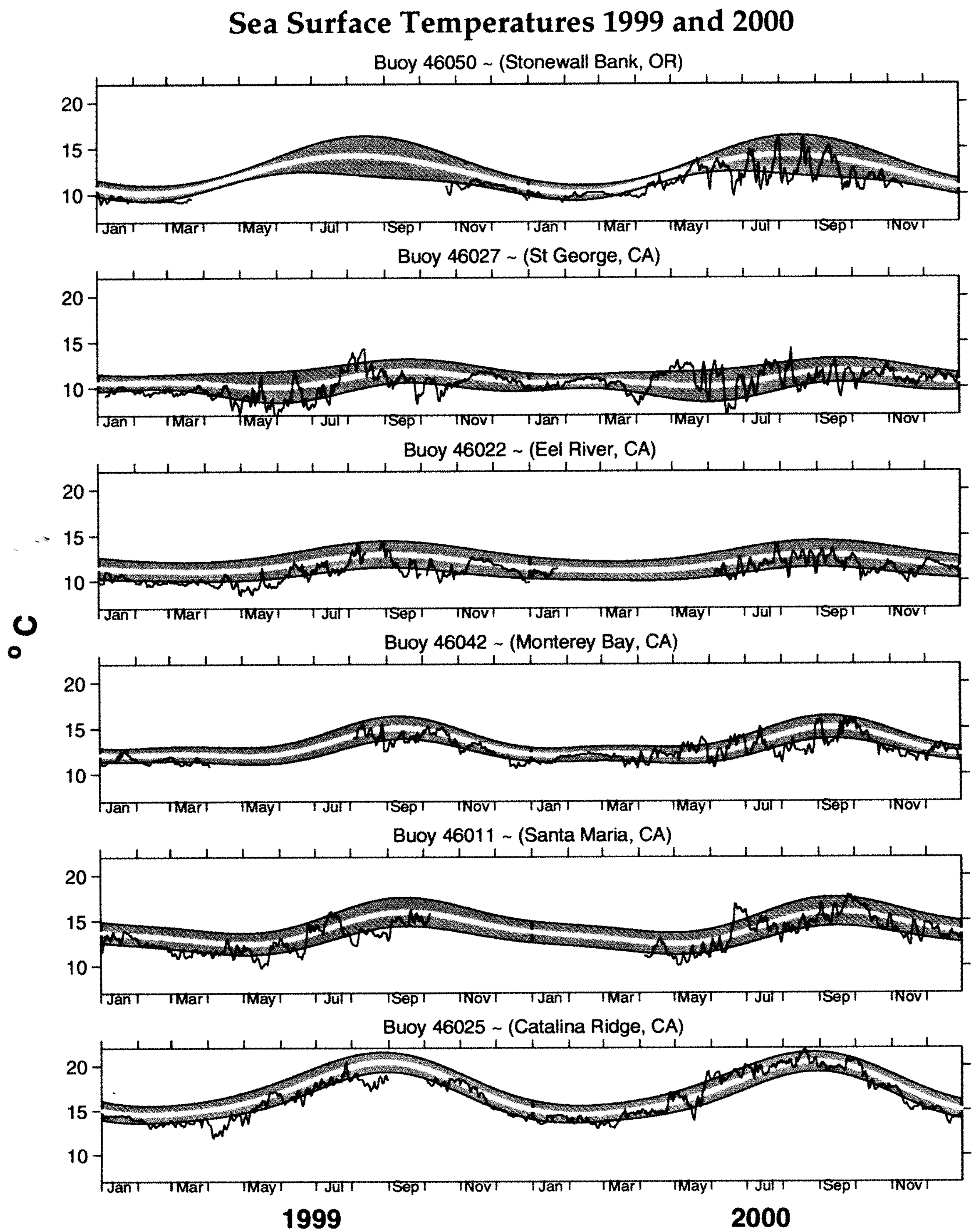

Figure 8. Time series of daily-averaged SST for January 1999–December 2000 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard error for each Julian day. The periods used for calculating the climatology at each site are shown in table 1.

June, and September 2000. Farther south, strong upwelling events occurred in May, August, and November 2000. The multiyear trend of below normal temperatures continued in the northern CCS, although the anomalies were not as extreme as in 1999. SSTs were near-seasonal off southern California through most of the previous year.

IMECOCAL SURVEY CRUISES

Data gathered during observations since last year's report are described below. Please refer to the IMECOCAL Web page (*http://imecocal.cicese.mx*) for more information about the program, 1997–2001 databases, and future cruise schedules.

0004 (4–24 April 2000). Equatorward flow parallel to the coast was the main characteristic during this cruise, as depicted by the near-surface geostrophic currents (fig. 9). The salinity minimum indicates that the core of the California Current lies approximately 200 km from the coast except off Punta Eugenia, where it veers around a small cyclonic eddy centered on station 117.55. Offshore, the flow follows two anticyclonic meanders, one east of Isla Guadalupe and the other centered on station 127.60. Both meanders are associated with warm and higher-salinity waters. Inshore, two upwelling regions, characterized by their low sea-surface temperatures near the coast, are noticeable, one off Ensenada related to a small cyclonic eddy on station 103.35 and the other south of Punta Eugenia. Except for the poleward flow around this cyclonic eddy, no Inshore Countercurrent is noticeable during the period of this cruise. Large values of chlorophyll *a* correspond to these upwelling regions, with concentrations above 1 mg/m^3 associated with temperatures below 15.5°C. In general, chlorophyll *a* concentrations were lower than those observed in 1999 (Bograd et al. 2000). However, March 2000 near-surface chlorophyll *a* estimates from SeaWIFS images reveal values comparable to those of April 1999 but greater than in April 2000. Temperatures on both upwelling regions were ~1°C lower than the climatological mean for the period 1950–78 (Lynn et al. 1982), while salinities were within the norm.

0007 (10–31 July 2000). A very energetic, meandering, California Current as well as coastal upwelling along northern Baja California were the typical conditions during this cruise (fig. 10). The California Current enters the survey region as an eastward flow, around stations 103.60 and 107.60, moves east and reaches the coast near Punta Baja, where it turns sharply to later follow an equatorward path around Punta Eugenia. At the southern limit of the survey region, it splits into two branches, one offshore that entrains warmer, more saline water from the west to finally flow south, and the other moving onshore to finally impinge on the coast south of Punta Eugenia. Inshore of the California Current core, poleward flows are associated with a cyclonic-anticyclonic eddy pair between lines 100 and 107. The cyclonic eddy entrains some California Current water, which is driven northward by the anticyclonic eddy to form the Inshore Countercurrent for the southern California region. North of 27°N, temperatures were minimal near the coast south of the coastal prominences Punta Banda (Ensenada), Punta Baja, and Punta Eugenia. High temperature (18.5°C) inside Bahía Vizcaino indicates that the summer-autumn anticyclonic eddy is well developed (Amador-Buenrostro et al. 1995). Large spatial gradients of up to 6°C/100 km between the inshore and offshore waters are discernible. The triangular coastal region of large spatial temperature gradients between Punta Baja and Punta Eugenia is also an area of high concentrations of chlorophyll *a*. Except for this region where 10 m temperatures were ~1°–2° below the climatological mean (Lynn et al. 1982), water temperatures were normal north of 28°N and warmer than normal south of this latitude.

0010 (10–31 October 2000). Near-surface geostrophic currents indicate that the California Current enters the survey area from the north and flows close to shore, as indicated by the lower salinities near the coast (fig. 11). A portion of the current moves farther offshore and back north as part of an anticyclonic meander to later return around the cyclonic eddy east of Isla Guadalupe. For this cruise, there was no clear indication for the presence of a poleward inshore countercurrent. Both 10 m temperature and salinities were close to normal (Lynn et al. 1982). Chlorophyll *a* concentrations larger than 1 mg/m^3 were observed only near shore on the northernmost portion of the survey region (stn. 100.30), while the rest of the surrounding area had low concentrations, in general associated with warmer (>19°C) and saltier ($33.7 < S < 34.3$) waters.

0101 (16 January–5 February 2001). During this cruise, near-surface currents depict a slow-moving and broad California Current, with weak onshore-offshore dynamic topography gradients (fig. 12). The same weak gradients were reflected in the other measurements. Chlorophyll *a* concentrations larger than 1 mg/m^3 were associated with the surroundings of Punta Eugenia as well as with a small upwelling region around station 103.30. Chlorophyll *a* concentrations during this cruise were larger than those reported for winter 2000 (Bograd et al. 2000). Throughout most of the region, 10 m temperature and salinity were normal.

CALCOFI SURVEY CRUISES

We summarize a portion of the data obtained on each of the quarterly CalCOFI cruises conducted since the preparation of last year's report, focusing on near-surface

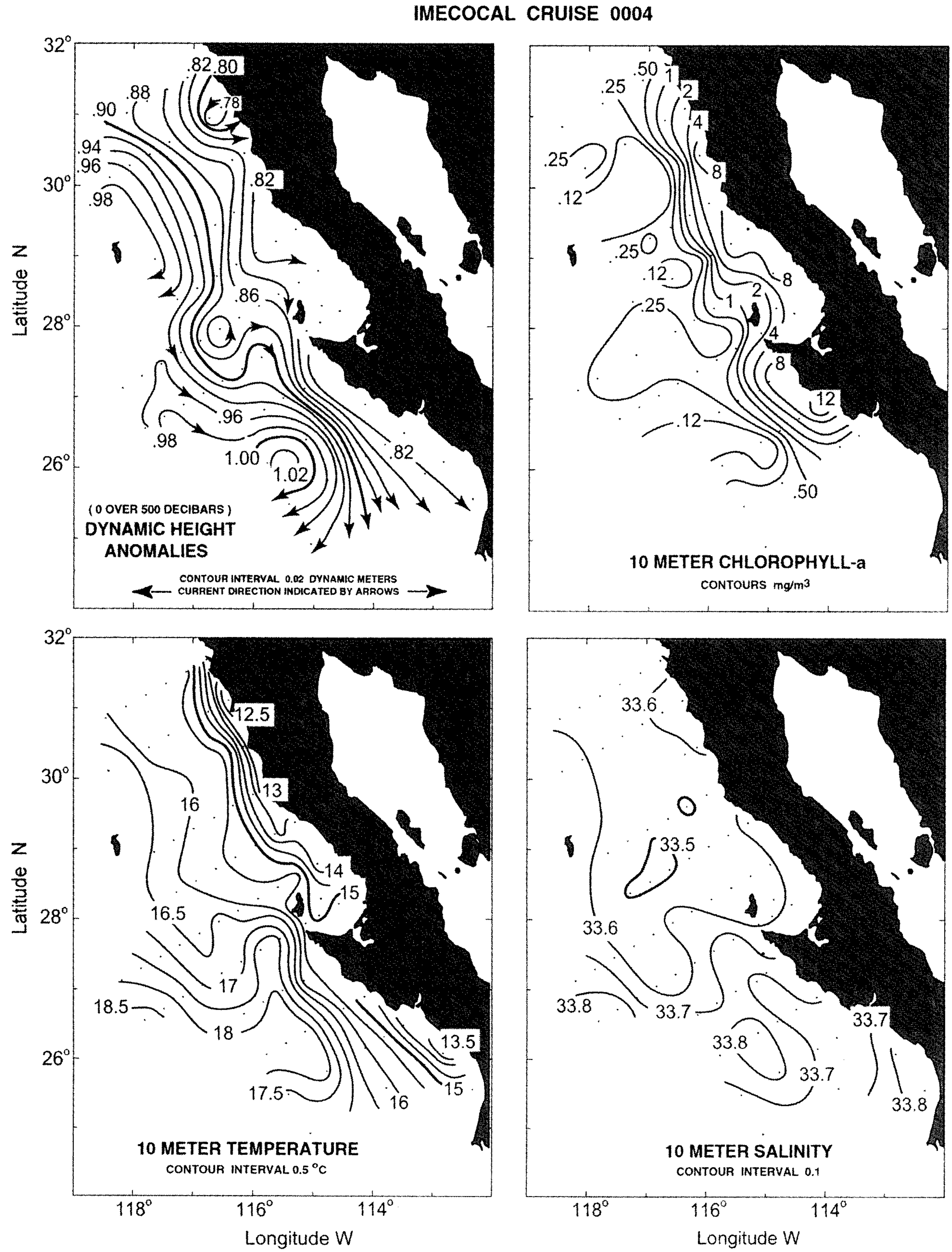

Figure 9. Spatial patterns for IMECOCAL cruise 0004 (4–24 April 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

