# THE STATE OF THE CALIFORNIA CURRENT, 2001–2002: WILL THE CALIFORNIA CURRENT SYSTEM KEEP ITS COOL, OR IS EL NIÑO LOOMING?

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

STEVEN J. BOGRAD
Pacific Fisheries Environmental Laboratory
National Marine Fisheries Service, NOAA
1352 Lighthouse Avenue
Pacific Grove, California 93950-2097

CURTIS A. COLLINS
Department of Oceanography
Naval Postgraduate School
833 Dyer Road
Monterey, California 93943-5114

GILBERTO GAXIOLA-CASTRO
Centro de Investigación Científica y de
Educación Superior de Ensenada
Apartado Postal 2732
22800 Ensenada, Baja California, México

JOAQUIN GARCÍA
Centro de Investigación Científica y de
Educación Superior de Ensenada
Apartado Postal 2732
22800 Ensenada, Baja California, México

RALF GOERICKE
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0227

JOSÉ GOMÉZ-VALDÉZ
Centro de Investigación Científica y de
Educación Superior de Ensenada
Apartado Postal 2732
22800 Ensenada, Baja California, México

ADRIANA HUYER
College of Oceanic and Atmospheric Science
Oregon State University
Corvallis, Oregon 97331-5503

K. DAVID HYRENBACH
Point Reyes Bird Observatory
Marine Science Division
4990 Shoreline Highway
Stinson Beach, California 94970

P. MICHAEL KOSRO
College of Oceanic and Atmospheric Science
Oregon State University
Corvallis, Oregon 97331-5503

BERTHA E. LAVANIEGOS
Centro de Investigación Científica y de
Educación Superior de Ensenada
Apartado Postal 2732
22800 Ensenada, Baja California, México
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0227

RONALD J. LYNN
Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
8694 La Jolla Shores Drive
La Jolla, California 92037-1508

ARNOLD W. MANTYLA
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0227

MARK D. OHMAN
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0227

WILLIAM T. PETERSON
National Marine Fisheries Service
Northwest Fisheries Science Center
Hatfield Marine Science Center
2030 South Marine Science Drive
Newport, Oregon 97365

ROBERT L. SMITH
College of Oceanic and Atmospheric Science
Oregon State University
Corvallis, Oregon 97331-5503

WILLIAM J. SYDEMAN
Point Reyes Bird Observatory
Marine Science Division
4990 Shoreline Highway
Stinson Beach, California 94970

ELIZABETH VENRICK
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0227

PATRICIA A. WHEELER
College of Oceanic and Atmospheric Science
Oregon State University
Corvallis, Oregon 97331-5503

## ABSTRACT

This report summarizes physical and biological conditions in the California Current System (CCS), from Oregon to Baja California, in 2001 and 2002. The principal sources of the observations described here are the CalCOFI (California Cooperative Oceanic Fisheries Investigations), IMECOCAL (Investigaciones Mexicanas de la Corriente de California), and U.S. GLOBEC-LTOP (Global Ecosystems Long-term Observation Program) programs. Large-scale atmospheric and oceanic conditions in the Pacific point to a fourth consecutive La Niña-like year. This has contributed to generally stronger than normal upwelling and uncharacteristically cool waters in much of the CCS, a pattern that has persisted since late 1998. Biological productivity has been generally higher as well, particularly off Oregon. Within the observed interannual fluctuations of recent years, these conditions suggest a generally elevated production off California and Oregon, but cool conditions have led to lower than normal zooplankton biomass off Baja California. Although the tropical Pacific has exhibited some indications of a developing El Niño, it is not likely to impact the CCS during the productive upwelling season of 2002. These observations are continuing evidence that a regime shift may have occurred in 1998, resulting in substantial change in ecosystem structure in the CCS. Continued monitoring and analysis of the state of the CCS in this context is needed. We outline a plan for an integrated monitoring program for the entire region, through the creation of ACCEO (Alliance for California Current Ecosystem Observation).

## INTRODUCTION

In 1994 a small group of scientists began an annual *CalCOFI Reports* tradition, preparing the first summary of recent physical and biological conditions in the California Current System (CCS) (Hayward et al. 1994). This concept has continued and has been expanded to include information from ongoing surveys off Baja California, Mexico, central California, and Oregon, and assessments of the large-scale conditions that affect the CCS region (Hayward et al. 1995, 1996, 1999; Lynn et al. 1998; Schwing et al. 1997; Bograd et al. 2000; Durazo et al. 2001).

Over this time period, these "State of the California Current" reports have documented the evolution of one of the strongest El Niño events on record in 1997–98 and the subsequent development of an extended period of unseasonably cool conditions in the CCS initiated by a strong La Niña in 1997. The recurrence of a cool, La Niña-type state over the past 4 years (1998–2002) at the time of this writing, along with major changes in a number of CCS populations, has led some scientists to suggest that the CCS and the north Pacific have undergone a fundamental climate shift, on the scale and significance of those documented in the early 1920s, mid-1940s, and mid-1970s (cf. Mantua et al. 1997; Hare and Mantua 2000). Others argue that this recent period has been a sequence of isolated La Niña events. To complicate matters further, the signals of a developing El Niño in the tropical Pacific are now being detected. The degree to which these interannual and longer-term climate phenomena evolve, interact, and compete for control of the CCS in the coming months will reveal a great deal about how climate variability influences the physics and biology of the CCS.

In this report, we summarize conditions in the CCS from about 24° to 45°N between January 2001 and April 2002, based on ship surveys and related at-sea sampling, monitoring from coastal buoys, and large-scale analyzed fields of atmospheric and oceanic variables. We focus on evidence for a possible climate regime shift in 1998 and speculate on early indicators of a developing El Niño in the tropical Pacific. This is not meant to be a complete description of all scientific activities in the CCS during the past 12 to 18 months but to characterize recent conditions based on representative physical and biological data and to highlight selected research programs in the region. This report demonstrates the value of continued monitoring of marine ecosystems such as the CCS and of integrating physical and biological factors from complementary regional field programs.

## DATA SETS AND METHODS

Large-scale anomalies for the Pacific Ocean region are summarized from NCEP (National Center for Environmental Prediction) reanalysis fields (Kalnay et al. 1996) from the NOAA-CIRES Climate Diagnostics Center, <http://www.cdc.noaa.gov/>. The reanalysis fields are monthly gridded (roughly 2° × 2°) anomalies of sea surface temperature (SST) and surface wind. The base period is 1968–96. Ocean temperature anomalies at 100 m depth were computed from the Global Temperature-Salinity Profile Program (GTSPP) 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. The anomalies were then averaged into 5° × 5° spatial boxes.

Monthly upwelling indices and their anomalies, relative to 1948–67, for the North American west coast (21°–51°N) are presented. Time series of the daily alongshore wind component and SST from six representative buoys throughout the California Current region (data courtesy NOAA National Data Buoy Center) are plotted against the harmonic mean of each record; the location and base period of each buoy are given in Table 1.

Ocean conditions in the CCS off southern California are described from quarterly CalCOFI surveys in 2001 and early 2002. The CalCOFI monitoring program began in 1949; a brief history of the program is given in Hewitt (1988). The present program consists of quarterly (normally Jan., Apr., July, and Oct.) cruises that occupy a grid of 66 stations off Southern California (fig. 1). The core time-series data set now collected at each station includes a conductivity-temperature-depth (CTD)/Rosette cast 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 phaeopigments), 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

TABLE 1
**Locations of Sea Surface Temperature and Alongshore Wind Time Series**

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

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

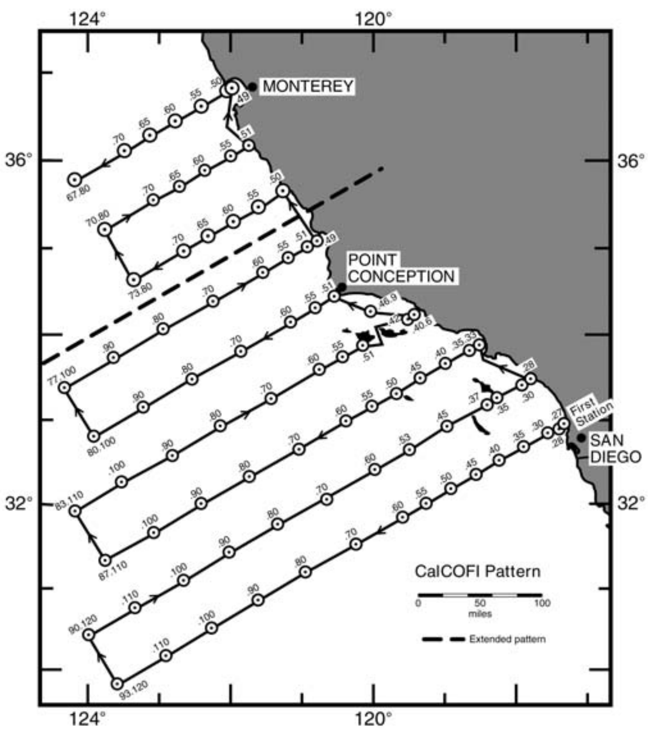


Figure 1. The standard CalCOFI sampling grid. The regular 66-station pattern occupied by CalCOFI since 1985 (lines 77, 80, 83, 87, 90, and 93) is shown by a solid line. The dashed line demarks the area of additional sampling north of the regular pattern (lines 67, 70, and 73).

near-surface measurements of temperature, salinity, and chlorophyll fluorescence are made from water pumped through the ship. Acoustic Doppler current profiler data are also recorded continuously, providing a measure of upper ocean currents as well as an estimate of zooplankton biomass based upon acoustic backscatter. During the winter and spring cruises, the continuous underway fish egg sampler (CUFES; Checkley et al. 1997) is used. More details on the methods, information about recent activities, and CalCOFI hydrographic data can be accessed online at <http://www.calcofi.org>. In addition, CalCOFI line 67, off Monterey, California, has been surveyed periodically by the Monterey Bay Aquarium Research Institute and Naval Postgraduate School.

Systematic surveys of the distribution and abundance of marine birds have been taken on CalCOFI cruises since 1987. Vessel-based observations have revealed that the overall abundance and composition of seabird communities fluctuate in response to interannual and longer-term variability in the physical and biological properties of the CCS (Veit et al. 1996; Hyrenbach and Veit, in press). Colony-based observations by the Point Reyes Bird Observatory Marine Science Program have monitored the reproductive performance of seabird populations breeding at the Farallon Islands (central California) since the early 1970s. These locally breeding populations are sensitive to fluctuations in ocean productivity and prey availability over interannual and decadal scales (Ainley et al. 1995; Sydeman et al. 2001). Our objective is to compare marine bird demography and community structure during 2000–2001 to the 1997–98 El Niño and the subsequent La Niña event, and to quantify the response of marine bird populations to the hypothesized 1998 regime shift.

The IMECOCAL program continued sampling the southern portion of the CCS, off Baja California, on a reduced CalCOFI grid of 93 stations (fig. 2). The data presented here were collected from April 2001 to January 2002. All the quarterly IMECOCAL cruises reported here were done aboard the CICESE (Centro de Investigación Científica y de Educación Superior de Ensenada) RV *Francisco de Ulloa*. 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 (0.505 mm mesh) oblique bongo tows are conducted, with one cod end dedicated to ichthyoplankton and the other to macrozooplankton. Continuous underway measurements of temperature, salinity, and fluorescence are also made. The Acoustic Doppler Current Profiler (ADCP) was used for continuous underway current profiling. Starting in January 2000, a CUFES system has been incorporated into the sampling. For more information about data collection, analysis, databases, and cruises schedules, refer to the IMECOCAL Web page, <http://imecocal.cicese.mx>.

TABLE 2
**Dates of GLOBEC LTOP Cruises in the Northern California Current, 2001–2002**

| Cruise name | Dates | Sections (latitude) |
|---|---|---|
| W0101B | 27–28 Jan. 2001 | NH (44.65°N) |
| W0103A | 15–18 Mar. 2001 | FM(43.2), RR (42.5) |
| W0103B | 20–24 Mar. 2001 | NH (44.65°N), FM(43.2), RR (42.5), CR (41.9) |
| W0107A | 6–8 July 2001 | NH (44.65°N) |
| W0109A | 4–10 Sept. 2001 | NH (44.65°N), HH (44.0), FM(43.2), RR (42.5), CR (41.9) |
| W0111B | 27–29 Dec. 2001 | Inshore portion of NH (44.65ºN) |
| W0202A | 19–21 Feb. 2002 | NH (44.65°N) |
| W0204A | 4–10 Apr. 2002 | NH (44.65°N), HH (44.0), FM(43.2), RR (42.5), CR (41.9) |

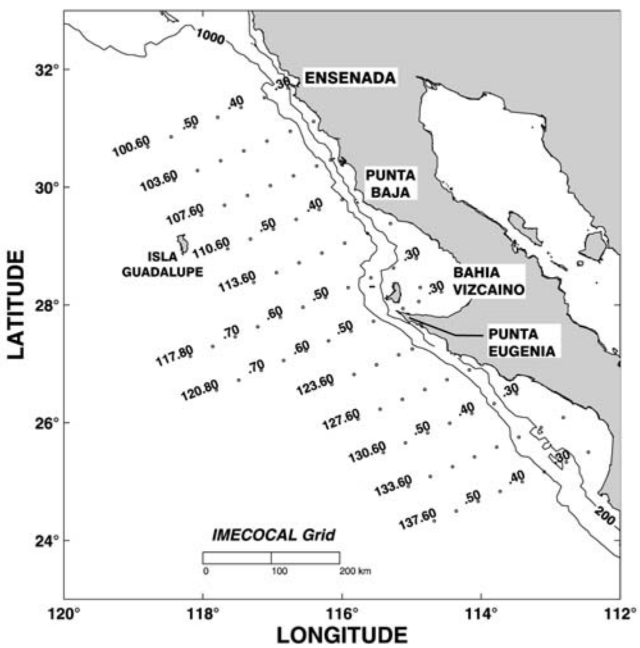


Figure 2. The standard IMECOCAL sampling grid. Solid dots represent the regular 93-station pattern (lines 100 to 137). Depth contours are in meters.

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 a year along the Newport Hydrographic (NH) Line at 44.65°N, and three times a year along a set of 4 or 5 zonal sections between 42°N and 45°N (Smith et al. 2001; Huyer et al. 2002). The NH line was occupied regularly from 1961 to 1971; Smith et al. (2001) have calculated long-term averages using data from this earlier decade for winter (1 Jan.–29 Feb.), summer (22 June–31 Aug.), and fall (1 Nov.–21 Dec.), and for each month in spring, late summer, and early fall. Dates for the 2001–2002 GLOBEC LTOP cruises are shown in Table 2.

Hydrography, nutrients, chlorophyll, and zooplankton are measured along the inner portions of the NH Line biweekly in spring, summer, and fall, and monthly in winter. This program began in 1996 and is supported by U.S. GLOBEC. Stations are 1, 3, 5, 10, and 15 mi from shore, with water depths ranging from 20 m to 95 m. Zooplankton is sampled with a 0.5 m net (0.2 mm mesh) towed vertically from the sea floor to the surface. Zooplankton are enumerated by species and developmental stage, and biomass is calculated by multiplying species abundance by their carbon weight and then summing over all species. Copepod biomass data are presented here.

## LARGE-SCALE OCEANIC AND ATMOSPHERIC CONDITIONS

Basin-scale anomalies in the Pacific during the past year reflect a continuation of the patterns that developed during the 1998–99 La Niña (Hayward et al. 1999; Bograd et al. 2000; Schwing and Moore 2000; Schwing et al. 2000; Durazo et al. 2001; Schwing et al. 2002b). Large-scale winds over the northeast Pacific displayed a generally anomalous clockwise flow, consistent with a stronger than normal North Pacific High and, at times, an unusually weak Aleutian Low (fig. 3a). For the CCS, this pattern means greater equatorward winds. During spring and summer, this translated into unseasonably strong coastal upwelling north of Point Conception. Much of Baja California experienced anomalously weak upwelling (poleward anomaly) winds.

The SST anomaly pattern seen since late 1998 also has persisted into 2002. The dominant feature in the north Pacific continues to be a horseshoe-shaped region of cooler than normal upper ocean water that covers much of the CCS and extends north into the Gulf of Alaska and to the southwest past Hawaii. This is a characteristic anomaly pattern associated with La Niña on interannual time scales (Schwing et al. 2002a,b) and the negative phase of the Pacific Decadal Oscillation (PDO) on longer scales (Mantua et al. 1997). The spring and summer 2001 SSTs (fig. 3a) in the northern CCS were unusually cool, where anomalous upwelling winds were observed. Weaker than normal winds corresponded with slightly above normal SSTs off southern California and Baja California.

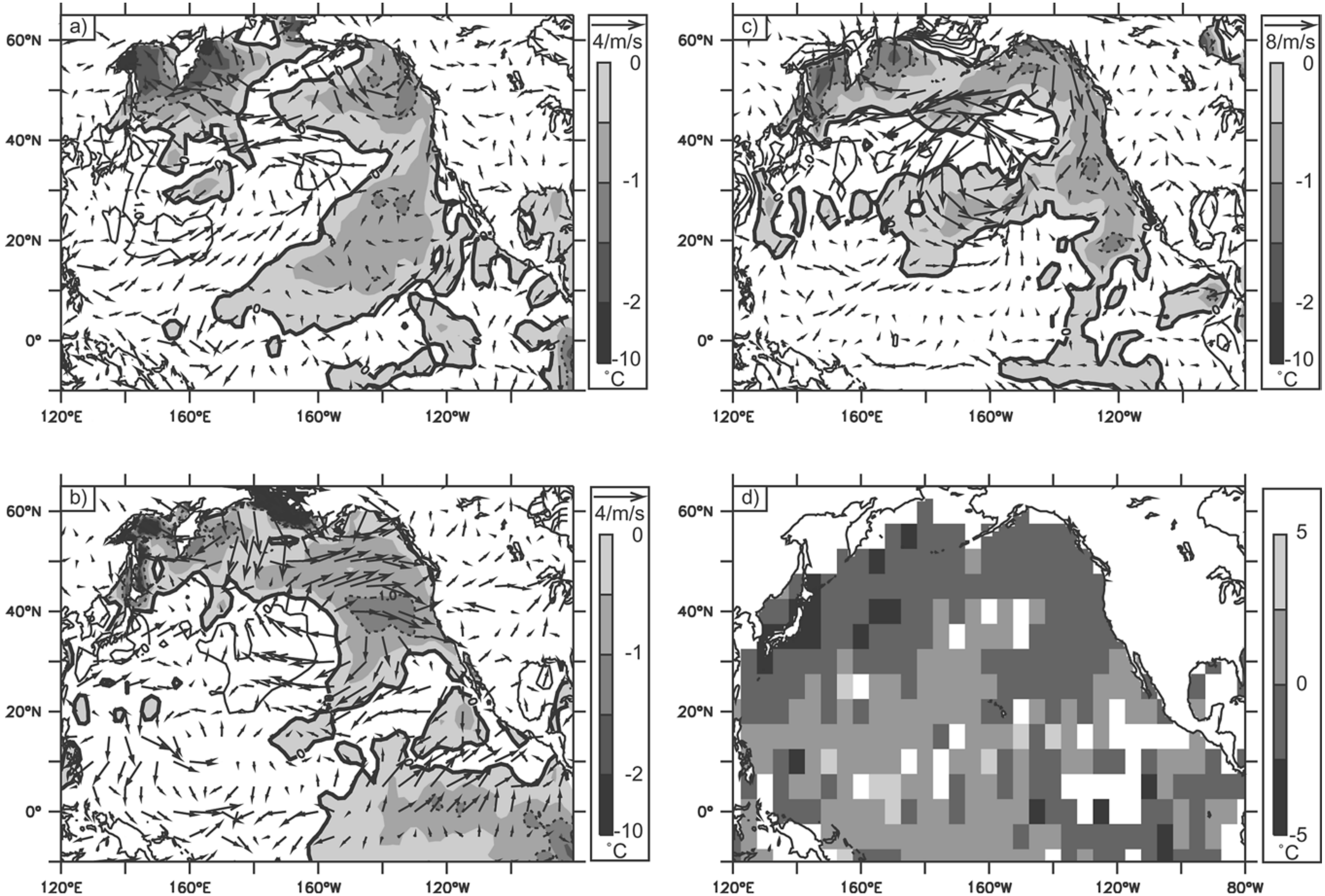


Figure 3. Anomalies of surface wind velocity and sea surface temperature (SST) in the north Pacific Ocean, for (*a*) May–July 2001, (*b*) Dec. 2001–Jan. 2002, and (*c*) Apr. 2002. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative (cool) 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. (*d*) Anomalies of ocean temperature at 100 m depth for Feb.–Apr. 2002, based on the Global Temperature-Salinity Profile Program database, for a base period 1945–96. Shading interval is 2.5°C; lighter shades denote positive (warm) anomalies. White areas denote no data for the period shown.

The summer wind and SST anomaly patterns continued into winter 2001–2002 (fig. 3b), although shifted more toward the northeast, and the maximum anomalies were centered off the West Coast to about 140°W. These anomalies show clear indication of being maintained into the 2002 upwelling season, based on the latest available data (Apr. 2002, fig. 3c). Stronger than normal upwelling-favorable winds along the West Coast were again part of clockwise wind anomalies, due to a premature decay of the Aleutian Low combined with a high-pressure center compressed near the West Coast.

Temperature anomalies at 100 m depth over the Pacific basin show these conditions are not limited to the surface. The upper ocean has featured a thermal anomaly pattern similar to that of SST (fig. 3d), indicating that the processes responsible for ongoing surface anomalies have affected temperatures in the thermocline of much of the north Pacific as well. Sea level height anomalies support this idea (Durazo et al. 2001). In summary, the upper 100–200 m of the CCS continues to be unusually cool, a pattern that began in late 1997. These temperature anomalies are associated with persistent stronger than normal equatorward winds throughout much of the CCS, suggesting that coastal upwelling and Ekman processes are a strong contributor to these ocean anomalies.

The Multivariate ENSO Index (MEI) is an index of El Niño and La Niña events, based on six tropical Pacific variables (Wolter and Timlin 1998). As indicated by negative MEI values, the winter of 2001–2002 marked the fourth consecutive year of weak to moderate La Niña conditions (fig. 4). The April 2002 MEI value shows a big increase toward El Niño conditions. This is the first time since June 1998 (45 months) that the MEI has attained weak El Niño status. Negative MEI values historically have persisted for periods of 20–35 months (e.g., 1995–97 La Niña), suggesting that multiyear La Niña events are common (Schwing et al. 2002a). However, this is the second longest non–El Niño stretch since before 1950, surpassed only by the April 1959–July 1963 period.

The Northern Oscillation Index (NOI) is another ENSO index, one that highlights the intensity of interannual climate events in the northeast Pacific (Schwing et al. 2002a). Positive NOI values, which indicate La Niña–like conditions, have prevailed since mid-1998 (fig. 4), further supporting the idea that the period following the 1997–98 El Niño has been unusually cool in the CCS region. A third commonly used climate index, the Pacific Decadal Oscillation or PDO (Mantua et al. 1997) identifies multi-decadal periods of variability in the Pacific; positive PDO values are associated with warmer than normal SST in the CCS. Summer-means of the PDO have been negative for the past 4 years; a negative PDO of more than 1-year duration has not been observed since the early 1970s.[1] The recent negative tendency of the PDO is consistent with the MEI and NOI in characterizing the northeast Pacific as being unusually cool since 1998. It also suggests that the transition from the 1997–98 El Niño could signal the shift to a new climate regime analogous to those seen in the early 1920s, mid-1940s, and mid-1970s (cf. Mantua et al. 1997; Hare and Mantua 2000).

