THE STATE OF THE CALIFORNIA CURRENT, 2002–2003: TROPICAL AND SUBARCTIC INFLUENCES VIE FOR DOMINANCE

ELIZABETH VENRICK
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California 92093-0227
evenrick@ucsd.edu

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

DAVID CHECKLEY
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California 92093-0218

REGINALDO DURAZO
UABC-Facultad de Ciencias Marinas
Apartado Postal 453
Ensenada, BC, México

GILBERTO GAXIOLA-CASTRO
Centro de Investigacion Cientifica y de
Educacion Superior de Ensenada
Apartado Postal 2732
22800 Ensenada, BC, México

JOHN HUNTER
Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
8694 La Jolla Shores Drive
La Jolla, California 92093-1508

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

K. DAVID HYRENBACH
Marine Science Division
Point Reyes Bird Observatory
Conservation Science Program
4990 Shoreline, California 94970

BERTHA E. LAVENIEGOS
Centro de Investigacion Cientifica y de
Educacion Superior de Ensenada
Apartado Postal 2732
22800 Ensenada, BC, México

ARNOLD MANTYLA
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California 92093-0230

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

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

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

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

ABSTRACT

This report summarizes conditions in the California Current system between February 2002 and spring 2003 from Oregon coastal waters nearly to Cape Lazaro in Baja California. A moderate El Niño peaked early in 2003 and began to decline. In the northern portion of the region the effects of El Niño were overshadowed by a large anomalous intrusion of subarctic water that was evident from British Columbia to the U.S.-Mexico border. First described off Oregon in July 2002, the anomalous mass was still evident off Oregon and Southern California in April 2003. At the time of this writing (July 2003) there is some evidence for La Niña conditions developing in the tropical Pacific.

INTRODUCTION

This segment of *CalCOFI Reports* was initiated in 1994 to provide preliminary summaries of the major observations from the past year's CalCOFI surveys. It has since expanded to include IMECOCAL to the south, observations by numerous groups in central California, and the GLOBEC LTOP (U.S. Global Ocean Ecosystem Dynamics Long-Term Observation Program) off Oregon. Topics have expanded from hydrography, chlorophyll, and macrozooplankton biomass to include near-surface fish eggs and avifauna. We continue this tradition of enhanced coverage. We hope that this foreshadows a more formal alliance between pelagic survey programs along the West Coast of North America that would form the basis for expanded observation of the entire California Current system. The concept of a West Coast alliance, first proposed by John Hunter at the 2001 CalCOFI Conference, has continued to be developed by Hunter and others (Schwing et al. 2002a). For further information, see the Web site for the proposed alliance (currently known as Pacific Coastal Observing System, PaCOS, formerly as ACCEO): http://swfsc.nmfs.noaa.gov/FRD/acceo/acceo1.htm.

Justification for this alliance was clearly demonstrated during the summer of 2002 when an anomalously strong intrusion of subarctic waters was observed off Oregon. It was quickly confirmed off Vancouver Island, and was evident off southern California. A flurry of e-mails between West Coast oceanographers (see Appendix) was proof that oceanography can still be exciting. This feature is discussed in the sections that follow and is the subject of several recent publications, cited in relevant sections below.

The present State of the California Current report covers primarily the period between April 2002 and

February–March 2003. Some data from April 2003 cruises are included. The moderate El Niño predicted last year developed and faded again. Late fall and winter of 2002–2003 was the only warm period in four consecutive cool years, and there is evidence for a return to cooler conditions in the near future. Evidence for a large-scale climate change in 1998–99, a reversal of that observed in the mid-1970s, is still being evaluated.

DATA SETS AND METHODS

Large-scale anomalies for the North Pacific Ocean are summarized from the National Center for Environmental Prediction reanalysis fields (Kistler et al. 2001) from the NOAA-CIRES Climate Diagnostics Center, http://www.cdc.noaa.gov. The reanalysis fields are monthly gridded (approximately 2° × 2°) anomalies of sea-surface temperature (SST) and surface winds. The base period is 1968–96. Ocean temperature anomalies at 100 m depth were computed from the Global Temperature-Salinity Profile Program database, monthly averaged on a 1° spatial grid. Anomalies were computed by subtracting the 1° monthly climatologies (base period 1945–96) of the World Ocean database 1998 (Levitus et al. 1998) from the gridded observations and were averaged into 5° × 5° boxes.

Monthly upwelling indexes and their anomalies for the west coast of North America (21°−52°N) are calculated relative to 1948–67. The daily alongshore wind component and SST are from the NOAA National Data Buoy Center (NDBC). Values from six representative buoys from the California Current system are plotted against the harmonic mean of each buoy.

The northern portion of the California Current system has been sampled seasonally by the Northeast Pacific Long-term Observation Program (LTOP) of the U.S. GLOBEC program since 1997. 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 four or five zonal sections between 42°N and 45°N. Cruise reports and data from this program are available on the LTOP Web site, http://ltop.oce.orst.edu/~ctd/index.html. The NH line was previously occupied regularly from 1961 to 1971, and long-term seasonal averages have been calculated from these historical data (Smith et al. 2001).

The CalCOFI program and the Investigaciones Mexicanas de la Corriente de California program (IMECOCAL) conduct closely coordinated, quarterly surveys off Southern California (fig. 1) and Baja California (fig. 2), respectively. Cruises covered in this report include April, July, and October–November 2002 and January–February 2003. Partial results for April 2003 are also included. Measurements by both programs include conductivity-temperature-depth (CTD) casts to 500 m (CalCOFI) or 1,000 m (IMECOCAL), depth permitting. Water samples are routinely collected to determine dissolved oxygen, nutrients, and chlorophyll. Standard (.505 mm mesh) oblique bongo tows are conducted to 210 m depth. Continuous underway measurements of near-surface temperature, salinity, fluorescence, and acoustic Doppler current profilers (ADCP) are made. Additional samples and sampling methods are discussed

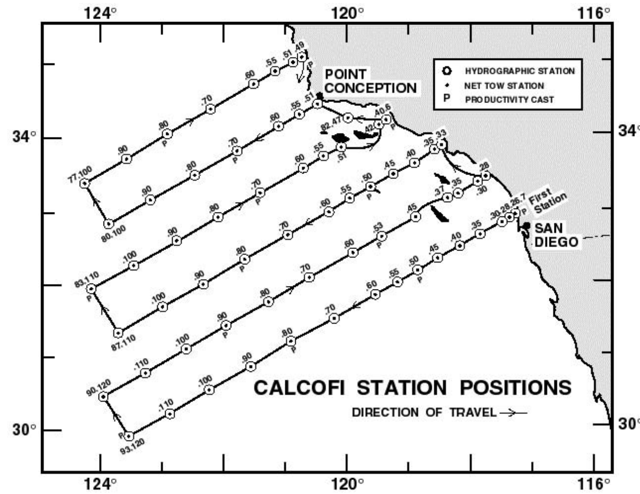

Figure 1. Standard CalCOFI cruise pattern.

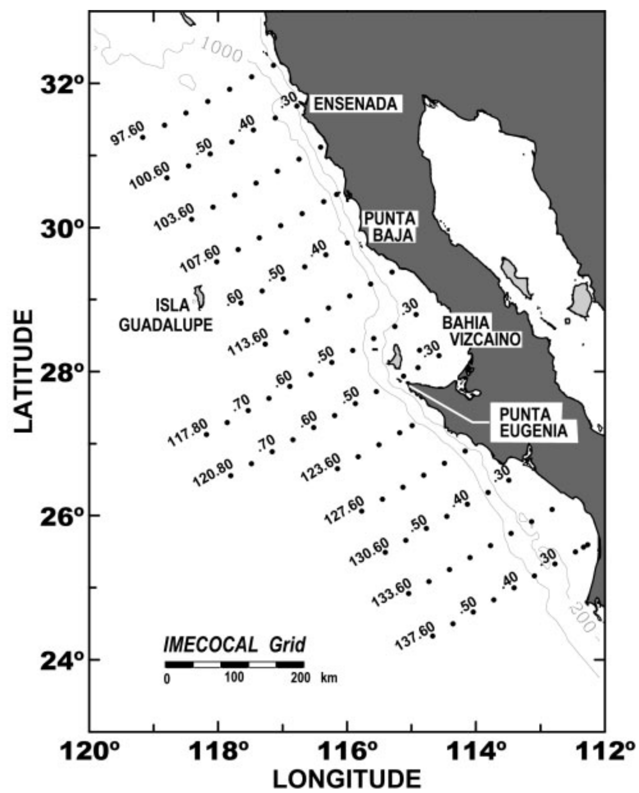

Figure 2. Standard IMECOCAL cruise pattern and station locations (*solid dots*). Line 97 is sampled during the spring cruise only. The 200 m and 1,000 m depth contours are shown.

in data reports and on Web sites (e.g., http://www-mlrg.ucsd.edu/calcofi.html and http://imecocal.cicese.mx).

CalCOFI cruises 0204, 0302, and 0304 were extended north of the usual pattern. The following discussion only includes observations from the standard CalCOFI grid. Data from cruises 0302 and 0304 are preliminary.

In October 2002 IMECOCAL performed CTD casts to 400 m only because of limited hydrographic cable. During April 2002 the IMECOCAL grid was extended to sample stations along line 97.

A continuous underway fish egg sampler (CUFES; Checkley et al. 1997) collects eggs near the surface on the winter and spring CalCOFI cruises and on all IMECOCAL cruises. When the Real-time Flow Imagining and Classification System (REFLICS; Iwamoto et al. 2001) is fully developed, it will image objects collected by CUFES and classify them as sardine eggs, copepods, bubbles, and so on.

Systematic surveys of the distribution and abundance of pelagic birds have been made on CalCOFI cruises since 1987. Personnel from the Point Reyes Bird Observatory (PRBO) Marine Science Program have assessed the reproductive performance of seabird populations at the Farallon Islands since the early 1970s.

BASINWIDE PATTERNS

The Multivariate El Niño/Southern Oscillation (ENSO) Index (MEI; Wolter and Timlin 1998) assesses the relative magnitude of El Niño and La Niña events based on six tropical Pacific variables. Following several years of negative MEI values, representing weak-to-moderate La Niña conditions in the tropics, the MEI became positive in spring 2002 and peaked in December 2002–January 2003 (fig. 3). This was the first El Niño since the large 1997–98 event, and it was considerably weaker. The 2002–2003 El Niño was comparable in intensity and duration to the 1965–66 event and produced an MEI value similar to the events of 1963–64, 1977–78, 1979–80, and 1994–95, that is, a moderately strong event. However, it did not evolve, or dissipate, like the canonical El Niño. Strong thermal anomalies did not fully develop on the South American coast, and the rapid decline in early 2003 contrasts to most strong El Niños, which often strengthen from winter to spring.

The Northern Oscillation Index (NOI; Schwing et al. 2002c) is an ENSO-related index that reflects the intensity of interannual climate events in the northeast Pacific. After four consecutive years of positive values (indicating La Niña-like conditions), the NOI reversed its sign in summer 2002 (fig. 3). It has remained positive through April 2003 but, like the MEI, is poised to change its sign again in summer 2003 as a La Niña develops. The Pacific Decadal Oscillation (PDO; Mantua et al. 1997) reflects multidecadal climate variability in the northeast Pacific, with positive (negative) values indicating warm (cool) SST anomalies in the California Current system. As with the other indexes, the PDO switched sign in mid-2002, reflecting a reversal to warm upper-ocean thermal anomalies in the California Current system from the pattern of cool anomalies that had persisted for several years (fig. 3). As with the MEI and NOI, the PDO appears to have reached its peak in early 2003 and may again reverse sign later this year.

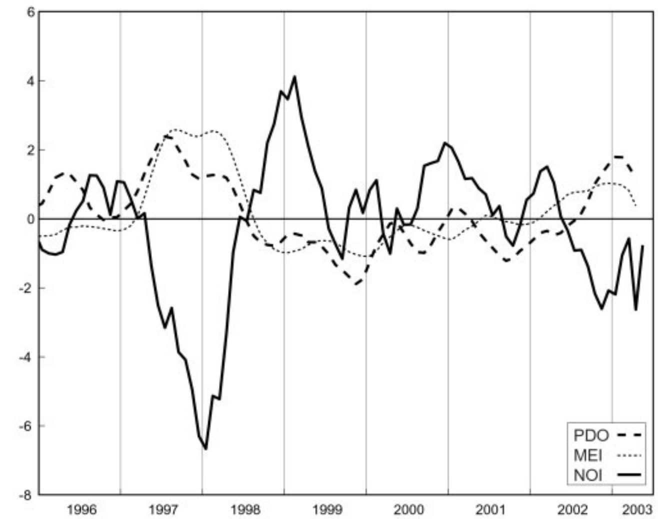

Figure 3. Monthly time series of the Pacific Decadal Oscillation (PDO), Multivariate ENSO Index (MEI), and Northern Oscillation index (NOI) for January 1996 through April (May) 2003 for PDO and MEI (NOI). Series have been smoothed with a 5-month running mean, except the last two months, which are raw values.

An unusually strong Aleutian Low in summer 2002 resulted in a large cyclonic wind anomaly over most of the northeast Pacific (fig. 4a). This pattern persisted through early 2003 (figs. 4b,c), contributing to weakened upwelling or downwelling conditions in the northern California Current system. The strongest cyclonic wind anomalies (January 2003; fig. 4c) occurred near the peak of the El Niño development, a pattern commonly observed when El Niño conditions are predominant in the equatorial Pacific (Schwing et al. 2002b). By April 2003, the cyclonic wind anomalies had broken down, replaced by a relatively stronger North Pacific High and anomalously high equatorward winds in the California Current system region (fig. 4d).