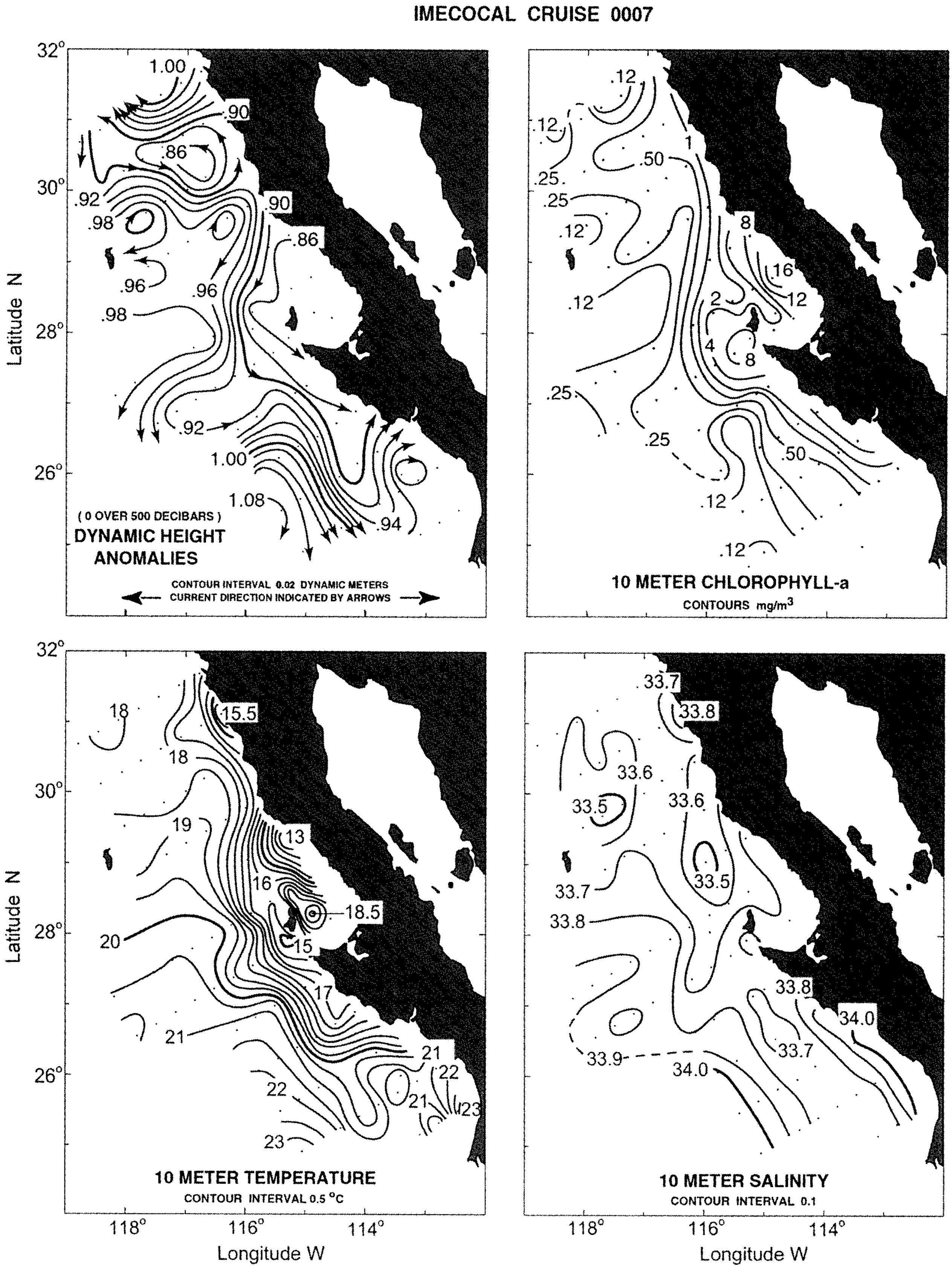

Figure 10. Spatial patterns for IMECOCAL cruise 0007 (10–31 July 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

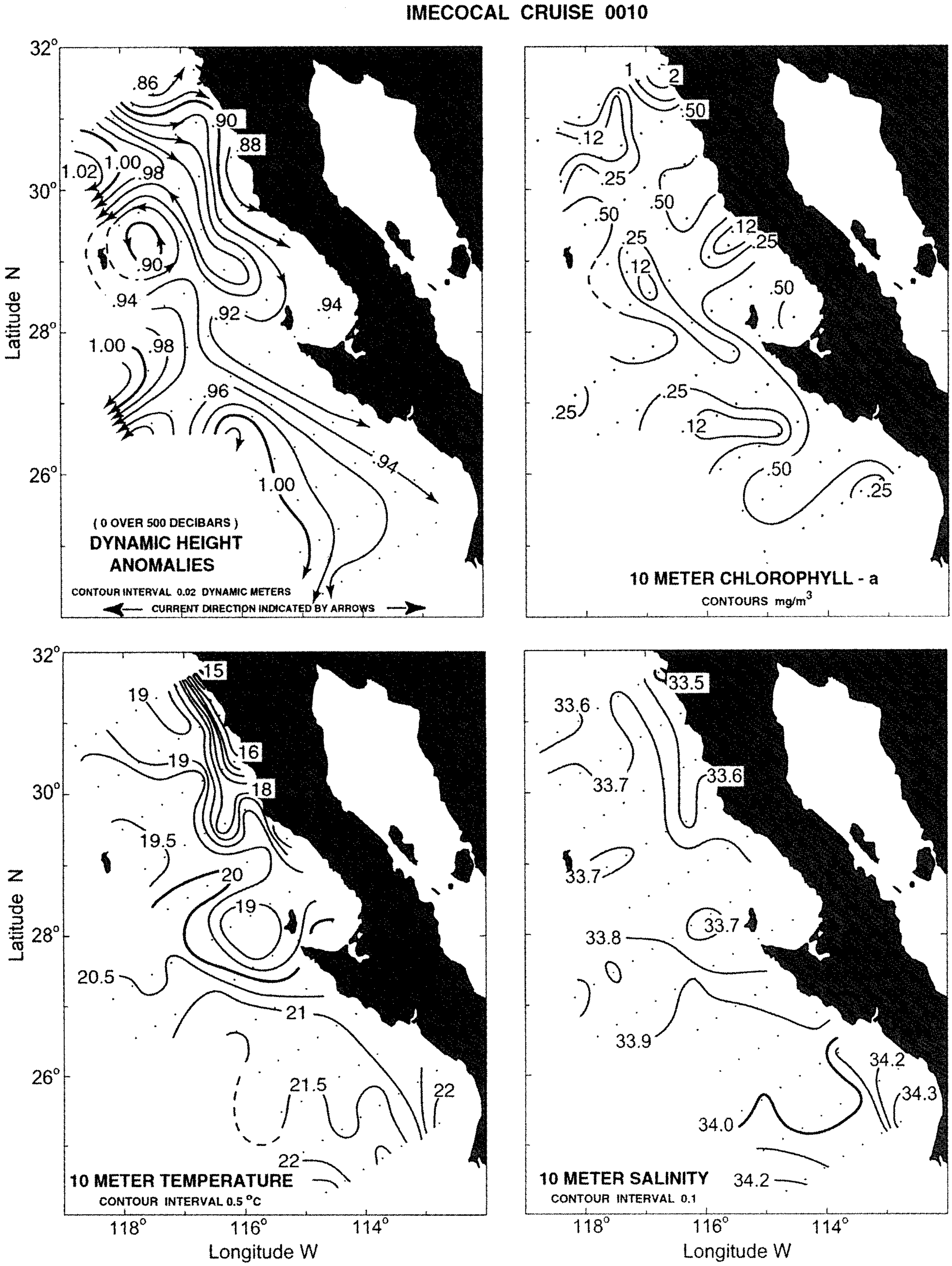

Figure 11. Spatial patterns for IMECOCAL cruise 0010 (10–31 October 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

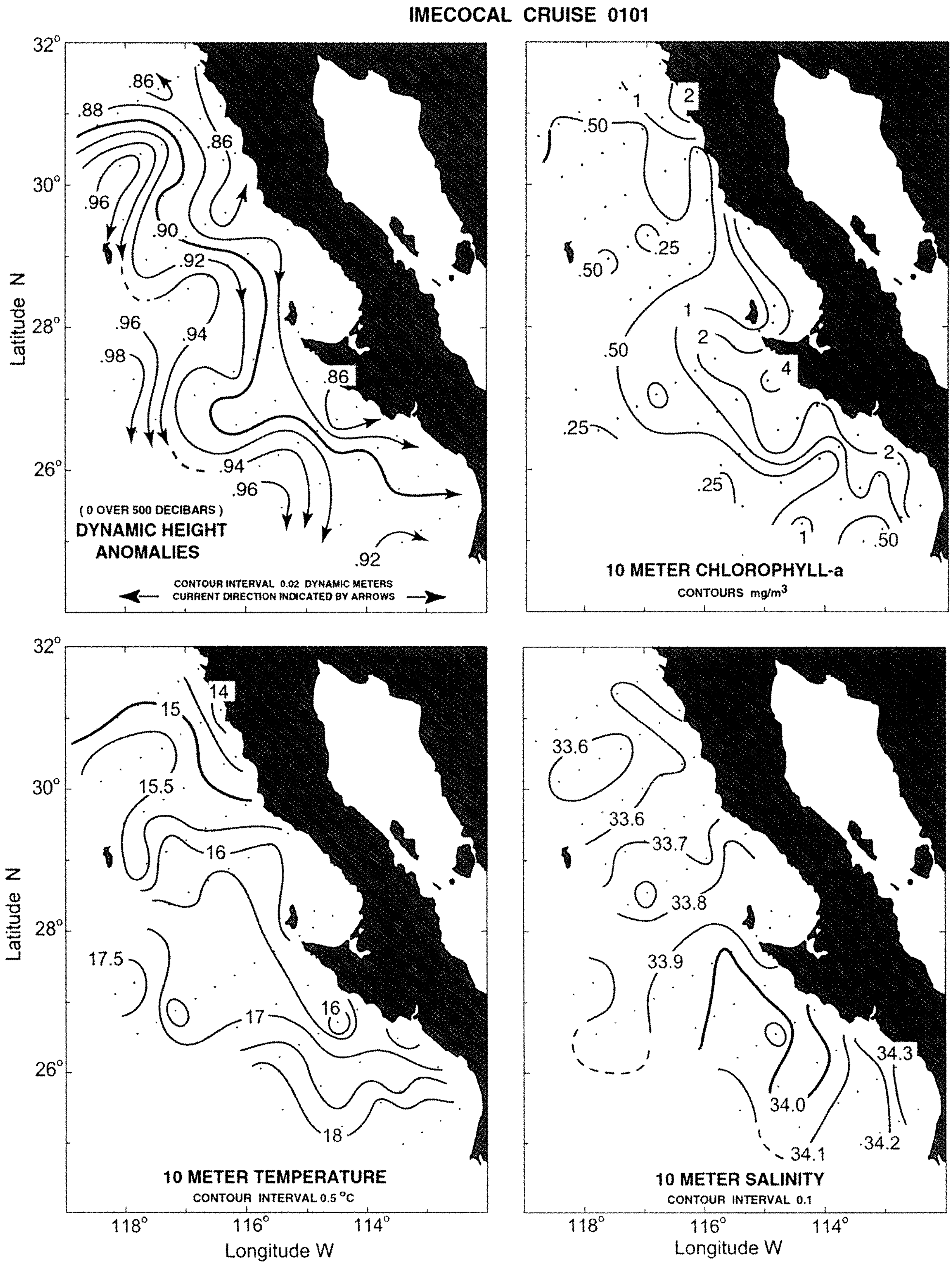

Figure 12. Spatial patterns for IMECOCAL cruise 0101 (16 January–5 February 2001), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

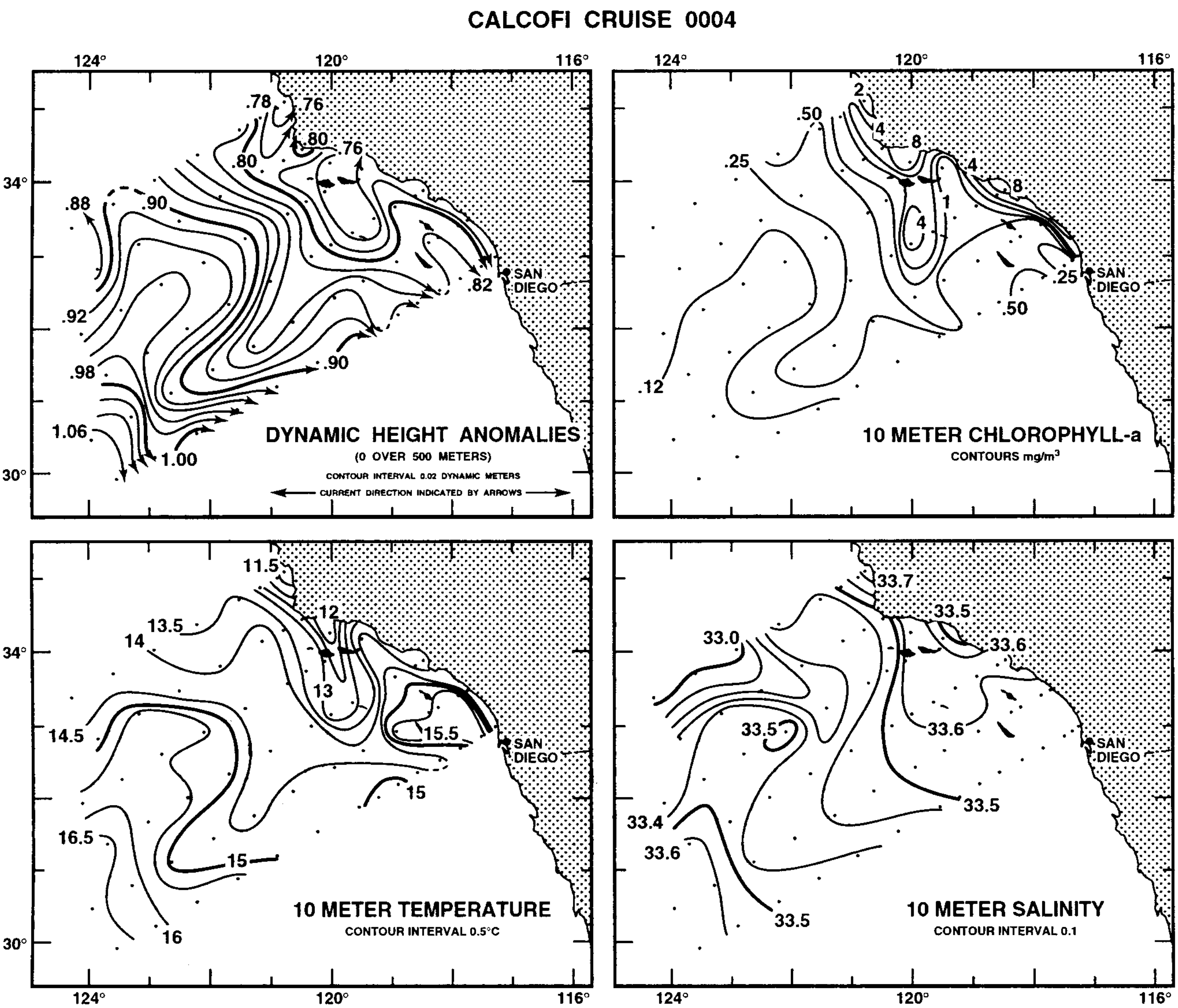

Figure 13. Spatial patterns for CalCOFI cruise 0004 (7–29 April 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

physical and biological fields. The reader is encouraged to refer to the cruise data reports (e.g., Scripps Institution of Oceanography 2000) or the CalCOFI Web page (*http://www.calcofi.org*) for a complete presentation of the data sets, as well as for updates on subsequent cruises. A CD-ROM containing the first 50 years of CalCOFI data (1949–99), as well as software tools for navigating and extracting data segments, is also available.