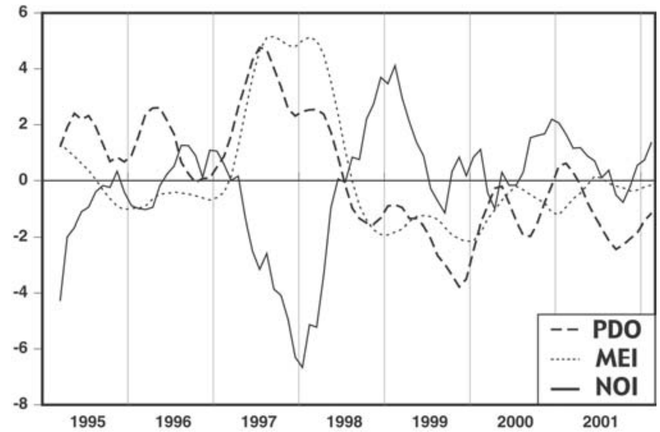

Figure 4. Monthly time series of the Pacific Decadal Oscillation (PDO), Multivariate ENSO Index (MEI), and Northern Oscillation Index (NOI), Jan. 1995–Apr. 2002. Series have been smoothed with a 5-month running mean.

Interannual differences in the CCS are connected to tropical Pacific Ocean anomalies, via atmospheric and oceanic teleconnections (Schwing et al. 2002b). Temperature anomalies at 100 m depth along the equator reflect the evolution of recent El Niño and La Niña events (fig. 5). Warm/cool anomalies at this depth are generally due to a deepening/shoaling of the thermocline. The west to east shift of positive (warm) anomalies in 1997 is part of the 1997–98 El Niño. The 1998–99 La Niña that followed can be identified by the eastward movement of negative (cool) anomalies. Subsequent years have seen this same shoaling thermocline pattern, which has intensified each summer during the seasonal westward expansion of cool water along the equator (Philander 1990).

During the past two winters, positive upper ocean temperature anomalies have developed east of the dateline along the equator (fig. 5). This has been interpreted by some as a sign of an impending El Niño. In early 2002, ocean temperature anomalies have moved east along the equator (NCEP 2002), deepening the thermocline and warming temperatures at 100 m (fig. 5). Coastal SSTs off Ecuador and Peru became unseasonably warm. March 2002 SSTs remained as much as 2–3°C above normal. The subsurface temperature at 60 m off

[1]Peterson, W. T., and F. B. Schwing. Recent changes in climate and carrying capacity in the California Current: a positive sign for recovery of salmon. (manuscript)

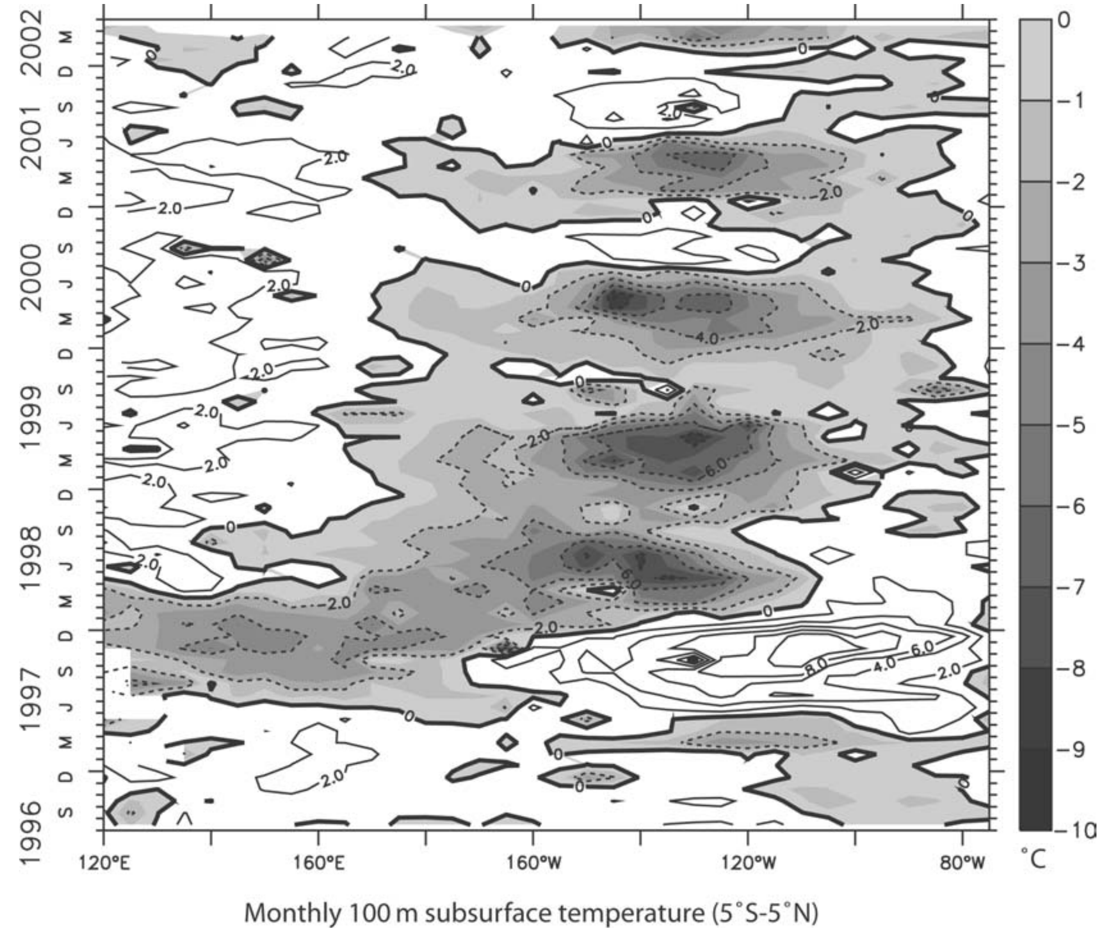


Figure 5. Monthly anomalies of equatorial temperature at 100 m, Aug. 1996–Apr. 2002. Anomalies are shown for 5°N–5°S region along equator (120°E–75°W), based on the Global Temperature-Salinity Profile Program database, for a base period 1945–96. Contour interval is 2°C. Shading denotes negative anomalies.

Paita, Peru (5°S), jumped from 15°C to 21°C in March (F. Chavez, pers. comm., see <http://www.mbari.org/bog/Projects/Peru/peru02_03.htm>). This warming has reportedly affected Peruvian marine fisheries, where warm-water species have replaced the cold-water anchovy. However, South American SSTs and sea levels have returned to more normal values in April 2002 (F. Chavez, pers. comm.; D. Enfield, pers. comm.; see also <www.aoml/noaa.gov/phod/epac>), suggesting that these earlier warm temperatures may have been a short-lived event rather than the onset of a new El Niño.

The thermocline deepening and warming of upper ocean waters in the eastern equatorial Pacific in early 2002 was due to an oceanic Kelvin wave that propagated eastward from the central equatorial Pacific starting in mid-December (NCEP 2002). This Kelvin wave was triggered by a westerly wind burst associated with intraseasonal (30–60 day) variability known as the Madden-Julian Oscillation (MJO). Whereas MJO activity was evident globally throughout the tropics during winter 2001–2002, and more generally since late 1998, the MJO was not active during March 2002. However, late spring is a critical time, when MJO-related westerly wind bursts or other short-lived westerly wind activity can generate Kelvin waves, and ultimately initiate El Niño. If MJO activity increases, a more rapid evolution toward mature El Niño conditions might occur through the spring and summer of 2002. Without such activity, the prospects of El Niño are greatly diminished.

Several dynamical and statistical models indicate a gradual evolution toward weak or moderate El Niño conditions during the next several months, although some analyses indicate that conditions will remain near neutral or even return to a weak La Niña state for the remainder of 2002. One scenario is for further development toward a weak to moderate mature El Niño, continuing into early 2003. However, one-third of El Niño–like events die off within a few months (K. Wolter, pers. comm.). This possibility is enhanced by the fact that we are currently in the negative (cool CCS and northeast Pacific) phase of the PDO (Mantua et al. 1997), a pattern that is thought to reduce/enhance the formation of strong El Niño/La Niña events. The continuing development of El Niño can be monitored online at <http://www.cpc.noaa.gov/products/analysis_monitoring/enso_advisory/> or <http://www.pmel.noaa.gov/tao/jsdisplay>.

## COASTAL CONDITIONS

Monthly coastal upwelling indexes (Bakun 1973; Schwing et al. 1996) have indicated generally stronger than normal upwelling in the CCS since the onset of La Niña in late 1998 (Hayward et al. 1999; Bograd et al. 2000; Durazo et al. 2001). Following record upwelling during 1999 (Schwing and Moore 2000; Schwing et al. 2000), upwelling was again extremely strong during the 2000 and 2001 upwelling seasons from about San Diego to the Columbia River, and off southern Baja California (fig. 6). The mean summer (May–Aug.) upwelling index at 36°N since 1999, for example, has been 275 $m^3/s/100$ m (33% above average), compared to 201 $m^3/s/100$ m for 1991–98. Other than the record 1999 upwelling, 2001 featured the highest mean summer upwelling index since 1981. The period following the 1997–98 El Niño has been the highest 4-year mean on record, extending back to 1946. Weaker than normal upwelling prevailed off northern Baja California in the 2001 upwelling season. April 2002 indexes indicate that the latest upwelling season is off to another strong start.

National Data Buoy Center (NDBC) coastal buoy winds in the CCS display the short-term variability associated with synoptic (1–2 week) 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 (tab. 1), so we show time series of the alongshore component of wind (fig. 7), the component directly linked with coastal upwelling. Coastal winds during 2001 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. The general impression from these series is that the spring transition occurred in early March. Visually, alongshore wind events during 2001 appear to be biased toward stronger than normal upwelling. This is supported by the monthly upwelling index anomalies (fig. 6).

The multiyear trend of below-normal temperatures in the CCS since 1998, described in previous reports, has continued through 2001 (fig. 8). On a seasonal scale, coastal SSTs during 2001 were unusually cool, with extended periods of near- or above-normal values in May, July, and September. Coastal SSTs cool/warm on synoptic scales in response to local upwelling/downwelling winds (fig. 7). Winter SSTs in early and late 2001 remained very steady despite strongly fluctuating winds. Strong downwelling episodes occurred in February, November, and December 2001 over most of the CCS. However, these did not have an obvious effect on buoy SSTs (fig. 8). Synoptic variations in SST are more evident in the upwelling season. Extended wind relaxation events (periods of weak upwelling-favorable wind) in May, July, and September 2001 did produce warmer SSTs. These are particularly evident south of Monterey Bay.

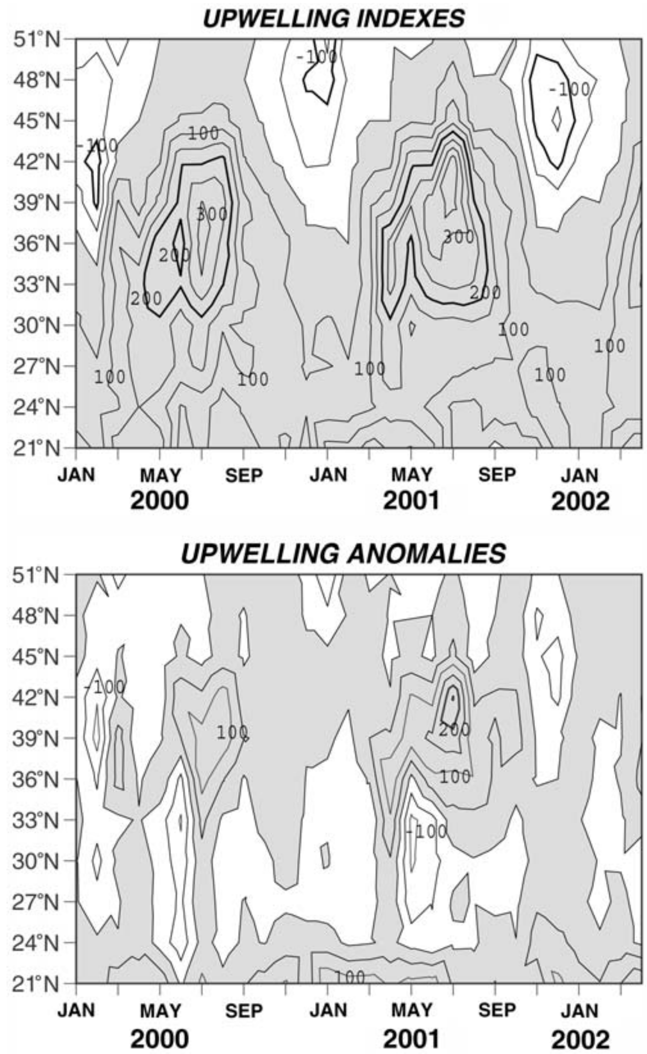


Figure 6. Monthly upwelling index and upwelling index anomaly for Jan. 2000–Apr. 2002. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in $m^3/s$ per 100 km of coastline.

## CALCOFI SURVEY CRUISES

### 0101 (7–26 Jan. 2001)

Although this cruise was reviewed in last year's report (Durazo et al., 2001), it is included here to show the strong change in coastal circulation that took place between the winter and spring 2001 cruises. The position of the main California Current jet is revealed by the

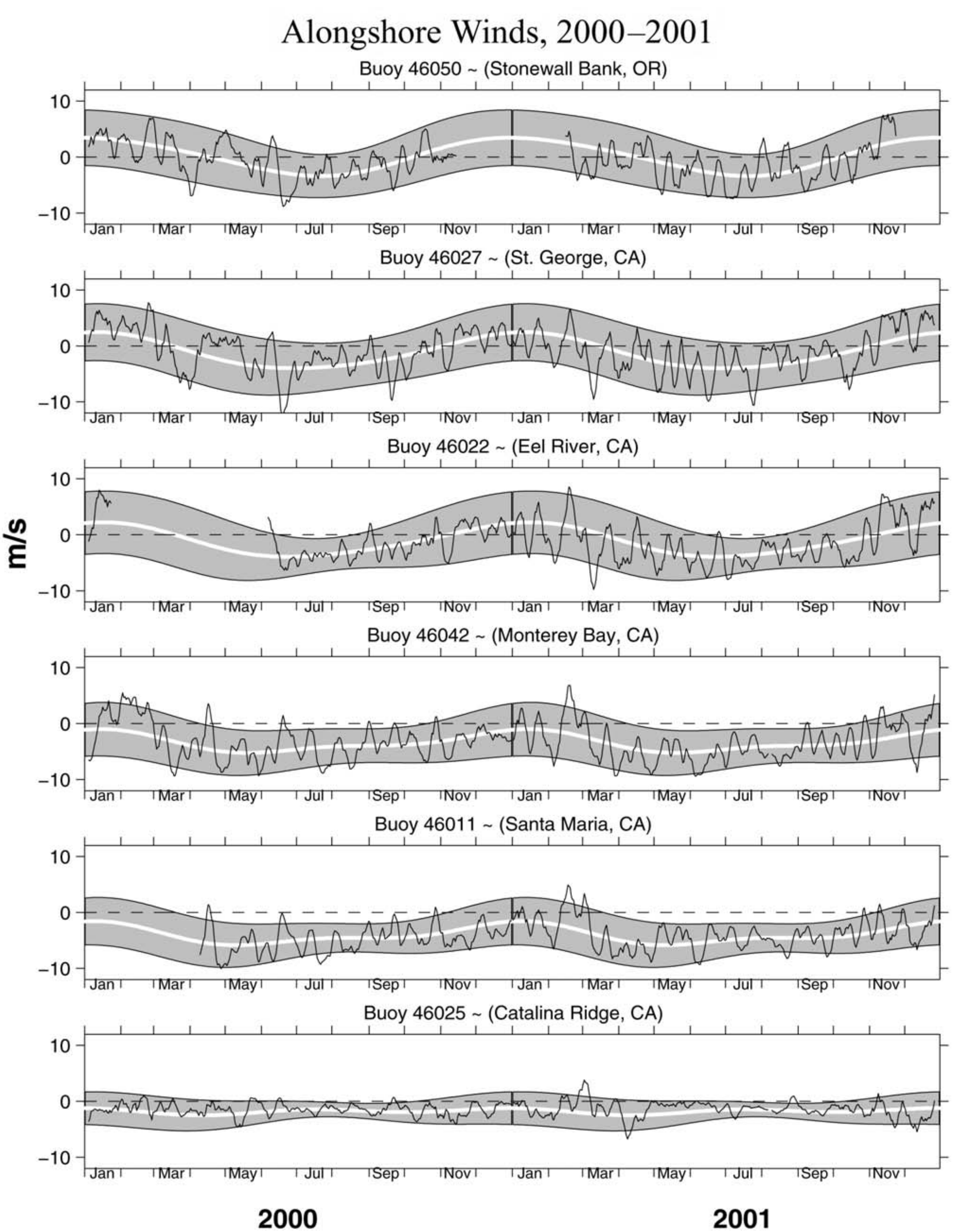


Figure 7. Time series of daily-averaged alongshore winds for Jan. 2000–Dec. 2001 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold white lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed 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. Data provided by NDBC.

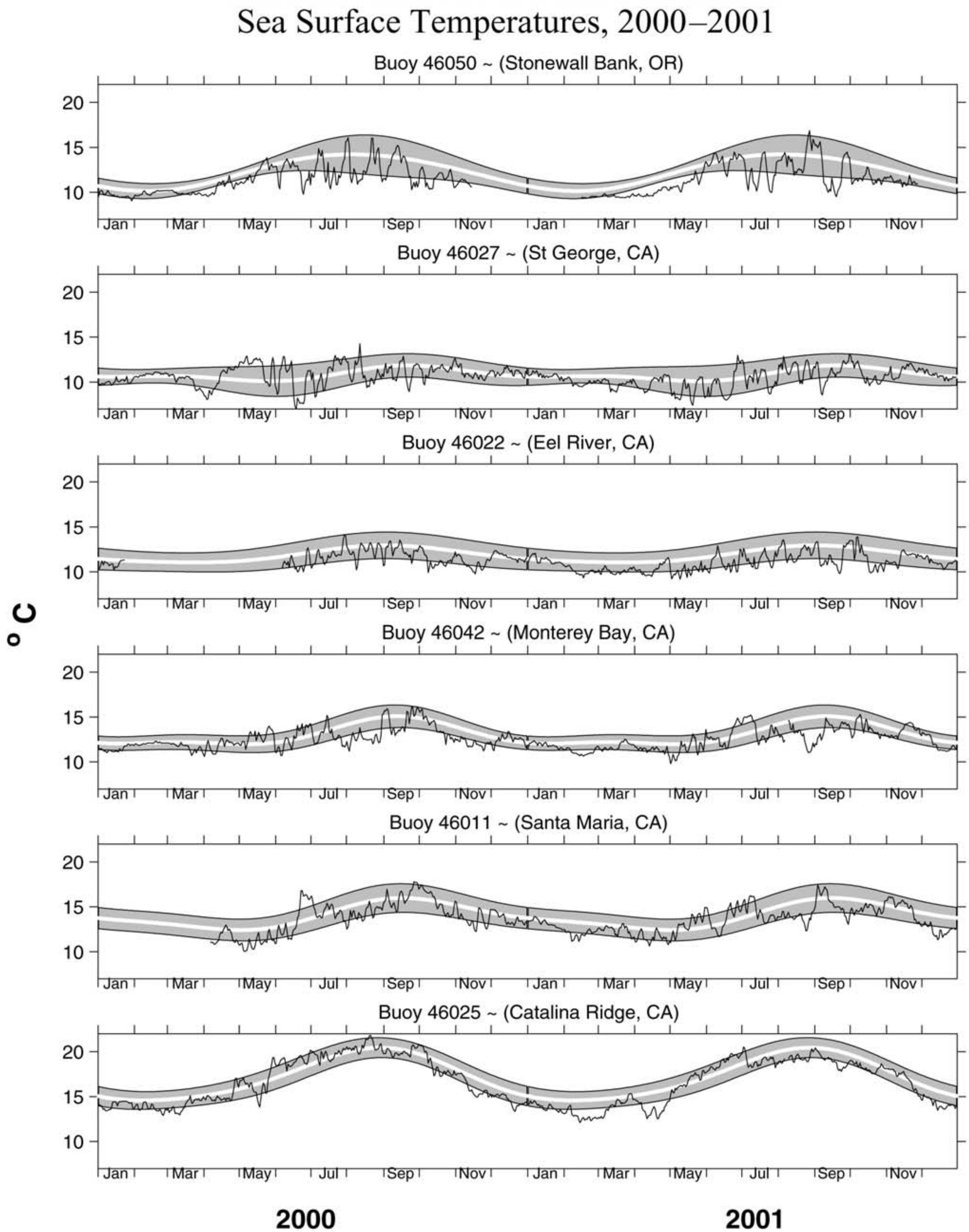


Figure 8. Time series of daily-averaged SST for Jan. 2000–Dec. 2001 at selected NDBC coastal buoys. Bold white lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. The periods used for calculating the climatology at each site are shown in table 1. Data provided by NDBC.

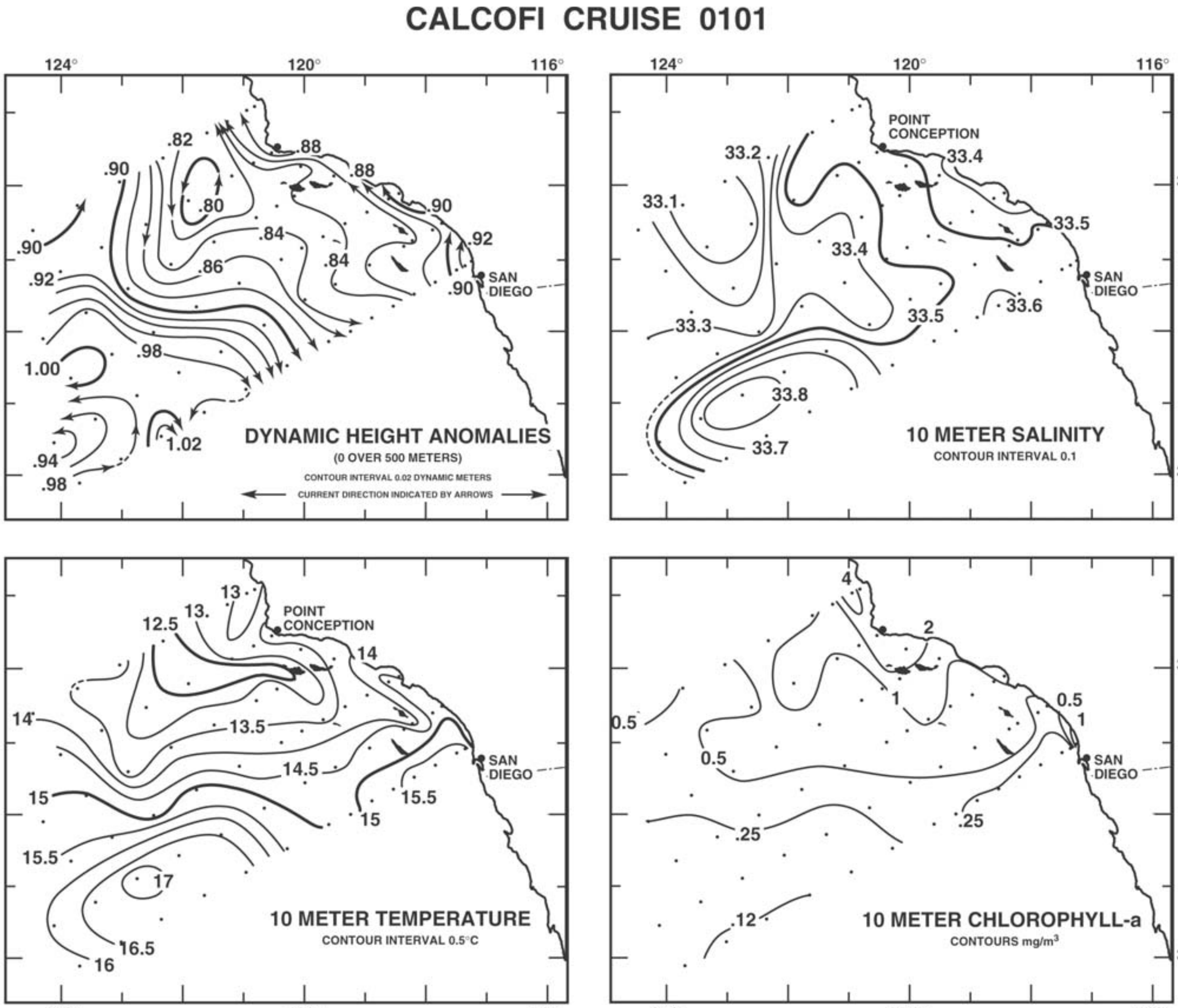


Figure 9. Spatial patterns for CalCOFI cruise 0101 (7–26 Jan. 2001), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

strong lateral gradient in the 0/500 dbar dynamic height contours through the middle of the cruise pattern, and by the location of the low-salinity water (<33.4) advected into the region from the north (fig. 9). A warm and saline eddy is seen in the southwest corner of the pattern, offshore of the main flow of the California Current. A broad northward coastal countercurrent was present between the coast and station 90.53. Near-coastal water between 100 and 300 m off San Diego was warmer and more saline than usual, an indication that the coastal undercurrent was also strong with an influx of water from the south. Surface chlorophyll was high off Point Conception and in the Santa Barbara Channel. Overall, the cruise-mean integrated chlorophyll and primary productivity were above normal (fig. 10a). SSTs were generally cooler than normal for the third consecutive winter.