The patterns of SST anomaly represent a direct ocean response to anomalies of the prevailing wind stress. Although positive temperature anomalies had developed in the tropics by summer 2002, and peaked in fall-winter at ~1.0−1. 5°C, the eastern North Pacific remained cool at this time (fig. 4a), continuing a pattern that had been seen since the 1998 La Niña. In the central North Pacific, however, positive temperature anomalies had developed by summer 2002; these spread throughout the northeast

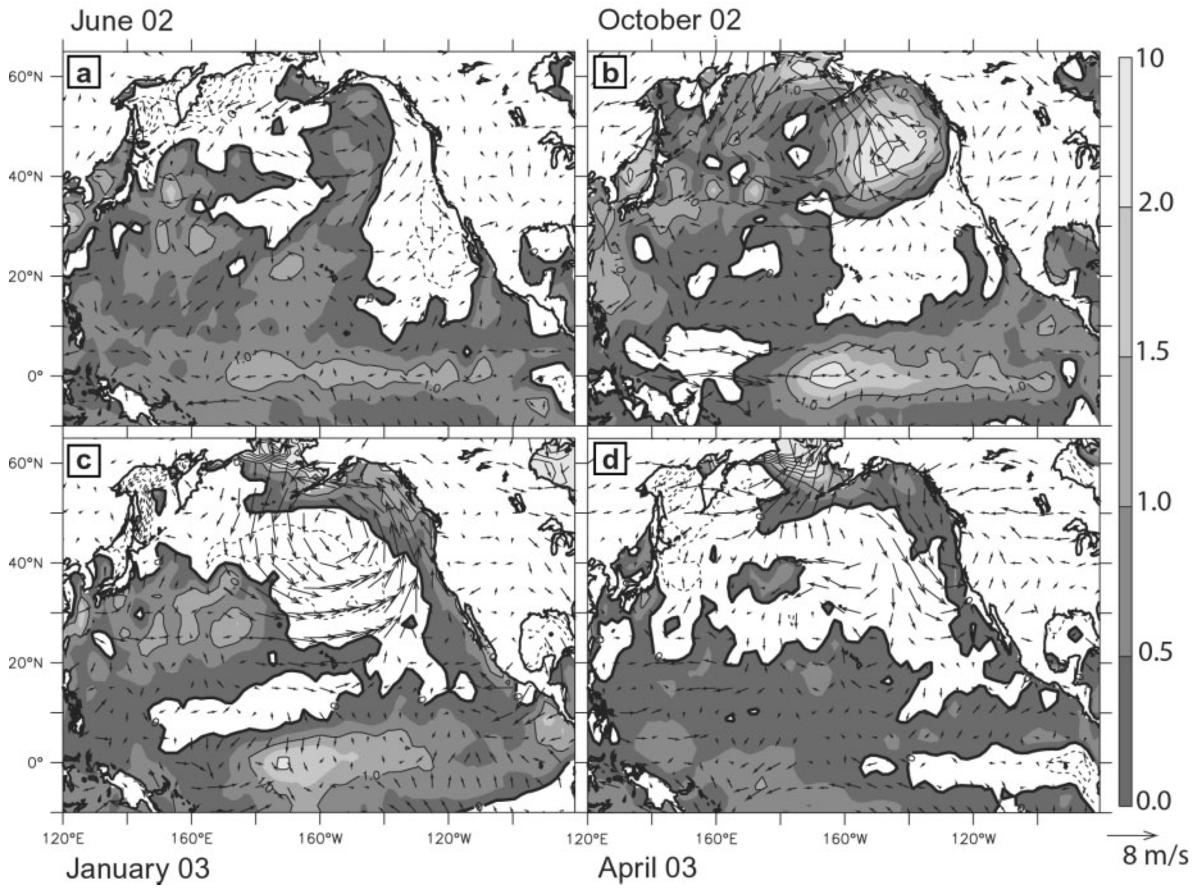

Figure 4. Anomalies of surface wind velocity and SST in the North Pacific Ocean for (*a*) June 2002, (*b*) October 2002, (*c*) January 2003, and (*d*) April 2003. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Positive (warm) SST anomalies are shaded. Wind climatology period is 1968–96. SST climatology period is 1950-79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

Pacific by October 2002 (fig. 4b). Strong positive temperature anomalies were seen all along the California Current system and into the northern Gulf of Alaska as the El Niño peaked in early winter 2002–2003, when anomalous downwelling-favorable winds covered much of the California Current system (fig. 4c). As in past El Niños, warm waters in the eastern North Pacific were primarily related to the local cyclonic wind stress anomalies (Schwing et al. 2002b).

The breakdown of the weak-to-moderate 2002–2003 El Niño was fairly rapid and somewhat unusual. Even as the western tropical Pacific remained anomalously warm, the eastern equatorial Pacific began to cool in early spring (figs. 4c,d). By April 2003, cool anomalies appeared to be spreading from east to west along the equator, and the thermocline had shoaled (not shown), signaling the end of the El Niño and possibly the initiation of yet another La Niña. If the La Niña develops through summer 2003, as it is predicted to do, this would be the fifth year of the past six with cool anomalies in the eastern tropical Pacific.

The large-scale wind stress anomalies in the Northeast Pacific during winter 2001–2002 (Schwing et al. 2002) set the conditions for the unusual water property and productivity observations made throughout the California Current system in summer 2002 (Murphree et al. 2003). Anomalously strong southward Ekman transport of subarctic waters into the North Pacific Current (NPC), as well as strong eastward flow of the NPC toward the North American coast, provided the source of subarctic waters into the California Current system. Additionally, unusually strong coastal upwelling in spring 2002 (fig. 5) and enhanced equatorward transport helped spread the anomalous waters throughout the California Current system during 2002.

COASTWIDE CONDITIONS

Monthly coastal upwelling indexes (Bakun 1973; Schwing et al. 1996) indicated stronger-than-normal upwelling through most of the California Current system in spring-summer of 2001 and 2002 (fig. 5), continuing the pattern of strong upwelling and cool SSTs

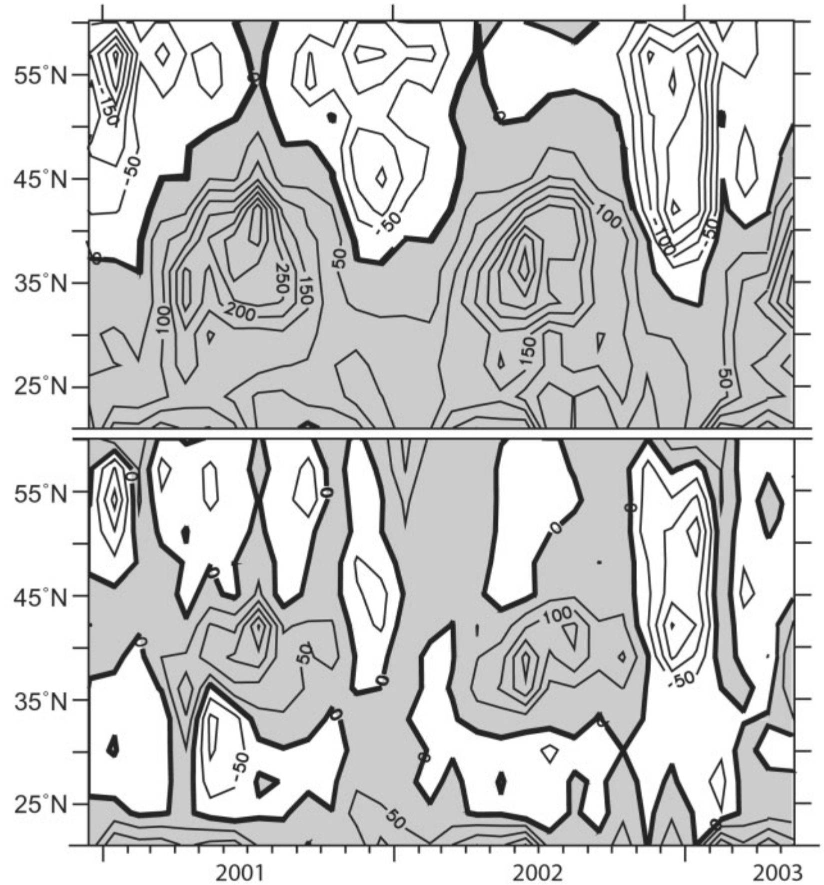

Figure 5. Monthly upwelling index and upwelling index anomaly for January 2001–May 2003. Shaded areas denote positive (upwelling) values in upper panel, and positive anomalies (greater-than-normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m³/s per 100 km of coastline.

since the onset of the 1998 La Niña (Hayward et al. 1999; Bograd et al. 2000; Durazo et al. 2001; Schwing et al. 2002a). Strongest upwelling occurred around 36–40°N in both years, while weak upwelling (negative anomalies) occurred off Baja. The 2002 upwelling period again extended this extraordinary period of persistently strong upwelling seasons (Schwing et al. 2002a). However, strong downwelling prevailed in the California Current system north of Point Conception during winter 2002–2003, reflecting the prevailing cyclonic wind anomalies (fig. 4c). Upwelling was strongest in the southern California Current system in early 2003, while downwelling persisted in the northern California Current system at least through April. Anomalously strong upwelling had returned to the California Current system, from Baja California to Washington, by May 2003.

National Data Buoy Center (NDBC) coastal buoy winds reveal synoptic-scale variability of atmospheric events in the California Current system, superimposed on the annual climatological cycle of generally southward winds in summer and northward or weak southward winds in winter (fig. 6). Coastal winds in 2001 showed the typical pattern of stronger magnitudes and higher variability off northern California and Oregon, and weaker magnitudes with less variability off southern California (Schwing et al. 2002a). The 2002 coastal winds were somewhat more variable throughout the California Current system. There were a number of anomalously strong southward wind events during the first half of 2002 over this part of the California Current system, contributing to the strong upwelling and cool coastal temperatures. In the latter half of 2002, there were a number of strong northward wind events, contributing to downwelling and warmer SSTs. The cyclonic wind anomalies seen around this time (figs. 4b,c) represent the integrated effect of a number of these synoptic events.

The buoy SSTs reflect these changes in alongshore wind forcing, with cool temperatures persisting through spring and summer 2002 (fig. 7). However, a sharp transition occurred around October–November 2002 as the strong downwelling episodes resulted in positive SST anomalies. This transition was particularly obvious

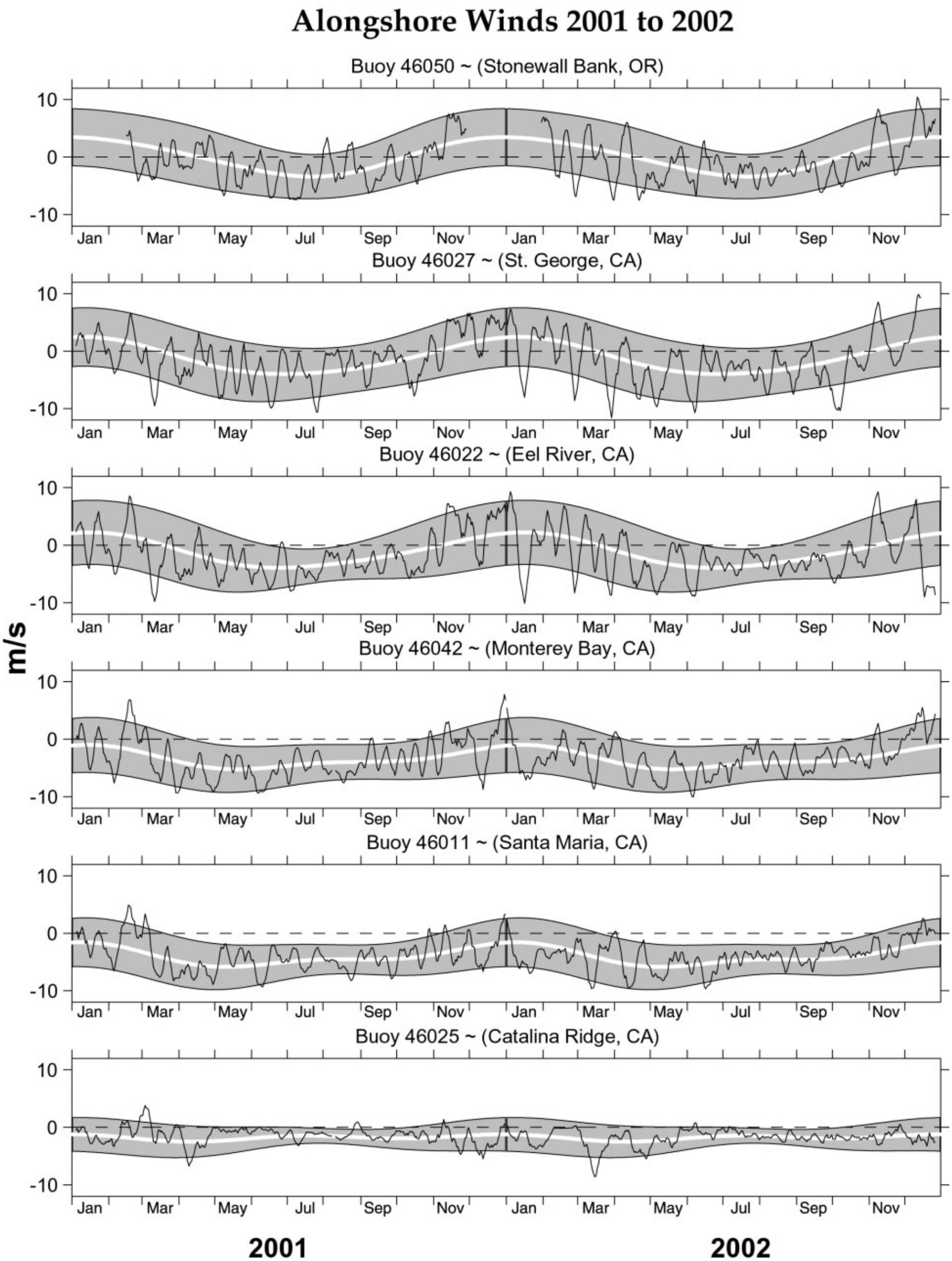

Figure 6. Time series of daily-averaged alongshore winds for January 2001–December 2002 at selected National Data Buoy Center coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a 7-day running mean. Data were provided by NOAA NDBC.