0004 (7–29 April 2000). Preliminary data from this cruise were included in last year's report (Bograd et al. 2000). As has been the case for the past several springs, this cruise surveyed farther north than usual, along lines 73, 70, and 67, performing underway measurements including the tracking of sardine and anchovy eggs with the CUFES (see the Biological Patterns section below). The 0/500 dbar dynamic height field reveals a strong California Current, which enters the region near stations 77.70–90 and meanders sharply between lines 87 and 93 (fig. 13). The zonal flow evident offshore may indicate the early stages of large eddy development. This region was characterized by relatively warm and saline near-surface waters. The inshore region consisted of two dynamic regimes: (1) an area of cool, saline, near-surface waters extending southward along the coast and offshore from Point Conception, which results from the lifting (upwelling) and offshore advection of deeper waters, and (2) a pool of warm water, apparently of southerly origin, encompassing the southeastern portion of the Southern California Bight. However, there was no evidence of significant poleward flow (the Inshore Countercurrent) during the period of this cruise. Chlorophyll *a* values were high within a narrow strip along the coast, and

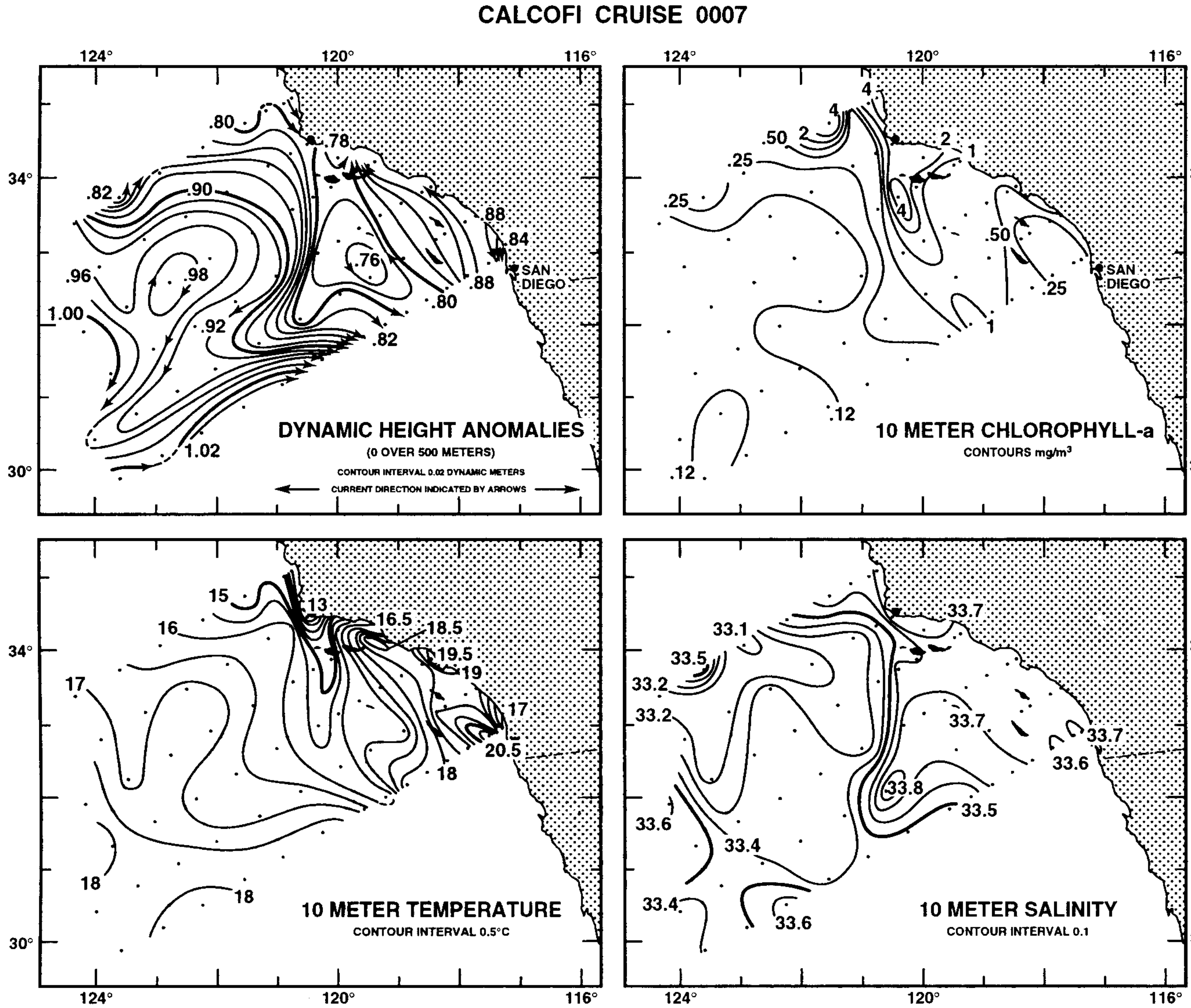

Figure 14. Spatial patterns for CalCOFI cruise 0007 (29 June–14 July 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

within the tongue of cool water extending south from Point Conception, but overall chlorophyll values were much lower than those observed the previous April (Bograd et al. 2000).

0007 (29 June–14 July 2000). The near-surface circulation pattern in July 2000 was similar to that seen in April, although we do not know whether this constituted a stable pattern over the intervening period (fig. 14). The California Current was vigorous, and again had a pronounced meander along lines 90 and 93. The 0/500 dbar dynamic height field reveals a closed circulation (anticyclonic eddy), characterized by relatively warm and saline waters, in roughly the same location as the large California Current meander seen in April (line 83). Again, we cannot infer the stability of this feature from the hydrographic cruises alone. The poleward Inshore Countercurrent had developed by this time, filling the near-surface Southern California Bight with warm and saline waters. Another closed circulation feature (a cyclonic eddy) is evident just west of the submerged gappy ridge that extends south from Santa Rosa Island (34.0°N, 120.1°W). The inshore area of cool temperatures and high chlorophyll *a* content was confined to the coast near Point Conception, and within the tongue that again extends southward just west of the ridge. Overall chlorophyll values were fairly typical for a midsummer cruise.

0010 (12–31 October 2000). The near-surface circulation in October 2000 was considerably more energetic than in a typical autumn cruise (fig. 15; e.g., see the mean seasonal circulation patterns in Bograd et al. 2000, fig. 10). The California Current entered the region at stations 77.90–100, and then meandered through the

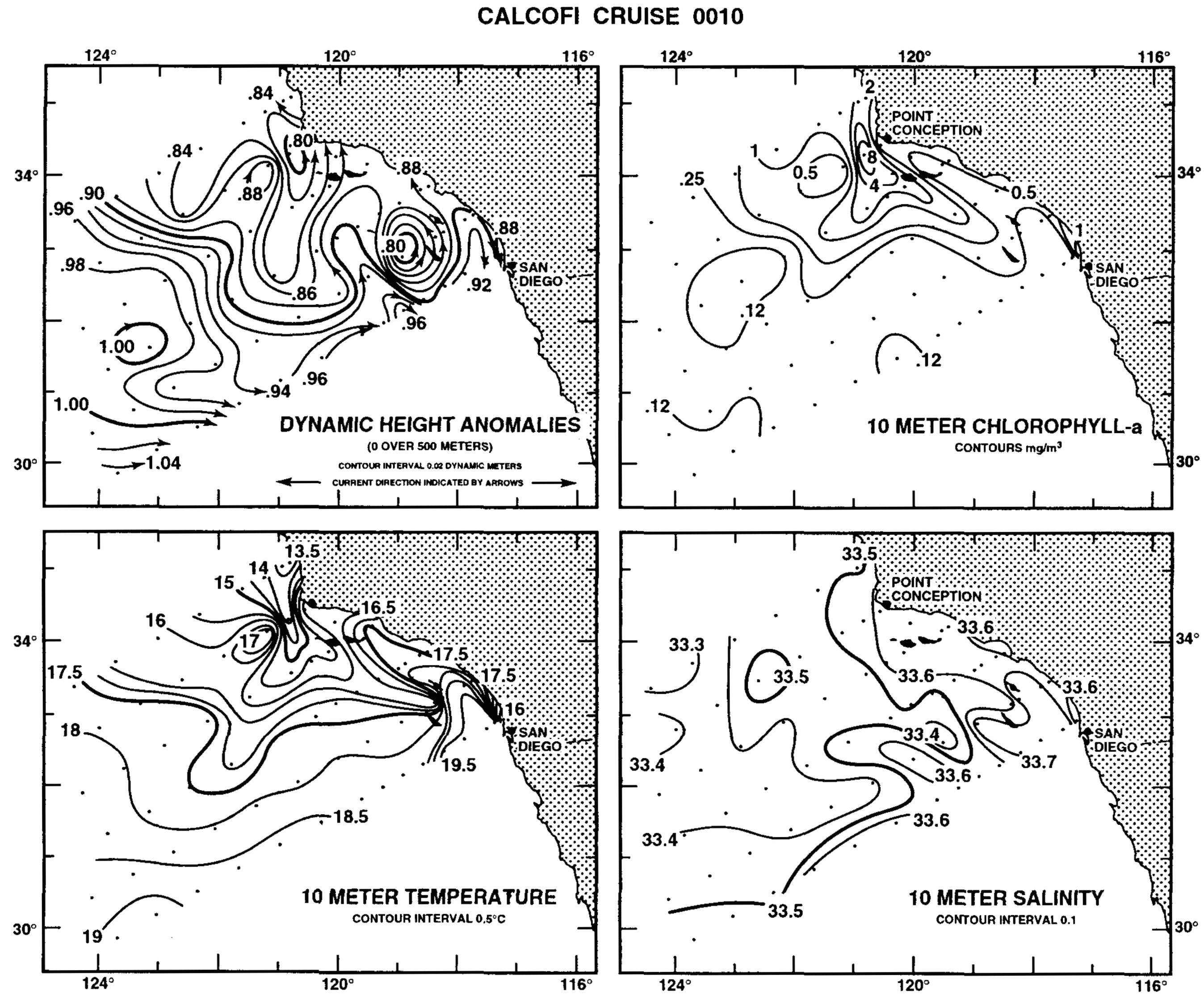

Figure 15. Spatial patterns for CalCOFI cruise 0010 (12–31 October 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

center of the grid and into the Southern California Bight. A vigorous cyclonic eddy, composed of cool, fresh water, was situated near the center of the bight. This feature shows up as a large SST anomaly (−3°C) in the line 90 temperature time series (fig. 18 below). The near-coastal poleward flow, which is often well developed at this time of the year, was confined to the southeastern portion of the bight, where 10 m temperatures approached 20°C. The upwelling regime surrounding Point Conception, which is characterized by cool, salty, high-chlorophyll near-surface waters, is again clearly evident. Chlorophyll values were fairly high for an October cruise.

0101 (7–26 January 2001). The near-surface circulation pattern during January 2001 (fig. 16) was again quite energetic on the offshore side of the grid, but quiescent inshore of station 70. The core of the California Current, as revealed by the circulation patterns and the 10 m salinity fields, was well offshore, and appeared to meander around a large anticyclonic eddy, centered near station 90.100, which had a pronounced near-surface temperature (warm) and salinity (salty) signature. Large eddies have often been observed on this portion of the grid. All features had weak horizontal gradients near shore, including the region around the Point Conception upwelling center. Chlorophyll values, highest near Point Conception and in the Santa Barbara Basin as always, were modest over most of the grid.

* * *

In 2000, NPS and MBARI occupied CalCOFI line 67 five times. Measurements from the September 2000 transect are shown in figure 17. The California Current