**0104 (6 Apr.–3 May 2001)**

Although the April offshore circulation and salinity were similar to January, the coastal flow was southward (fig. 11). Associated with this strong flow was intense coastal upwelling, as shown by very cool coastal temperatures and high salinities (greater than 33.8 in the Santa Barbara Channel). The nearshore countercurrent that defines the Southern California Eddy was not evident; the dynamic height pattern shows only a slight suggestion of northward flow. An isolated cyclonic eddy was present, centered at station 80.90 (ca. 33°N 123°W). Surface chlorophyll was exceptionally high in April, especially at the shallow continental shelf stations. The cruise-mean integrated chlorophyll was exceeded only by the 1999 cruise mean (fig. 10a). SST anomalies were cooler than the long-term means throughout the region,

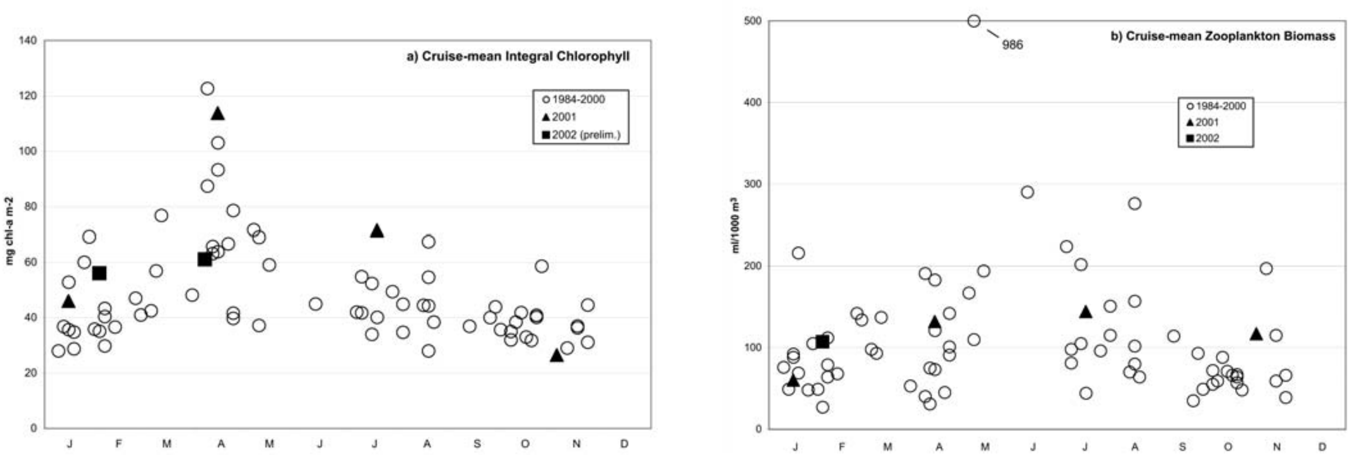


Figure 10. Cruise means of (*a*) vertically integrated chlorophyll and (*b*) macrozooplankton biomass plotted versus month for CalCOFI cruise from 1984 to Apr. 2001 for chlorophyll *a* and Jan. 2001 for zooplankton. Each point represents the mean of all measurements on a cruise (usually 66). Open circles indicate the 1984–2000 cruise values. Solid triangles and rectangles indicate values from 2001 and 2002, respectively.

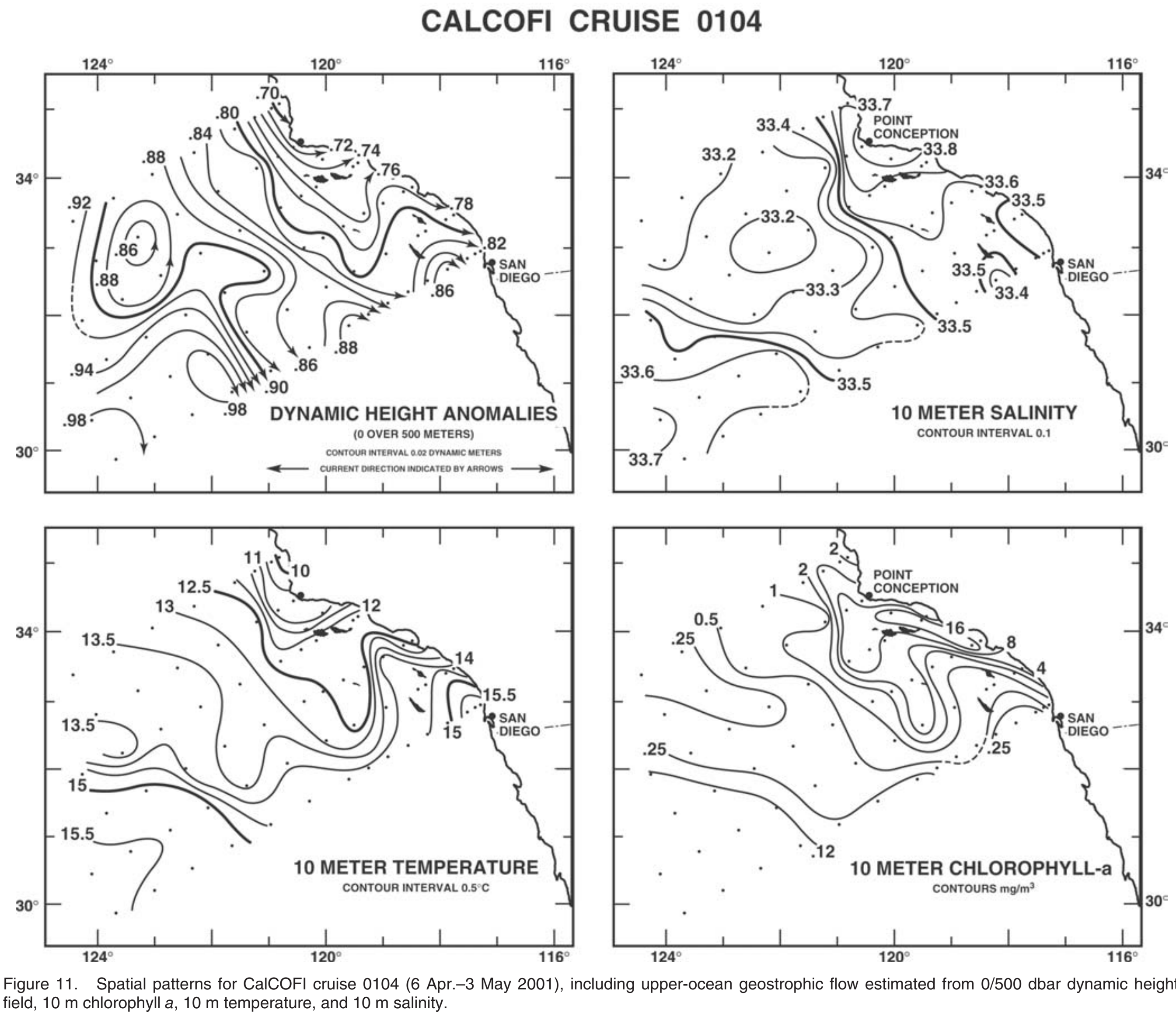


Figure 11. Spatial patterns for CalCOFI cruise 0104 (6 Apr.–3 May 2001), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

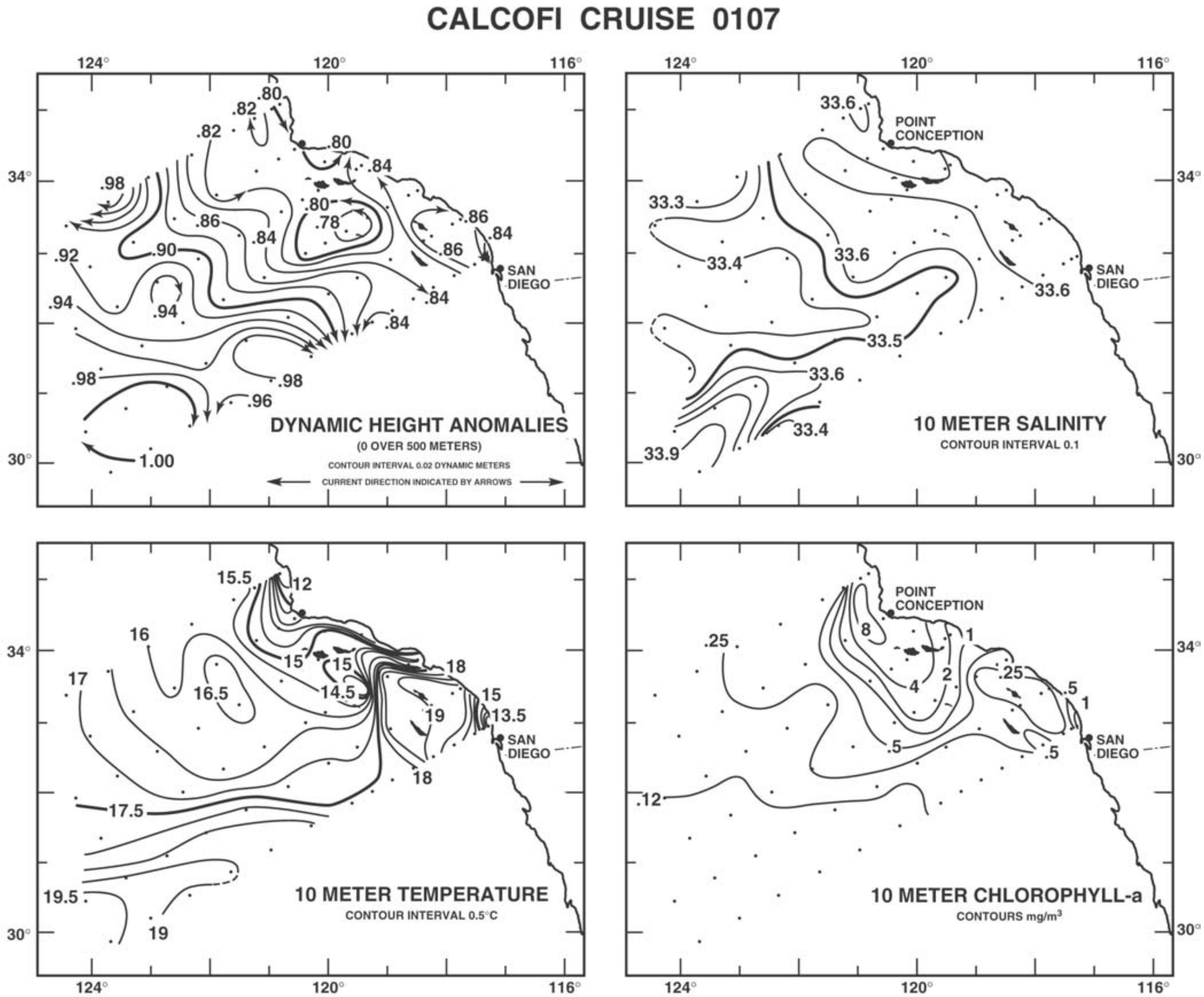


Figure 12. Spatial patterns for CalCOFI cruise 0107 (10–27 July 2001), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

exceeding 2°C below normal on the shelf stations of line 87.

### 0107 (10–27 July 2001)

The circulation in July reverted to a more normal state for the season, with a southern California cyclonic eddy present but with southward flow on the shelf north of Santa Barbara and off San Diego (fig. 12). Both of these shelf areas were unusually cool; a cold patch was also seen in the center of the cyclonic eddy, at stations 87.45 and 87.50 near San Nicolas Island. The flow from the offshore edge of the pattern was largely zonal, bringing in relatively low salinity (<33.4) water along the northwestern edge and warm high salinity (>33.7) water from the southwestern corner. Both signals were carried eastward well into the region. The shallow warm patch of water in the southeast part of the pattern is typical for summer. The temperature-salinity curve there is quite close to the long-term historical mean. Surface chlorophyll, cruise-mean integrated chlorophyll (fig. 10a), and primary productivity were very high for summer.

### 0110 (25 Oct.–9 Nov. 2001)

The California Current in October featured a wide meander, with offshore flow on the outer part of line 77 and an eastward flow between lines 80 and 83 that turns southward between stations 60 and 90 of line 83 (fig. 13). The Southern California Eddy, centered at station 87.45 on cruise 0107, had moved south and was centered on station 90.53. The northward coastal coun-

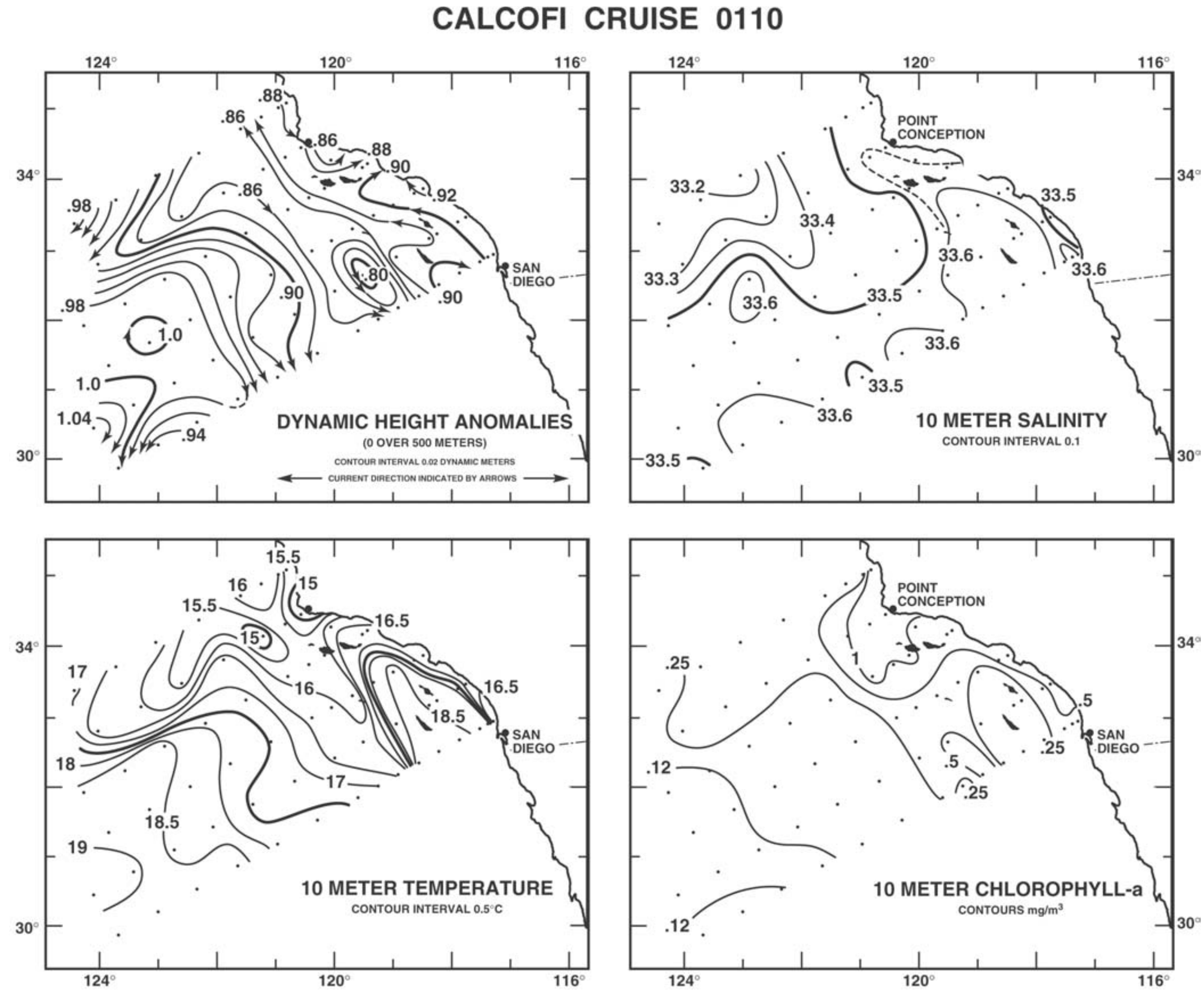


Figure 13. Spatial patterns for CalCOFI cruise 0110 (25 Oct.–9 Nov. 2001), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

tercurrent was wide and resumed the typical fall pattern. Surface chlorophyll also subsided to low values that are typical of fall.

**0201 (24 Jan.–11 Feb. 2002)**

The surface dynamic height field again shows a strong meander in the outer part of the pattern (fig. 14), but this was shifted compared to October. Whereas the flow was offshore on line 77 during the previous fall, it was now eastward, turning westward between lines 80 and 83. The northward nearshore countercurrent was present but somewhat further offshore than usual. A cyclonic/anticyclonic pair of eddies was seen in the southwest corner of the pattern. Along the coast, chlorophyll levels were again quite unseasonably high, especially near Point Conception. There was also a patch of elevated chlorophyll (greater than 0.5 µg/l) offshore in the region where surface chlorophyll is usually low. This was in the vicinity of the cyclonic current loop.

**0204 (27 Mar.–12 Apr. 2002)**

The offshore circulation map for April 2002 (fig. 15) shows the same zonal current loops that were present in January, perhaps shifted slightly southward. These cruise data are in the preliminary stages of being processed, so the 0/500 dbar dynamic heights were not available. The temperature at 100 m depth has been a useful proxy for the surface circulation in the past, especially in relation to the California Current jet. However, it is less successful in depicting the coastal countercurrent. Nonetheless, there was an apparent absence of any surface countercurrent and the Southern California eddy. These

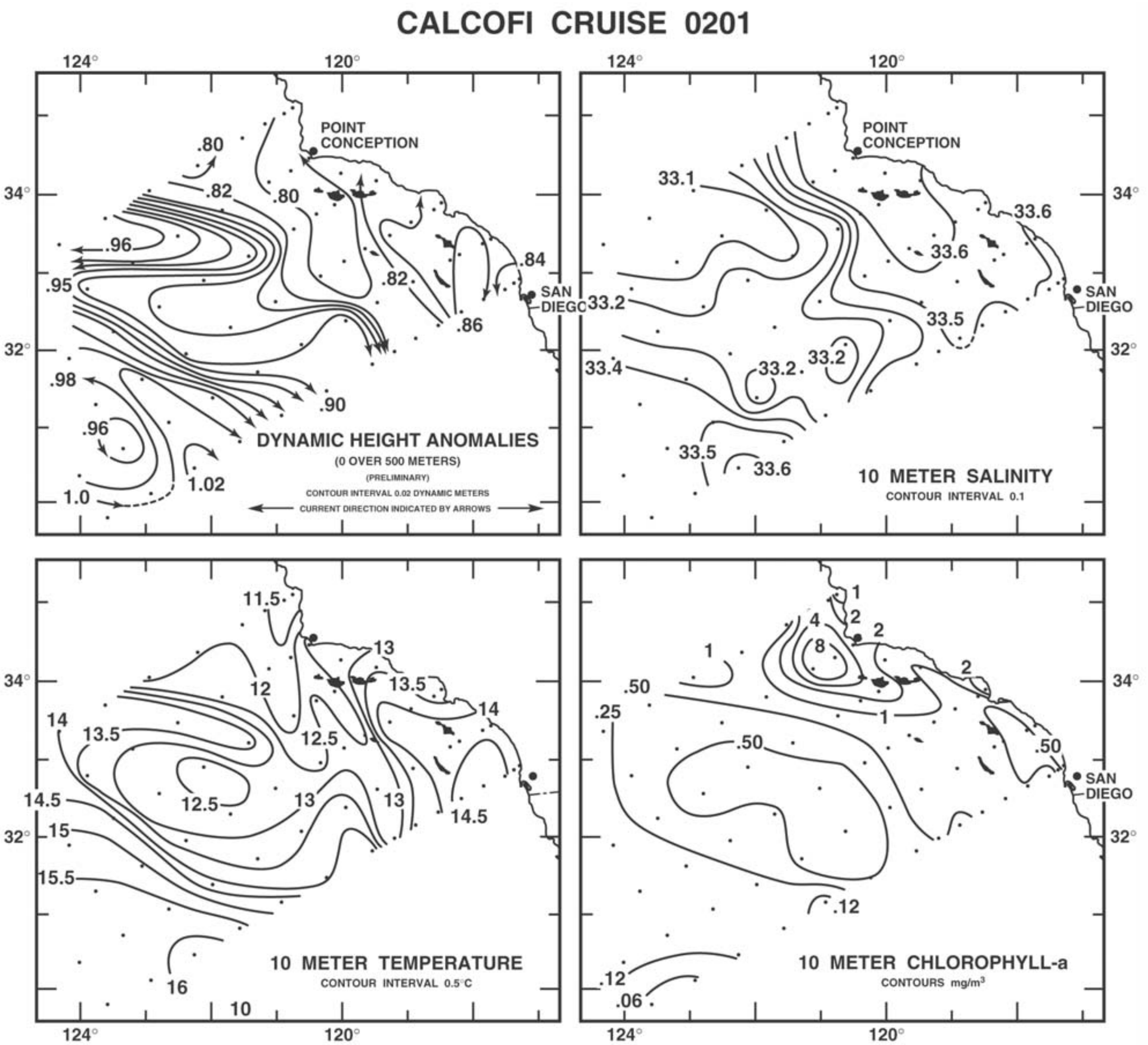


Figure 14. Spatial patterns for CalCOFI cruise 0201 (24 Jan.–11 Feb. 2002), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

near-surface patterns are somewhat unusual for spring, with the main core of the California Current apparently well offshore and little evidence of an equatorward upwelling jet. Upwelling was strong, with cooler than normal nearshore temperatures and high surface salinities. Chlorophyll levels were very high around the northern Channel Islands, where the phytoplankton was dominated by *Pseudonitzschia australis* instead of species in the genus *Chaetoceros* that are more usual in spring; *P. australis* exceeded 1,000 cells/ml at station 83.51, south of Santa Rosa Island. Another unusual biological observation was the high abundance of the chondrophore *Velella velella* over much of the survey region. The cruise track was extended another 40 nmi offshore on lines 77 and 80 to sample sardine egg concentrations. An unscheduled sample taken at 79.110 (not plotted) showed surprisingly high surface chlorophyll (0.45 μg/l) for a station so far offshore, whereas relatively low chlorophyll was present in the anticyclonic loop seen on the offshore ends of lines 80 and 83. That current loop is also the only part of the cruise that has positive 10 m temperature anomalies. The rest of the region remained cooler than normal, as it has been for the previous three springs.