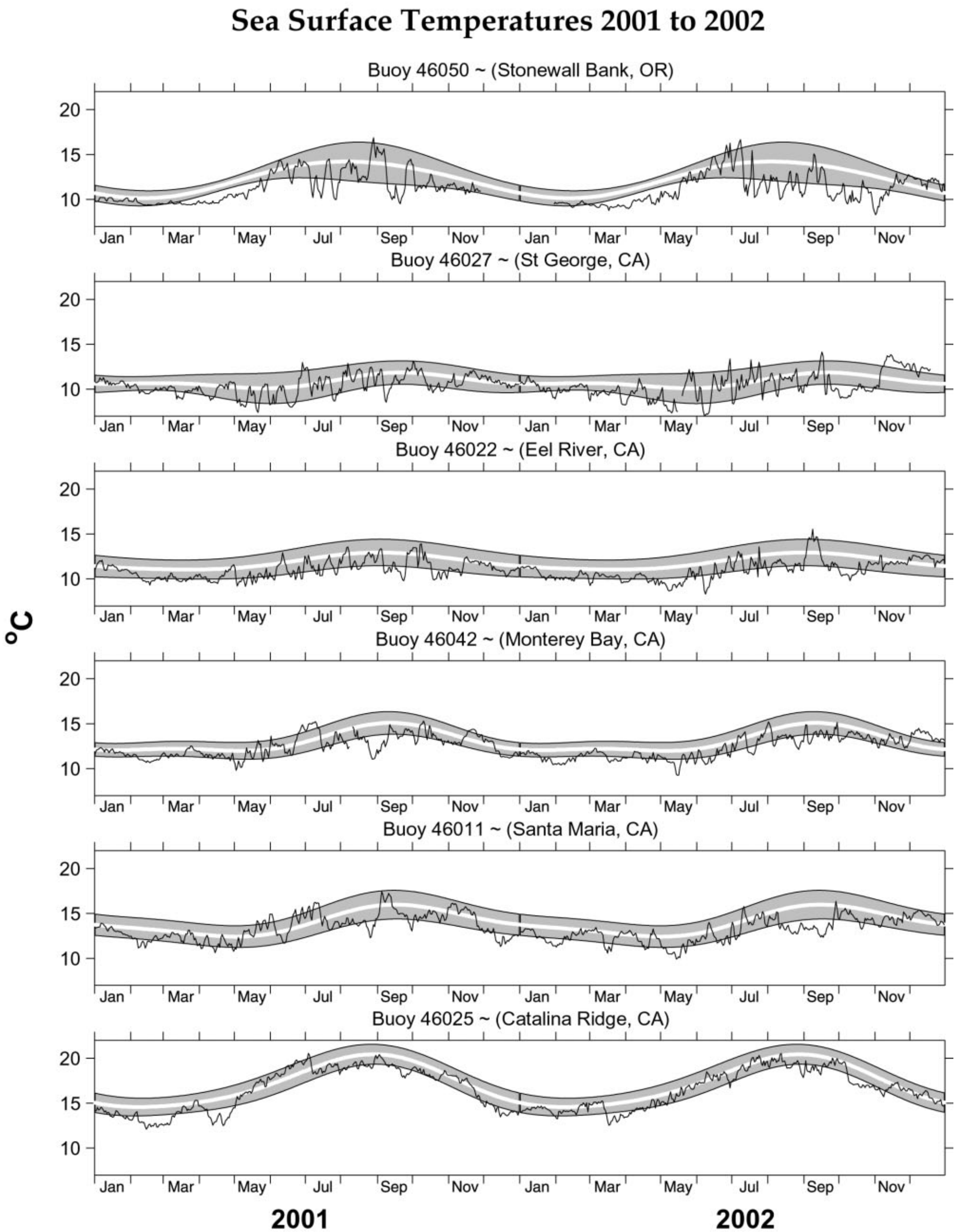

Figure 7. Time series of daily-averaged SST for January 2001–December 2002 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Data provided by NOAA NDBC.

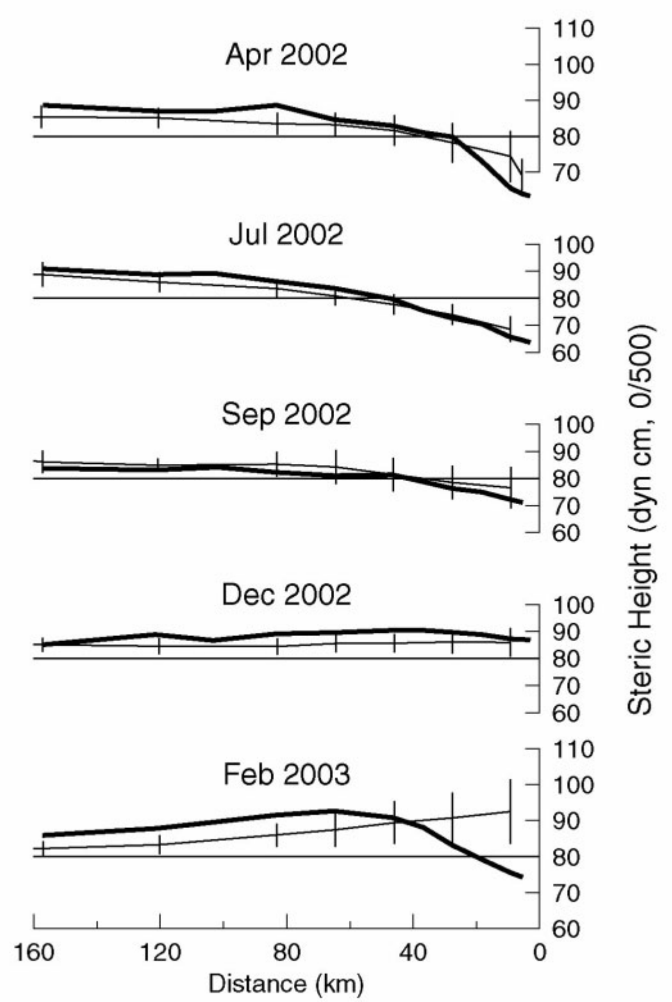

Figure 8. Steric height profiles of the sea surface relative to 500 dbar along the NH line at 44.65°N since April 2002 (*thick line*) shown with the long-term (1961–71) seasonal or monthly average provided by Smith et al. (2001). Vertical bars indicate 1 standard deviation above and below the average. Values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976).

off northern California (St. George buoy). With the collapse of the 2002–2003 El Niño event, it might be expected that coastal temperatures will return to the cool values seen in recent years.

REGIONAL STUDIES

Oregon Coast: GLOBEC LTOP Cruises

Observations off the Oregon coast suggest that El Niño had a relatively minor impact while the anomalous intrusion of subarctic water dominated the ecosystem.

Water temperatures off central Oregon were near normal during the La Niña of 1998–2001 (Schwing et al. 2002a), except that waters over the continental slope tended to be above normal at depths of 30–100 m in summer (fig. 27 in Schwing et al. 2002a). By February 2002, the entire section was colder than normal, and steric height was lower than normal (Schwing et al. 2002a).

Steric heights along the NH line remained near normal through spring and summer 2002 (fig. 8), though the gradient over the shelf was steeper than normal, indicating enhanced southward flow. By early December, steric heights were slightly above normal along most of the section. Steric heights offshore were still elevated in February 2003, but inshore values were very low, indicating strong southward flow over the shelf, presumably because of upwelling-favorable winds during the first ten days of February.

Temperature sections along the NH line in 2002–2003 (fig. 9a) show the usual seasonal cycle in the upper ocean: deep mixed layers and weak horizontal gradients in winter, and very strong stratification with temperature decreasing toward shore in summer. There are also some striking anomalies: very cold (< 7.5°C) subsurface waters over the outer shelf in July 2002, and complex inversions in fall and winter. Each section contains both positive and negative anomalies that differ from the seasonal average by more than one standard deviation. Positive anomalies are seen at depths between 200 m and 500 m in all sections, and in the surface layer in winter. These positive anomalies are probably associated with the 2002–2003 El Niño.

The remarkably cold water (<7.5°C) over the outer shelf in July 2002 (fig. 9) occurred in the upper halocline and was the coldest in this salinity range yet observed off Newport (fig. 10). This anomaly was part of a large-scale subarctic intrusion that also affected water masses off Vancouver Island (Freeland et al. 2003) and southern California (Bograd and Lynn 2003).

This water mass anomaly can be explained by enhanced southward advection, which was detected by moorings (Kosro 2003) and satellite-tracked drifters (Barth 2003) and in satellite altimeter data (Strub and James 2003). The cold halocline had relatively high nutrient concentrations (Wheeler et al. 2003), and upwelling of these nutrient-rich waters produced higher-than-normal chlorophyll concentrations off Oregon and northern California (Wheeler et al. 2003; Thomas et al. 2003). These anomalous conditions apparently resulted from large-scale atmospheric forcing in the northeast Pacific Ocean (Murphree et al. 2003). The cold halocline anomaly was already present off central Oregon in April 2002, and was still present in February 2003 when its peak amplitude occurred at a depth of 110 m, 100 km from shore (fig. 9b).

Regional surveys were made in April, July, and September 2002. As in recent years (Durazo et al. 2001; Schwing et al. 2002a), surface temperatures were nearly homogeneous in April 2002 (fig. 11a), though there was

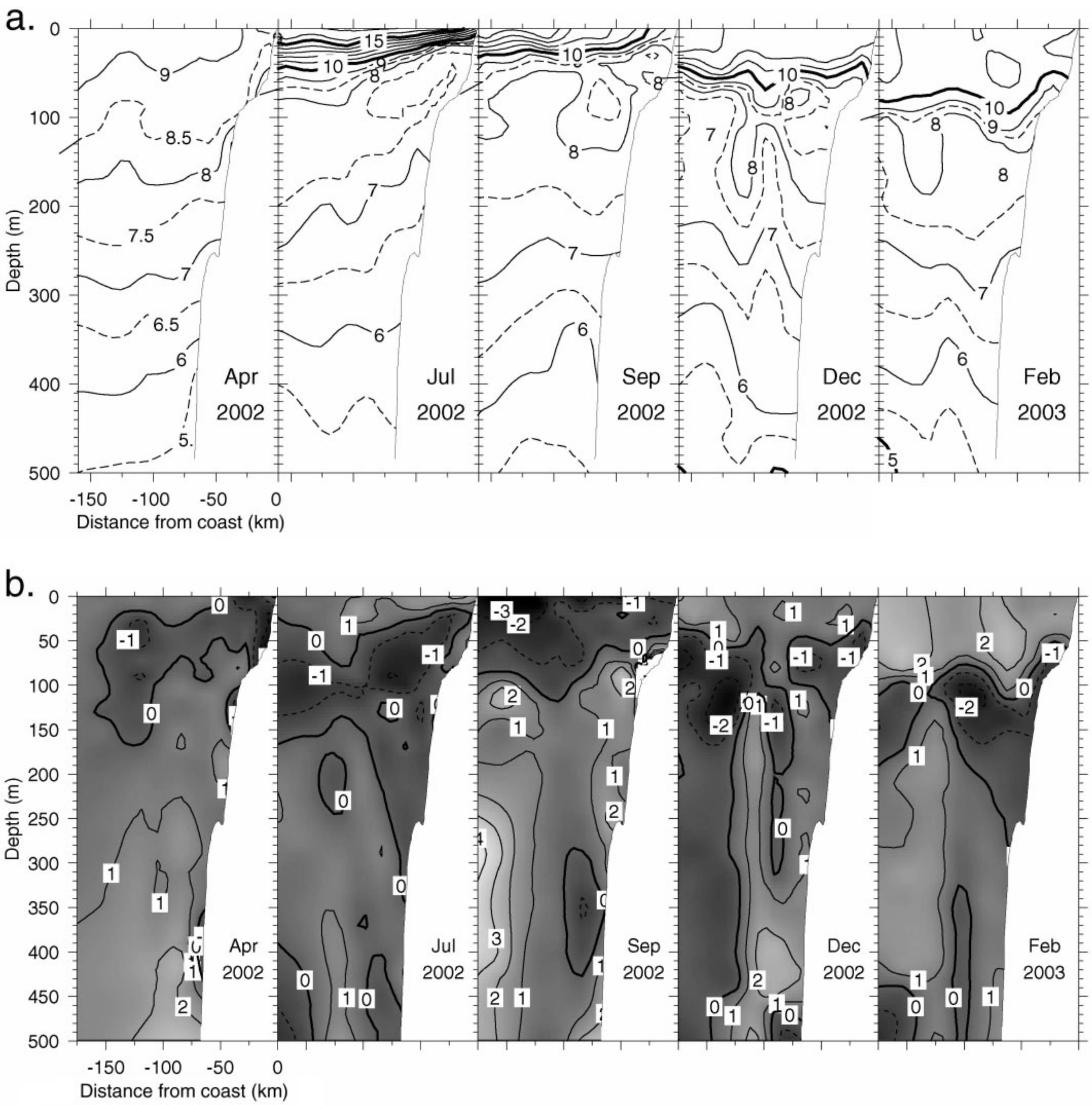

Figure 9. Temperature along the NH line at 44.65°N, for sections since April 2002. (*a*) Temperature, in °C (*dashed lines* are intermediate contours). (*b*) Temperature anomalies normalized by historical standard deviations; positive (negative [*dashed lines*]) anomalies indicate that present values 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.