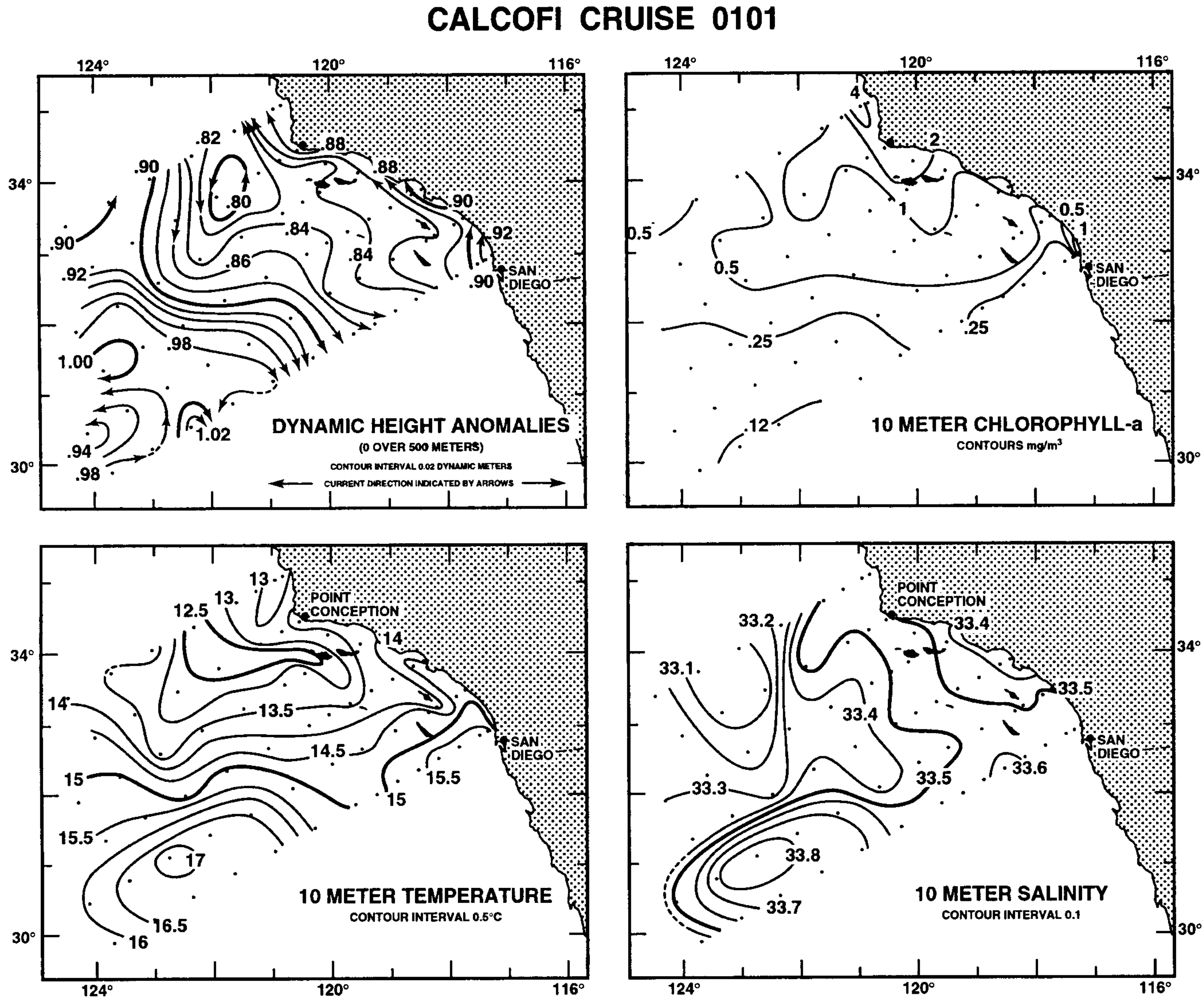

Figure 16. Spatial patterns for CalCOFI cruise 0101 (7–26 January 2001), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

is clearly evident between 150 and 350 km from shore. This region is marked by isotherms that shoal toward the coast as well as by equatorward geostrophic flow. In the upper 100 m, the core of the California Current is marked by S<33.4, geostrophic velocity <−10 cm/s, and a deepening of the nutricline and oxycline from 40 dbar inshore to 80 dbar. There is a subsurface oxygen maximum at the depth of the nutricline at the offshore edge of the California Current. This shallow oxygen maximum was probably formed by photosynthetic oxygen production trapped by the strong stratification in the upper 50 dbar of the water column. Poleward geostrophic flow occurred inshore between 75 and 150 km from shore as well as west of 350 km from shore. Below 170 dbar, the spiciness of the poleward-moving water was similar, >0.1 kg/m^3, but oxygen and nitrate levels were higher in the offshore poleward flow. For the offshore poleward flow, the water mass characteristics near the surface were similar to those observed in the equatorward flow immediately to the east; this may indicate the presence of an eddy at this location.

The time series of 10 m temperature anomalies along line 90 displays the sequence of strong interannual changes experienced over the last four years (fig. 18). This updated figure from last year's report (Bograd et. al. 2000) covers the period from 1997 through January 2001. The first half of the series is dominated initially by near-surface warming, then cooling, both associated with the strong 1997–98 El Niño–La Niña cycle (Bograd and Lynn 2001; Lynn and Bograd, in press). After spring 1999, near-surface temperatures in the southern CCS were near their climatological means for much of the

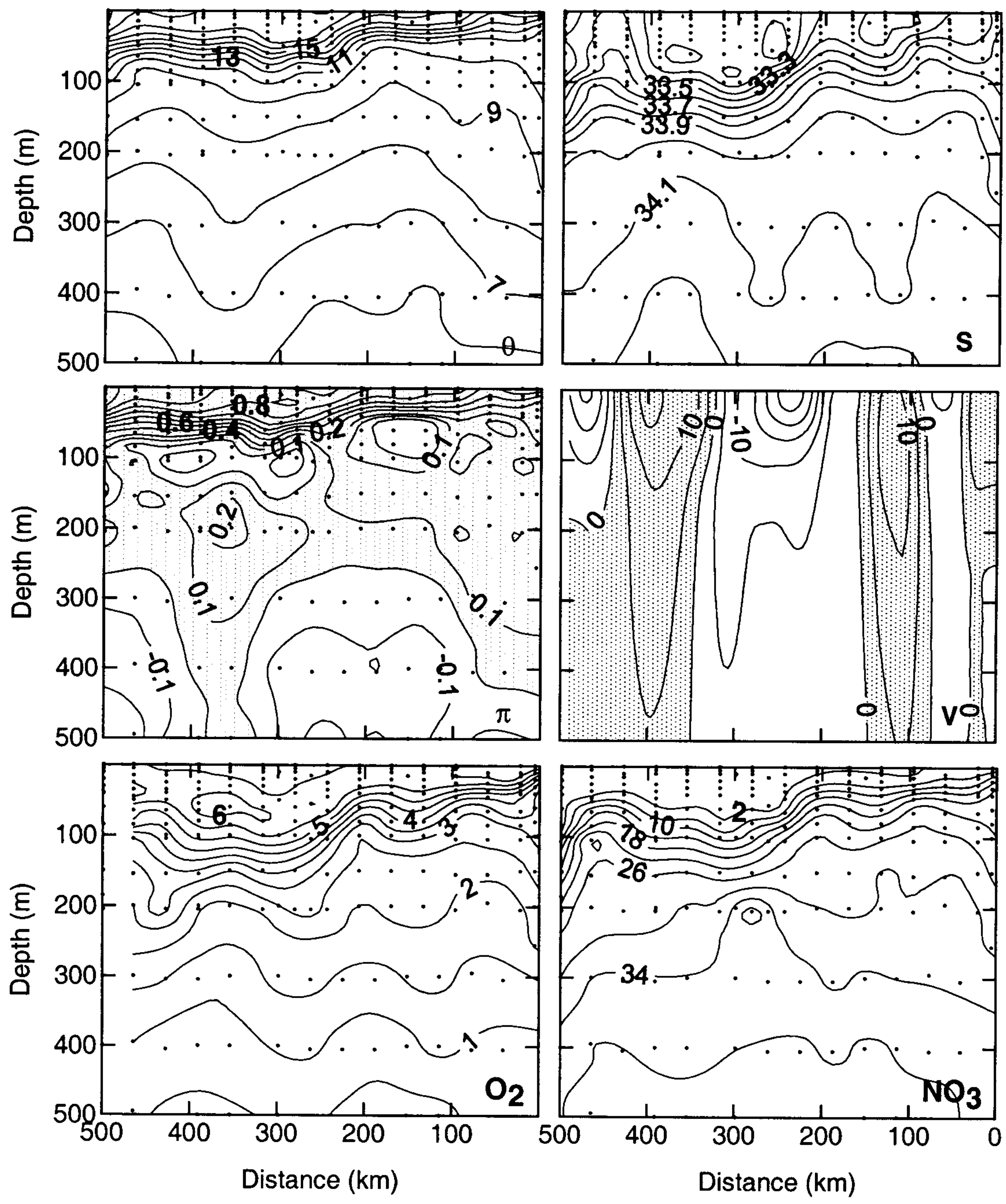

Figure 17. Cross-sections of temperature (°C), salinity, spiciness, geostrophic velocity (cm s^{-1}) referenced to 500 m, dissolved oxygen (ml l^{-1}), and concentration of nitrate (µmol l^{-1}) from CalCOFI line 67 in September 2000. A positive velocity refers to poleward flow, and a negative velocity (shaded) refers to equatorward flow.

remainder of the year and into early 2000. A strong cool event (anomalies greater than ~3°C) was observed in October 2000, centered within the bight, but temperatures were again near normal by January 2001. The interpretation of temperature events along line 90 can be placed in a larger context by the regional SST anomaly series provided on the El Niño Watch page of the West Coast CoastWatch Web site (fig. 19). The regional anomaly series for southern California shows a trend toward smaller anomalies from the negative anomalies of the first half of 1999. The anomalies seesaw about positive and negative values mostly less than 0.5°C from neutral, to end the series at zero. There is a strong coherence among the three U.S. West Coast regions. The ENSO-related warming was of comparable magnitude and duration in each region, and followed by a period of relatively cool surface temperatures and, most recently, near normal conditions. The NOAA/NCEP-derived records

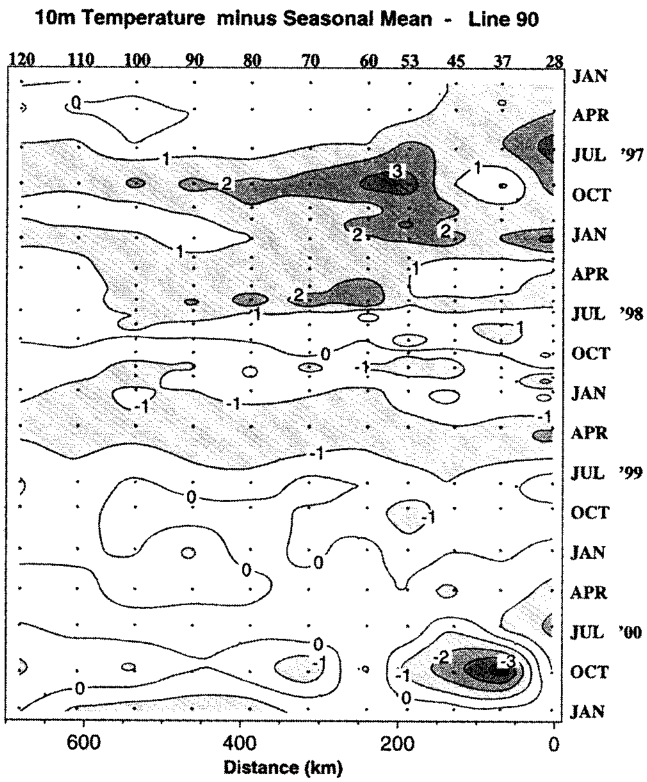

Figure 18. Ten-meter temperature anomalies for January 1997 through January 2001 for line 90 stations. Anomalies are based on the 1950–98 harmonic means.

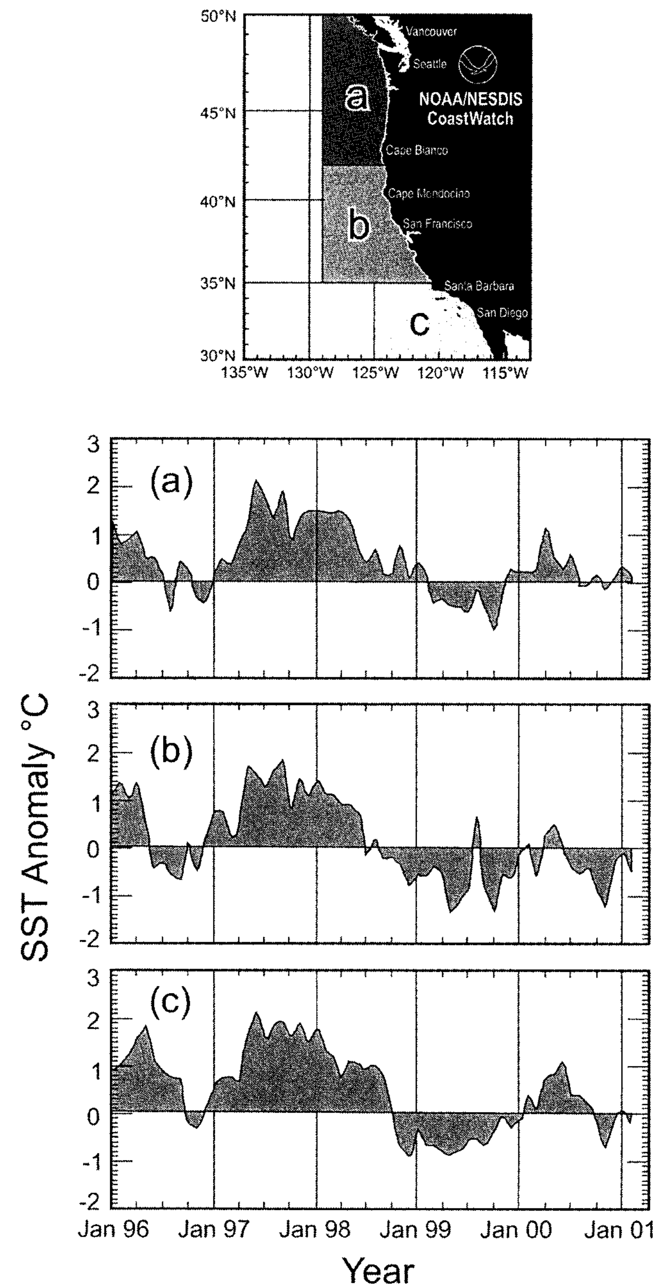

Figure 19. Regional mean SST anomalies for (*a*) the Pacific Northwest, (*b*) central coast, and (*c*) southern California. Figure has been redrawn from El Niño Watch page of West Coast CoastWatch Web site: *http://cwatchwc.ucsd.edu.* SST data are supplied by NOAA's National Center for Environmental Prediction.

suggest a broad coherence in forcing near-surface ocean conditions in the eastern North Pacific.

An example of composite pictures of concurrent measurements is presented in figure 20. We have constructed combined images of the geostrophic circulation using figures 9–12 from the IMECOCAL program and figures 13–16 from the CalCOFI program, allowing a better visualization of the surface flows within the sampling domain. We can discern that the open meander on the northeastern portion of the IMECOCAL region during the July 2000 cruise (fig. 10) is an anticyclonic eddy bound to the SCB eddy. We also see that the Inshore Countercurrent, described above for the southeastern portion of the CalCOFI survey area (fig. 14), is in reality the continuation of the Southern California Bight cyclonic eddy typical of this season. Similar interpretations may be deduced from the other frames that show how combining concurrent observations from separate programs expands our spatial coverage of the CCS and provides a clearer view of the meandering California Current.