## TEMPERATURE AND SALINITY TIME SERIES 1995–2001: STATION 90.37

The temperature and salinity time series over the upper 500 m at station 90.37, which lies between San Clemente and Catalina Islands, represent events within the Southern California Bight. Water mass properties

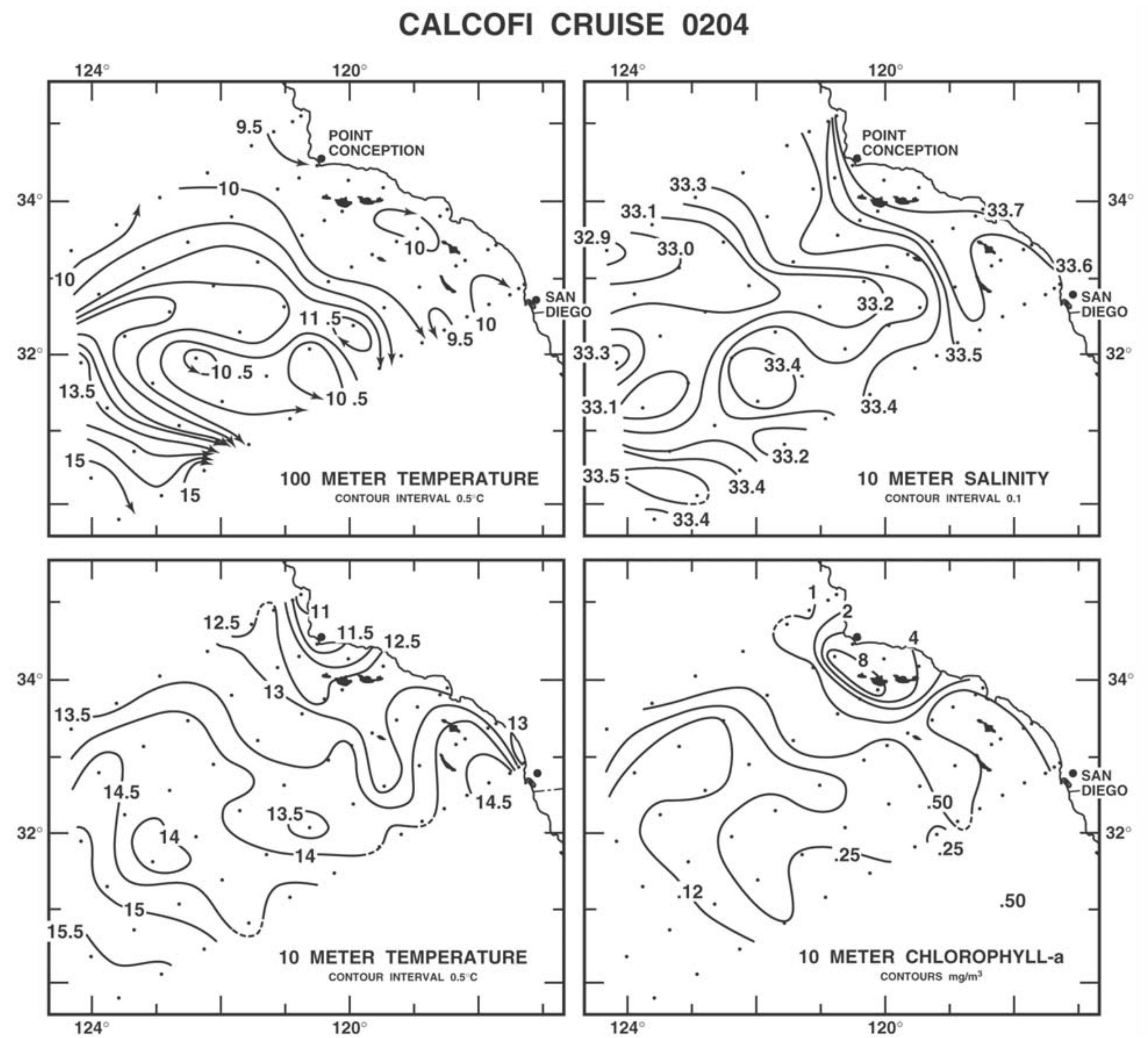


Figure 15. Spatial patterns for CalCOFI cruise 0204 (27 Mar.–12 Apr. 2002), including 100 m temperature (proxy for upper-ocean geostrophic flow), 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

are influenced by seasonal, interannual, and episodic circulation events, all evident in Figure 16. Seasonal cooling/warming and an associated salinity decrease/increase are evident above 30 m, associated with stronger upwelling in spring and summer/weaker upwelling in fall and winter. The strong 1997–98 El Niño followed by a strong La Niña provide the strongest signals at middepths. Anomalously warm and saline waters initially appeared at depth (175–250 m) in July 1997. The surface manifestation of El Niño appeared during the fall and winter of 1997.

After mid-1998, La Niña produced a strong freshening and unseasonable cooling from the surface to 400 m. The seasonal cycle in temperature between 150 m and 400 m that existed prior to the 1997–98 El Niño does not appear afterward. The early period variation is likely related to seasonal variability in the geostrophic balance of the California Undercurrent. Since mid-1998, this portion of the water column has also been cool and fresh relative to the 1995–97 observations shown here. One explanation for this is a reduction in the transport of the Undercurrent beginning in 1998, resulting in more subarctic water in the Bight. An examination of these time series suggests that an expanded study using this methodology would be of some interest.

## IMECOCAL SURVEY CRUISES

### 0104 (3–15 Apr. 2001)

Only a few stations were occupied during this survey because of unfavorable sea conditions and continuous ship problems. The core of the California Current was

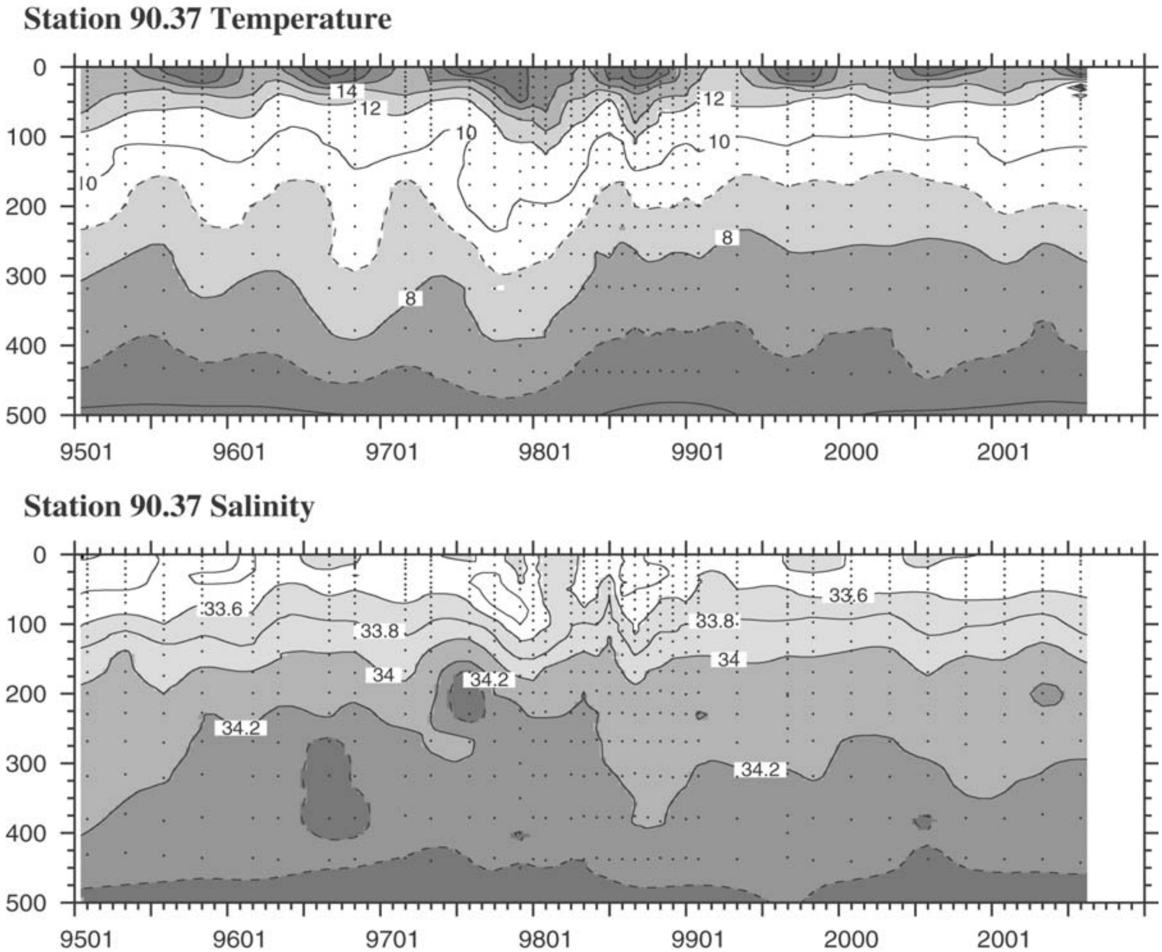


Figure 16. Time series of temperature and salinity over the upper 500 m at CalCOFI station 90.37 (between San Clemente and Catalina Islands), 1995–2001. Temperature contour interval is 2°C for T >10°C, 1°C for T < 10°C. Salinity contour interval is 0.2. Dots denote positions of samples.

located about 100 km off Punta Colonet (3°N) (fig. 17), in association with low SST (14.0–15.0°C) and salinity (33.50–33.60). Inshore 10 m water temperatures below 14.0°C and salinities up to 33.70 were related to upwelling in the northern region. Inshore waters had high dissolved oxygen (>6.0 ml $l^{-1}$) (fig. 17), and high phytoplankton biomass (10 m chlorophyll *a*) with concentrations above 8.0 mg $m^{-3}$ (fig. 18). These values indicate high production off Baja California for spring 2001. During April, zooplankton biomass in northern Baja California was relatively low (<70 ml/1,000 $m^3$), with only a local patch of high biomass off Punta Colonet (fig. 19).

**0106 (26 June–17 July 2001)**

Inshore of the core of the California Current, which was still ~100 km off Punta Colonet, a cyclonic eddy had developed (fig. 20). This eddy had a lens of relatively high salinity (33.60) and high surface water temperature. Off Punta Eugenia, the core of the California Current was pushed offshore by a stronger cyclonic eddy. This eddy also had a warm (>20°C) saline lens. The temperature field shows an upwelling-type pattern over most of the IMECOCAL region. The warmest water (>20°C) occurred from Punta Eugenia to the south in the offshore region, associated with two high saline (34.0) cores. One was entering the region from the west and the other from the south. The 10 m dissolved oxygen distribution was homogeneous, with some high concentrations (>6.0 ml $l^{-1}$) near the coast. High (>8.0 mg $m^{-3}$) chlorophyll values were found in inshore waters off southern Baja California (fig. 18). In July, an increase of zooplankton biomass was observed in the entire sampled area, but was particularly high near the coast (fig. 19). Zooplankton biomass exceeded 1,000 ml/1,000 $m^3$ at some stations off southern Baja California. The main centers of high zooplankton biomass appear to be associated with high 10 m chlorophyll concentrations in coastal areas along the Baja California Peninsula.

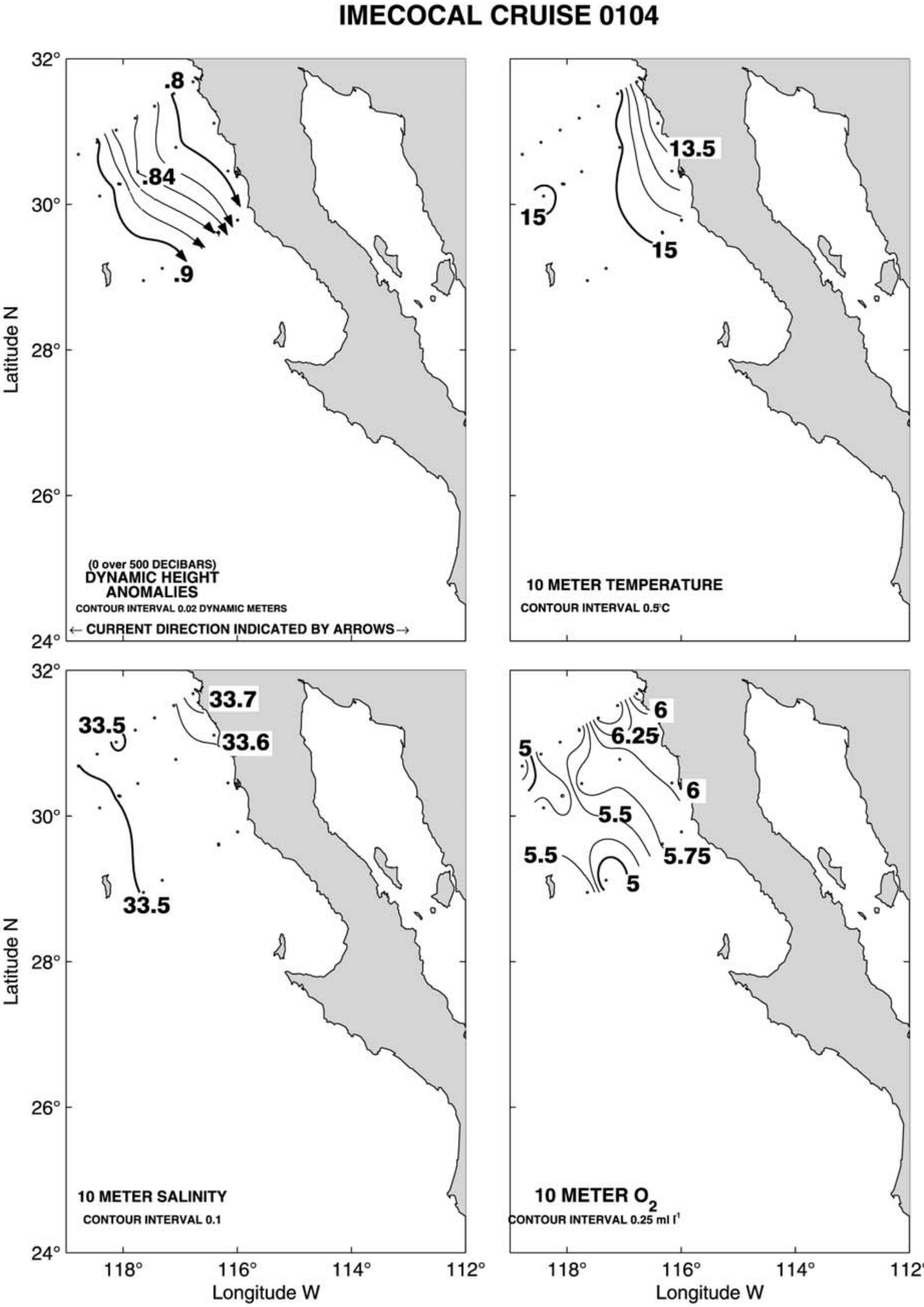


Figure 17. Spatial patterns for IMECOCAL cruise 0104 (3–15 Apr. 2001), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height anomalies, 10 m temperature, 10 m salinity, and 10 m oxygen.

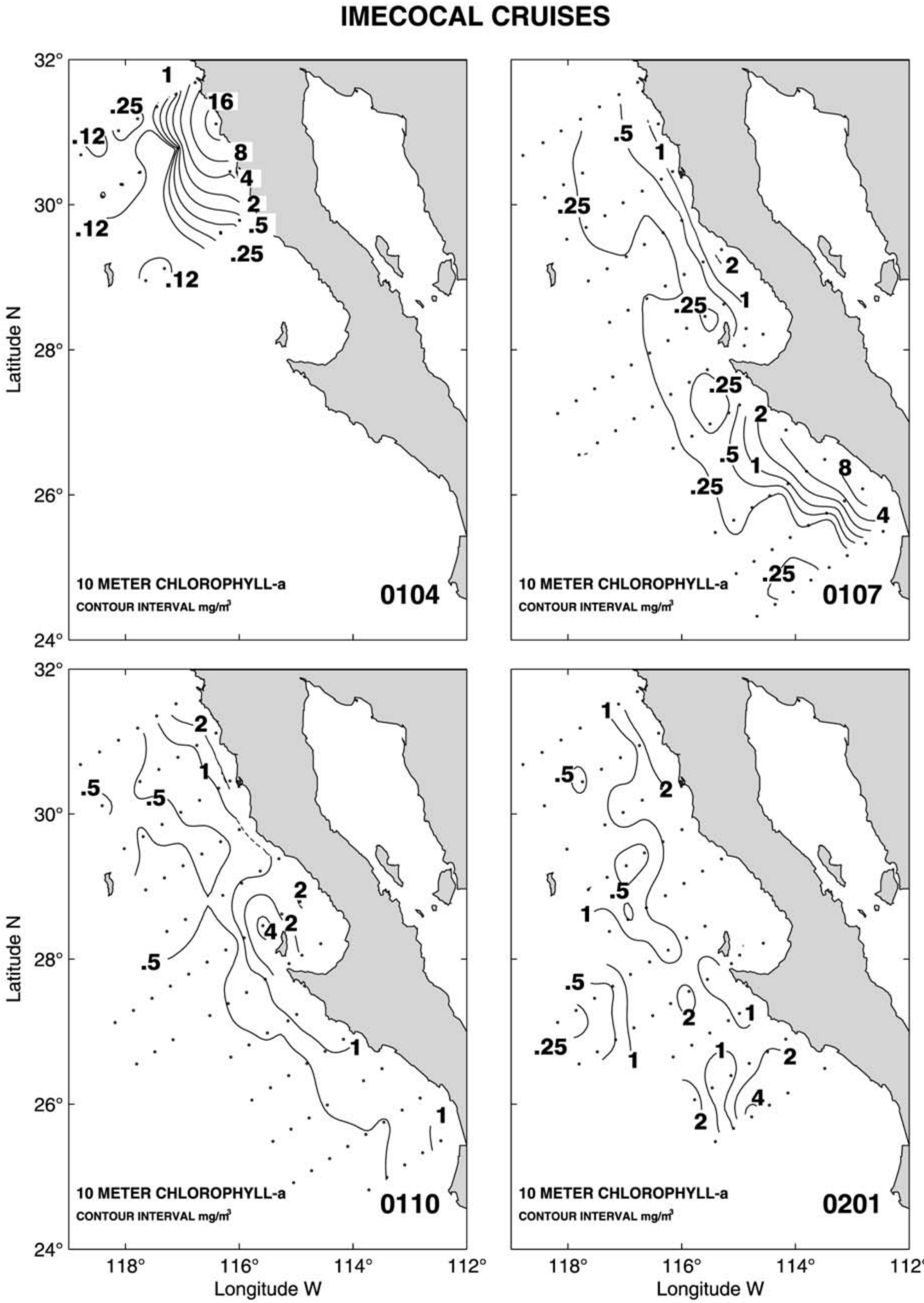


Figure 18. 10 m Chlorophyll *a* measured during the IMECOCAL surveys of Apr., July, and Oct. 2001, and Jan. 2002 in the southern region of the California Current.

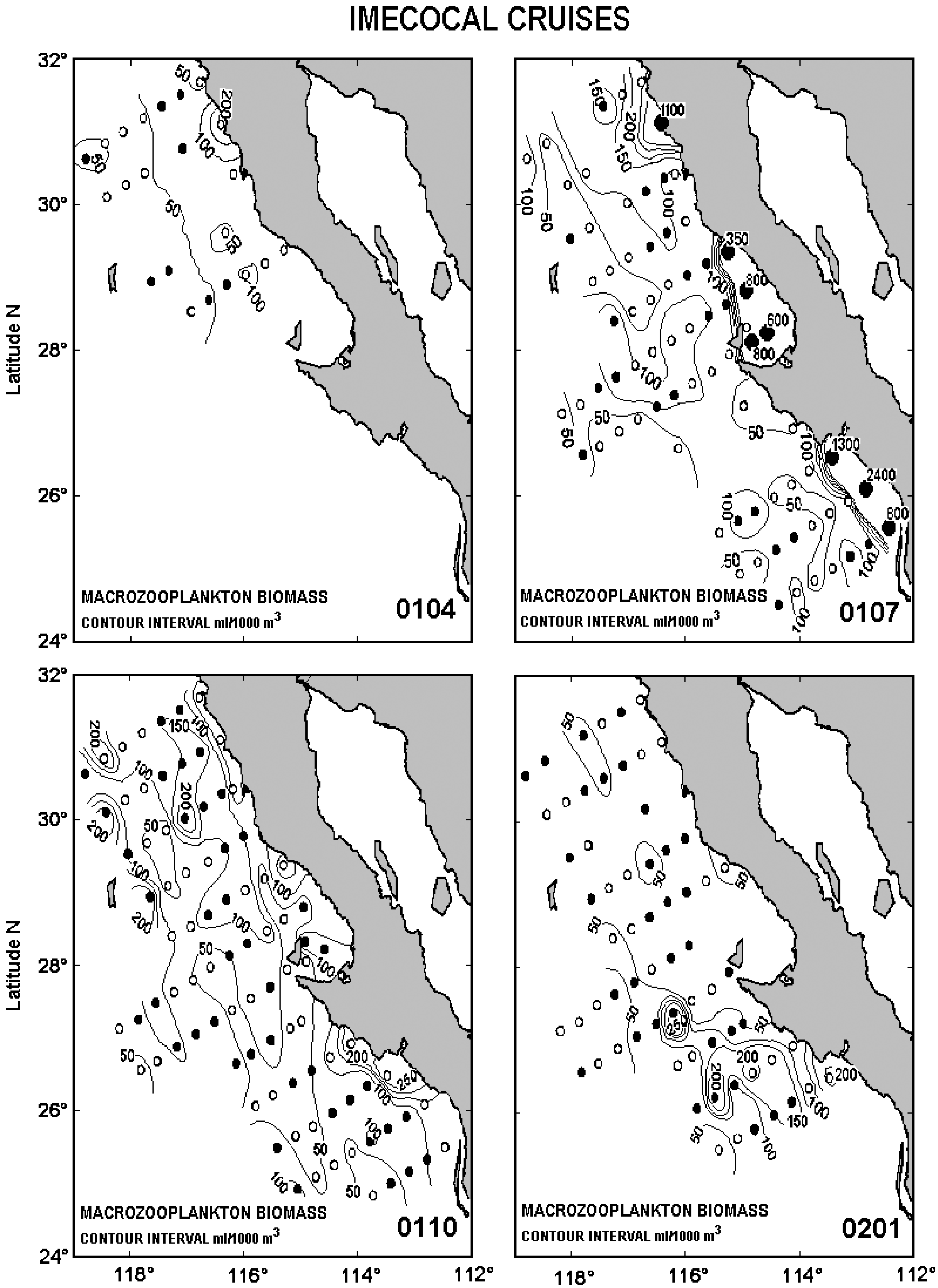


Figure 19. Macrozooplankton biomass distribution off Baja California during Apr., July, and Oct. 2001, and Jan. 2002. The open circles represent the stations visited during daylight hours, and the solid circles, nighttime. The large dots in the upper-right diagram represent very high biomass values.