a strong, narrow equatorward jet near the coast (fig. 11b). A narrow low-salinity tongue (fig. 11c) coincided with the core of the jet, indicating southward advection of Columbia River plume water. By July 2002, there were strong surface temperature gradients: inshore waters were 6–7°C colder than offshore waters, and offshore waters were 1–2°C warmer off Newport than off Crescent City (fig. 11a). Geostrophic flow at the surface, relative to 500 dbar, was equatorward throughout the survey region (fig. 11b), and low-salinity Columbia River plume waters (salinity < 32.5) covered all but the inshore portion of each section (fig. 11c). By late September, zonal

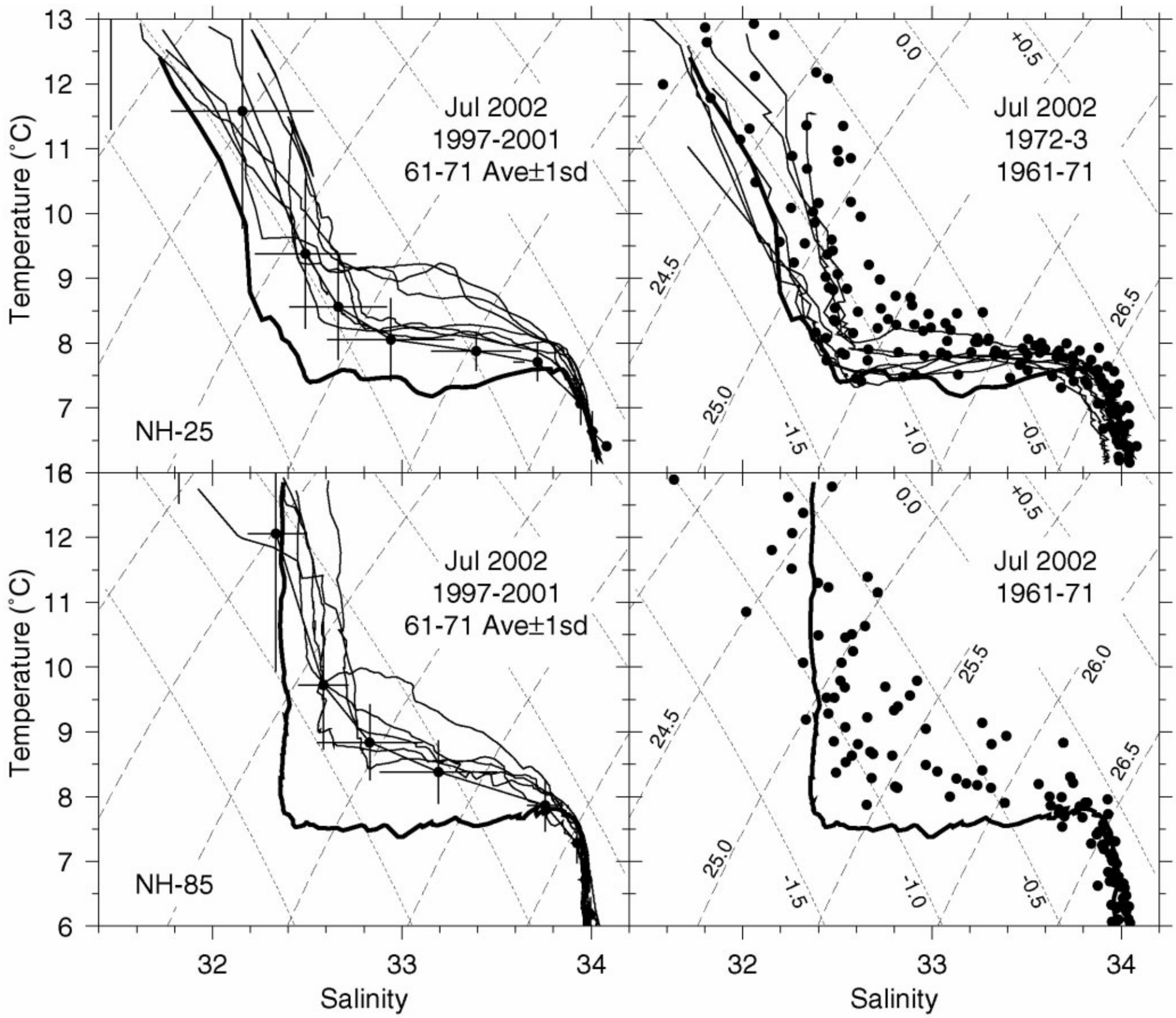

Figure 10. Temperature and salinity diagrams for the shelf-break station (NH-25, *upper panels*), and the offshore station (NH-85, *lower panels*). *Left*, continuous CTD data from July 2002 (*thick line*) compared to recent summers (*thin lines*) and the mean (±1 SD) of historical data (*cross bars*); *right*, data from July 2002 (*thick line*) compared to historical continuous (*thin lines*) and discrete (*dots*) summer data.

gradients of surface temperature and dynamic topography fields had weakened, and there seemed to be some eddies off Crescent City (which were not resolved because we did not have enough time to sample our standard section at 42.5°N). Low-salinity Columbia River plume waters (salinity < 32.5) were observed only in the northwest corner of our grid; these low salinity surface waters were still 2–4°C warmer than the offshore waters at Crescent City. Winds had continued to be favorable for upwelling through most of September—that is, longer than usual—and this continued upwelling was reflected in the cold, dense waters observed in the coastal strip at the end of September.

Chlorophyll *a* concentrations on all three 2002 surveys were generally high, exceeding 4 µg/l over most of the shelf in both April and July. Even at the end of September, most of the inner shelf region had values > 4 µg/l. These high chlorophyll values apparently reflect the enhanced subarctic influence (Wheeler et al. 2003).

As of this writing, the weak-to-moderate El Niño in the equatorial Pacific seems to be fading, though the most recent value (for Feb.–Mar. 2003) of the MEI (Wolter and Timlin 1998) is still positive. Our results suggest that this El Niño has had only a minor impact on the northern California Current system, expressed in higher-than-normal surface temperatures in late winter, and isolated

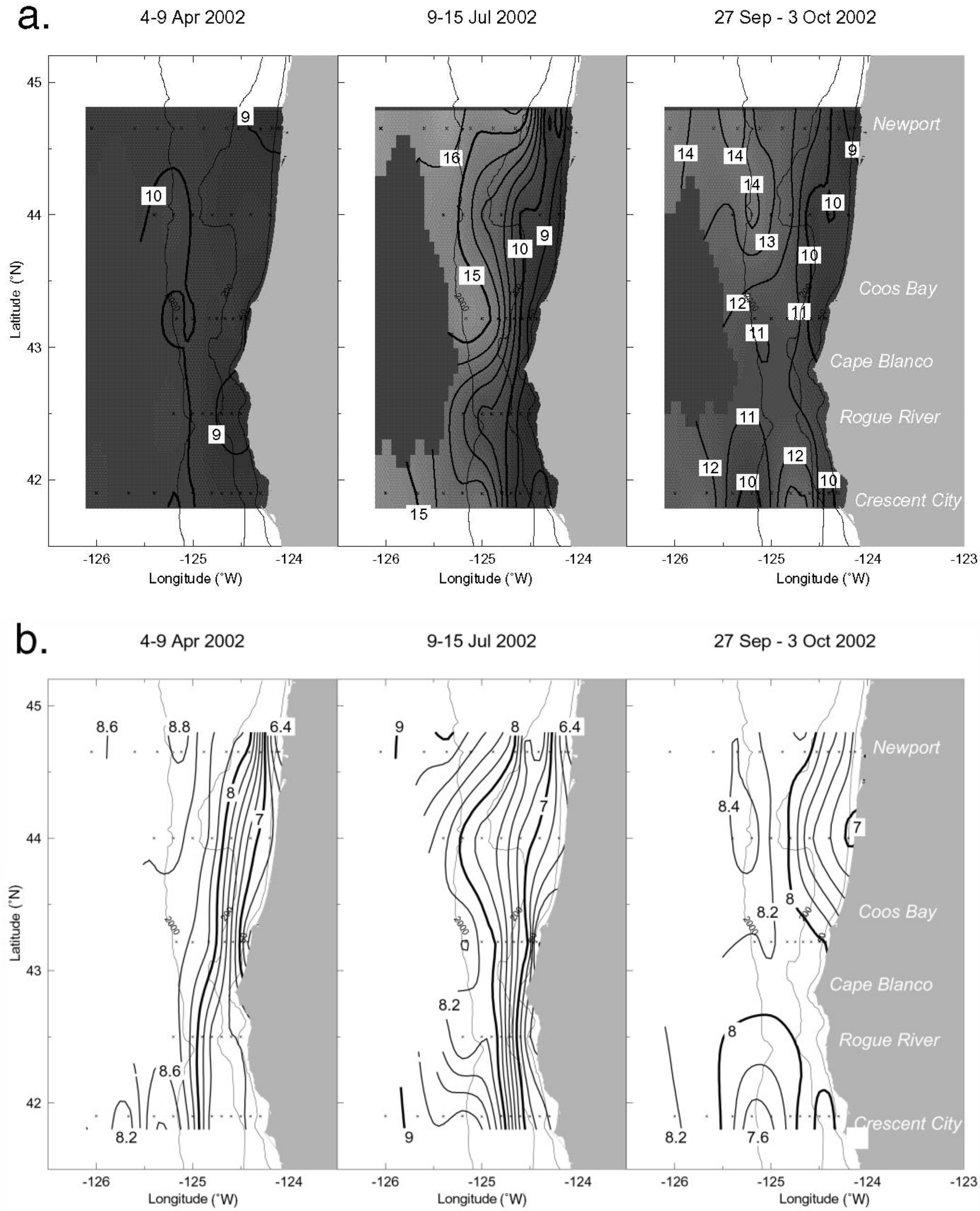

Figure 11. Spatial patterns for GLOBEC LTOP cruises: (*a*) 10 m temperature (˚C), (*b*) geopotential anomaly (J/kg) of the sea surface relative to 500 dbar.

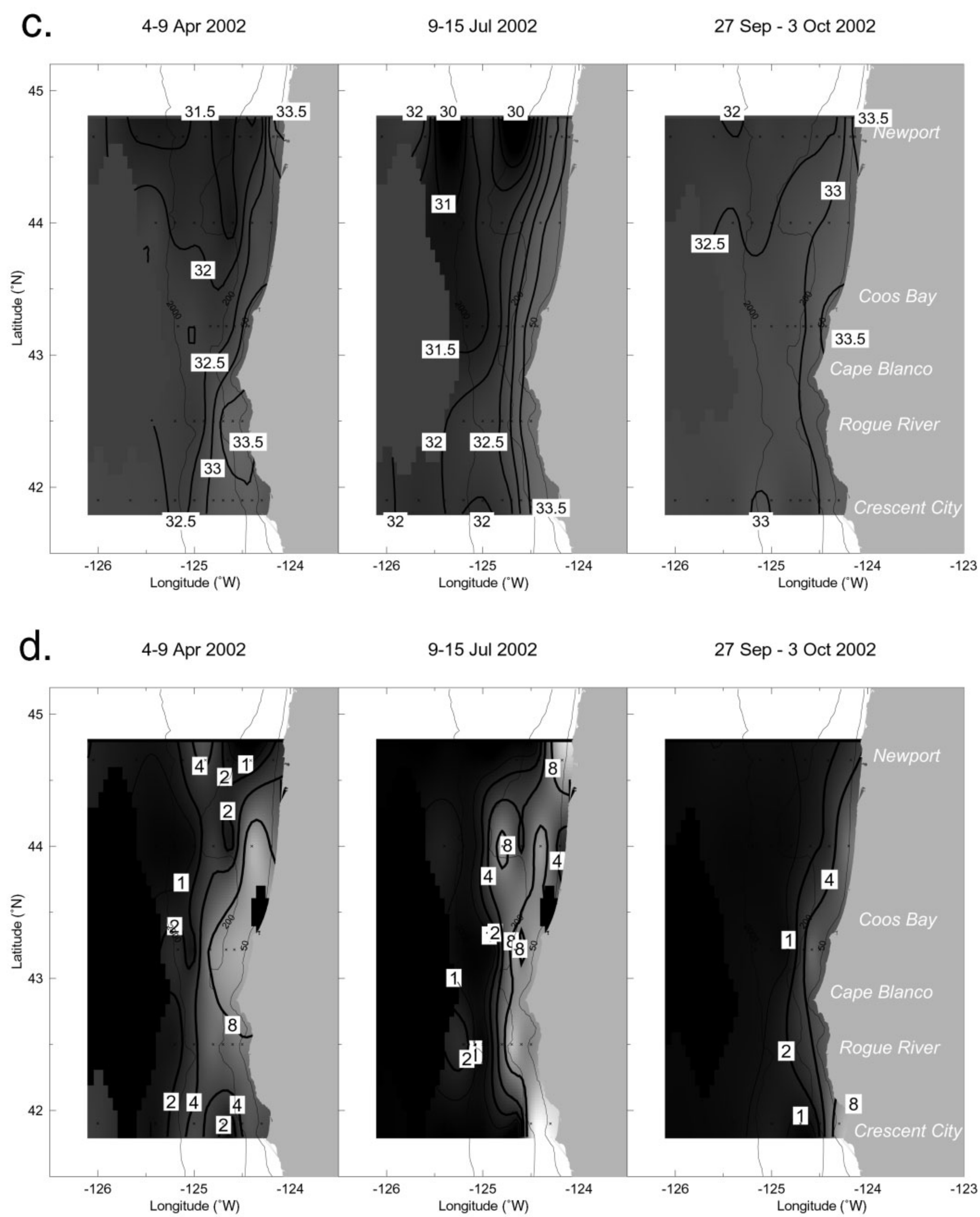

Figure 11 (*continued*). (*c*) 10 m salinity, (*d*) 10 m chlorophyll (µg/l).