GLOBEC LTOP CRUISES

The U.S. GLOBEC Northeast Pacific Program began a series of seasonal cruises in the northern California Current in July 1997 as part of its long-term observation program (LTOP). Observations are made five times per year along the Newport hydrographic (NH) line at 44.65°N, and three times per year along a set of 4 or 5 zonal sections between 42°N and 45°N. The NH line was occupied regularly from 1961 to 1971; Smith et al. (in press) have calculated long-term averages using data from this earlier decade for winter (1 Jan. to 29 Feb.), summer (22 June to 31 Aug.), and fall (1 Nov. to 21 Dec.), and for each month in spring, late summer, and early fall.

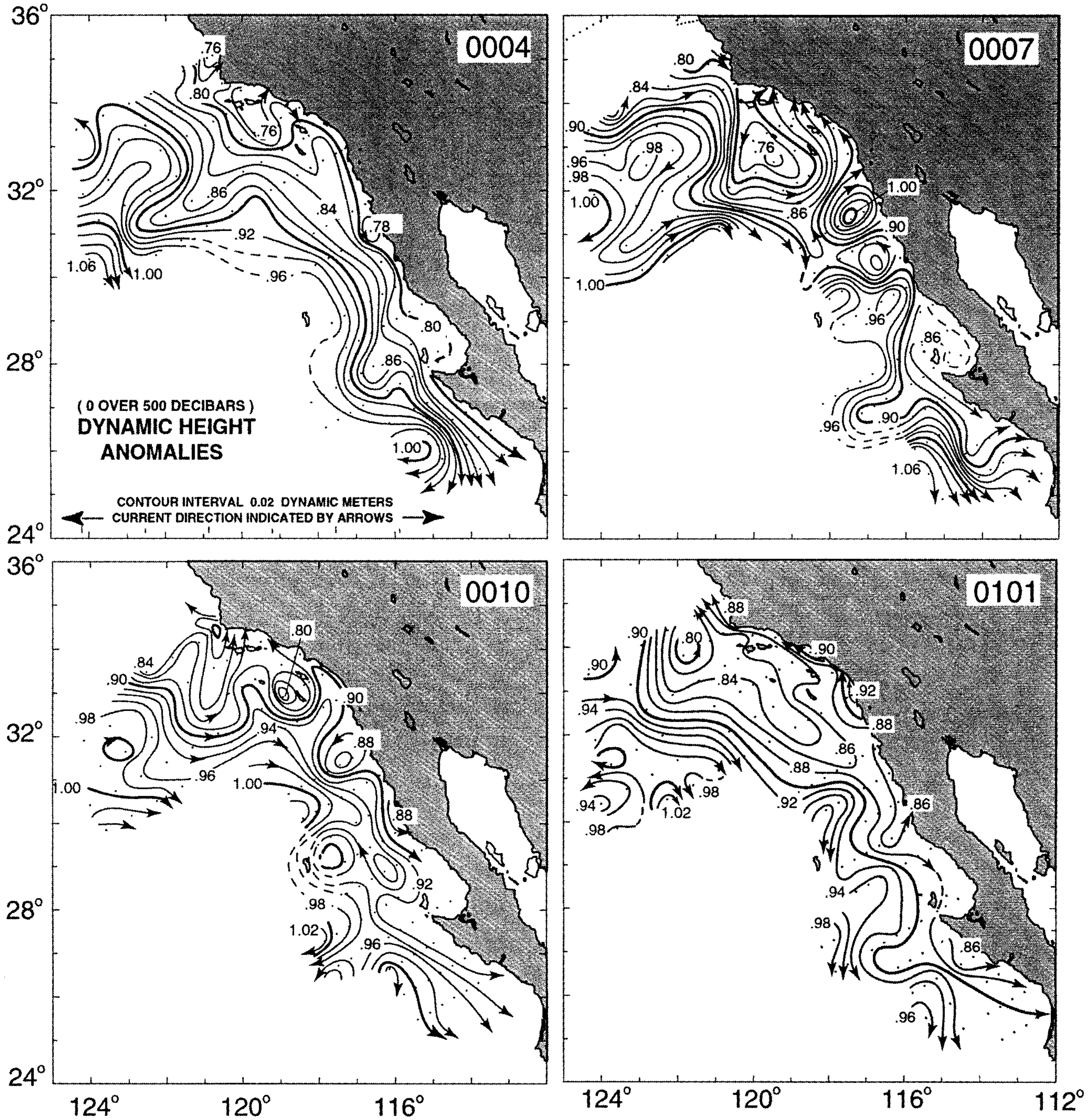

Figure 20. Spatial patterns of the ocean geostrophic flow estimated from the 0/500 dbar dynamic height fields for CalCOFI and IMECOCAL cruises during 2000–2001.

Dates for the 2000–2001 GLOBEC LTOP cruises are shown in table 2. Previous observations had shown the impact of the 1997–98 El Niño in this portion of the California Current, peaking in midwinter 1997–98 and receding by the following winter (Huyer et al., in press). By late 1999, temperatures along the NH line were slightly colder and steric heights were lower than for the corresponding 1961–71 seasonal average values (Smith et al. 2001). During 2000 and early 2001, steric heights of the sea surface along the NH line were generally within 1 standard deviation of 1961–71 seasonal average values (fig. 21). The only exception occurred in April 2000, when the inshore steric height was lower than normal, presumably because winds had been more strongly favorable for upwelling than normal during the preceding three weeks.

Temperature distributions along the NH line (fig. 22a) show the typical seasonal cycle: deep mixed layers with

TABLE 2
GLOBEC LTOP Cruises in the Northern California Current, 2000–2001

Cruise name	Dates	Sections (latitude)
W0002A	1–2 Feb. 2000	NH (44.65°N)
W0004B	11–17 Apr. 2000	NH (44.65°N), HH (44.0) FM(43.2), RR (42.5), CR (41.9)
W0007A	7–13 July 2000	NH (44.65°N), HH (44.0) FM(43.2), RR (42.5), CR (41.9)
W0009A	7–12 Sept. 2000	NH (44.65°N), HH (44.0) FM(43.2), RR (42.5), CR (41.9)
W0101B	27–19 Jan. 2001	NH (44.65°N)

weak horizontal gradients in winter, and very strong stratification in the upper 50 m in summer, with temperature decreasing toward shore over the shelf. The April 2000 section is typical for the beginning of the upwelling season (e.g., see fig. 15 of Huyer 1983): a strong onshore density gradient across the shelf is restricted to the lower half of the water column, while surface waters are still uniformly cool. The distributions of normalized temperature anomaly for 2000–2001 (calculated by subtracting the 1961–71 seasonal or monthly average and dividing this difference by the corresponding standard deviation) shows that temperatures at most depths and most stations were not significantly different from the 1961–71 epoch: values of >2 (corresponding to 95% significance) are observed in relatively small regions (fig. 22b). The surface layer values of >3 in April 2000 probably result from the unseasonably sunny weather preceding this cruise. Only a few small areas are more than 1 standard deviation colder than the 1961–71 seasonal averages. This is consistent with what we know of the Pacific decadal oscillation (PDO; Mantua et al. 1997): although we are currently in a negative phase of PDO, recent PDO values are not as low as those prevailing during the 1961–71 decade.

The regional surveys in April, July, and September 2000 show that the horizontal structure in this region varies over the upwelling season (fig. 23a–d). In April, the near-surface temperature is nearly homogeneous (fig 23a): only the coastal waters near Cape Blanco show the obvious influence of coastal upwelling. In July, the inshore band of water cooler than 10°C extends along the entire coast from 42° to 45°N, but this band is clearly wider at the California border than off central Oregon, and coldest waters are observed in the lee of Cape Blanco. In September, the inshore strip is less homogeneous, but the band cooler than 13°C is still widest downstream of Cape Blanco, though the 13°C isotherm has already crossed the shelf break near Heceta Bank at 44°N.

Maps of dynamic topography (fig. 23b) show strong southward flow. In April, this southward current was restricted to the continental margin, and it was particularly narrow off Newport, where it was confined to the shelf. By July, the current was wider; off Crescent City, the core of the current lay near 126°W, the offshore end of our section. By September, the current over the continental margin was much weaker, and two cyclonic eddies had formed: one off Crescent City and one near Heceta Bank.

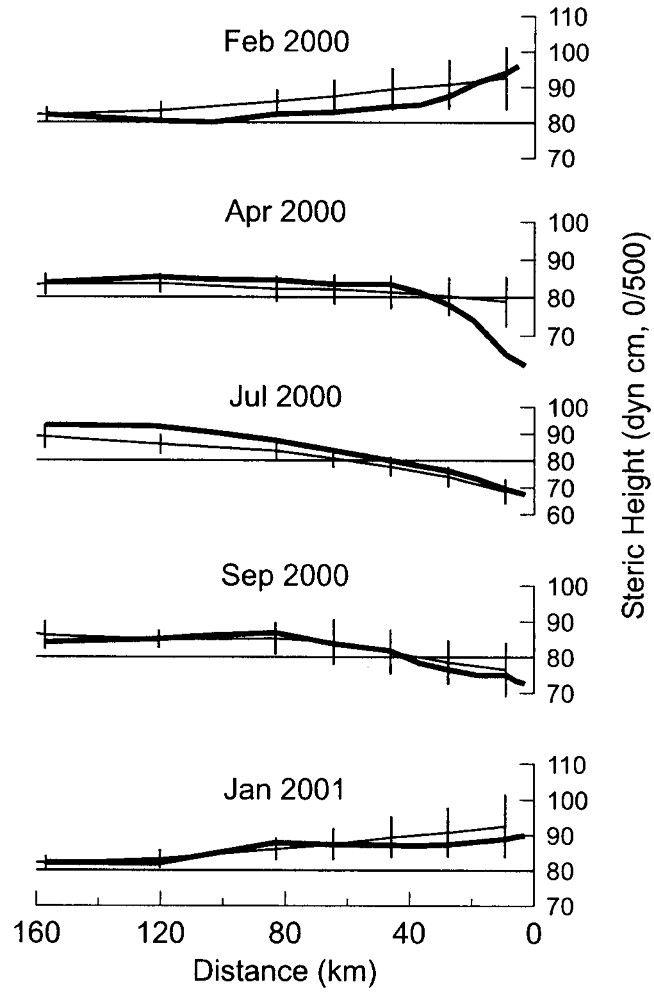

Figure 21. Steric height profiles of the sea surface (relative to 500 dbar) along the NH line at 44.65° N during 2000–2001 (heavy line) shown with the long-term (1961–71) seasonal or monthly average provided by Smith et al. (in press). Vertical bars indicate one standard deviation above and below the average at each standard station. Steric height values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976).

The surface salinity distributions (fig. 23c) confirm southward advection along the coast. The only large source of fresh water in the region is the Columbia River, whose mouth is at 46.25°N, 180 km north of Newport. The Columbia estuary is strongly stratified during the high-flow spring and summer seasons, and it is not uncommon for surface salinities at the mouth to be less than 25 psu (Jay and Smith 1990). The salinity at the core of the plume increases gradually with distance from the mouth, but the plume remains discernible from the background of subarctic surface waters so long as salin-

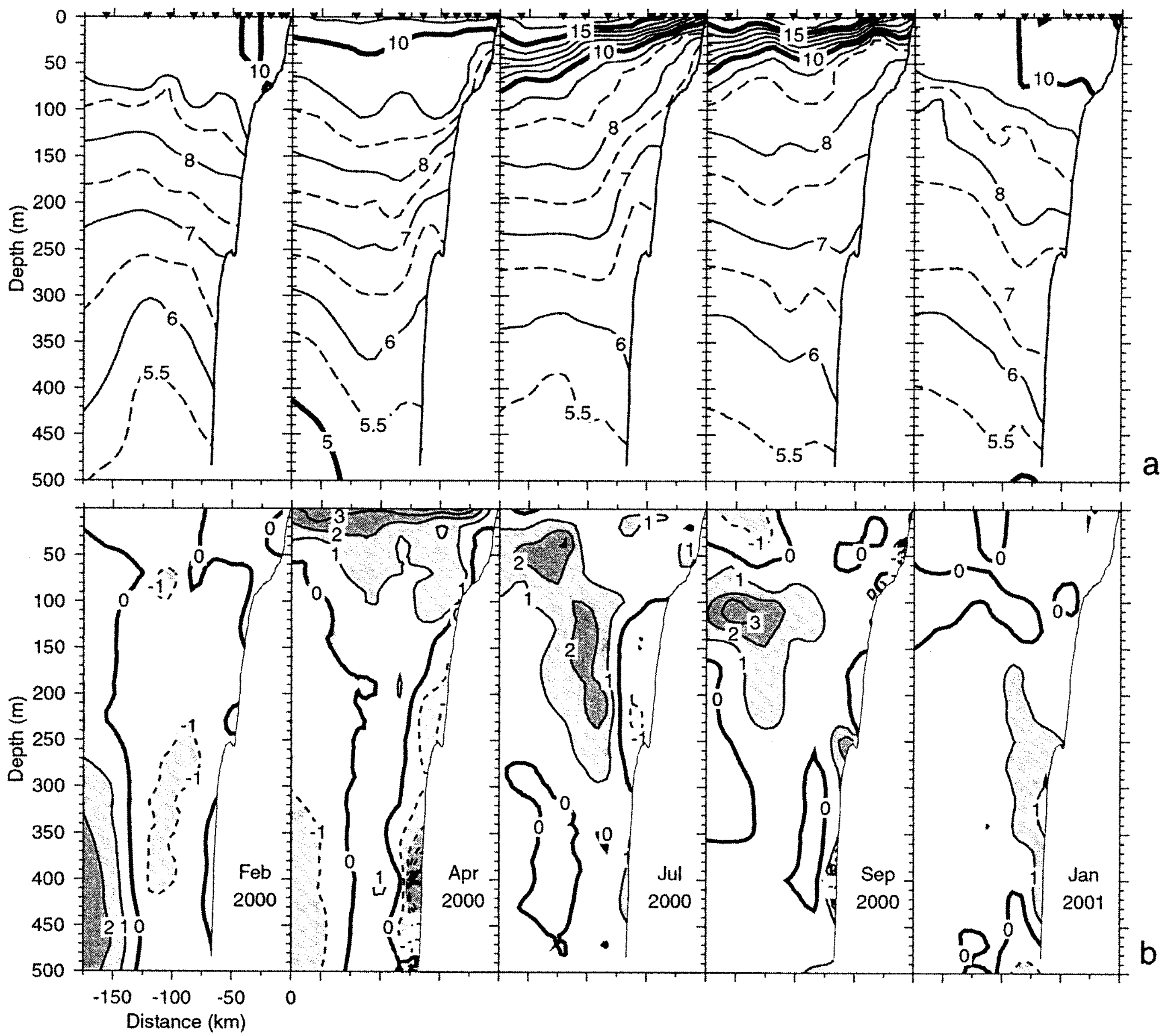

Figure 22. *a*, Temperature along the NH line at 44.65° N. Inverted triangles at top show the location of CTD stations. *b*, Normalized temperature anomalies for the NH line at 44.65° N. Positive (negative, dashed contours) anomalies indicate that present values are warmer (colder) than the historical (1961–71) seasonal or monthly averages. Values greater than 1 (2, 3) are significant at the 90% (95%, 99%) level.

ity remains less than 32.5 psu (Barnes et al. 1972). In April, minimum surface salinities (<31.5 at several stations) occurred over the continental margin, consistent with the strong coastal current inferred from the dynamic topography (fig. 23b); subarctic Pacific waters (S >32.5) were observed at the offshore end of each section. By July, the core of the Columbia River plume lay farther from shore, and high-salinity, freshly upwelled waters (S >33.5) lay adjacent to the coast. By September, the Columbia River plume was quite diffuse, and coastal salinities had decreased, though inshore values remained significantly higher (S >33) than the offshore background of subarctic water.