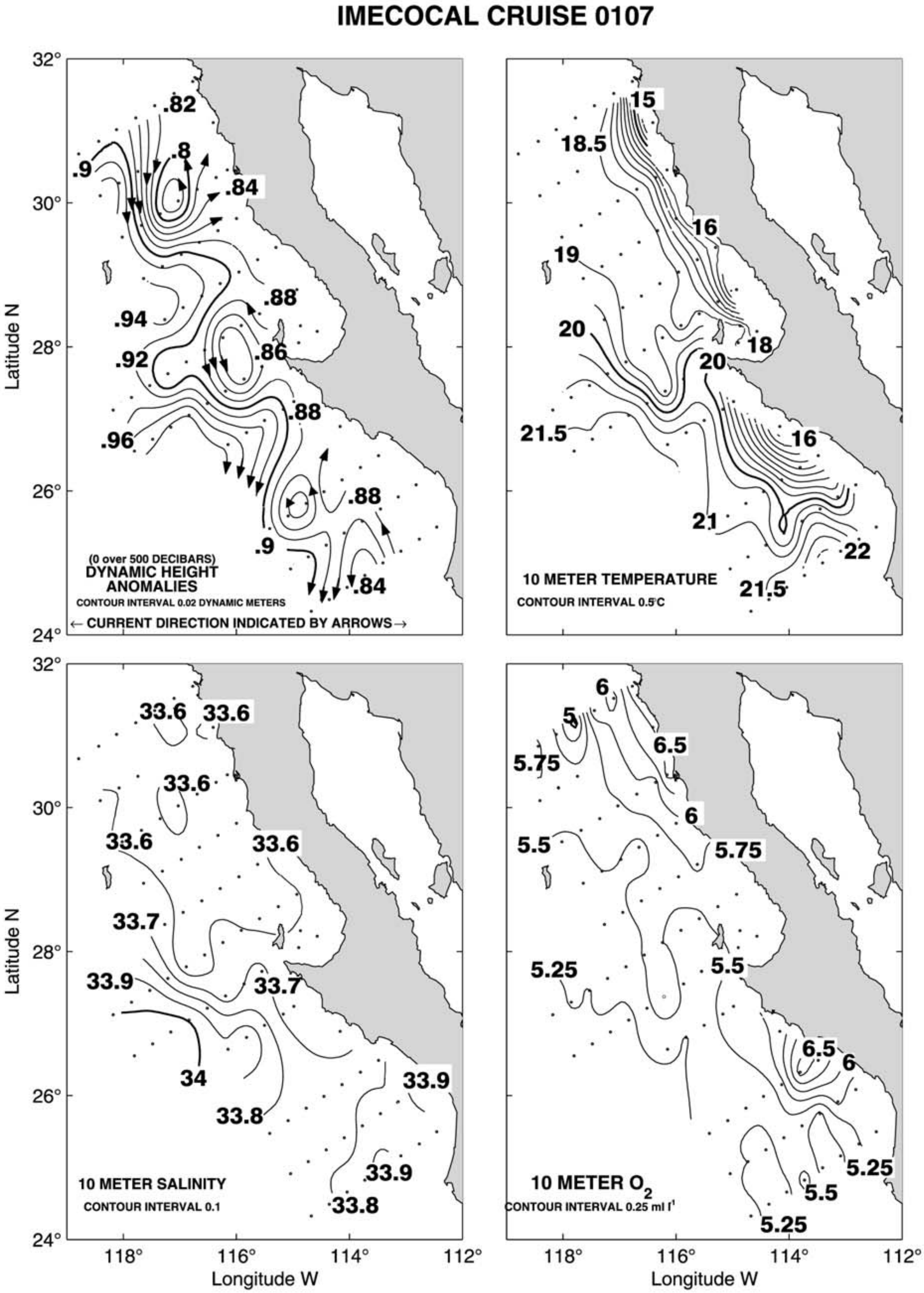


Figure 20. Spatial patterns for IMECOCAL cruise 0107 (26 June–17 July 2001), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height anomalies, 10 m temperature, 10 m salinity, and 10 m oxygen.

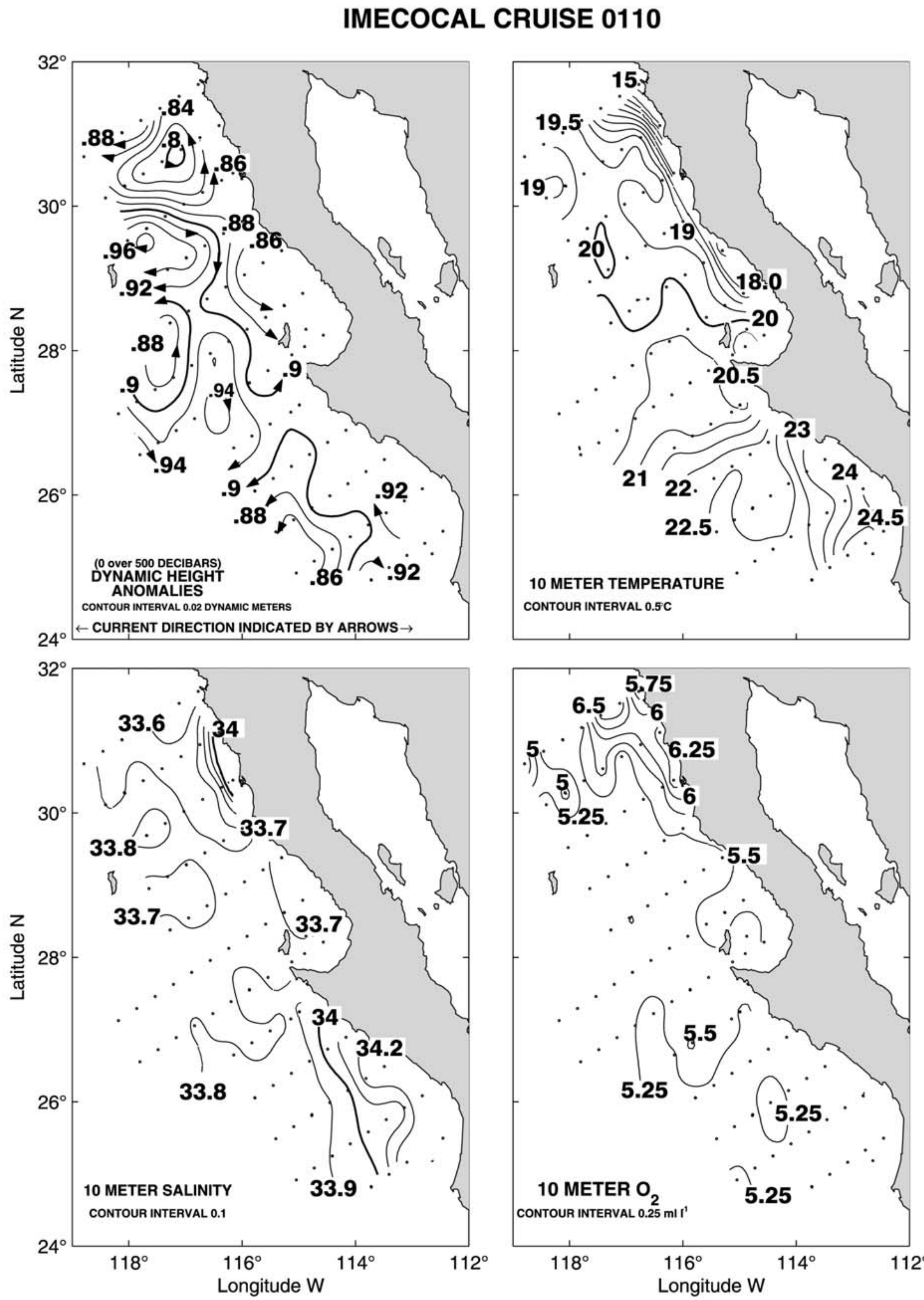


Figure 21. Spatial patterns for IMECOCAL cruise 0110 (3–24 Oct. 2001), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height anomalies, 10 m temperature, 10 m salinity, and 10 m oxygen.

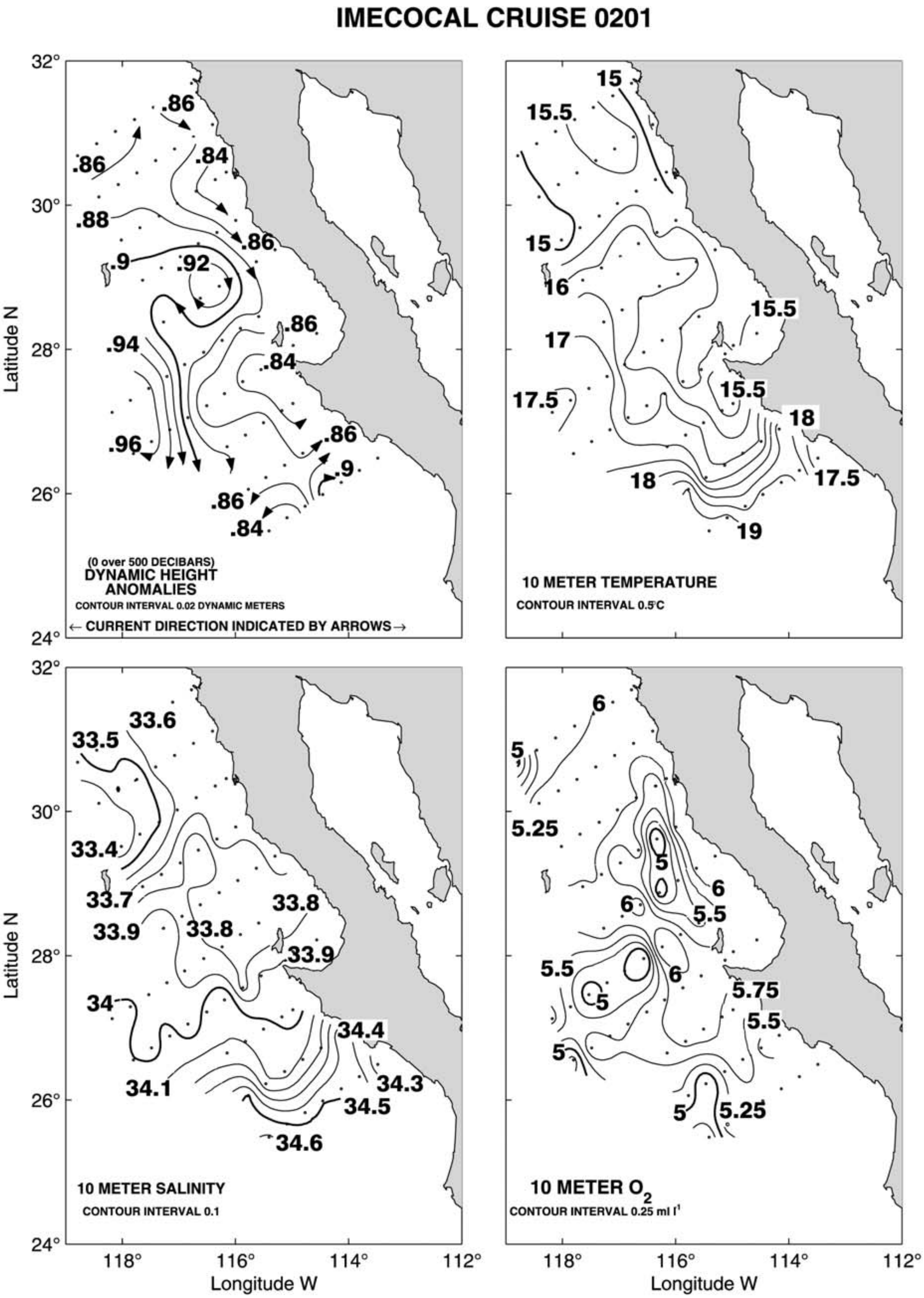


Figure 22. Spatial patterns for IMECOCAL cruise 0201 (19 Jan.–7 Feb. 2002), including upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height anomalies, 10 m temperature, 10 m salinity, and 10 m oxygen.

**0110 (3–24 Oct. 2001)**

During fall, the core of the California Current, characterized by the 19.5°C isotherm and 33.7 isohaline, was located offshore of Punta Colonet (fig. 21). The eddy off Punta Colonet was now stronger than during summer. From Punta Baja to Ensenada, the high salinity (>34.0), low temperature (<14.5°C), high dissolved oxygen, and high chlorophyll (>2 mg $m^{-3}$; fig. 18) fields show the occurrence of coastal upwelling. An eddy off Punta Eugenia, characterized by low dissolved oxygen (<5 ml $l^{-1}$), was pushed offshore by an intrusion of the California Current (fig. 21). An inshore frontal zone was established south of Punta Eugenia, characterized by high salinity (34.3) and temperature (24.5°C). In this region, the main geostrophic flow was northward, turning to the west off Punta Eugenia. During October, zooplankton biomass near the coast continued to be uncharacteristically high (fig. 19), with patch concentrations up to 300 ml/1,000 $m^3$. Some patchy zooplankton distribution was noted from Guadalupe Island to the north.

**0201 (19 Jan.–7 Feb. 2002)**

During winter the core of the California Current was reestablished in the northern part of the IMECOCAL region. A clockwise eddy was established off Punta Baja (fig. 22), and the Punta Eugenia eddy had vanished. The frontal region south to Punta Eugenia was stronger during this period than it was in October and was associated with high temperature (>18.5°C) and salinity (>34.5), anomalous low dissolved oxygen (<5 ml $l^{-1}$) (fig. 22), and high 10 m chlorophyll (>4.0 mg $m^{-3}$; fig. 18). In January 2002, the tendencies in zooplankton biomass were strikingly different from north to south, with most values below 50 ml/1,000 $m^3$ north of Punta Eugenia (fig. 19). In the southern region, zooplankton biomass was up to 250 ml/1,000 $m^3$ in the frontal region described above. The usually rich zooplankton region of Bahia Vizcaino was not sampled in this survey.

The intensity of the California Current from April 2001 to January 2002 in the IMECOCAL surveys was very similar to the earlier period reported by Durazo et al. (2001). The main differences were in the southern region of Baja California, where a strong frontal zone developed during October 2001 and has remained at least until January 2002. In this frontal region a westward flow was evident during the last two reported seasons and was associated with high near-surface temperature and salinity. During the 2001–2002 surveys, 10 m dissolved oxygen varied between 5.2 ml $l^{-1}$ and 6.2 ml $l^{-1}$; the higher values were seen at inshore stations during spring, summer, and fall. Only during winter (Jan.–Feb. 2002) were the values very similar over the whole area, with a wide zone of values higher than 6.0 ml $l^{-1}$ extending offshore of the northern region. During January 2002, 10 m dissolved oxygen concentrations were about 0.6 ml $l^{-1}$ higher than those reported by Hayward et al. (1999) during winter 1998–99. Dissolved oxygen in the IMECOCAL area increased during winter 1999 to 5.6–5.9 ml $l^{-1}$ (Hayward et al. 1999), with a similar tendency in winter 2002. Chlorophyll values for spring 2001 were very similar to those reported during 2000 (Durazo et al. 2001), with higher concentrations for inshore waters (fig. 18). Moreover, chlorophyll values during summer 2000 in the chlorophyll maximum area in Bahia Vizcaino were 5- to 8-fold higher than for 2001 but only twice as large as 2001 south of Punta Eugenia (fig. 18). The high-chlorophyll frontal region located south of Punta Eugenia during January 2002 was absent during January 2001.

## CENTRAL CALIFORNIA SURVEY CRUISES

Off Central California, data have been collected along CalCOFI Line 67 by the Naval Postgraduate School and the Monterey Bay Aquarium Research Institute from April 1988 to April 1991 and from January 1997 to January 2002. Temperature and salinity variations for these data are shown on the 2, 80, and 450 dbar surfaces in Figures 23 and 24, respectively. At 2 dbar, seasonal heating and cooling dominate temperature variability, and coastal upwelling increases the salinity of surface water during spring and summer at the coast as well as reducing its temperature. The most distinctive feature of the line 67 time series was the 1997–98 El Niño, which extended the seasonal warming at the surface through the fall of 1997 and early winter of 1998 and depressed the thermocline, resulting in warming at 80 and 450 dbar. The El Niño warming was accompanied by an increase in salinity. The warming ended abruptly in March 1998 when cooler, fresher water appeared along line 67. The upper ocean remained cooler in 1999, and the salinity increased.

Subsequently, conditions along Line 67 appear to be returning to those observed during the 1988–92 period. The 80 dbar surface is sensitive to the depth of the thermocline and halocline. Features observed at this surface during 1988–91 included warming (temperature >10°C) and freshening (salinity <33.4) to within 150 km from shore in fall as well as nearshore winter warming (T > 10°C). The offshore features appeared in summer 2000 and late fall 2001, although the 80 dbar salinity remained higher than observed during 1988–91. In late 2001 the fresh (salinity <33) near-surface subarctic waters reappeared along the outer portion of line 67, and by late January 2002 these waters had penetrated to within about 150 km of shore. The salinity patterns observed at 2 and 80 dbar were similar.

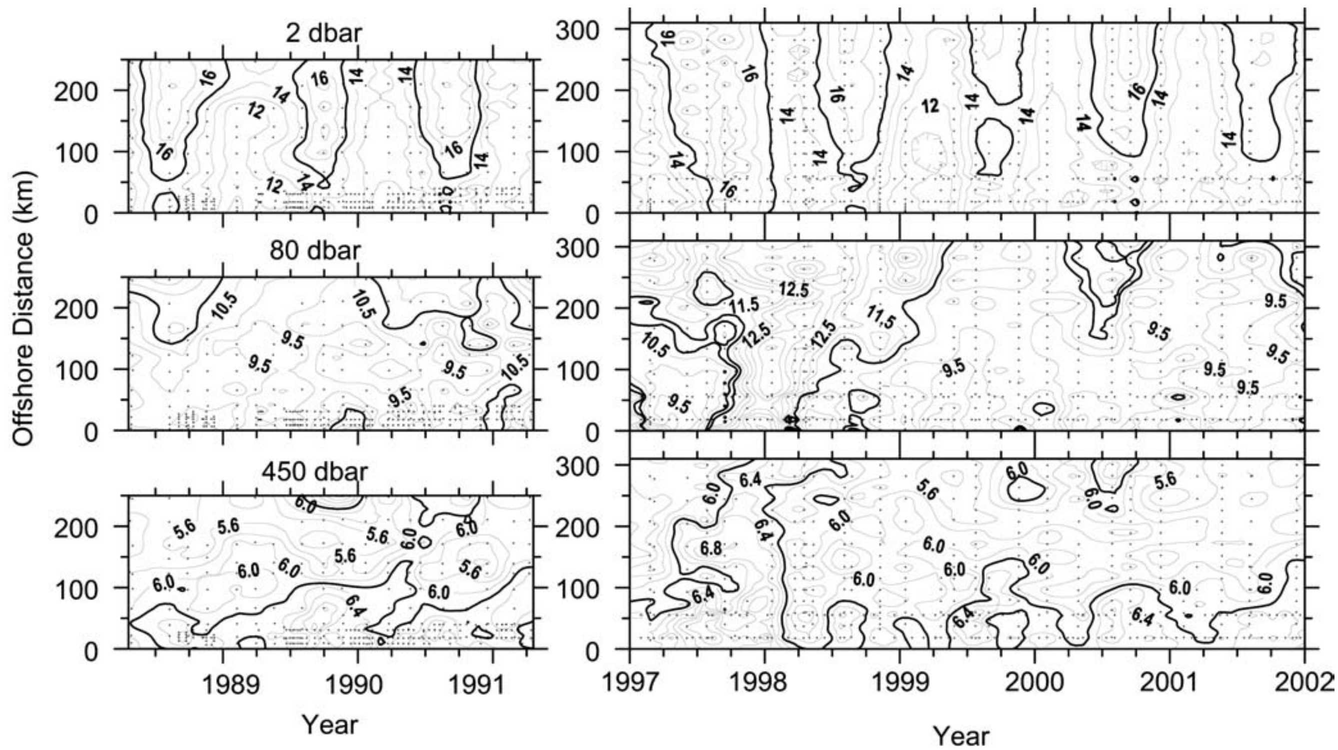


Figure 23. Time series of temperature at 2, 80, and 450 dbar surfaces along CalCOFI line 67 (off Monterey Bay), Apr. 1988–Apr. 1991 and Jan. 1997–Jan. 2002. Vertical axis is distance from coast. Contour interval is 1.0, 0.5, and 0.2°C at 2, 80, and 450 dbar, respectively. The 15, 11, and 6.2°C isotherms are highlighted at 2, 80, and 450 dbar, respectively. Dots denote sample positions.

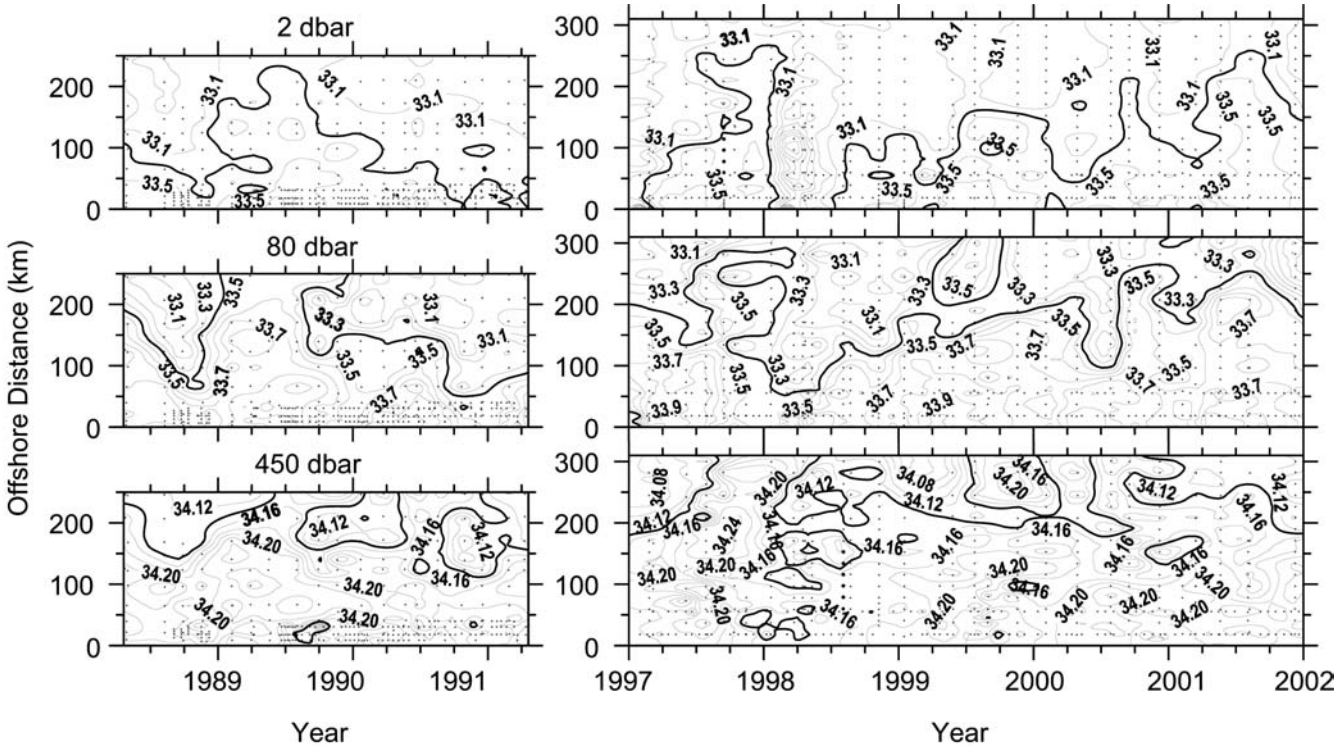


Figure 24. Time series of salinity at 2, 80, and 450 dbar surfaces along CalCOFI line 67 (off Monterey Bay), Apr. 1988–Apr. 1991 and Jan. 1997–Jan. 2002. Vertical axis is distance from coast. Contour interval is 0.2, 0.1, and 0.02 at 2, 80, and 450 dbar, respectively. The 33.3, 33.4, and 34.14 isohalines are highlighted at 2, 80, and 450 dbar, respectively. Dots denote sample positions.

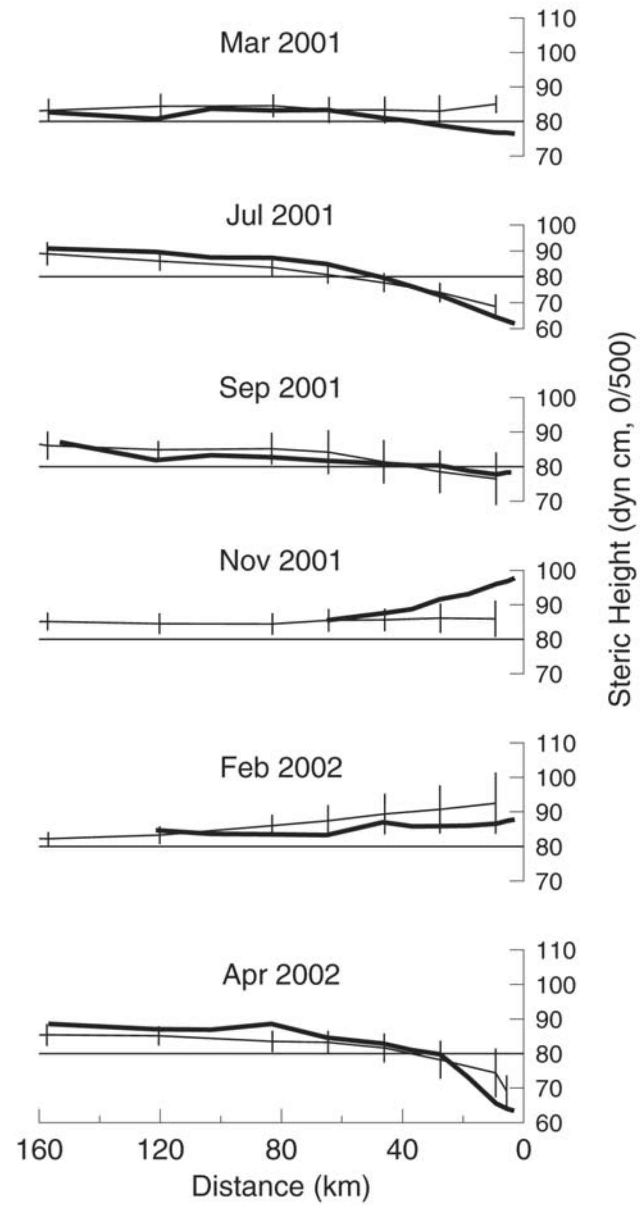


Figure 25. Steric height profiles of the sea surface relative to 500 dbar along the NH line at 44.65°N since Mar. 2001 (heavy line) shown with the long-term (1961–71) seasonal or monthly average provided by Smith et al. (2001). Vertical bars indicate one standard deviation above and below the average. Values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976). For the incomplete section of Feb. 2002, we estimated the profile by assuming that the surface steric height at the most offshore (65 km) station was the same as the 1961–71 average.