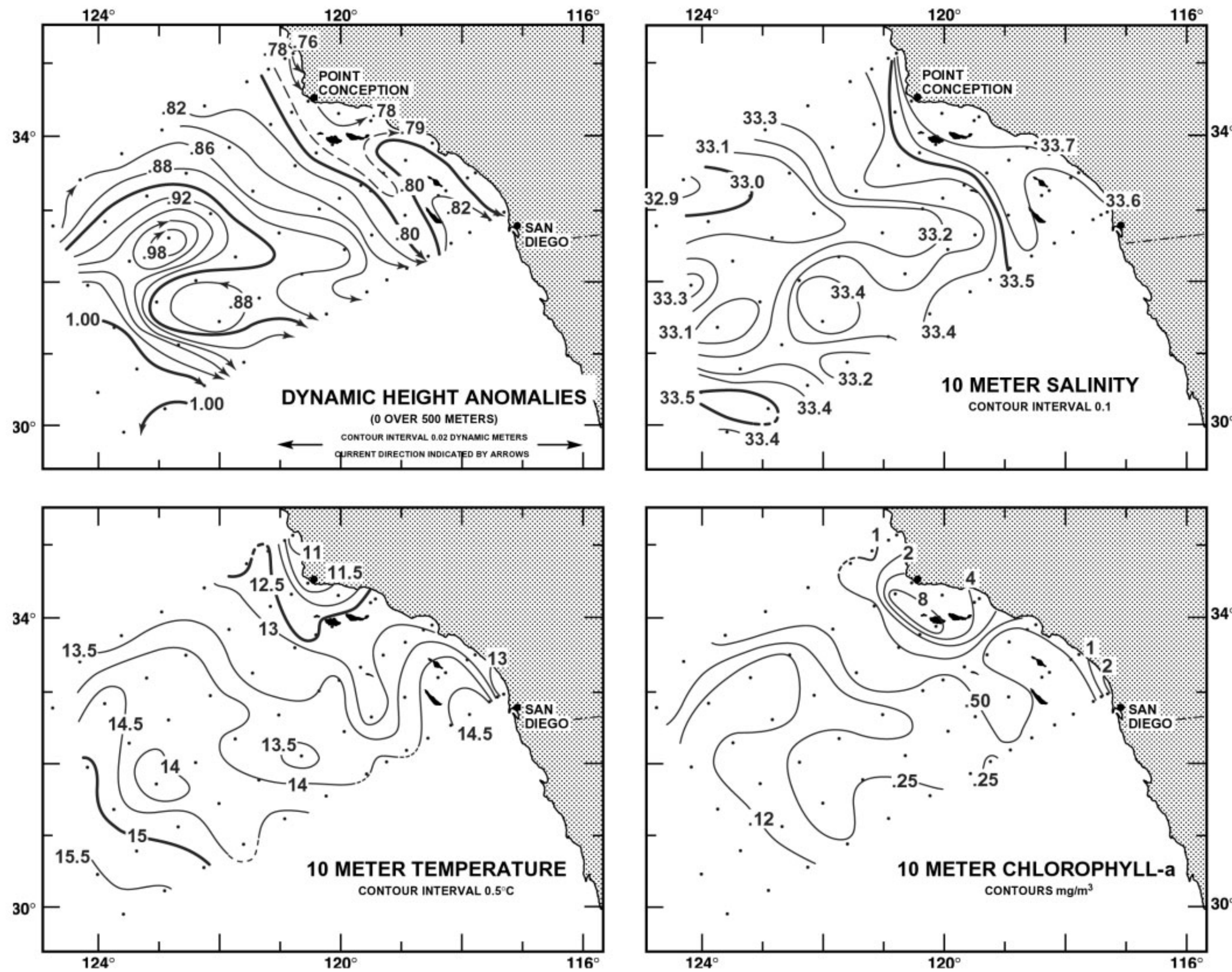

Figure 12. Spatial patterns for CalCOFI cruise 0204 (27 Mar.–12 Apr. 2002) including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

warm anomalies at depths of 200–500 m. In contrast, the subarctic intrusion of cool freshwater has had a significant ecosystem impact, causing elevated nutrient concentrations, high chlorophyll concentrations, and even hypoxic waters over the inner shelf off Oregon (Wheeler et al. 2003). Whether and to what extent the subarctic influence will continue through 2003 remains to be seen.

Southern California Bight: CalCOFI Cruises

0204 (27 Mar.–12 Apr. 2002). The dynamic height map shows pronounced onshore-offshore meanders in the outer half of the cruise pattern (fig. 12). The uniform southward flow on the continental shelf and cool temperatures and high salinities close to shore are indicative of coastal upwelling. Chlorophyll levels were highest in the northeast quadrant of the cruise, but maximum values did not reach the values usually seen in spring. In retrospect, the first occurrence of anomalously cold, fresh subarctic waters could be seen at four offshore stations (tab. 1).

0207 (2–18 July 2002). The California Current still showed strong meanders, but these had shifted somewhat southward compared to 0204 (fig. 13). The cyclonic eddy that was centered between stations 87.90 and 90.90 on 0204 strengthened and moved to station 90.110. The narrow Southern California Eddy seen on 0204 had broadened, and the northward flow on the inshore side had strengthened, proceeding through the Channel Islands past Point Conception. At 10 m, the center of the elongated Southern California cyclonic eddy had cool temperatures and higher salinities, characteristic of water from below. There was also a clockwise warm-core eddy around and north of San Clemente Island. Chlorophyll levels decreased from those on the spring cruise.

TABLE 1
Selected Hydrographic Parameters Summarized for the Most Recent Six CalCOFI Cruises, Showing the Development and Decline of the 2002–2003 El Niño and the Presence of the Anomalous Intrusion of Subarctic Waters

Cruise	10 m mean temperature anomaly (°C)	10 m mean salinity anomaly	Estimated number of stations with cold, fresh anomaly
0201	−0.6	+0.09	N.A.
0204	−0.5	+0.05	4
0207	0.0	−0.03	15
0211	−0.04	−0.13	26
0302	+1.0	−0.16	28
0304	−0.03	−0.18	20

Note: The subarctic anomaly was considered to be present when the minimum salinity was less than 0.3 salinity units from the long-term station mean and generally occurred at depths between 50 m and 125 m at offshore stations.

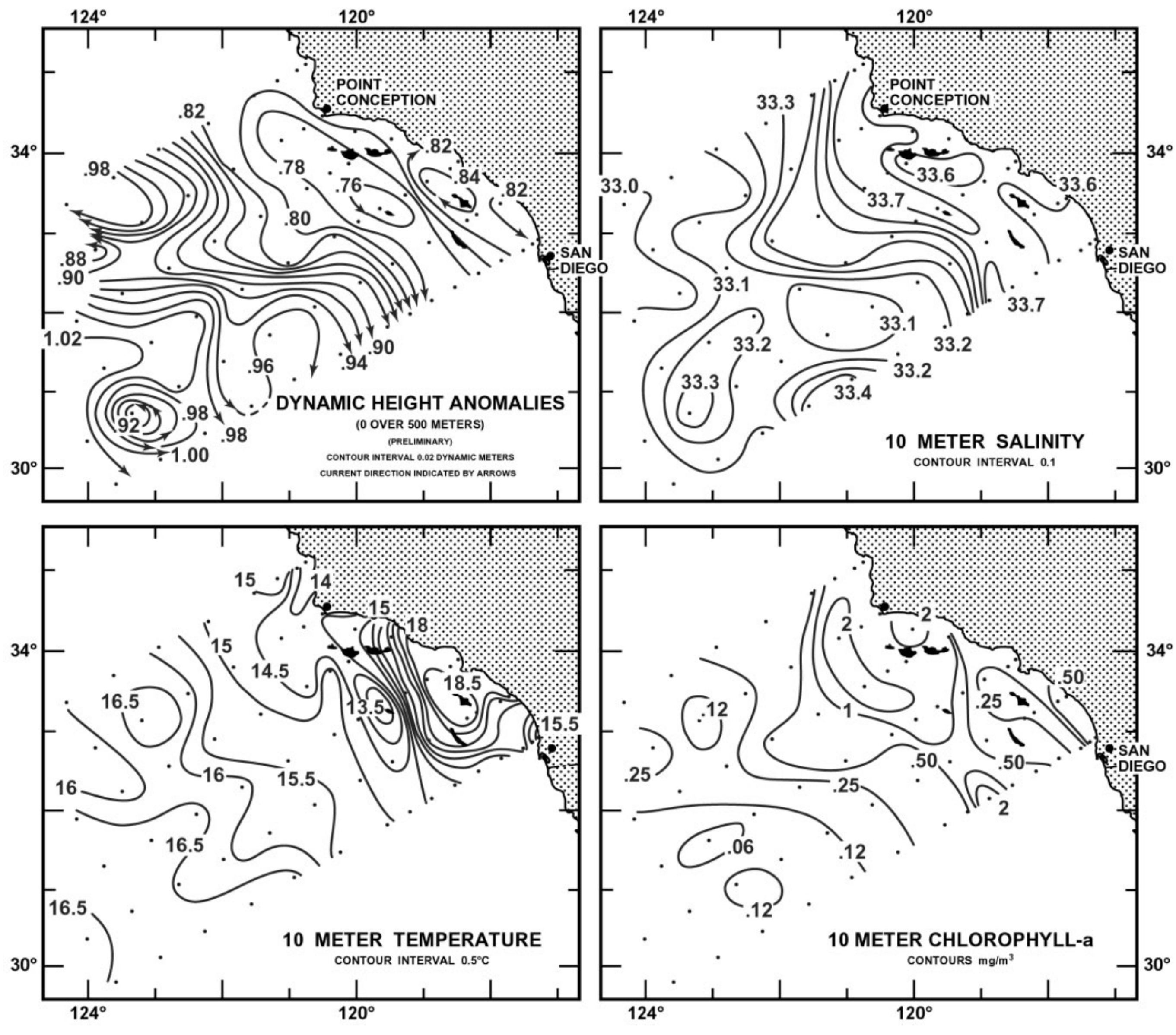

Figure 13. Spatial patterns for CalCOFI cruise 0207 (2–18 July 2002) including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

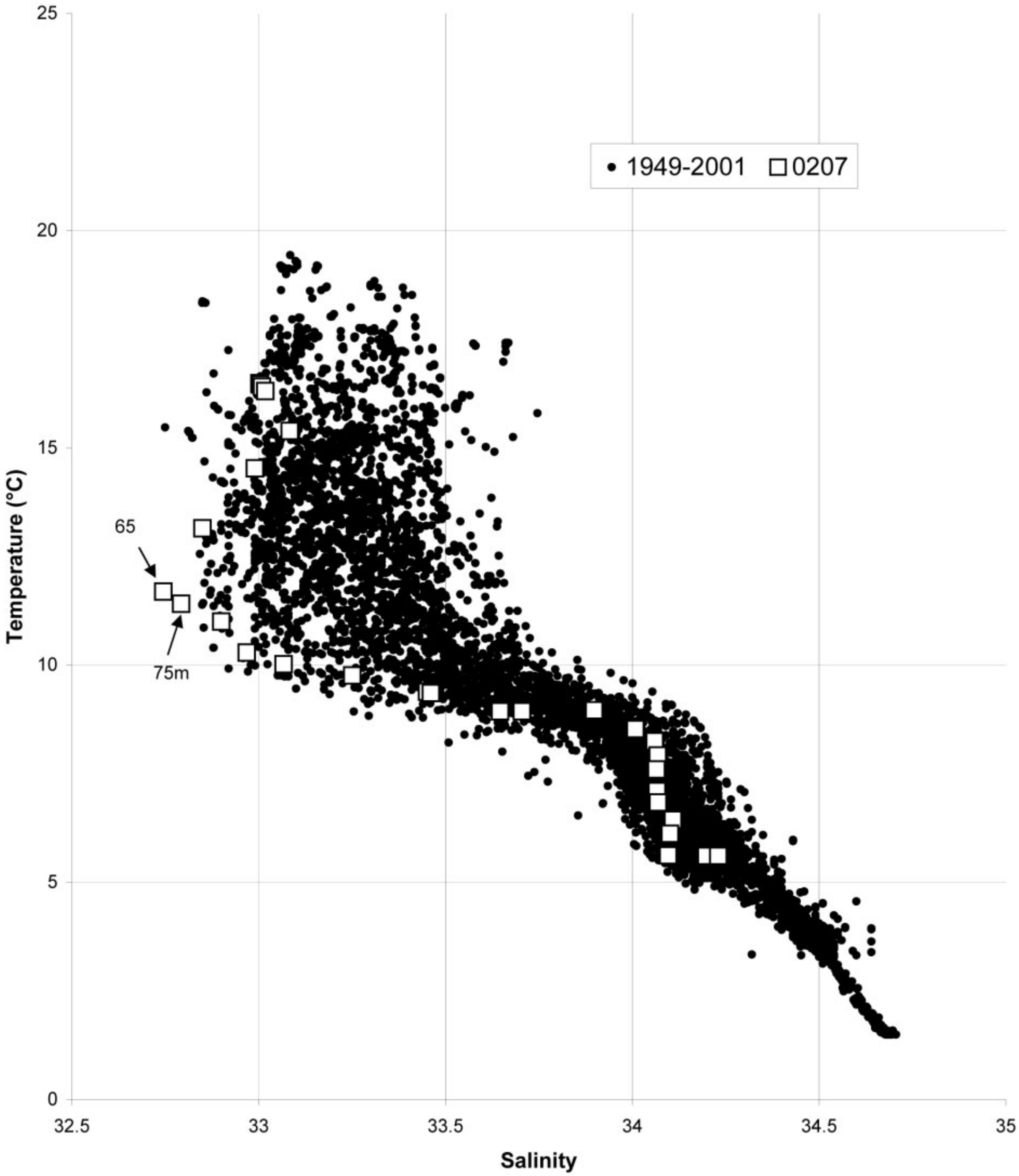

Figure 14. Temperature/salinity plot for station 80.80 on CalCOFI cruise 0207 against T/S point from all hydrographic casts at that station since 1941.