The 10 m chlorophyll distributions (fig. 23d) strongly reflect the influence of coastal upwelling. In April, maximum values of chlorophyll coincide roughly with the inshore locations of minimum temperature (<10.5°C) and maximum salinity (~33 psu); highest values along the NH line in February 2000 were all less than 1 mg/m^3. In July, the high-chlorophyll region (>2 mg/m^3) coincides well with the region of high-salinity coastal waters (S >33 psu). In September, chlorophyll values are substantially reduced, but still relatively high in the coastal strip (except at 42°N, where values were <1 at all stations).

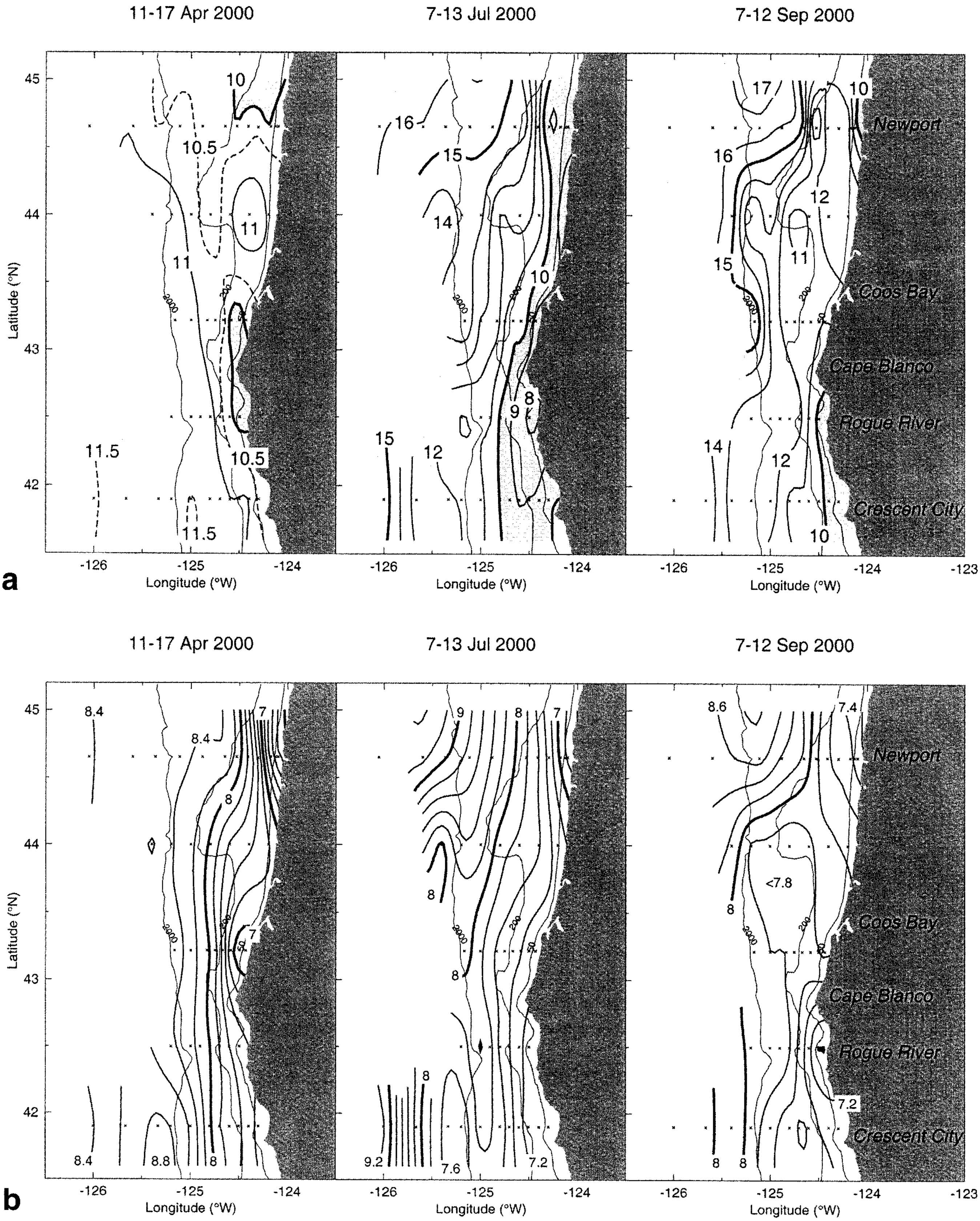

Figure 23a, b. (See next page for 23c and d.) Spatial patterns for GLOBEC LTOP cruises: *a*, 10 m temperature; b, geopotential anomaly (J/kg) of the sea surface relative to 500 dbar. Values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976).

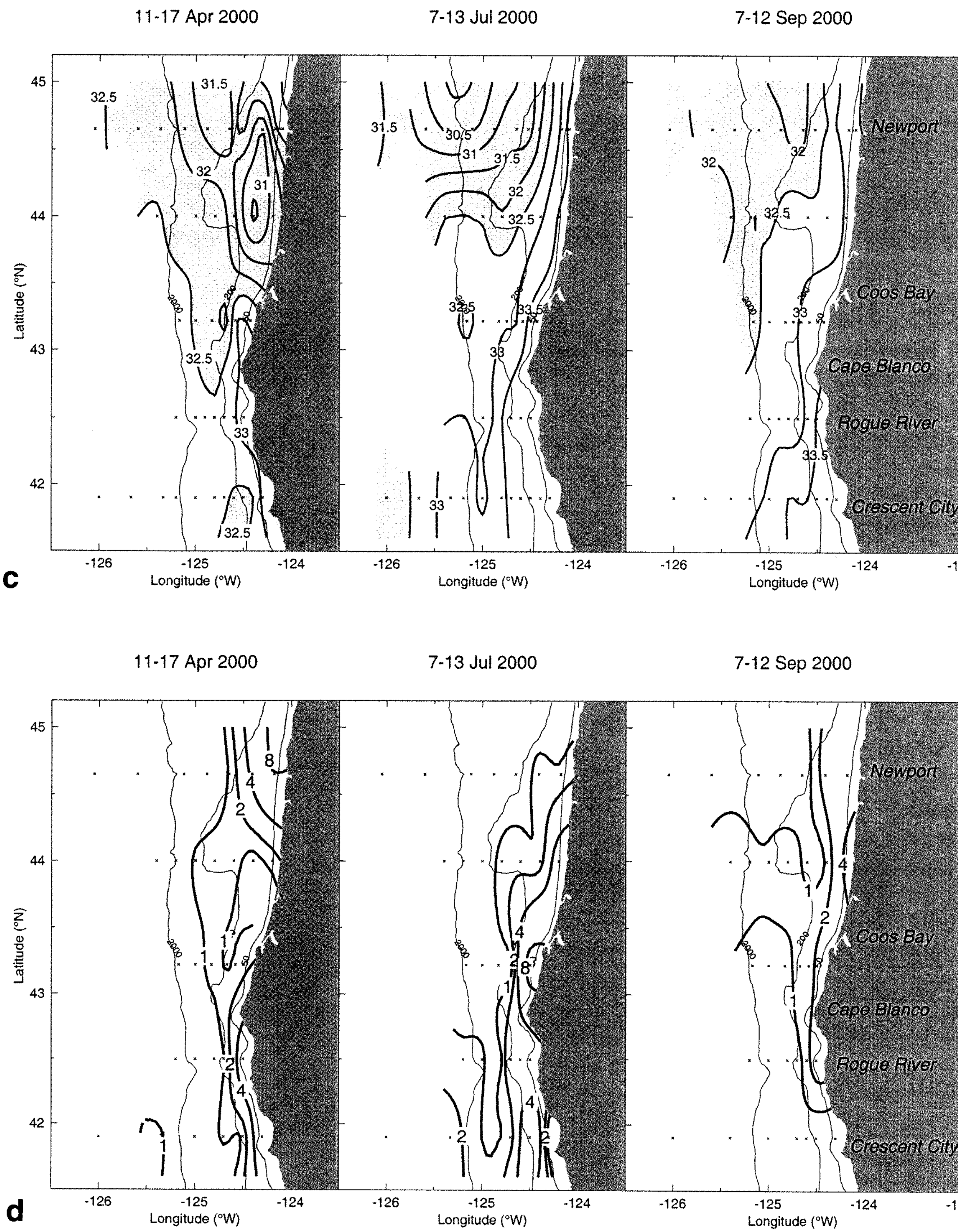

Figure 23c, d. Spatial patterns for GLOBEC LTOP cruises: *c*, 10-m salinity (psu) and *d*, 10 m chlorophyll *a* (mg/m³).

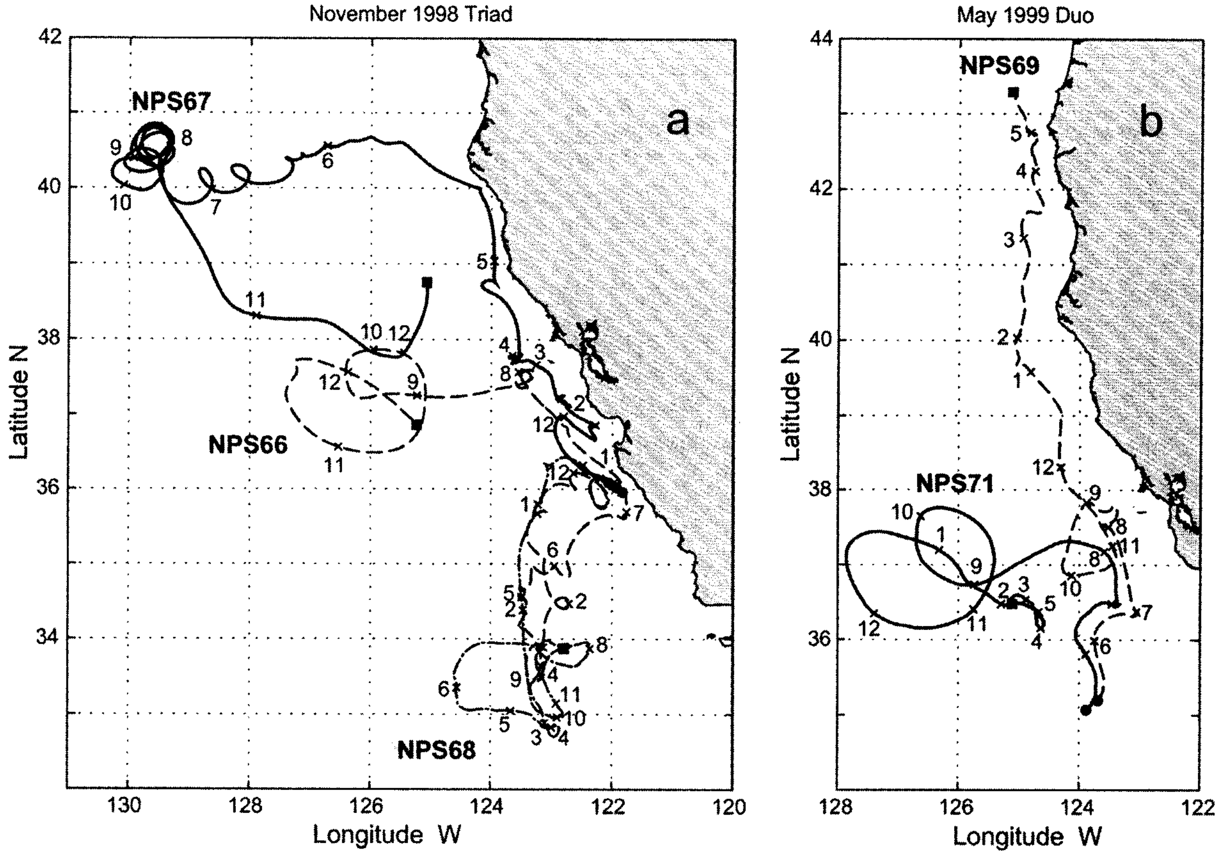

Figure 24. Subsurface (400 dbar) drifter trajectories of NPS RAFOS floats deployed in November 1998 and May 1999. The launch sites are indicated by solid circles; the location where each float surfaced is indicated by solid squares. Numbers along the trajectories denote month of the year. Note the different latitudinal ranges on the two frames.

DRIFTER STUDIES

The subsurface poleward flow of the California Undercurrent (CU) is generally topographically constrained to the continental slope (Lynn and Simpson 1987). The CU is relatively narrow, and peak speeds occur in relatively shallow water (~150 m) above the continental margin. In order to obtain Lagrangian estimates of the current it is necessary to have floats that are navigated in situ underwater, not floats that surface for a position determination and then resubmerge for transport by the current. While at the surface, the latter type of float would be advected offshore, out of the CU. For this reason, the RAFOS technology (Rossby et al. 1986) is the most appropriate way to measure the flow defining the CU.