## GLOBEC LTOP CRUISES

Previous observations on the NH line off Oregon (44.65°N) have 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. 2002). Between March and early April 2001, steric sea surface heights along the NH line were generally within one standard deviation of 1961–71 seasonal average values (fig. 25). Recall that the reference period for this line coincided with the negative phase of the PDO (Mantua et al. 1997), when the CCS is typically in a relatively cool state. There were three exceptions—March 2001, when the inshore steric height was lower than normal, presumably because seasonal upwelling had begun before the survey; November 2001, when inshore steric heights were high because of a series of winter storms; and April 2002, when offshore values were above normal, though very low inshore values reflect the onset of strong upwelling.

Temperature distributions along the NH line (fig. 26) show the typical seasonal cycle: deep mixed layers with weak horizontal gradients in winter and very strong stratification in the upper 50 m in summer with temperature decreasing shoreward over the shelf. The March 2001 section is typical for the end of winter; surface waters are uniformly cool, although isopycnals bend upward over the continental margin. The distribution of normalized temperature anomalies for 2001–2002 (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) were observed in relatively small regions (fig. 27).

One exception was in midsummer at a depth of 100–200 m, seaward of the shelf break, where anomalously warm water suggested enhanced poleward advection by the California Undercurrent. A second major exception was a large pool of anomalously warm water at a depth of 400–500 m near the continental slope in April 2002. Note that the offshore end of the 5.5°C isotherm was 75–100 m deeper in April 2002 than in any other section since April 2000 (fig. 26; see also Durazo et al. 2001, fig. 22).

Regional surveys were made in March and September 2001; a survey planned for July was aborted because of ship propulsion failure. The early spring survey (fig. 28) took place very soon after the spring transition (cf. fig. 7). Near-surface temperatures were nearly uniform and about 1°C colder than in April 2000 (cf. Durazo et al. 2001, fig. 23). Values of geopotential anomaly decreased toward shore, particularly in the region south of Coos Bay, indicating that the coastal upwelling jet had already formed. The jet was not as wide, nor as far offshore, as in April 2000. Near-surface salinities were nearly uniform, with values of 32.5–33.0, typical of subarctic waters. A very weak salinity minimum extended southward along the coastal jet, that is, along the 7.8 or 8.0 contour of geopotential anomaly. The salinity minimum was much less pronounced than in April 2000. This is likely due to the 2000–2001 winter drought, which greatly

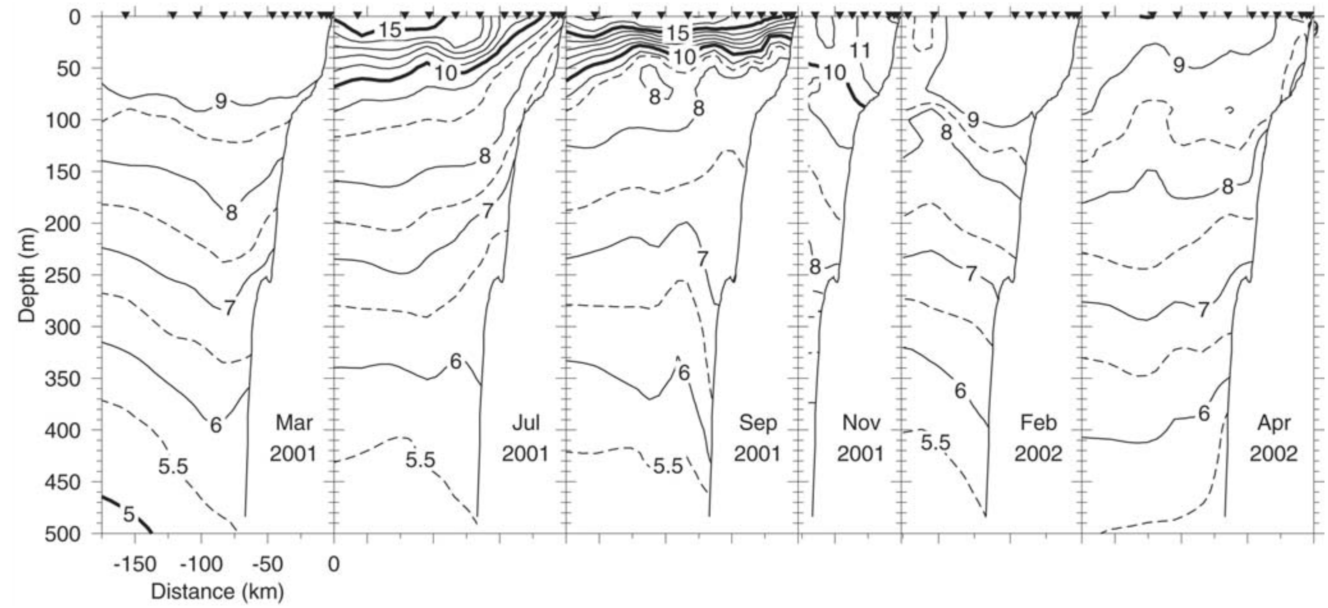


Figure 26. Temperature along the NH line at 44.65°N, for sections since Mar. 2001. Inverted triangles at top show the location of CTD stations.

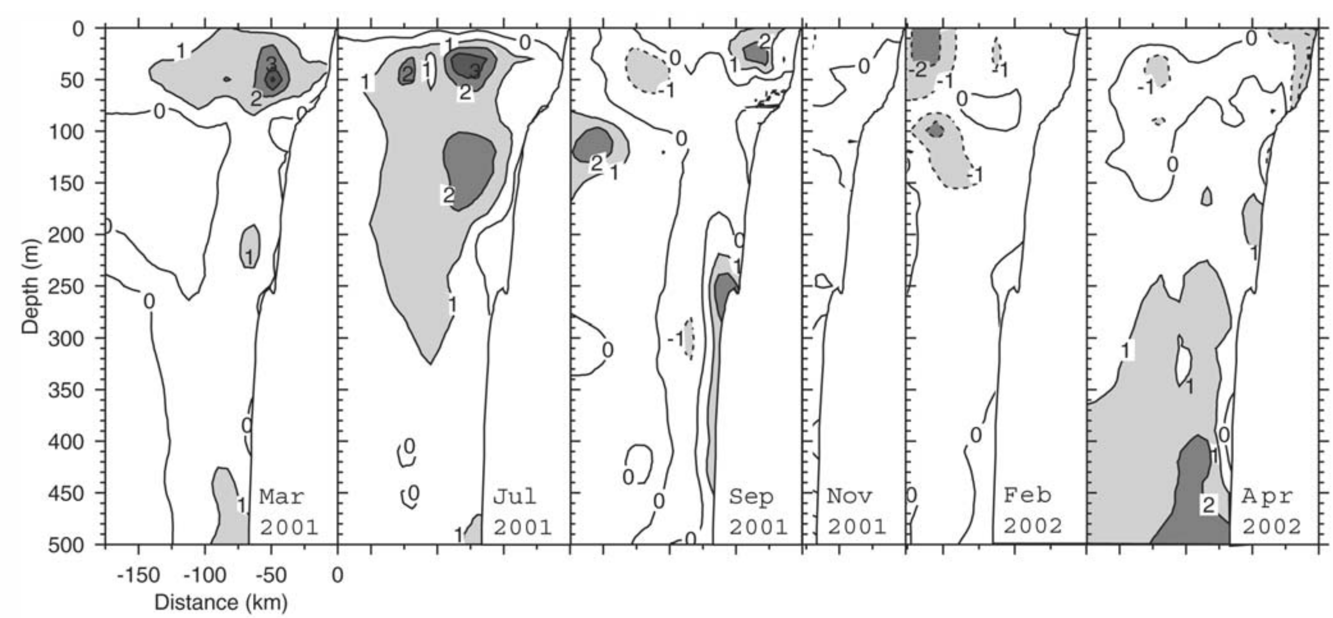


Figure 27. Normalized temperature anomalies for the NH line at 44.65°N. Positive (negative, dashed contours) anomalies indicate that present values are warmer (colder) than the historical (1961–71) seasonal or monthly averages. Values greater than 1 (2, 3) are significant at the 90% (95%, 99%) level, and shaded.

reduced Columbia River discharge in spring 2001. Chlorophyll values were substantially lower in March 2001 than in April 2000, perhaps reflecting the 2001 survey's occurring two weeks earlier in the season.

Surface waters in September 2001 (fig. 29) were generally cooler than in September 2000 (cf. Durazo et al. 2001, fig. 23). As in the previous year, the coastal jet was wider and lay farther from shore in September than in early spring. There were offshore anticyclonic eddies off Coos Bay and off Crescent City, and there was a weak cyclonic eddy offshore of Heceta Bank at 44°N. The thermal front lay far offshore at 42°N (Crescent City) and over the inner shelf at 44.65°N (off Newport), congruent with generally stronger upwelling favorable winds in the south. The 14°C and 15°C isotherms and the 31.5°C isohaline also lay far offshore at 44°N, over or beyond the shelf-break of Heceta Bank. Waters over Heceta Bank were relatively cool, salty, and enriched in

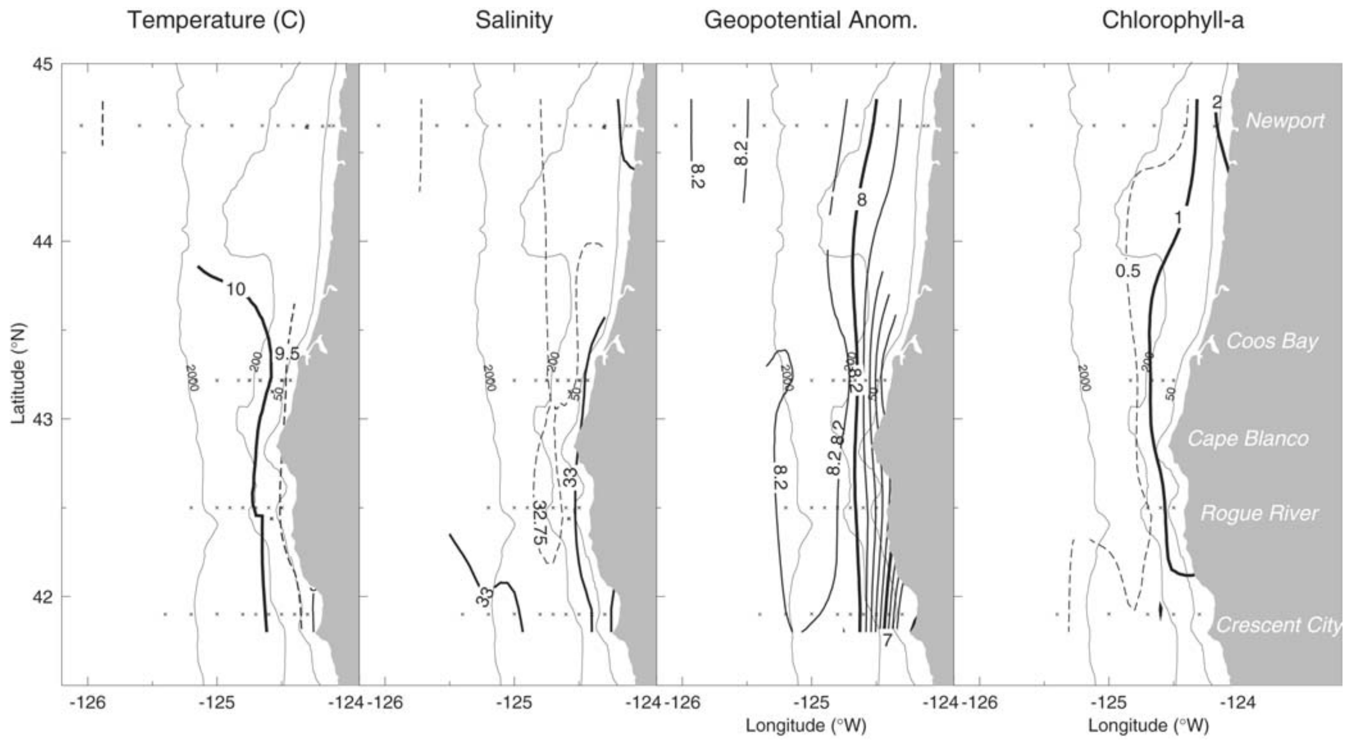


Figure 28. Temperature, salinity, and chlorophyll *a* at 10 m, and geopotential anomaly (J/kg) of the sea surface relative to 500 dbar, 15–24 Mar. 2001.

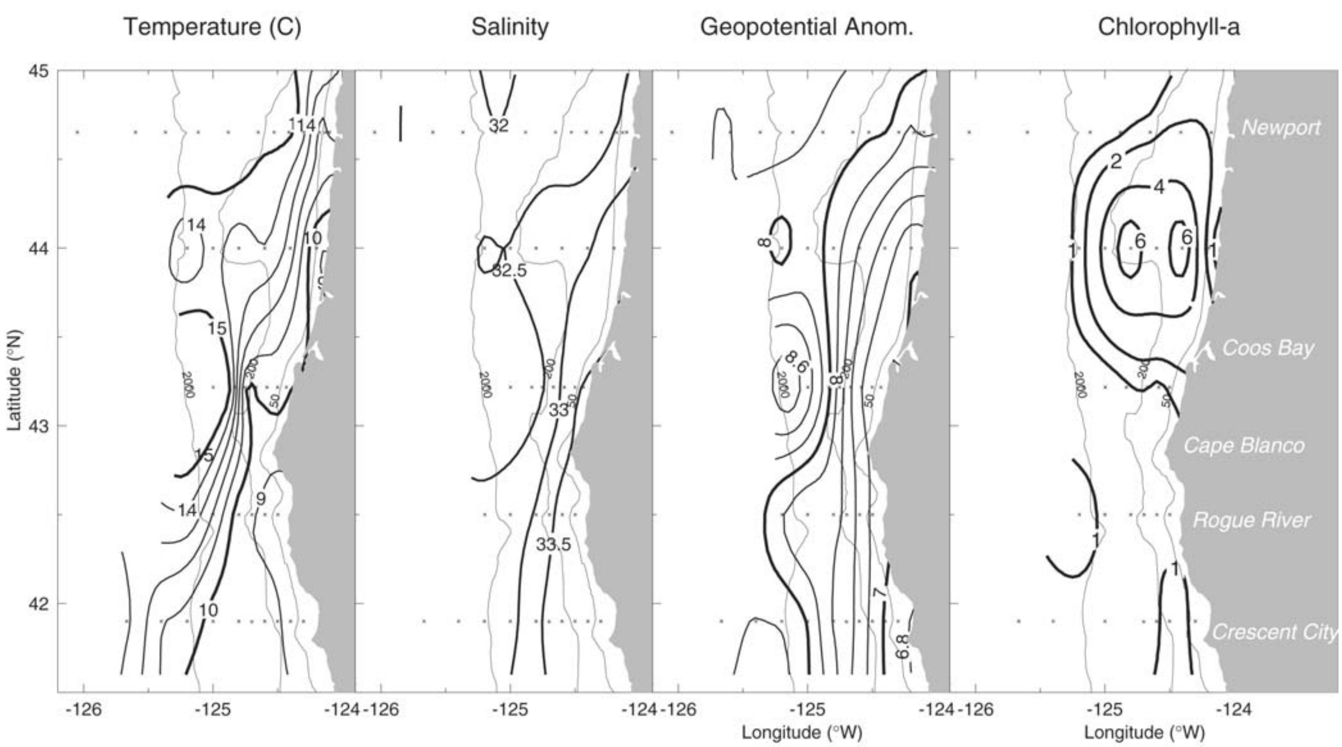


Figure 29. Temperature, salinity, and chlorophyll *a* at 10 m, and geopotential anomaly (J/kg) of the sea surface relative to 500 dbar, 4–10 Sept. 2001.

chlorophyll compared to adjacent waters. Chlorophyll concentrations over the Bank were much higher (>7 mg/l) in September 2001 than in September 2000.

As mentioned earlier, a deepening of the thermocline on the equatorial Pacific, suggestive of an ocean Kelvin wave, reached South America in March 2002. This may have propagated poleward along the North American west coast as a coastal Kelvin wave. The downward translation of isotherms and subsurface warming at a depth of 400–500 m (fig. 26) in April 2002 may represent the arrival of this remote signal. Otherwise, most of the northern CCS during 2001 and early 2002 was not significantly warmer or colder than it was during 1961–71.

## BIOLOGICAL PATTERNS

### Chlorophyll and Macrozooplankton

Surface maps from recent CalCOFI surveys indicate that chlorophyll *a* concentrations were elevated during 2001 and have been elevated in 2002. Area means of vertically integrated (0–200 m) chlorophyll *a* for each cruise support this conclusion, when compared to past cruise means since 1984 (fig. 10a). The summer and spring 2001 cruise means had the highest and second highest chlorophyll *a* values for their seasons, respectively. The preliminary estimate for spring 2002 is near the seasonal median for this period. Chlorophyll levels in early 2001 and 2002 were also unseasonably high.

These relatively high concentrations of chlorophyll may be part of a longer term tendency of higher production in the CCS. As a preliminary step toward assessing the possibility of a regime shift following the 1997–98 El Niño, we compare the average cruise-mean chlorophyll concentration by season (winter is Jan.–Mar., spring is Apr.–June, etc. ) for the 1998–2001 period to the previous two 7-year periods (fig. 30). CalCOFI observations indicate that recent levels are substantially higher than historical values. The spring and summer means for the past 4 years represent a 14% increase from 1991 to 1997, and a roughly 40% enhancement over the period prior to 1991. For reference, summer coastal upwelling at 36°N during 1998–2001 was 27% stronger than during 1991–97.

Cruise mean macrozooplankton biomass has also rebounded in recent years (fig. 10b), especially when compared with the record low biomass during 1998 (Bograd et al. 2000; Durazo et al. 2001). Compared to zooplankton levels prior to 1991, recent biomass values remain relatively modest. However, biomass since 1998 is 20–30% higher than during 1991–97, depending on the season. There is considerable interannual variability within these longer periods. Nevertheless the recent increases in zooplankton biomass and, especially, primary production suggest that monitoring must be sustained to assess whether the postulated regime shift in 1998 continues and is reflected in the biological productivity of southern California.

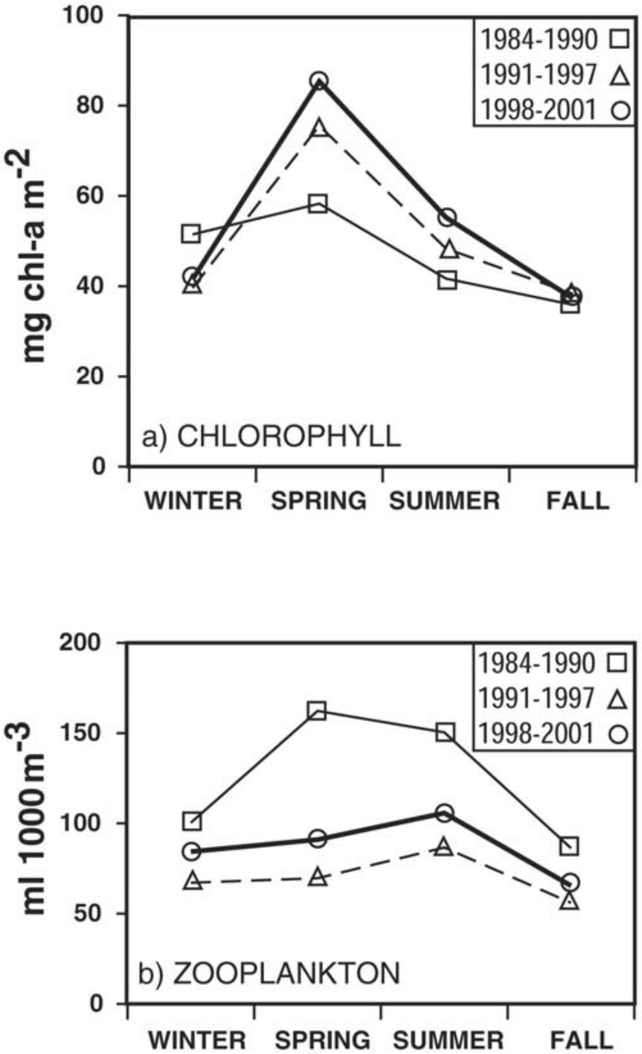


Figure 30. Seasonal averages of (*a*) chlorophyll *a* and (*b*) macrozooplankton biomass from the CalCOFI cruise means, comparing seasonal means for 1984–90 (*squares*), 1991–97 (*triangles*), and 1998–2001 (*circles*).

Analysis of individual salp species collected by CalCOFI nets in the southern portion of the CCS reveals remarkable long-term variations in abundance (fig. 31). The biomass values have been corrected for the 1.68-fold greater abundance of salps collected by the bongo net (post-1977) relative to the ring net (pre-1977; see Ohman and Lavaniegos, this volume). Salps tend to show highly aggregated distributions (Berner 1967; Andersen 1998), hence there is considerable uncertainty associated with biomass estimates. Moreover, the absence of individuals from a species in these springtime collections does not imply that they were not present in the CCS, but only that their abundance was below our detection threshold in this region.

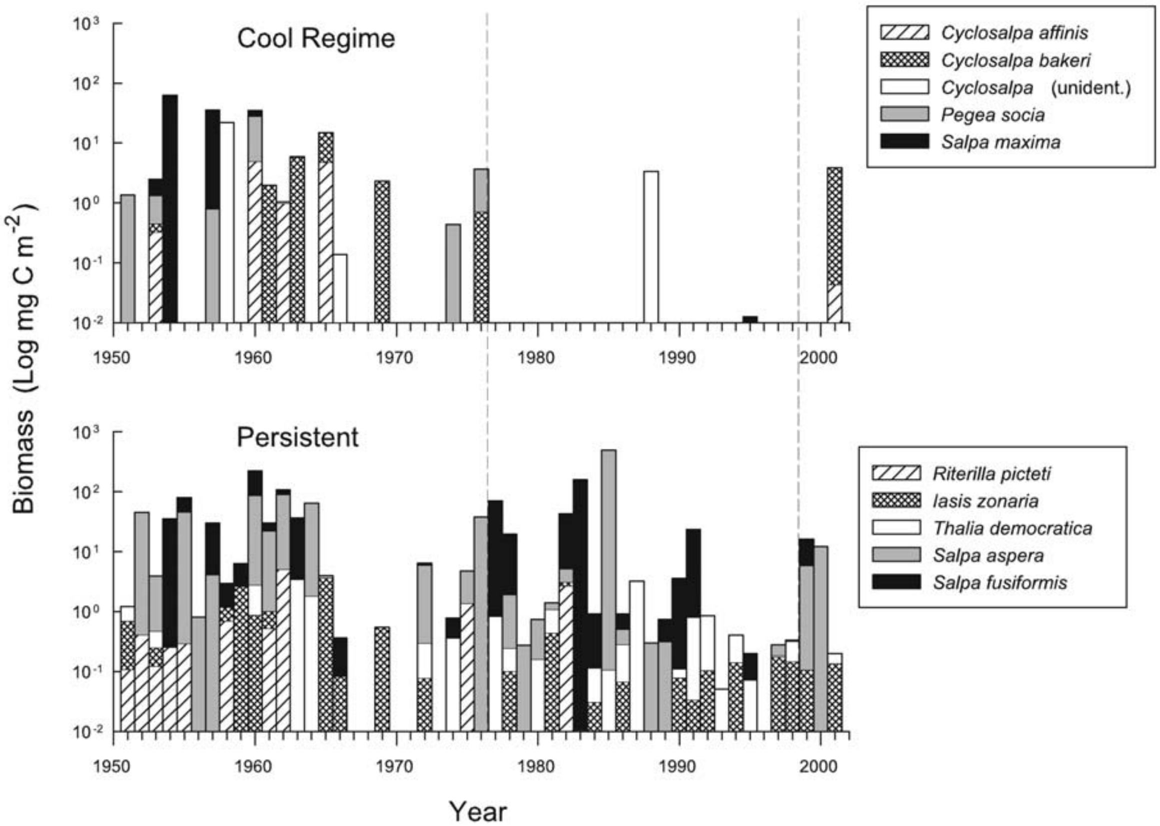


Figure 31. Interannual variation in springtime biomass of nine species of salps from CalCOFI samples in the southern sector of the California Current. The stations analyzed extended offshore to station 70, from lines 80 through 93, inclusive. Dashed lines indicate previously proposed transitions between ecosystem states in the northeast Pacific. Biomass was reconstructed from enumerations by species and size class, with application of length-carbon regressions from Madin and Deibel 1998 and references therein (see also Lavaniegos and Ohman, *Long term changes in pelagic tunicates of the California Current* [manuscript]).