During this cruise, the unusually cool and low-salinity layer, first reported off Oregon, was seen in the upper pycnocline in our region. The feature was strongest at stations 80.80 and 80.90 as well as 83.110 at depths of 65–90 m. Temperature and salinity values were outside the range of all previous observations at these stations (fig. 14).

0211 (10–26 Nov. 2002). The big zonal offshore meander of the previous cruise moved southward and was centered along lines 87 to 93; the cyclonic eddy that was present in the last two cruises in the southwest quadrant was no longer within the cruise pattern (fig. 15). The Southern California Eddy was present, with northward coastal flow from La Jolla to Avila Beach. Some

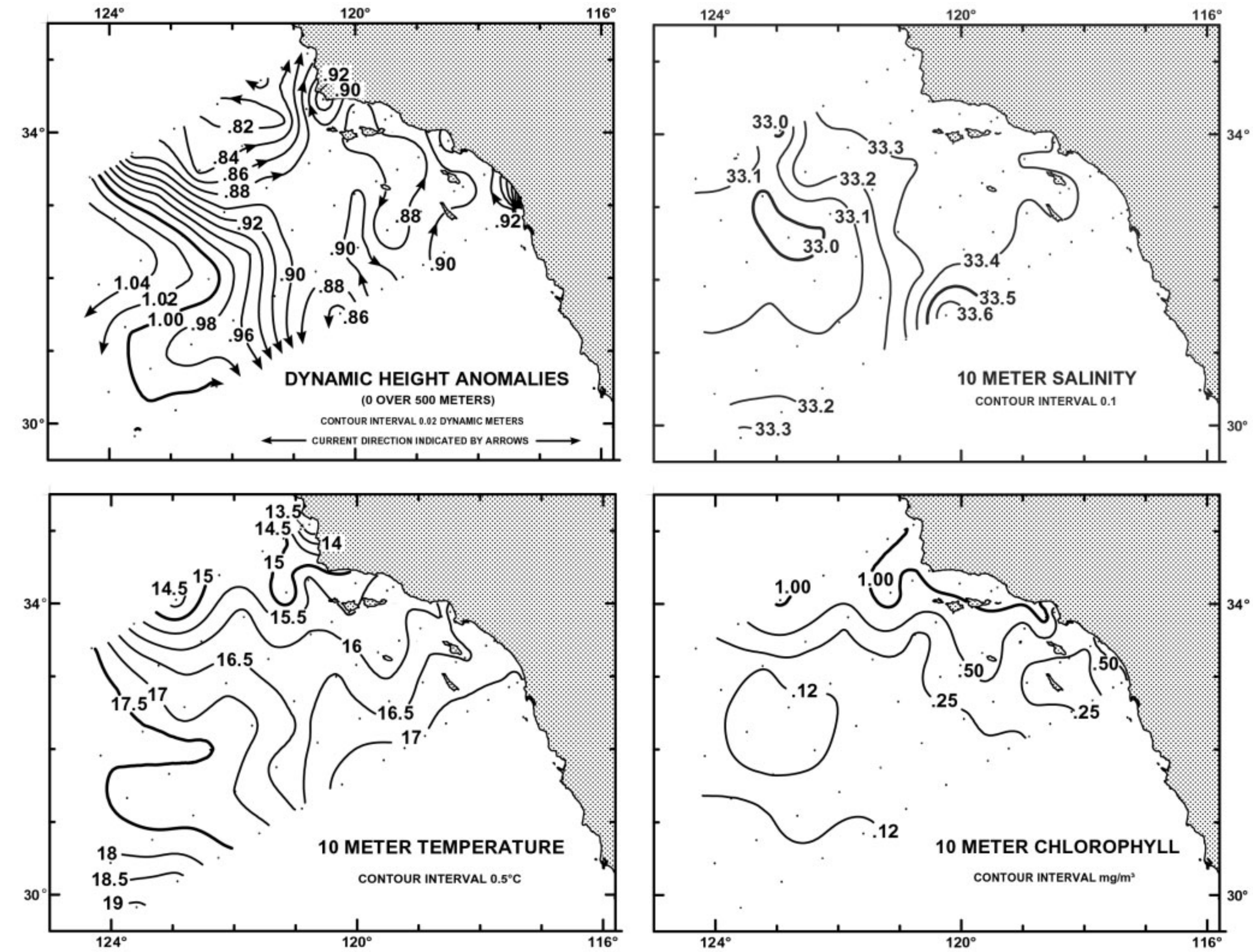

Figure 15. Spatial patterns for CalCOFI cruise 0211 (10–26 Nov. 2002) including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

upwelling was seen off Avila Beach, but overall the SSTs were close to normal. Surface chlorophyll levels decreased; they were highest in the Santa Barbara Channel and at the northern edge of the pattern.

The anomalously low subsurface temperature and salinity feature seen during the summer was still strong, especially at stations 90.100, 90.110, and 93.90. In contrast, the deeper SE coastal waters had a layer of warmer and more saline water at depths between 125 and 300 m, an indication of an enhanced northward subsurface coastal countercurrent.

0302 (30 Jan.–25 Feb. 2003). These data are still at a preliminary stage of processing at the time of this writing (fig. 16). Maps of surface flow show a strong surface coastal countercurrent all the way from La Jolla to at least Monterey. This is a common winter circulation feature, but it appeared to be stronger than usual on this cruise, consistent with the coastwide, poleward wind-stress anomalies (fig. 4). The poleward flow resulted in downwelling at the coast. The main California Current jet remained far offshore. A strong clockwise eddy was present in the southwest corner of the cruise pattern, where there had been an inshore, offshore meander the previous July. The minimum in surface salinity, which is generally a good indicator of the location of the California Current jet, can be seen to enter the region from the outer end of line 80. Surface chlorophyll levels were generally low, as is typical of fall and winter cruises. This cruise continued to document the progressive change from cold, saline waters the previous winter (0201) to warmer and less saline waters (tab. 1). In March, SST averaged about 1°C above normal, after a long period of cooler-than-normal SSTs, reflecting the arrival of the moderate El Niño state of the ocean locally.

The sub-surface anomaly was similar to that seen on the fall cruise, cooler and much less saline than normal at about 75–100 m on some of the offshore stations (especially 83.110), near the σ_t = 25 surface, and warmer

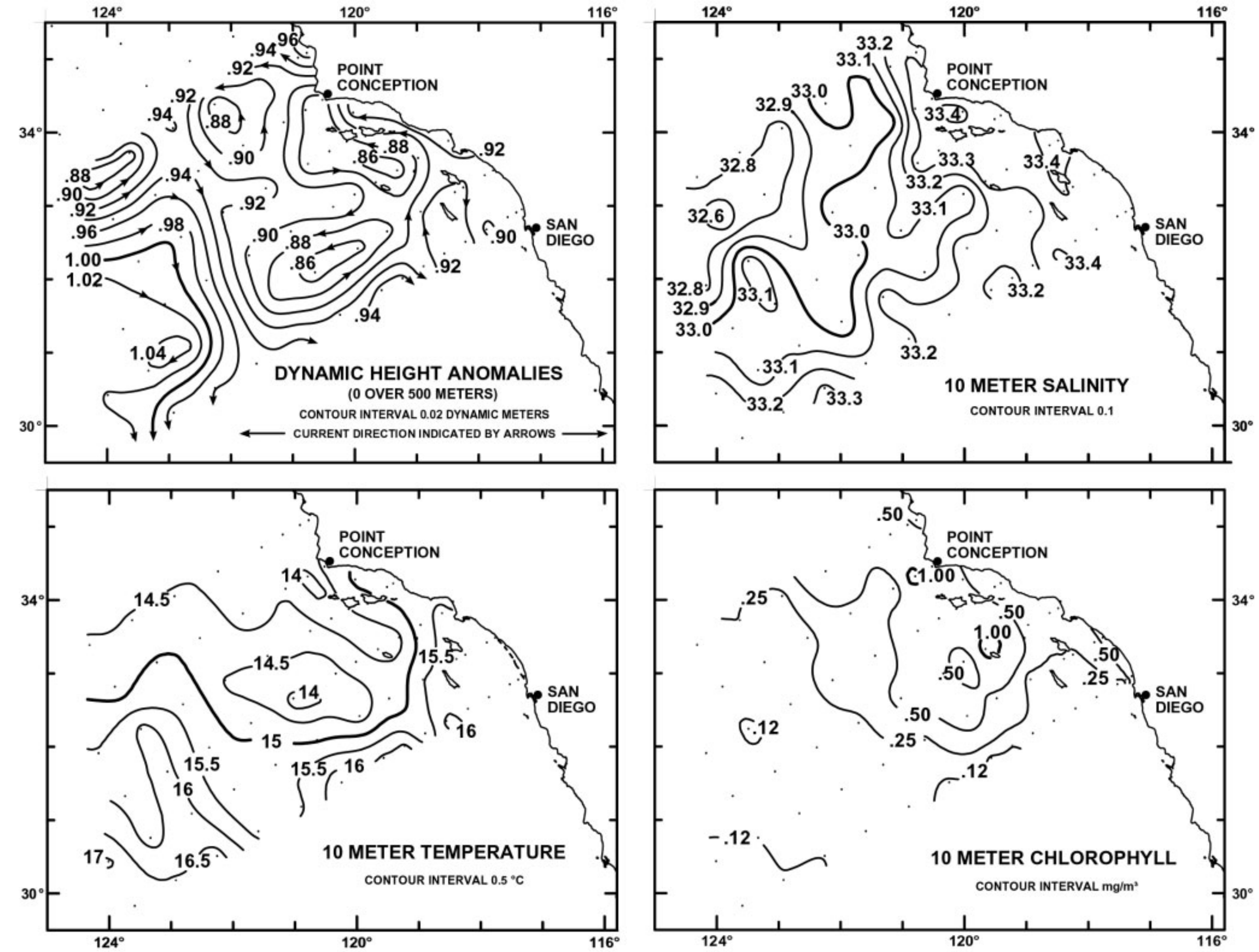

Figure 16. Spatial patterns for CalCOFI cruise 0302 (30 Jan.–25 Feb. 2003) including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

and more saline than normal at deeper depths in the southeastern stations. It was observed at fewer stations (tab. 1), which might be a sign of weakening, or movement offshore.

0304 (4–25 Apr. 2003). These data are also still at a preliminary stage. The map of nearsurface flow reveals the main jet of the California Current at the outer edge of the pattern, confirmed by the lowest salinities found there (fig. 17). A clockwise eddy was present in the southwest corner, and a pair of cyclonic eddies occurred on the inshore edge of the California Current jet. There was another ribbon of meandering flow down the center of the pattern, but it was not as strong as the outer band of flow.

At 10 m, the shelf stations had cool temperatures and higher salinities, characteristic of upwelling. The 10 m temperature anomalies (not shown) were cooler than normal, suggesting stronger-than-normal upwelling. The 10 m chlorophyll levels were quite high all along the shelf stations, as well as in a band just beyond the outer Channel Islands. The cold, low-salinity upper thermocline feature seen on previous cruises was still present at the offshore stations, again near the $\sigma_t = 25$ surface.