Lagrangian trajectories for isobaric (400 dbar) subsurface floats that completed their mission in 2000 are shown in figure 24. Previously, trajectories have fallen into three patterns: poleward flow along the coast, alongshore reversing flow, and offshore flow in eddies (Garfield et al. 1999). For floats launched in November 1998, poleward flow along the coast was observed from January through May 1999 for NPS67 and from mid-July to mid-August 1999 for NPS66 (fig. 24a). NPS67 left the coast to the south of Cape Blanco, and moved rapidly offshore in June in a jet that became unstable at 127°W; as it moved farther west, it became entrained in a nearly stationary eddy near 40.5°N, 130°W from August through October. After November launch, floats NPS66 and NPS68 moved southward until March, when NPS66 returned northward (reaching the coast in July) and NPS68 remained near 33.5°N, 123°W.

The two floats launched in May 1999 followed similar trajectories until August 1999, when NPS71 moved westward and was entrained in an anticyclonic eddy in September (fig. 24b). NPS71 made two loops around the eddy before leaving the eddy at 126°W in February; it subsequently moved very slowly, remaining near 36.5°N, 125°W. In August 1999, NPS69 became entrained in an anticyclonic eddy near 37.5°N, 124°W, but after one loop around the eddy, it reentered the poleward flow along the coast in November 1999, transiting to 43°N and surfacing in June 2000.

These float releases show two types of flow that had not been observed earlier: extensive onshore flow (as opposed to shoreward flow as a portion of flow around

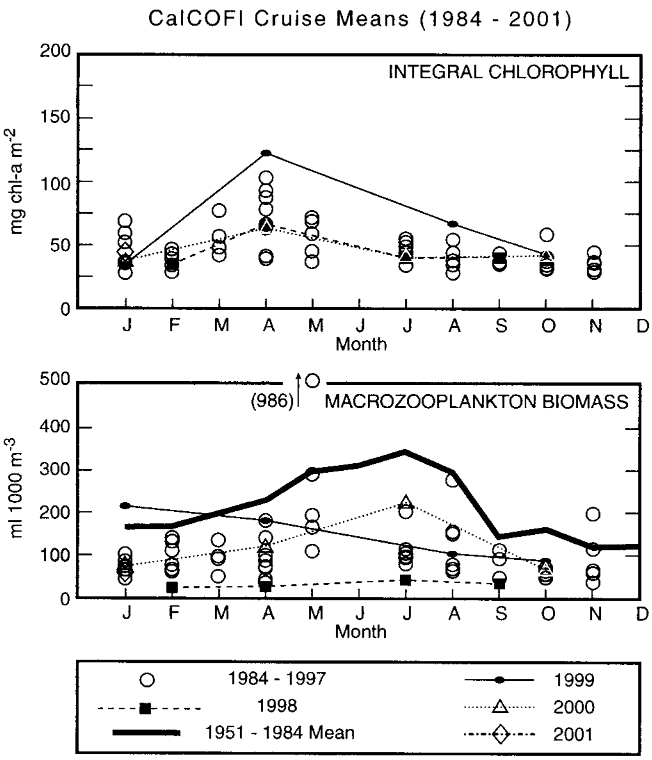

Figure 25. Cruise means of vertically integrated chlorophyll and macrozooplankton biomass plotted versus the month for CalCOFI cruises from 1984 to January 2001. Each point represents the mean of all measurements on a cruise (usually 66). Open circles indicate the cruises that took place from 1984 to 1997. The solid symbols are cruises from 1998 and 1999; cruises from individual years are connected with lines. The bold line in macrozooplankton biomass indicates the monthly means for 1951–84.

an eddy) and small-scale cyclonic motion. The former behavior was exhibited by both NPS67 and NPS66, but at different times of the year. Because of smoothing, the small-scale (10 km) cyclonic motion of NPS66 is difficult to see in figure 24a. NPS66 enters this eddy shortly after launch in November 1998, and makes 12 rotations before leaving the eddy in June 1999.

BIOLOGICAL PATTERNS

Chlorophyll and Macrozooplankton

Cruise-mean values of vertically integrated chlorophyll *a* and macrozooplankton biomass for April 2000 through January 2001 are given in the context of the historical CalCOFI time series (fig. 25). As described in last year's report and elsewhere (Bograd et al. 2000; Bograd and Lynn 2001; Lynn and Bograd, in press), there was a dramatic transition in both the physical and biological environment of the CCS between El Niño (1997–98) and La Niña (1998–99) periods. Zooplankton biomass was the lowest ever recorded throughout 1998, but rebounded strongly in the winter and spring of 1999 (Bograd and Lynn 2001). The biological patterns on the 2000 and January 2001 cruises generally fell between the extremes of 1998 and 1999. Chlorophyll production was much lower in the spring and summer of 2000 than it had been the previous year, but was near normal levels. Zooplankton biomass was high in July 2000, but below the levels of 1999 for the other cruises. It does not appear that the dramatic rebound in secondary production observed in 1999 was a precursor to a reversal in the long-term decline of zooplankton in the CCS.

Sardine Spawning

The use of CUFES on CalCOFI surveys was begun in 1996. Results from CUFES now provide annual updates on the location, dimensions, and general character of the spawning habitat of the sardines and anchovies. Mapping of sardine and anchovy egg distributions show that sardine spawning had spread to offshore areas of the California Current north of Point Conception by spring 1996. In contrast, anchovy eggs were found farther inshore, mainly limited to the region of the Southern California Bight, and were much less abundant (Checkley et al. 2000). The 1997 survey showed sardine spawning again located offshore, and distributed from the southernmost CalCOFI line to the area off Monterey in central California. The sardine egg concentrations were again higher north of Point Conception, while the anchovy spawning was much lighter and limited to the Southern California Bight area (Checkley et al. 2000). In the spring of 1998 there was a discernible northward shift in the spawning, and the eggs were found in more inshore waters, compressed toward the coast (Lynn et al. 1998) during the period of strong warming associated with El Niño effects on the CC in 1997–98.

Sardine spawning in April 1999, as measured by CUFES, was spread over most of the extended CalCOFI sampling grid, reaching at least to 400 km off central California (fig 26). This offshore expansion of sardine eggs appears to be in response to the highly anomalous conditions that prevailed in the CCS concurrently with the equatorial La Niña. Coastal upwelling reached record proportions in 1999 (Schwing et al. 2000); CC transport was anomalously strong (Lynn and Bograd, in press); and the core of the CC jet was displaced far offshore, as evidenced by the fields of dynamic height and salinity (Hayward et al. 1999). The broad distribution of sardine eggs in April 1999 is in stark contrast to the narrow band of eggs found in April 1998 (Lynn et al. 1998).

On the IMECOCAL surveys, routine use of CUFES began in January 2000. The winter 2000 distribution of sardine eggs in the IMECOCAL region (not shown) was confined mainly to inshore areas from central Baja California southward to Magdalena Bay, where the cruise terminated. Most of the eggs were concentrated in the near-coastal area of the bight just north of Bahía Magdalena (24°N). Only one egg was found in the en-

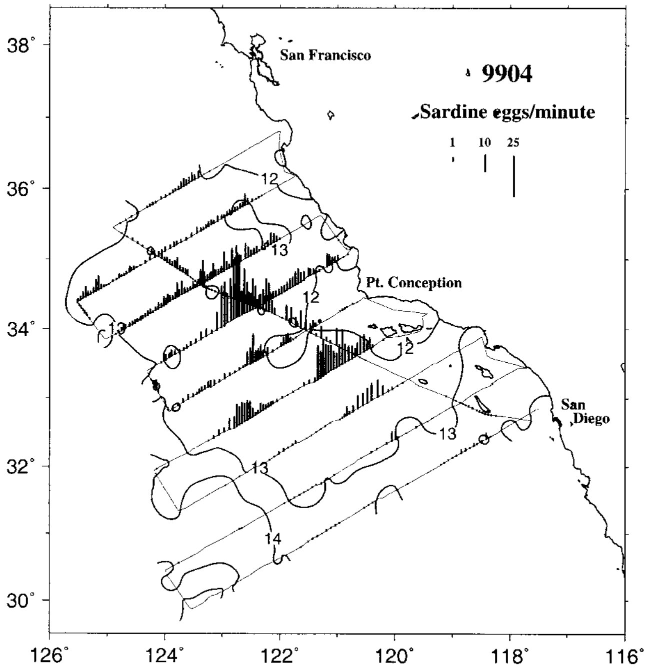

Figure 26. The distribution of sardine eggs as collected by the continuous underway fish egg sampler (CUFES) for CalCOFI survey 9904 (1–20 April 1999).

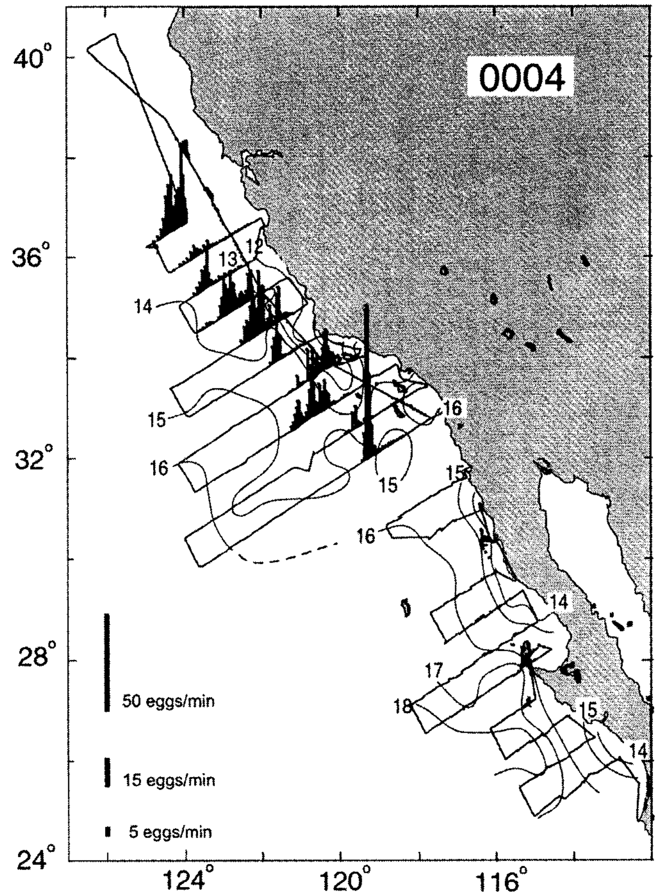

Figure 27. The distribution of sardine eggs as collected by the continuous underway fish egg sampler (CUFES) for CalCOFI and IMECOCAL surveys of April 2000.

tire CalCOFI region (D. Griffith, pers. comm.). The spring 2000 distribution of sardine eggs in the CC is shown in figure 27, which covers both the CalCOFI and IMECOCAL regions. The eggs were found distributed from just south of Punta Eugenia (approximately 27°N) to the waters offshore of San Francisco, just north of 38°N. However, there is a striking contrast in the concentration and distance offshore of the sardine eggs in the CalCOFI region compared to the IMECOCAL region in figure 27.

In spring 2000, the distribution of eggs was much more extensive from line 93 northward and much more abundant than in the south. The eggs were also found generally farther offshore in the CalCOFI region. There were some scattered occurrences of sardine eggs offshore in the IMECOCAL region between Punta Eugenia and Punta Baja, but most eggs were found near shore. Unfortunately, the transition in the pattern of distribution from north to south is obscured by the lack of sampling along line 97 in the space between the CalCOFI and IMECOCAL surveys. The change in distribution appears to coincide with the onshore sweep of the CC seen in the April 2000 dynamic heights (fig. 20) and may be related to an abrupt change in available food for spawning adults, in relation to the presence of a recurrent anticyclonic eddy southwest of Point Conception (Haury et al. 1986; Pelaez and McGowan 1986). Compared to April 1999 (fig. 26), the sardine eggs in April 2000 were found in higher concentrations farther north. The offshore extent of eggs in the spring 1999 CalCOFI survey was much greater, reaching to the end of almost all the lines north of Point Conception. The more compressed onshore distribution and occurrence farther north in spring 2000 compared to spring 1999 coincided with the mild warming of the CC and return to more normal conditions after the cool La Niña period in the CC.

Avifauna

Vessel-based surveys since 1987 have revealed that seabird populations respond to interannual (e.g., El Niño/La Niña events) and longer-term (e.g., decadal ocean warming) variability in the properties of the California Current (Ainley 1976; Veit et al. 1996; Hyrenbach 2001). Colony-based studies of seabird demography and diets underscore the results of at-sea surveys. The PRBO Marine Science Program has monitored the reproductive performance of seabird populations breeding at the Farallon Islands (central California) since the early 1970s. These long-term studies have revealed that locally breeding marine bird populations are sensitive to fluctuations in ocean productivity and prey availability (Ainley et al. 1995; Sydeman et al., in press).

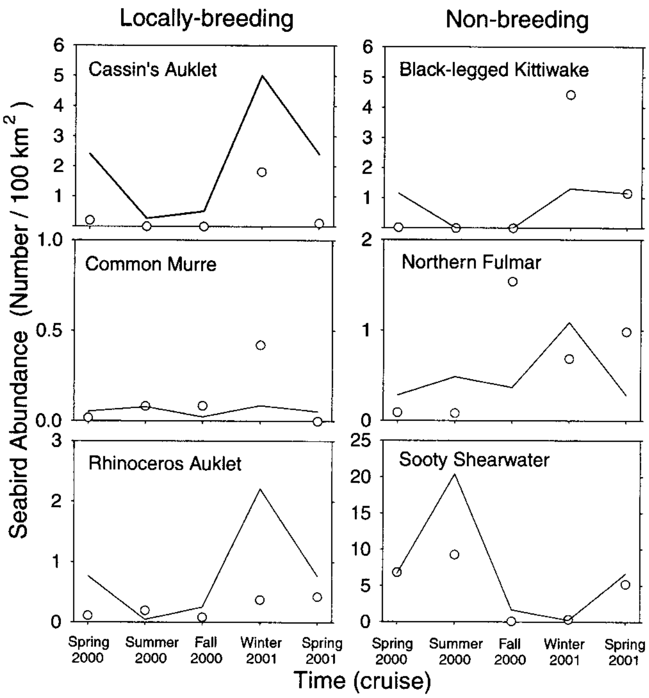

Figure 28. Abundance of three locally breeding and nonbreeding seabird species with an affinity for cold water between spring 2000 and spring 2001. For reference, the line indicates the long-term means of seasonal abundance (spring 1990–spring 2001).