The salps cluster into two species groups. The first group consists of five persistent species (*Ritteriella picteti*, *Iasis zonaria*, *Thalia democratica*, *Salpa aspera*, and *Salpa fusiformis*) that were found irregularly but recurred throughout the 50-year time period. The second group (*Cyclosalpa affinis*, *Cyclosalpa bakeri*, *Pegea socia*, *Salpa maxima*) was markedly abundant from 1951 to 1976, after which all four species became essentially undetectable for 24 years until *C. bakeri* and *C. affinis* were positively identified in spring 2001. An unidentifiable species of *Cyclosalpa* occurred in the spring 1988 samples, and a very small number of *S. maxima* were found in spring 1995. However, most species of this second group were below our detection limits for an extended period of time corresponding to the warm phase of the northeast Pacific associated with a positive PDO and negative NOI (fig. 4) and have begun to reappear in the more recent period since the cooling trend that began in late 1998. Although this analysis is restricted to salps, it suggests that components of the zooplankton assemblage may have changed over time, in addition to the fluctuations in overall biomass seen in the CalCOFI surveys.

In the context of the September 1997–January 2002 IMECOCAL cruises, macrozooplankton biomass values during April 2001 and January 2002 were the lowest in the record (fig. 32). The mean zooplankton biomass of January 2002 was markedly lower than the January 1998 mean, the highest in the IMECOCAL record (1997–2002). This is an atypical response of the Baja California region to El Niño conditions, perhaps due to the increase of subtropical zooplanktonic groups usually inhabiting the sampled area. Regarding the seasonal pattern, we have only information for spring 1999 and 2000, and April 2001 was sampled only in the most northern lines. The mean biomass during the 0104 and 0201 IMECOCAL cruises was lower than the 95% confidence limit of the long-term (1951–84) mean for the CalCOFI cruises. The lowest summer and fall values were obtained during La Niña in 1999, suggesting again the importance of the subtropical component in our study area. Baja California appears to have responded positively during the 1997–98 El Niño but negatively during the 1999–2000 La Niña. The low zooplankton biomass values during 0104 and 0201 are also unex-

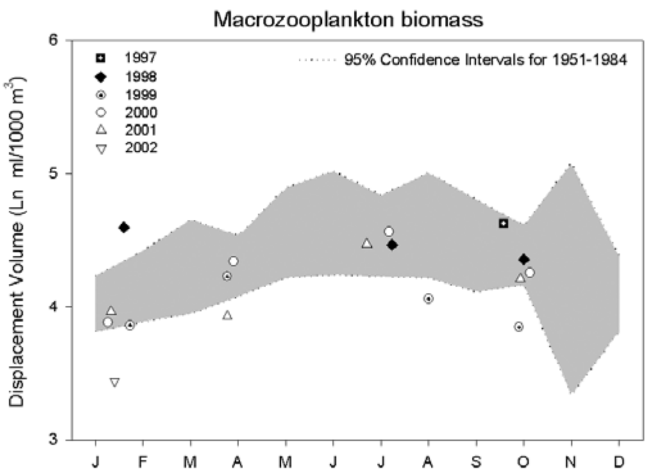


Figure 32. Mean zooplankton biomass of the seventeen IMECOCAL cruises performed from Sept. 1997 to Jan. 2002. The shaded area represents the 95% confidence interval for the historic mean (1951–84) of CalCOFI surveys realized in the area off Baja California. All data were transformed to logarithms.

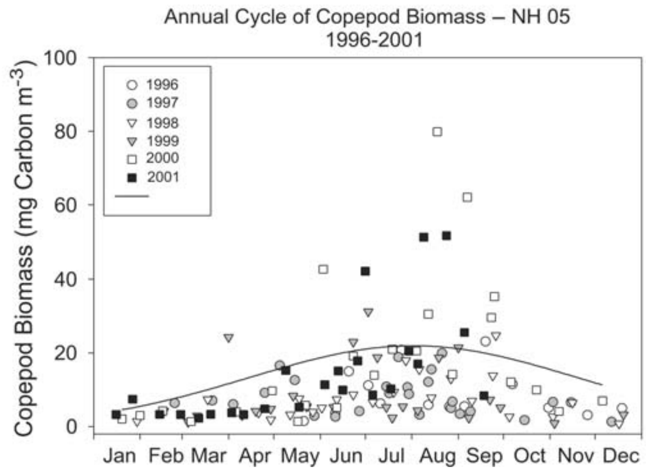


Figure 34. Annual cycle of copepod biomass at station NH 05 (60 m water depth) off Newport, Oregon, shown as a composite for 6 years of data.

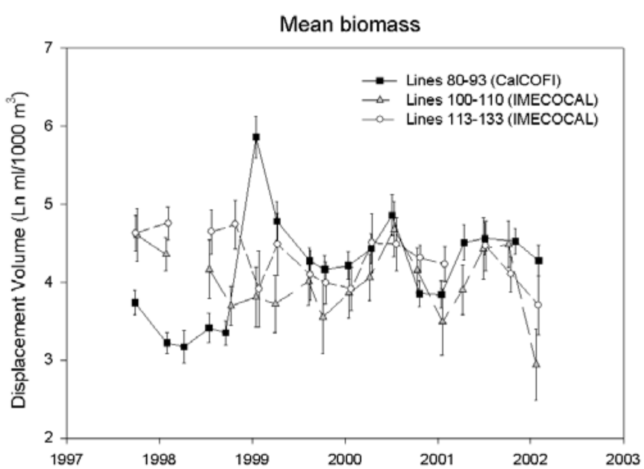


Figure 33. Mean zooplankton displacement volume in three regions of the California Current: CalCOFI surveys (lines 80–93), and IMECOCAL surveys (lines 100–110, and 113–133) performed from Sept. 1997 to Jan. 2002. The bars indicated the 95% confidence interval of the mean.

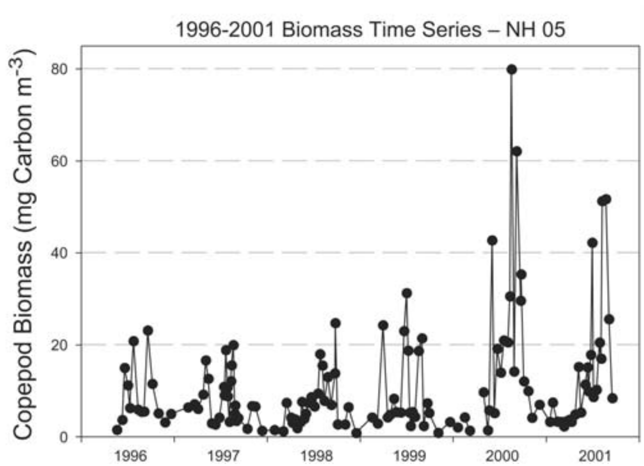


Figure 35. Time series of copepod biomass at station NH 05 (60 m water depth) off Newport, Oregon, 1996–2001.

pected, and further analysis of the taxa composition and biophysical interactions is required to understand these low values. The time tendencies were different between the southern California (Lines 80–93), northern Baja California (Lines 100–110), and central Baja California (Lines 113–133) regions during the 1997–98 El Niño event (fig. 33). In this particular event, southern California waters were poor in zooplankton biomass, but biomass was high in Baja California waters. In contrast, zooplankton biomass remained low in Baja California during the 1998–99 La Niña, while the southern California region experienced a strong rebound.

## Oregon Copepod Biomass

The seasonal cycle of copepod biomass at Station 5 (water depth 60 m) on the NH line off Oregon is shown in Figure 34. Seasonality is not strong, with winter and summer values differing on average by only a factor of four or so. There is no evidence for a spring peak in copepod biomass. Rather, peak values are seen usually in August through October, near the end of the upwelling season. These observations suggest that there is considerable loss of biomass (and production) to offshore waters during the active upwelling season (May–July) and that biomass in shelf waters does not begin to increase until upwelling weakens in late summer.

Over the period of our 6-year time series (fig. 35), copepod biomass was constant for the first 4 years but has increased by 200% during the past 2 years. Averaged over the period May through September, biomass for the first 4 years of our sampling was approximately 10 mg carbon per cubic meter (9.2 mg carbon per cubic meter in 1996, 9.7 in 1997, 10.1 in 1998, and 11.0 mg per cubic meter during the summer of 1999). Although dramatic changes in species composition did take place in 1999 (Peterson et al. 2002), it was not until summer 2000 that dramatic changes in biomass occurred. Copepod biomass averaged 25.5 mg carbon per cubic meter during that summer and remained high through 2001, averaging 21.5 mg per cubic meter.

What does this mean for the state of the California Current? During 1996 and 1997, and during the 1997–98 El Niño, copepod biomass was low and copepod species that are indicators of productive conditions (i.e., species with affinities for more northern waters) had negative abundance anomalies (Mackas et al. 2001; Peterson and Mackas 2001). The dominant members of this group include species that dominate the waters of the Bering Sea shelf, the coastal Gulf of Alaska, British Columbia coastal waters, and the Washington-Oregon coastal upwelling zone—*Pseudocalanus mimus*, *Acartia longiremis*, and *Calanus marshallae*. Species with southern and offshore affinities were unusually abundant in coastal water from 1996 to 1998. This group includes *Mesocalanus tenuicornis*, *Paracalanus parvus*, *Ctenocalanus vanus*, *Clausocalanus pergens*, *Clausocalanus arcuicornis*, and *Clausocalanus parapergens*. This suggests that at least during the 3-year period 1996–98 reduced coastal upwelling and low productivity characterized shelf waters of the northern California Current. However, since the onset of cool, La Niña–like conditions, copepod biomass has doubled, and positive anomalies in the abundance of northern copepod species are now the norm for shelf waters off Newport (and off Vancouver Island; Mackas et al. 2001), suggesting increased transport out of the coastal Gulf of Alaska and/or greater coastal upwelling.

Coincidently, euphausiid spawning intensity also increased. Prior to 1999, single spawning peaks were observed at the inner shelf station. However, beginning in 1999, multiple spawning peaks were observed, and seasonally integrated egg densities were an order of magnitude higher than before.[2] Salmon stocks have also increased in abundance, as evidenced by greatly increased survival rates of coho salmon and near-record return rates of chinook salmon. Numbers seen during the past 2 years rival those not seen since the high productive years of the 1960s and 1970s.

[2]Feinberg, L., and W. Peterson. 2002. Year-to-year variations in abundances of euphausiid eggs from 1996 through 2001 in coastal waters off central Oregon. (manuscript)

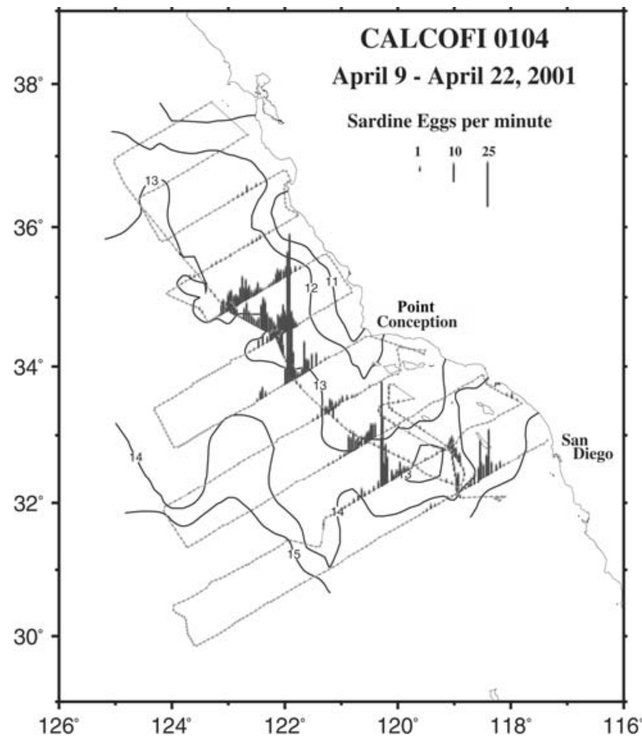


Figure 36. Distribution of sardine eggs as collected by the continuous underway fish egg sampler (CUFES) for CalCOFI survey 0104.

## Sardine Spawning

The use of the continuous underway fish egg sampler (CUFES) on CalCOFI surveys, which began in 1996, has served to document the offshore expansion of sardine spawning north of Point Conception (Durazo et al. 2001). During the 1997–98 El Niño, sardine eggs were compressed toward the coast and shifted to the north, presumably in association with a general warming (Lynn et al. 1998). In contrast, eggs observed during the 1999 survey were spread very far offshore, probably in response to strong coastal upwelling, unusually cool waters, and the offshore displacement of the core of the California Current. SST in the entire CCS north of 32°N—the area where most of the eggs occur—was less than 12°C (Durazo et al. 2001). The distribution of eggs in spring 2000 was again relatively extensive along the core of the California Current, and generally farther offshore. However, the cross-shore distribution of high egg counts was not as broad as it was in 1999. SSTs in 2000 were 13–15°C in the spawning area off California.

The April 2001 survey revealed that sardine eggs were once again centered very far offshore (fig. 36), similar to the distribution in 1999. The entire spawning area was located in surface waters with temperatures greater than 12°C, and the peaks straddled the 13°C isotherm.

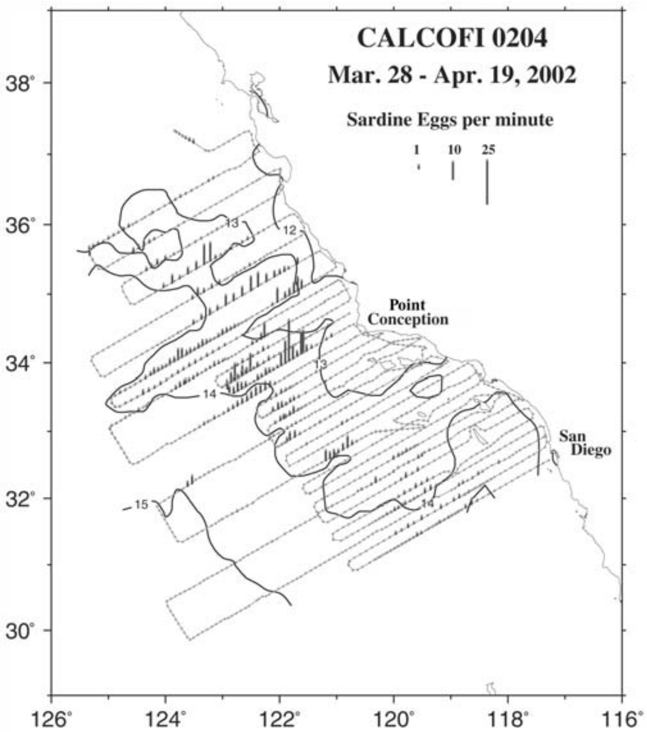


Figure 37. Distribution of sardine eggs as collected by the CUFES for CalCOFI survey 0204.

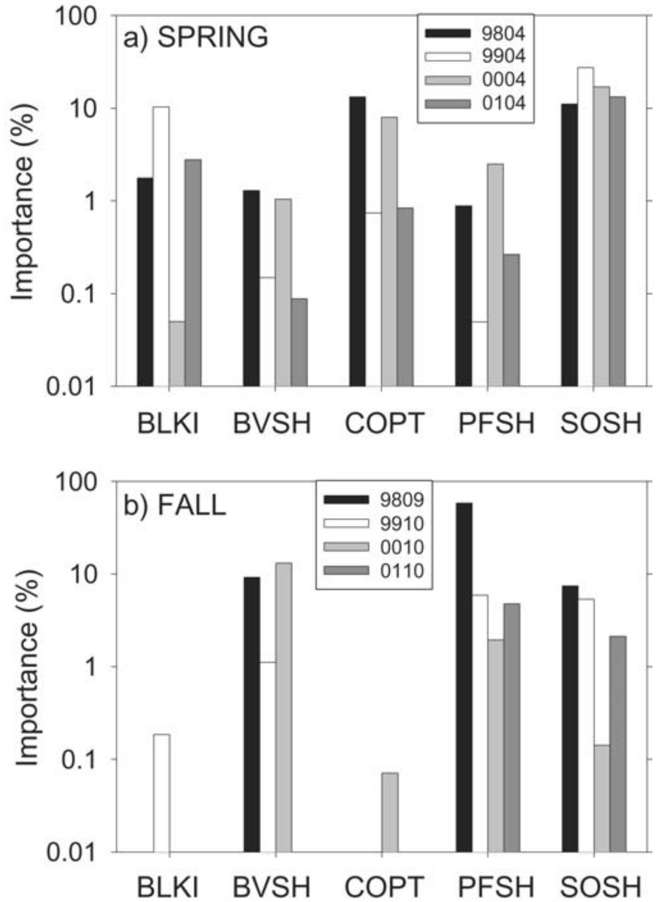


Figure 38. Relative abundance of five seabirds with an affinity for distinct temperature and biogeographic domains off southern California, for (*a*) spring and (*b*) fall surveys, 1998–2001. Importance was computed by dividing the number of individuals of a given species by the total number of seabirds sighted during each cruise. Subtropical/warm-water taxa: black-vented shearwater (BVSH), pink-footed shearwater (PFSH), Cook's petrel (COPT); subarctic/cold-water taxa: sooty shearwater (SOSH), black-legged kittiwake (BLKI).

The area was roughly in the main flow of the California Current and immediately offshore of the salinity front and high chlorophyll zone (fig. 11). In 2001, 13°C SSTs extended much farther offshore than in the previous spring (cf. Durazo et al. 2001). The survey indicated spawning had occurred at least as far south as the U.S.–Mexico border (fig. 36). However, very few eggs were found north of line 73.

As in 2001, the center of the sardine egg distribution in spring 2002 was about 100 km off Point Conception (fig. 37). However, there were several notable differences between the 2 years. Peak values in 2002 were much lower than in 2001, and the overall number of eggs in the survey region may have been reduced. The cross-shore extent over which eggs were found in 2002 was wider, roughly within the 13–14°C isotherms. Eggs were found unusually far offshore along line 77 in what was possibly an upwelling filament, based on its physical character and relatively high surface chlorophyll concentrations (fig. 15). Unlike 2001, when the core of the California Current southwest of the Southern California Bight displayed high counts (fig. 36), very few eggs were found in 2002 south of 33°N (fig. 37). An onshore intrusion of low salinity water was seen along lines 80 and 83 (fig. 15).

## Avifauna

At-sea (CalCOFI) surveys of marine bird communities suggest that the changes in community structure observed during 1999 were transient fluctuations, apparently in response to enhanced upwelling and cool water conditions associated with La Niña. By spring 2000, however, the marine bird community reverted back to the preceding warm-water El Niño event (Bograd et al. 2000). This return to a more subtropical community was particularly evident during spring 2000, with a concurrent increase in the relative abundance of three southern species with an affinity for warm water—black-vented shearwater (*Puffinus opisthomelas*), Cook's petrel (*Pterodroma cooki*), and pink-footed shearwater (*Puffinus creatopus*)—and a decrease in the importance of two northern cold-water indicators—sooty shearwater (*Puffinus griseus*) and black-legged kittiwake (*Rissa tridactyla*) (fig. 38a). This

TABLE 3
**Comparison of the Productivity of Six Seabird Species Breeding at the Farallon Islands, Central California, in Conjunction with the 1998 Regime Shift**

| Seabird species | Productivity (chicks fledged/pair) (mean ± SD) (1990–98) | (1999–2001) | Proportional change (%)[a] | Mann-Whitney U | *P* value |
|---|---|---|---|---|---|
| Brandt's cormorant | 1.38 ±0.93 | 2.22 ±0.22 | +60 | 4 | 0.079 |
| Cassin's auklet | 0.62 ±0.24 | 0.90 ±0.13 | +45 | 2 | 0.033 |
| Common murre | 0.66 ±0.27 | 0.82 ±0.01 | +24 | 10 | 0.509 |
| Pelagic cormorant | 0.54 ±0.64 | 1.58 ±0.59 | +193 | 2 | 0.032 |
| Pigeon guillemot | 0.54 ±0.38 | 1.21 ±0.09 | +123 | 2 | 0.033 |
| Rhinoceros auklet | 0.48 ±0.16 | 0.64 ±0.03 | +31 | 3.5 | 0.064 |

[a]The proportional change in seabird productivity was quantified as PC = 100% * [(after) − (before) / (before)].
Positive PC values are indicative of increasing productivity.

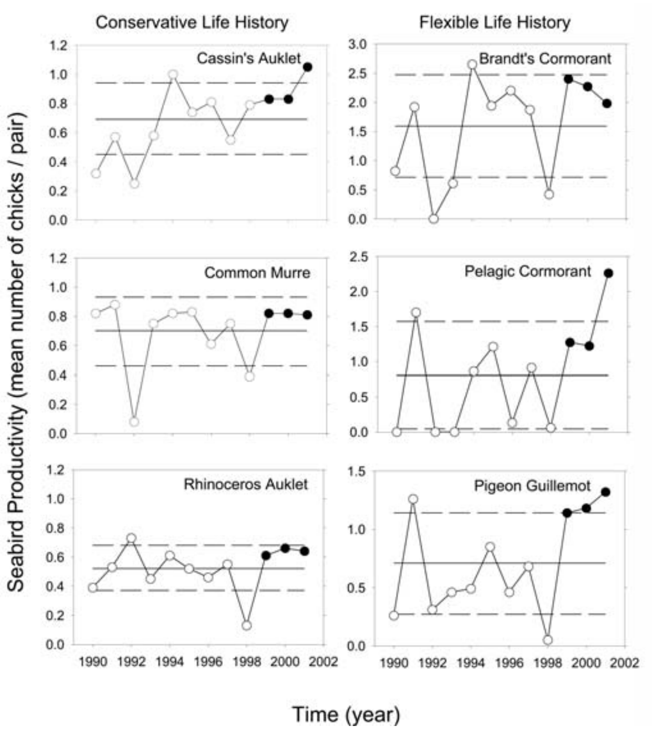


Figure 39. Anomalies of productivity for six seabird species breeding at the Farallon Islands (central California). The long-term averages (1990–2001) are depicted by the solid horizontal lines, and the variability (mean ± SD) by the dashed lines. Solid circles highlight productivity anomalies after 1998.

mixed avifauna, intermediate between the warm-water and cold-water communities observed during the preceding El Niño and La Niña events, respectively, was also evident during fall 2000. This period was characterized by positive (+2–3°C) temperature anomalies off southern California, resulting in the increased importance of subtropical species. Most notably, subtropical Cook's petrels were observed within the CalCOFI region, and the subtropical black-vented shearwater increased to account for over 10% of all birds censused (fig. 38b). Conversely, at-sea observations during spring 2001, when SSTs were near-normal, were suggestive of a subarctic avifauna, with concurrent increases/decreases in the proportional abundance of cold water/warm water (fig. 38).