Baja California: IMECOCAL Cruises

0204 (19 Apr.–9 May 2002). Geostrophic currents were equatorward with slight meandering, conditions typical of a spring transition (fig. 18). With the exception of two weak, small-scale gyres between Isla Guadalupe and Punta Eugenia, no conspicuous eddy structures were noticeable. The core of the California Current, as depicted by the salinity minimum at 10 m and 50 m (not shown), was near the coast on sections 97 and 100 but south of these lines it was displaced southwestward. Three coastal, low-temperature upwelling regions were present south of coastal prominences: Ensenada, Punta Baja, and Punta Eugenia. These inshore locations were associated with high chlorophyll *a*

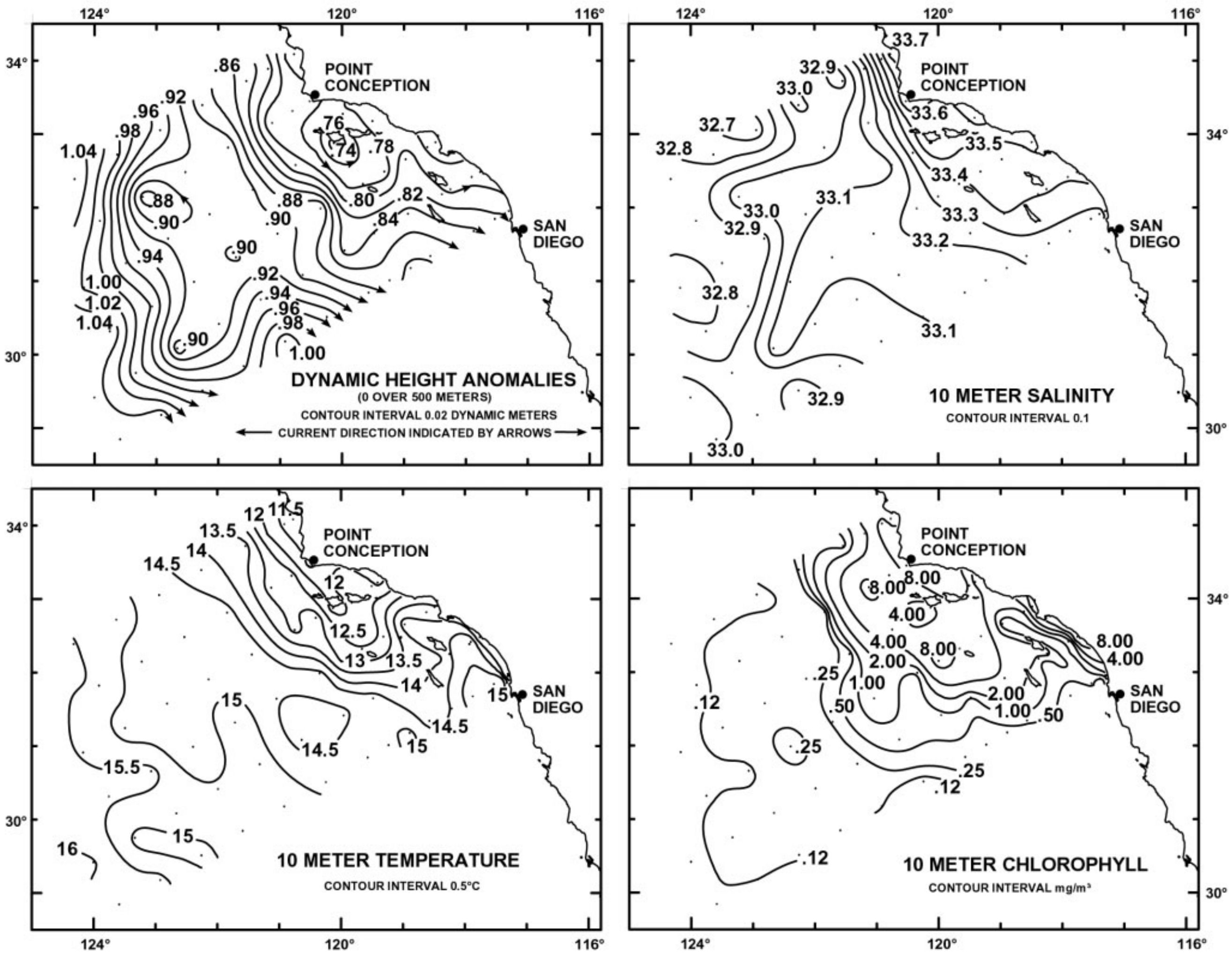

Figure 17. Spatial patterns for CalCOFI cruise 0304 (4–25 Apr. 2003) including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

values (> 8 mg/m^3). Chlorophyll *a* patterns followed those of geostrophic currents and were similar to those described for April 1999 by Lavaniegos et al. (2002) during La Niña conditions, that is, high coastal concentrations associated with upwelling centers and diminishing concentrations offshore.

0207 (12 July–2 Aug. 2002). An eddy-rich California Current was characteristic of this summer season, the most noticeable feature being the quite energetic anticlockwise gyre west of Punta Eugenia (fig. 19). The California Current entered the survey region from the outermost part of sections 100 and 103 and divided into two branches; the northern branch gave rise to a return flow that was part of the Southern California eddy (fig. 13). The other branch flowed southeastward towards Vizcaino Bay and was entrained into the mesoscale cyclonic gyre off Punta Eugenia. South of this gyre, the California Current reappeared as a southward flow along the outer part of sections 127 to 137. Inshore, lower temperatures indicated upwelling off Ensenada, Punta Baja and Punta Abreojos (27°N) related to higher values of chlorophyll *a*. High concentrations of chlorophyll *a* were also present around Vizcaino Bay where contours suggest these rich waters were transported offshore by the northern limb of the gyre. Low values of chlorophyll *a* were associated with the outer clockwise circulation. South of Punta Eugenia, the cyclonic circulation off the Gulf of Ulloa (26°N) and the high salinity wedge nearshore indicated the presence of a poleward near surface coastal flow.

0210 (23 Oct.–13 Nov. 2002). Near surface geostrophic currents and the salinity distribution at 10 m (and 50 m, not shown) indicate that the California Current core entered the survey region from the west at Guadalupe Island (fig. 20). A branch of this core flowed north on what appeared to be the southern limb of the Southern California eddy (fig. 15), which extends further south during this season (Lynn and Simpson 1987).

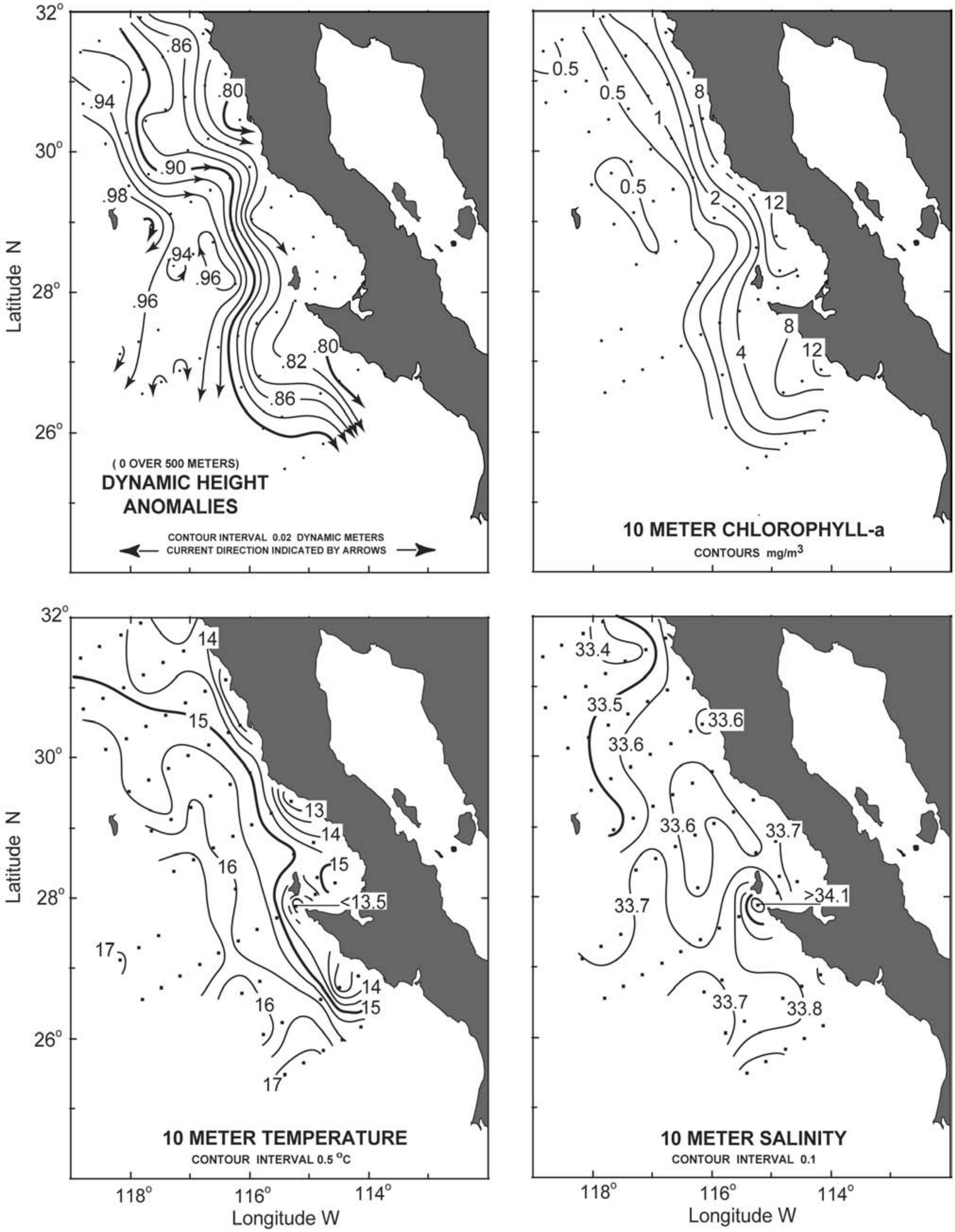

Figure 18. Spatial patterns for IMECOCAL cruise 0204 (19 Apr.–9 May 2002) including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

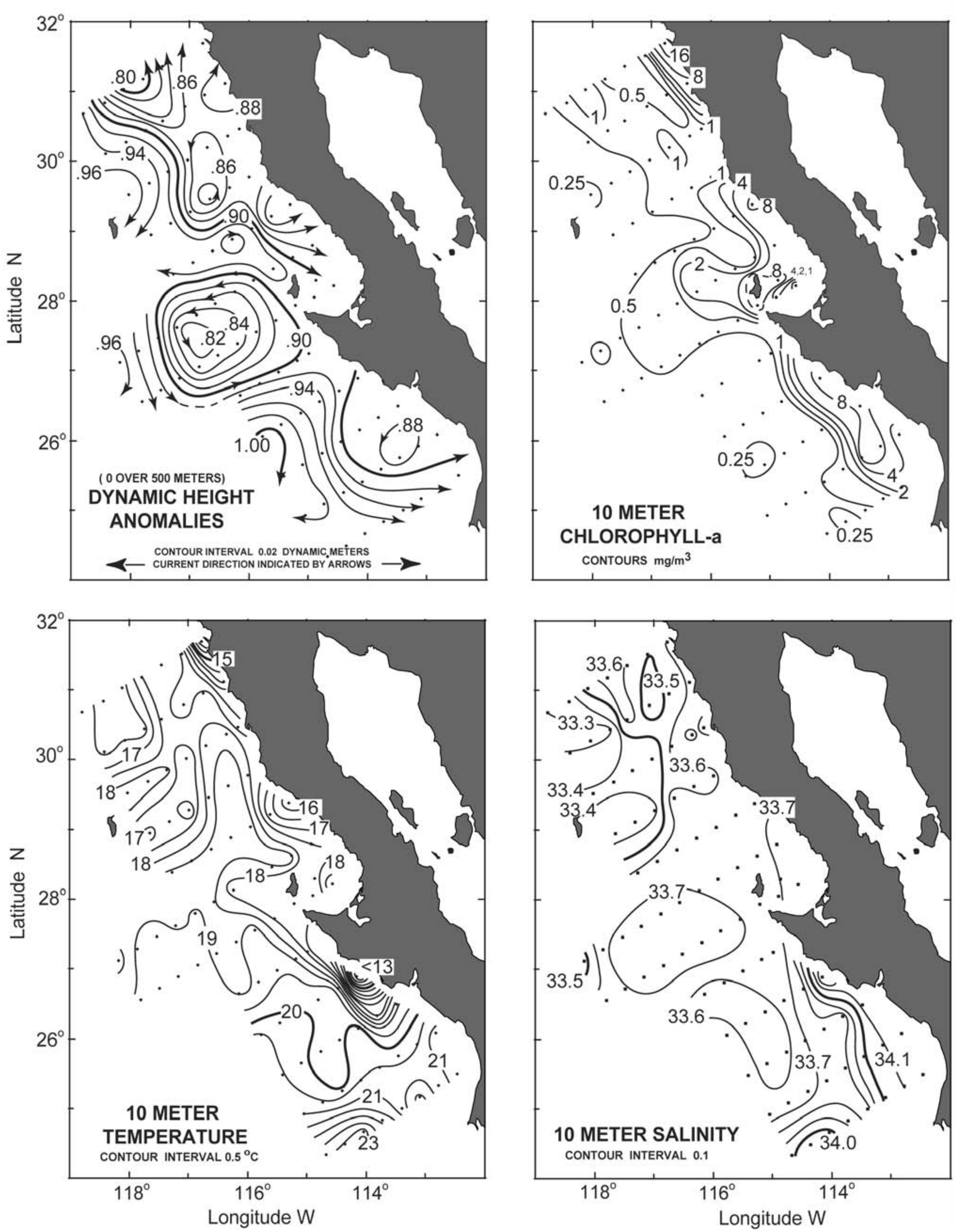

Figure 19. Spatial patterns for IMECOCAL cruise 0207 (12 July–2 Aug. 2002) including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