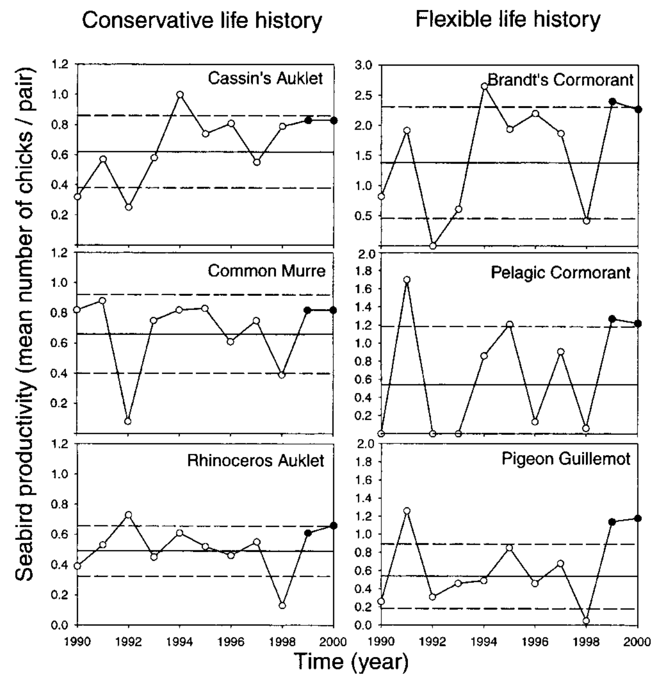

Figure 29. Anomalies of productivity for six seabird species breeding at Southeast Farallon Island (central California). The long-term averages (1990–2000) are depicted by the solid lines; the hatched lines illustrate the variability (mean ± SD). Filled circles highlight productivity anomalies after the hypothesized regime shift during the winter of 1999.

TABLE 3
Changes in Abundance of Six "Cold-Water" Seabird Species in the CalCOFI Study Area, in Conjunction with the Hypothesized Regime Shift during Winter 1999

Seabird species	Abundance (birds/100 km²) (mean±SD) (1990–1998)	(1999–2001)	Proportional change (%)[a]	Mann-Whitney U	p value
Black-legged kittiwake	0.47 ± 1.54	1.17 ± 1.77	+146	124.5	0.710
Cassin's auklet	2.33 ± 4.19	0.34 ± 0.61	−85	194	0.063
Common murre	0.05 ± 0.12	0.07 ± 0.14	+39	144	0.796
Northern fulmar	0.54 ± 0.93	0.45 ± 0.56	−16	195	0.059
Rhinoceros auklet	0.91 ± 1.78	0.17 ± 1.15	−81	215	0.011
Sooty shearwater	7.47 ± 1.22	6.31 ± 6.17	−15	144	0.798

Comparison of standardized seasonally adjusted anomalies of abundance "before" (34 cruises between winter 1990 and fall 1998) and "after" (8 cruises between winter 1999 and spring 2001) the regime shift.
[a]Quantified as PC = 100% * [(before) − (after)]/(before).

Vessel-based surveys between spring 2000 and spring 2001 did not reveal concurrent increases in the abundance of cold-water seabird species. In fact, only four of the six taxa considered surpassed their long-term (spring 1990–spring 2001) abundance during at least one cruise (fig. 28). The locally breeding common murre (*Uria aalge*) increased in abundance during the winter, and the rhinoceros auklet (*Cerorhinca monocerata*) increased in the summer. But the most numerous locally breeding species—the Cassin's auklet (*Ptychoramphus aleuticus*)—remained well below its long-term abundance. Nonbreeding species behaved similarly, with sporadic increases during certain cruises. For instance, we documented positive anomalies of black-legged kittiwake (*Rissa tridactyla*) abundance during winter 2001. On the other hand, the northern fulmar (*Fulmarus glacialis*) was most abundant during fall 2000 and spring 2001. Conversely, the once numerically dominant sooty shearwater (*Puffinus griseus*) consistently remained below its long-term abundance. Overall, we detected no significant increases in the abundance of cold-water seabirds after the winter of 1999 (table 3).

Surveys of six seabird species breeding at the Farallon Islands revealed high reproductive performance during 2000, following large increases between 1998 and 1999 (fig. 29). In 1998, only the productivity of the Cassin's

TABLE 4
Changes in the Productivity of Six Seabird Species Breeding at the Farallon Islands (Central California), in Conjunction with the Hypothesized Regime Shift during Winter 1999

Seabird species	Productivity (chicks fledged/pair)[a] (mean±SD) (1990–1998)	(1999–2001)	Proportional change (%)[b]	Mann-Whitney U	p value
Brandt's cormorant	1.38 ± 0.93	2.33 ± 0.09	+69	2	0.098
Cassin's auklet	0.62 ± 0.24	0.83 ± 0.00	+33	2	0.098
Common murre	0.66 ± 0.27	0.82 ± 0.00	+24	6	0.468
Pelagic cormorant	0.54 ± 0.64	1.24 ± 0.03	+130	0	0.034
Pigeon guillemot	0.54 ± 0.38	1.16 ± 0.03	+117	2	0.098
Rhinoceros auklet	0.48 ± 0.16	0.63 ± 0.03	+31	2.5	0.124

Comparison of the average seabird productivity "before" (1990–1998) and "after"(1999–2000) the regime shift.
[a]Expressed as the mean number of chicks fledged per nest during the breeding season.
[b]Quantified as PC = 100% ⋆ [(before) − (after)|/(before).

auklet surpassed its long-term (1990–2000) average. Conversely, in 1999 and 2000, we recorded positive productivity anomalies for all six taxa analyzed. In particular, the productivity of three species with more "flexible" life histories—Brandt's cormorant (*Phalacrocorax penicillatus*), pigeon guillemot (*Cepphus columba*), and pelagic cormorant (*Phalacrocorax pelagicus*)—was markedly higher (anomalies exceeding one standard deviation) after the hypothesized regime shift during the winter of 1999. Overall, we detected a significant increase in the productivity of the pelagic cormorant, and documented increases that were marginally significant ($0.10 < p < 0.05$) for three other species (pigeon guillemot, Brandt's cormorant, and Cassin's auklet; table 4).

The analysis of marine bird populations breeding at the Farallon Islands (central California) revealed increases in seabird productivity during 1999 and 2000, when compared to conditions during the preceding warm-water regime (1990 through 1998; table 3). However, this demographic response varied according to species-specific life-history characteristics. The Brandt's cormorant, pigeon guillemot, and pelagic cormorant showed the strongest response in productivity after the winter of 1999. In fact, for the pigeon guillemot and the pelagic cormorant, the mean number of chicks successfully fledged by a breeding pair more than doubled between 1990–98 and 1999–2000. These species have broad diets, inhabit neritic waters and estuaries, and have been shown to respond very strongly to enhanced prey availability off central California (Ainley et al. 1995; Sydeman et al. 1997, in press). On the other hand, the productivity of seabird species with more "conservative" reproductive strategies and restricted dietary and habitat preferences increased only slightly (24%–33%) during 1999 and 2000. The Cassin's auklet, common murre, and rhinoceros auklet forage along the continental shelf, where they feed largely on juvenile rockfish (*Sebastes* spp.), anchovies (*Engraulis mordax*), and cold-water euphausiids (*Euphausia pacifica* and *Thysanoessa spinifera*; Sydeman et al. 1997).

Vessel-based surveys and demographic research at colonies suggest that seabird distributions and productivity are influenced by interannual variability in the properties of the California Current. The productivity of locally breeding seabirds increased during 1999 and 2000, apparently in response to enhanced upwelling and ocean productivity (Ainley et al. 1995; Sydeman et al., in press; figs. 6 and 25). Moreover, far-ranging cold-water seabirds became more numerous off southern California in response to cool ocean temperatures (fig. 4) and increasing primary and secondary production (fig. 25) during 1999 (Hayward et al. 1999; Bograd et al. 2000). Subsequently, these species vacated the region as a result of declining productivity during 2000.

These findings underscore the notion that life-history traits constrain the ability of seabirds to respond to climatic fluctuations. In particular, differences in mobility and adaptability modulate species-specific responses to changing ocean temperature and food availability. Seabirds are highly mobile marine predators capable of shifting their foraging ranges in response to changes in ocean productivity and water-mass distributions (Ainley 1976; Veit et al. 1996). Additionally, the ability of breeding seabirds to enhance their reproductive success during periods of elevated ocean productivity and prey availability appears to be influenced by species-specific habitat and dietary preferences (Ainley et al. 1995; Sydeman et al., in press).

However, it remains unclear to what degree physical-biological interactions influence the ability of seabird populations to cope with climatic variability via behavioral (e.g., redistribution) and demographic (e.g., reproductive success) mechanisms. The integration of CalCOFI at-sea surveys and PRBO colony-based studies will enhance our knowledge of the mechanisms linking oceanographic forcing, prey availability, and seabird demography. Understanding the way marine bird dispersion and foraging opportunities influence reproductive success is essential for anticipating the response of seabird populations to oceanographic variability in the highly variable CCS.

DISCUSSION

As indicated by the MEI (Wolter and Timlin 1998), the period from January 2000 to May 2001 marked the third consecutive year in which a weak to moderate La Niña state persisted over the tropical Pacific. The observations described here, however, indicate that from Oregon to Baja California, the oceanographic conditions within the CCS were not significantly warmer or colder than the climatological mean. Zooplankton biomass, which rebounded to high levels in 1999 after a decline during El Niño, showed near normal values during 2000–2001. Likewise, seabird surveys did not reveal persistent increases in the abundance of cold-water species off southern California. The numerically dominant locally breeding (Cassin's auklet) and visiting (sooty shearwater) seabirds remained consistently below their long-term seasonal abundance. These species have declined significantly over the long term off southern (1987–98) and central (1985–94) California (Hyrenbach 2001; Oedekoven et al. 2001).

Record low coastal sea level associated with extremely high levels of coastal upwelling for northern California in 1999 (Schwing et al. 2000), as well as the rebound in zooplankton abundance from the lowest in the CalCOFI record to above normal levels (Bograd et al. 2000) have been suggested as possible indicators of a North Pacific warm-cold regime shift in 1998–2000. Is this hypothesized cold-water regime manifested in the CCS? The answer is not straightforward.

Over the last decade, there has been an increased interest in studying the response of ecosystems to recurrent patterns of atmosphere-ocean climate variability on decadal and interdecadal scales. Changes in environmental variables and departures from normal conditions due to climate shifts have been shown to modify zooplankton biomass (Roemmich and McGowan 1995), fish stocks (Mantua et al. 1997), and seabirds (Hyrenbach 2001; Oedekoven et al. 2001). Moreover, a climate transition brings changes in the mechanisms that regulate the ecosystem, but these changes are virtually impossible to characterize at the time they occur (Mantua et al. 1997). Since stepwise climate shifts occur on an average of every 23 years (Gedalof and Smith 2001), and since the last shift took place in 1976–77 (Mantua et al. 1997), it is very tempting to associate dramatic changes in the CCS ecosystem with a period of climate transition. The observations presented here, while not yet supporting the notion of a transition to a cold-water regime of enhanced upwelling and elevated production, do provide a proxy for understanding how the CCS may respond to future interannual changes and decadal climate shifts. The uncertainty of the different indicators used as a proxy for climate shifts not only highlights the need for continuing and expanding the CalCOFI monitoring, but also emphasizes the value of long-term observations.

The constriction of the CalCOFI program in 1984 (Hewitt 1988) to the region delimited in figure 1, while adequately resolving some of the temporal variability critical for describing the biophysical response to interannual climate forcing, compromises our knowledge of spatial variability over the system by greatly reducing the active area of the sampling grid. The IMECOCAL and GLOBEC-LTOP programs, when coordinated with CalCOFI, provide much of the extra spatial coverage needed to describe fundamental changes in the physical and biological structure over the extent of the CCS (figs. 20 and 27). These programs may also provide better estimates of the abundances of commercially important species, as well as better descriptions of the significant latitudinal shifts in their ranges.

Besides the clear utility of having concurrent measurements along the CCS, from Canada to Baja California (see dynamic height anomalies in fig. 20), the recent developments in oceanographic instrumentation are particularly important, because they allow us to observe in near-real time the spatial distributions of organisms. Sardine egg distributions as measured by the CUFES system presented above (fig. 27) are an excellent example of the importance of simultaneous measurements. Continuing this type of monitoring will undoubtedly improve our knowledge of this and other species' abundance. The preliminary results shown here, however, have raised additional questions. For example, why did sardines spawn only in the coastal regions surrounding Punta Eugenia and not at all off California during January 2000, while the reverse was true during spring 2000? What kind of physical interactions define the ideal spawning conditions? Are fronts and coastal enrichment by upwelling and eddies the key processes that determine egg distributions? Are there any rapid responses of predators to the presence or absence of sardine eggs, or is predator dispersion controlled mainly by currents?

After 52 years of the CalCOFI program, it still remains unclear to what degree physical-biological interactions influence the ability of marine populations to cope with climatic variability via behavioral (e.g., redistribution) and demographic (e.g., reproductive success) mechanisms. The expansion of the new monitoring methodologies and the future integration of the large suite of environmental data that is now being routinely collected along the CCS, from northern California and Oregon to Baja California, will certainly enhance our knowledge of the mechanisms linking environmental change with marine ecosystem response.

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