Prey availability during egg-laying, incubation, and chick-rearing periods influences the reproductive performance of these species (Ainley et al. 1995; Sydeman et al. 2001). Marine bird productivity (mean number of offspring produced per breeding pair per year) provides an integrated measurement of reproductive performance and prey availability to seabirds throughout the breeding season (ca. Mar.–Sept.). Productivity during 2001 was high at the Farallon Islands, central California (fig. 39, tab. 3). In particular, annual mean productivity reached the highest value in the entire time series (1971–2001) for the Cassin's auklet (*Ptychoramphus aleuticus*), with an average of 1.05 chicks fledged per breeding pair. 2001 represents the third consecutive year of positive seabird productivity anomalies across the board.

Productivity data from 2001 continues to show enhanced seabird productivity after the 1998 regime shift (Durazo et al. 2001; PRBO unpublished data). The period 1999–2001 yielded significant increases in the productivity of three seabirds—Cassin's auklet, pelagic cormorant (*Phalacrocorax pelagicus*), and pigeon guillemot (*Cepphus columba*), and marginally significant ($0.10 < p < 0.05$) increases in the productivity of two additional species—Brandt's cormorant (*Phalacrocorax penicillatus*) and rhinoceros auklet (*Cerorhinca monocerata*). Only one species, the common murre (*Uria aalge*), did not display a significant increase in productivity after 1998 (tab. 3).

To assess whether marine bird populations have changed in conjunction with the hypothesized regime shift, we compared the normalized variances in productivity before and after the winter of 1999. Reproductive performance is less variable after 1998 for the six species considered in this analysis (tab. 4). Locally breeding seabird populations have experienced a sustained period of enhanced productivity since 1998 (tab. 3, fig. 39). This pattern contrasts sharply with the large interannual fluctuations and lower overall productivity evident during the preceding warm-water decade (tab. 4).

TABLE 4
**Changes in the Dynamics of Six Seabird Species Breeding at the Farallon Islands, Central California, in Conjunction with the 1998 Regime Shift**

| | Variability of productivity (Coefficient of variation) | |
|---|---|---|
| Seabird species | (1990–98) | (1999–2001) |
| Brandt's cormorant | 67.06 | 9.70 |
| Cassin's auklet | 38.45 | 14.06 |
| Common murre | 40.91 | 0.71 |
| Pelagic cormorant | 118.27 | 37.04 |
| Pigeon guillemot | 70.95 | 7.79 |
| Rhinoceros auklet | 33.33 | 3.950 |

*Note:* Variability in seabird productivity during the warm-water (1990–98) and the cold-water (1999-2001) periods was quantified using the coefficient of variation, C.V. = 100% * (SD/mean). A paired nonparametric Wilcoxon test revealed that seabird productivity, when all species were considered, was more variable during the warm-water decade than after 1998 ($Z = -2.201$, df = 5, $p = 0.028$).

Hierarchical clustering of the seabird productivity data for 1990–2001 provided more evidence of a shift in 1998 (fig. 40). The first cluster (1990, 1992, 1993, and 1998) is characterized by low overall bird productivity and warm-water conditions (Lynn et al. 1995, 1998; Hayward et al. 1999). Breeding failures were frequent in taxa with flexible life histories (i.e., larger clutches and broader diets), with zero reproductive success in 33% (4/12) of the instances and 67% of the productivity below one chick/pair. Species with conservative life histories (i.e., fewer eggs per clutch and narrower diets) were also impacted during these "bad" years. Overall, 58% of the productivity values for the common murre, the Cassin's auklet, and the rhinoceros auklet fell below 0.5 chicks per pair.

The second cluster included 1994 and 1996, 2 years of intermediate productivity. Two of the species with flexible life histories (pelagic cormorant and pigeon guillemot) had low reproductive success, below one chick per pair, in these years. Conversely, Brandt's cormorant had high productivity, well above two chicks per pair. This species appears to be somewhat buffered from the impact of low ocean productivity by its use of bays and estuaries within a larger foraging range (Ainley et al. 1995; Sydeman et al. 2001). Similarly, taxa with conservative life histories did well during 1994 and 1996, with 83% (5/6) above 0.5 chicks per pair.

The third cluster included all breeding seasons after 1998, as well as 1991, 1995, and 1997. Productivity for species with conservative life histories surpassed 0.5 chick per pair every year, whereas reproductive success of taxa with more conservative life histories exceeded one chick per pair on 83% (15/18) of the instances. These results suggest that breeding seabird populations have responded to the recent shift in conditions in 1998. However, it is not clear how the breeding seasons before and after the

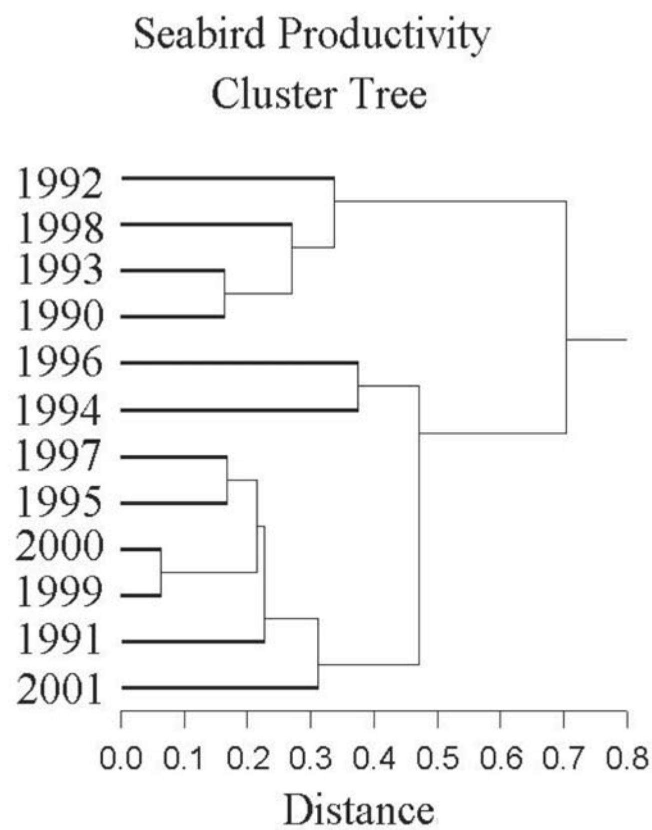


Figure 40. Cluster trees of seasonal marine bird productivity for six species breeding at the Farallon Islands (central California), between 1990 and 2001. The euclidean distances are based on a hierarchical clustering technique using the median linkage algorithm.

winter of 1999 compare. All the years in the second and third clusters were characterized by positive/negative values of the NOI/PDO (fig. 4), suggestive of large-scale cool conditions over the north Pacific.

Recent colony-based and at-sea observations have provided additional evidence that seabird populations of the CCS responded to the 1998 regime shift. Conditions during 1999–2001 were characterized by episodic increases in the relative abundance of subarctic species at sea (fig. 38) and by enhanced seabird productivity at local colonies (fig. 39). The change in seabird productivity was particularly striking, suggesting that breeding populations have benefited from the prolonged period of enhanced upwelling and ocean productivity after the regime shift (tab. 3). Because seabird populations integrate the variability in ocean and prey conditions during the breeding season, annual mean productivity responds strongly to interannual changes in ocean productivity and prey availability (Ainley et al. 1995; Sydeman et al. 2001). The response of at-sea communities to the regime shift is more difficult to detect. Overall, the seabird community is in an intermediate state with episodic changes in ocean conditions favoring a cold-water community in 1999 and 2001 and a warm-water community in 2000.

## DISCUSSION

Most of the physical data from the CCS, from Oregon to Baja California, indicate that 2001 and early 2002 have been uncharacteristically cool and featured stronger than normal coastal upwelling. These anomalous temperatures are part of a pattern that covers the entire Pacific and that is consistent with concurrent atmospheric anomalies. This pattern also represents a continuation of conditions that developed during the 1998–99 La Niña, and is very similar to patterns typically seen during La Niña events (Schwing et al. 2002b), as well as the decadal-scale SST anomaly pattern defined as the negative phase of the PDO (Mantua et al. 1997). Although some signs indicate a new El Niño developing in the equatorial Pacific, it is unlikely to impact the CCS during the productive upwelling season of 2002. Prospects for El Niño in the winter of 2002–2003 are less certain. However, if the climate has shifted to a cooler state in the northeast Pacific, as suggested initially by Schwing and Moore (2000), the coming winter may look much like the previous one.

There is some evidence of a higher level of biological productivity in much of the CCS, based on comparisons of recent chlorophyll concentrations and macrozooplankton biomass to values over the past 19 years. In particular, productivity during the past 4 years has been substantially higher than in the 1990s. Changes in copepod biomass, species composition, spawning, and salmon production point to a major shift in the carrying capacity of the northern CCS.[3] This is possibly aided by more favorable conditions for reproduction by subarctic zooplankton species. The striking change in seabird productivity in the CCS suggests that breeding populations have benefited from enhanced upwelling and ocean productivity after 1998. Marine bird communities respond to changes in ocean temperature within a few months (Veit et al. 1996; Hyrenbach and Veit, in press) because seabirds are highly mobile predators capable of adjusting their distributions in response to transient oceanographic conditions.

Paradoxically, zooplankton concentrations in the waters off Baja California were very low in 2001 and 2002, perhaps because the unusually cool conditions have depressed the numbers of subtropical fauna. During El Niño conditions, this relationship seems to reverse, with higher/lower zooplankton biomass off Baja California/Oregon and California. If subtropical species decline under cooler conditions, then the role of higher primary production in raising total zooplankton biomass (mainly through more subarctic animals) will be mitigated in the southern domain of the CCS. This may be responsible for less prey for sardines, hence a lack of spawning south of about 33°N. At the same time, cooler water could be reducing the spawning habitat from the north (i.e., off Monterey). If this pattern continues for many years—for example, as a "cool" PDO regime—it could lower the sardine population in a pattern reminiscent of the 1940s. Likewise, a cooler CCS is trophically more favorable for seabirds off central California than off southern California.

Although it may be too soon to declare that a regime shift has occurred, it is noteworthy that the present "extended" La Niña is now in its fourth year. Additional research is necessary, however, to determine the mechanisms linking large-scale physical forcing with changes in the availability of prey and the feeding success and reproductive energetics of marine populations.

We are still trying to understand and appreciate the fine distinctions between interannual and long-term climate variability. There is no argument that the CCS and greater Pacific have experienced a series of La Niña–like years since 1998 and these have apparently led to a lengthy period of cooler-than-normal conditions in the CCS and a notable swing in ecosystem structure. What is less certain over this short period (in the climate context) is whether we have witnessed a persistent shift in the state of the CCS or merely a series of weak La Niña and near-neutral years that were a respite from an El Niño–favorable climate state that culminated in the "El Niño of the century " in 1997–98. Change may be afoot once again, as signs of an El Niño appear on the horizon. If this does occur, it will be with a new background characterized by a negative PDO pattern. A natural experiment will take place in the coming months, as interannual and decadal climate processes battle it out for control of future conditions in the CCS.

The future of CalCOFI, and of multidisciplinary monitoring of the California Current in general, has been the subject of intense discussion over the past year. There are important societal rationales for continuing the CalCOFI survey program and even expanding it north toward its historical domain. This is an economically important region for commercial and recreational fishing, shipping, and recreation. Variations in marine conditions impact coastal erosion, water quality, and weather patterns. Intrinsically, the CCS is a vital marine ecosystem that is threatened by overfishing, oil spills and pollution, and harmful algal blooms. Of course, there is a basic scientific motivation for monitoring interannual and longer-term climate variability.

Two meetings have been held (Monterey, Jan. 2002, and Seattle, Mar. 2002) in an attempt to assess and fos-

[3]Peterson and Schwing. (manuscript)

ter interest in a coordinated CCS monitoring system, resulting in the creation of the Alliance for California Current Ecosystem Observation (ACCEO, <http://swfsc.nmfs.noaa.gov/frd/acceo/acceo1.htm>). Participants at these meetings have agreed on the following mission statement for ACCEO:

> To facilitate and coordinate monitoring of the pelagic ecosystem of the entire California Current, to promote integration of California Current regional pelagic monitoring programs to the larger benefit of all, to understand the dynamics of the California Current and its populations, and to determine how the chemistry and biology of the California Current populations are affected by interdecadal to seasonal changes in physical forcing and water mass distributions.

Discussion also centered on the logistics of a synoptic, California Current–wide monitoring program, leading to the development of a preliminary plan anchored around CalCOFI and other ongoing regional programs (fig. 41). Although there is widespread recognition of the need for such a program, the funding and logistics required to see it materialize are not yet in place. ACCEO will proceed through the collective and coordinated effort of scientists involved in its component programs, as well as through proposals for external funding.

Thanks to some external support, the 2003 January CalCOFI survey will be extended north to San Francisco to cover the lines historically occupied by CalCOFI prior to 1985. This resumption of a major portion of the former January CalCOFI pattern will provide much better coverage of the spawning areas of hake and various groundfish species and will enlarge the survey area for evaluating the 1998 regime shift and monitoring future El Niño/La Niña events. Plans are also forming to conduct baseline plankton surveys of the Cowcod Conservation Area off southern California in February 2003.

There is a clear and urgent need for an integrated sampling program comprising the *entire* California Current System. Observations over the past two decades have shown that variability in the physical environment over a spectrum of time scales—from changes in the seasonal cycle, to El Niño/La Niña events, to regime shifts—leads to a pronounced but varying ecosystem response in different parts of the CCS. A holistic understanding of physical-biological coupling in the CCS requires a synoptic, California Current–wide sampling that the ACCEO plan would only minimally accomplish. A more comprehensive monitoring of the CCS, in real-time, will require the West Coast deployment of a large-scale, multiplatform, moored observation network similar in concept to the TOGA-TAO array in the equatorial Pacific.

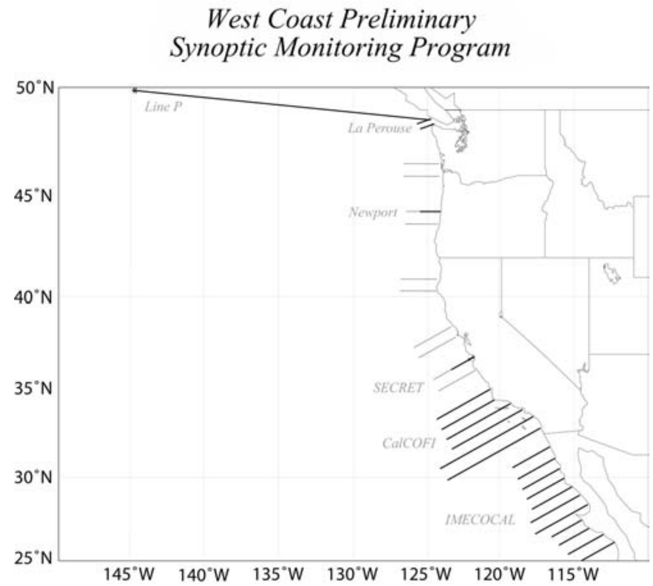


Figure 41. A preliminary monitoring plan for the California Current System, developed for ACCEO discussion in spring 2002. Programs with ongoing ship surveys on standard lines are shown in black. Ten additional lines (gray) have been proposed for U.S. waters (with Canadian participation anticipated), each located near existing marine laboratories to simplify logistics. Proposed lines extend approximately 300 km offshore (varying with latitude to assure sampling of the CCS) and consist of ten stations 30 km apart. Maximum benefit would be achieved with quarterly, synoptic occupations of all lines and sampling following standard CalCOFI protocol.

## ACKNOWLEDGMENTS

We thank the continuing efforts of the superb seagoing CalCOFI team and the many highly competent scientists, technicians, and support staff who helped collect, process, and analyze the data presented in this report. Thanks to Francisco Chavez, Sherry Cummings, Leah Feinberg, Phaedra Green-Jessen, Jo Griffith, Julie Keister, Mark Pickett, and Tarry Rago for their assistance in the preparation of this manuscript. We are also grateful for the editorial assistance of Kevin Hill and Joni Harlan and for the support of the CalCOFI Coordination Office and Program. Cornelia Oedekoven and Sophie Webb conducted seabird surveys during CalCOFI cruises 0104 and 0010, respectively. Christine Abraham compiled the seabird productivity data. We are very grateful to the captain and crew of the RV *Francisco de Ulloa* and to the students and technicians participating during the IMECOCAL surveys.

A portion of this research and publication was supported as part of the U.S. GLOBEC Northeast Pacific Project, with support from the National Science Foundation, Division of Ocean Sciences (NSF Grant OCE-0000733) and the National Oceanic and Atmospheric Administration, Coastal Ocean Program Office. This is U.S. GLOBEC contribution number 337. The IMECOCAL program is funded from the CONACYT project (G-35326-T) and by CICESE.

## LITERATURE CITED

Ainley, D. G., W. J. Sydeman, and J. Norton. 1995. Upper trophic level predators indicate interannual negative and positive anomalies in the California Current food web. Mar. Ecol. Prog. Ser. 118:69–79.

Andersen, V. 1998. Salp and pyrosomid blooms and their importance in biogeochemical cycles, pp. 125–137. *In* The biology of pelagic tunicates, Q. Bone, ed. Oxford: Oxford University Press.

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

Berner, L. D. 1967. Distributional atlas of Thaliacea in the California Current region. Calif. Coop. Oceanic Fish. Invest. Atlas 8:1–322.

Bograd, S. J., P. M. DiGiacomo, R. Durazo, T. L. Hayward, K. D. Hyrenbach, R. J. Lynn, A. W. Mantyla, F B. Schwing, W. J. Sydeman, T. Baumgartner, B. Lavaniegos, and C. S. Moore. 2000. The state of the California Current, 1999–2000: forward to a new regime?. Calif. Coop. Oceanic Fish. Invest. Rep. 41:26–52.

Checkley, D. M., Jr., P. B. Ortner, L. R. Settle, and S. R. Cummings. 1997. A continuous, underway fish egg sampler. Fish. Oceanogr. 1:32–38.

Durazo, R., T. R. Baumgartner, S. J. Bograd, C. A. Collins, S. de la Campa, J. Garcia, G. Gaxiola-Castro, A. Huyer, K. D. Hyrenbach, D. Loya, R. J. Lynn, F. B. Schwing, R. L. Smith, W. J. Sydeman, and P. Wheeler. 2001. The state of the California Current. 2000–2001: a third straight La Niña year. Calif. Coop. Oceanic Fish. Invest. Rep. 42:29–60.

Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Prog. Oceanogr. 47:103–146.

Hayward, T. L., A. W. Mantyla, R. L. Lynn, P. E. Smith, and T. K. Chereskin. 1994. The state of the California Current in 1993–94. 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 1994–95: 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 1995–96: continuing declines in macrozooplankton biomass during a period of nearly normal circulation. Calif. Coop. Oceanic Fish. Invest. Rep. 37:22–37.

Hayward, T. L., T. R. Baumgartner, D. M. Checkley, R. Durazo, G. Gaxiola Castro, K. D. Hyrenbach, A. W. Mantyla, M. M. Mullin, T. Murphree, F. B. Schwing, P. E. Smith, and M. Tegner. 1999. The state of the California Current, 1998–99: transition to cool-water conditions. Calif. Coop. Oceanic Fish. Invest. Rep. 40:29–62.

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

Huyer, A., R. L. Smith, and J. Fleischbein. 2002. The coastal ocean off Oregon and northern California during the 1997–8 El Niño. Prog. Oceanogr. 54:311–341.

Hyrenbach, K. D., and R. R. Veit. 2002. Ocean warming and seabird assemblages of the California Current System (1987–1998): response at multiple temporal scales. Deep-Sea Res. In press.

Levitus, S., T. P. Boyer, M. E. Conkright, T. O'Brien, J. Antonov, C. Stephens, L. Stathopolos, D. Johnson, and R. Gelfeld. 1998. NOAA Atlas NESDIS 18, World ocean database 1998. Vol. 1: introduction. Washington, D.C.: U.S. GPO.

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., T. Baumgartner, C. A. Collins, J. Garcia, T. L. Hayward, K. D. Hyrenbach, A. W. Mantyla, T. Murphree, A. Shankle, F. B. Schwing, K. M. Sakuma, and M. Tegner. 1998. The state of the California Current, 1997–98: transition to El Niño conditions. Calif. Coop. Oceanic Fish. Invest. Rep. 39:25–49.

Mackas, D. M., Thomson, R. E., and Galbraith, M. 2001. Changes in the zooplankton community of the British Columbia continental margin, 1985–1999 and their covariation with oceanographic conditions. Can. J. Fish. Aquat. Sci. 58:685–702.

Madin, L. P., and D. Deibel. 1998. Feeding and energetics of Thaliacea. *In* The biology of pelagic tunicates, Q. Bone, ed., pp. 81–103. Oxford: Oxford University Press.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Metereol. Soc. 78:1069–1079.

National Centers for Environmental Prediction. 2002. Climate Diagnostics Bulletin, March 2002. Climate Prediction Center, NOAA/NWS/NCEP. No. 02/3.

Ohman, M. D., and B. E. Lavaniegos. 2002. Comparative zooplankton sampling efficiency of a ring net and bongo net with comments on pooling of subsamples. Calif. Coop. Oceanic Fish. Invest. Rep., this volume.

Peterson, W., and Mackas, D. 2001. Shifts in zooplankton abundance and species composition off central Oregon and southwestern British Columbia. PICES Press 9:28–31.

Peterson, W. T., J. E. Keister, and L. R. Feinberg. 2002. The effects of the 1997–99 El Niño-La Niña events on hydrography and zooplankton off the central Oregon coast. Prog. Oceanogr. 54:381–398.

Reid, J. L., and A. W. Mantyla. 1976. The effect of geostrophic flow upon coastal sea elevations in the northern North Pacific Ocean. J. Geophys. Res. 81: 3100–3110.

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. Mem. NOAA-TM-NMFS-SWFSC-231, 207 pp.

Schwing, F. B., T. L. Hayward, K. M. Sakuma, T. Murphree, A. S. Mascarenas Jr., A. W. Mantyla, S. I. Larios Castillo, S. L. Cummings, K. Baltz, D. G. Ainley, and F. Chavez. 1997. The state of the California Current, 1996–1997: mixed signals from the tropics. Calif. Coop. Oceanic Fish. Invest. Rep. 38:22–47.

Schwing, F. B., and C. S. Moore. 2000. A year without summer for California, or a harbinger of a climate shift? Transactions, American Geophysical Union 81(27):301ff.

Schwing, F. B., C. S. Moore, S. Ralston, and K. M. Sakuma. 2000. Record coastal upwelling in the California Current in 1999. Cal. Coop. Ocean. Fish. Invest. Rep. 41:148–160.

Schwing, F. B., T. Murphree, and P. M. Green. 2002a. The Northern Oscillation Index (NOI): a new climate index for the northeast Pacific. Prog. Oceanogr. 53:115–139.

Schwing, F. B., T. Murphree, L. deWitt, and P. M. Green. 2002b. The evolution of oceanic and atmospheric anomalies in the northeast Pacific during the El Niño and La Niña events of 1995–2001. Prog. Oceanogr. 54:459–491.

Smith, R. L., A. Huyer, and J. Fleischbein. 2001. The coastal ocean off Oregon from 1961 to 2000: is there evidence of climate change or only of Los Niños? Prog. Oceanogr. 49:63–93.

Sydeman, W. J., M. M. Hester, J. A. Thayer, F. Gress, P. Martin, and J. Buffa. 2001. Climate change, reproductive performance, and diet composition of marine birds in the southern California Current system, 1969-1997. Prog. Oceanogr. 49:309–329.

Veit, R. R., P. Pyle, and J. A. McGowan. 1996. Ocean warming and long-term change of pelagic bird abundance within the California Current System. Mar. Ecol. Prog. Ser. 139:11–18.

Wolter, K., and M. S. Timlin. 1998. Measuring the strength of ENSO: how does 1997/98 rank? Weather 53:315–324.