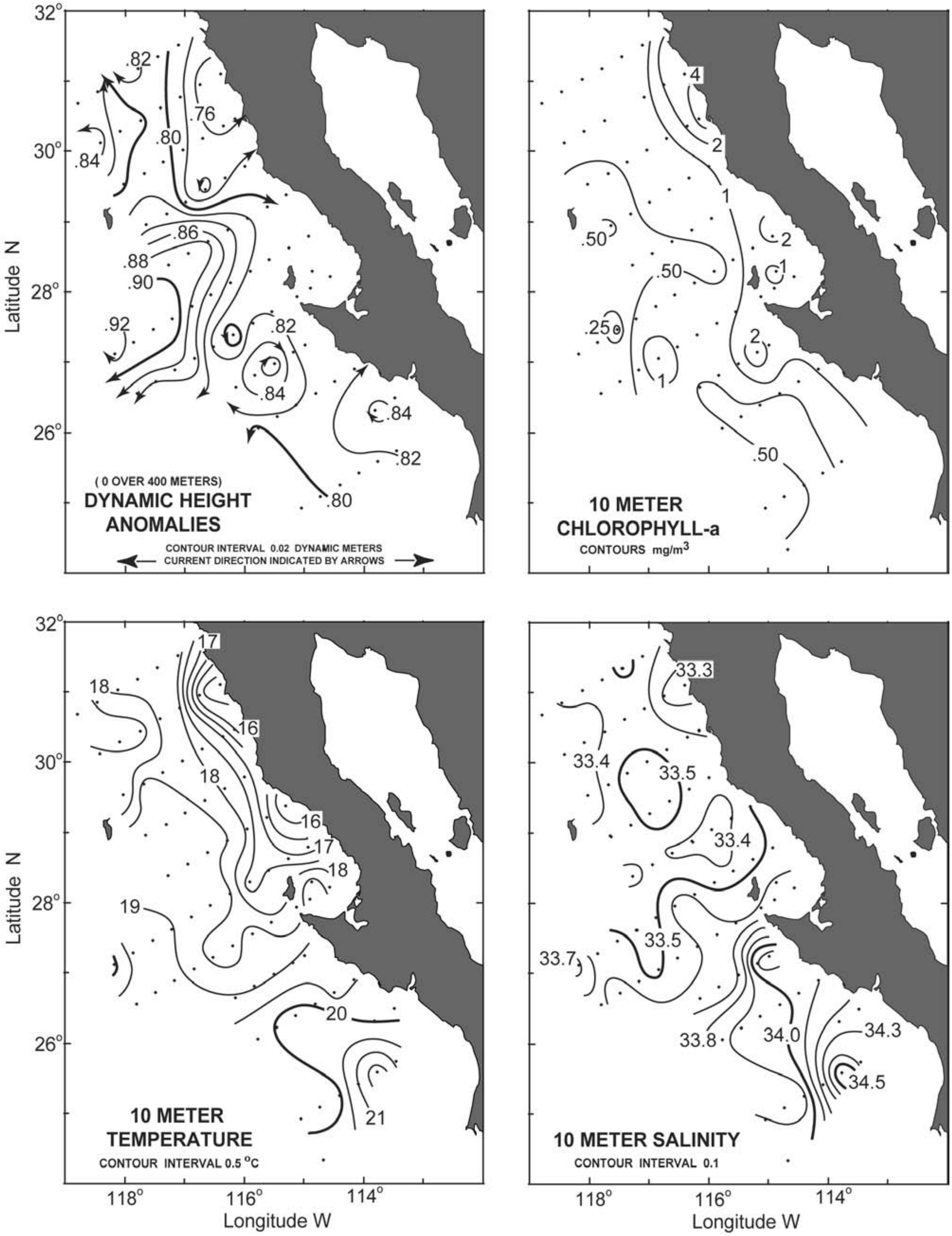

Figure 20. Spatial patterns for IMECOCAL cruise 0210 (23 Oct.–13 Nov. 2002). Note that upper-ocean geostrophic flow was estimated from the 0/400 dbar dynamic height field. Also included are the 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

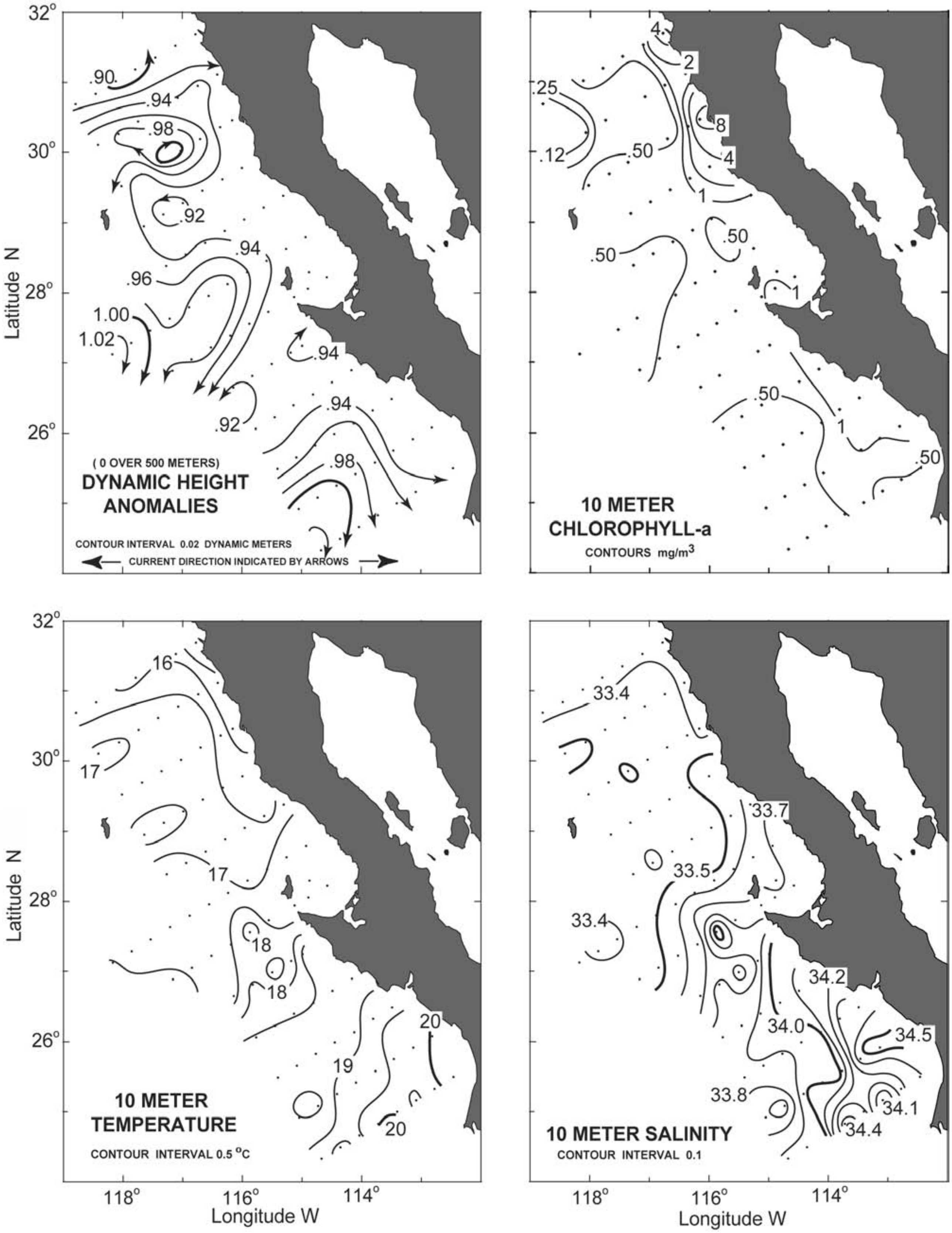

Figure 21. Spatial patterns for IMECOCAL cruise 0301 (30 Jan.–20 Feb. 2003) including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

The other branch moved east to merge with an upwelling, high chlorophyll *a* coastal southward flow. Both flows veered south and circulated around the clockwise eddy centered at 28°N and exited the survey area as an offshore jet at 26.5°N. This gyre was a typical structure of the season as it appears in the climatological means of Lynn and Simpson (1987). The gyre also delimited low chlorophyll *a* concentrations (~0.5 mg/m^3). In general, mesotrophic conditions prevailed (chlorophyll *a* < 0.5 mg/m^3) in offshore areas. Nearshore, low temperatures centered at station 103. 30 were associated with southward flow, low salinities, and the highest concentrations of chlorophyll *a* observed during this cruise. Note that part of this coastal southward flow returned as a coastal poleward current as indicated by dynamic height anomaly contours. South of Punta Eugenia a wedge of high temperatures and salinities (T > 20°C, S > 34) suggest the entrainment of transitional waters as a near surface coastal poleward flow.

0301 (30 Jan.–20 Feb. 2003). During this winter season, the California Current entered the survey area as an eastward flow on the northernmost portion of the survey grid (fig. 21). Upon reaching the coast near Ensenada, it flowed equatorward meandering along cyclonic and anticyclonic gyres while remaining offshore. The California Current left the survey region off Punta Eugenia. South of 26°N, geostrophic currents indicated the presence of an eastward flow carrying waters from the southwest (T > 18°C, S > 34). Salinity contours suggest that this flow was later constrained to the coastal region. Low chlorophyll *a* concentrations were observed throughout the cruise, with high values (> 4 mg/m^3) at some inshore locations. Chlorophyll *a* concentrations of 0.5 mg/m^3 followed closely the meandering of the current.

BIOLOGICAL PATTERNS

Chlorophyll *a*

Off Southern California, integrated chlorophyll values fell well within the range of past values (fig. 22). The seasonal cycle was depressed in 2002, but this may have been partly due to timing if the April cruise missed the peak bloom period. However, the low upwelling index off southern California that spring (fig. 5) suggests that the reduced springtime maximum of chlorophyll *a* may be partially real. Mean cruise chlorophyll values have not been very sensitive to El Niño conditions in the past. Nevertheless, it is tempting to attribute the low value observed in February 2003 to El Niño. The 0302 value was lower than the fall-winter values observed during the 1994–95 event (38.4 µg/l and 36.8 µg/l, respectively), which was of comparable magnitude and timing. In contrast, the chlorophyll *a* concentrations observed on the following cruise, in April 2003, were elevated, the third highest concentration in the past 20 years.

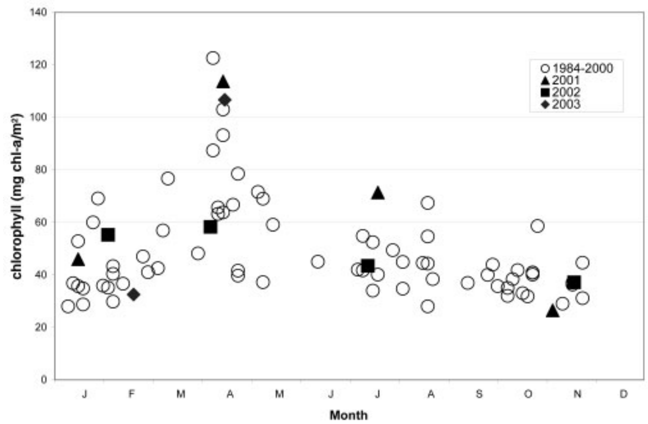

Figure 22. CalCOFI cruise mean integral chlorophyll concentrations. Concentrations observed in 2001, 2002, and February and April 2003 (preliminary) compared with concentrations observed since 1984.

It is unlikely that this elevated chlorophyll *a* concentration was the result of the intrusion of subarctic water, unlike the situation in waters off Oregon. The intrusion appeared to be too far offshore and too deep to influence coastal upwelling or regional productivity or biomass. The depth of the anomaly coincided with the start of the nutricline, and the nutrient content was not noticeably elevated.

One unusual aspect of the phytoplankton in April 2002 was the dominance of *Pseudo-nitzschia australis* in the vicinity of Point Conception. The contours of abundance followed those of chlorophyll *a* quite well (Schwing et al. 2002a, fig. 12). This species is one of the major producers of domoic acid, responsible for deaths of marine mammals and birds and even humans. Pelagic fish species, which are less susceptible to the toxin, act as vectors. Subsequent reports indicated that the 2002 bloom was widespread; samples from Monterey Bay also showed a bloom in April,[1] and there were numerous marine mammal strandings reported up and down the coast later that summer. Although *P. australis* occurs frequently in CalCOFI samples, especially in the northern inshore region, it is unusual for it to dominant the flora.

Elevated abundances of *P. australis* were again seen in the Santa Barbara Channel on 0304, but the flora was dominated by the more typical spring-bloom species of hyalochaete *Chaetoceros*. High concentrations of domoic acid were detected that spring and summer between Santa Barbara and Santa Cruz, and the toxin was present as far south as northern San Diego County.[2]

[1]M. Silver, pers. comm.

[2]G. Langlois, pers. comm.

Macrozooplankton Biomass

In 2002, the cruise mean zooplankton biomass off Southern California (fig. 23) was markedly elevated in April and a bit so the previous February. However, values in July and November were below the recent monthly averages for 1984–2001, and the February 2003 value (not shown) was the sixth lowest on record; all volumes lower than this also occurred during El Niño events, as is characteristic of the El Niño conditions.

The complete IMECOCAL zooplankton series from September 1997 to February 2003 shows the highest variability in fall and winter (fig. 24). As to the north, values in February 2003 were low; this was the second consecutive winter with mean values lower than the historical mean for the period 1951–84 (CalCOFI cruises in the Baja California region). These low values contrasted strongly with the warm winter of 1998. The rest of the 2002 cruises had mean biomass values within the confidence interval of the period 1951–84. The largest biomass for the IMECOCAL series occurred in July 2002, but this appeared to be typical for that time of year in the historic context.

Mean tendencies in macrozooplankton biomass among regions (fig. 25) showed that during February and April 2002 biomass was highest off Southern California (CalCOFI lines 80–93) and lowest off northern Baja California (IMECOCAL lines 100–110), with values off central Baja California (lines 113–133) falling between these. From July 2002 to February 2003 the three regions showed similar mean values. Considering previous years, the regions have been responding in coherence from July 2000, with the exception of winter and spring 2001 and 2002, when low volumes off northern Baja California were the rule. During the period September 1997–April 1999, when the California Current was influenced by a strong warming and a subsequent cooling (El Niño and La Niña), the regions had very different values and trends.

Fish Eggs

In spring 2002, egg concentrations of sardine, anchovy, and jack mackerel were, in general, typical of recent spring values (fig. 26). Sardine eggs occurred broadly between the California Current and nearshore waters and were most abundant between Point Conception and Monterey Bay, although they also occurred on the southern- and northernmost lines. Anchovy eggs were confined to the Southern California Bight, and jack mackerel eggs were offshore of the sardine eggs, with relatively little overlap. Overall, sardine eggs were far more abundant than anchovy or jack mackerel eggs, but peak abundances were less in spring 2002 than in the prior two springs and in the spring of 2003 (preliminary; for more information, see http://swfsc.nmfs.noaa.gov/FRD/CalCOFI/CurrentCruise/currentcruise.htm).

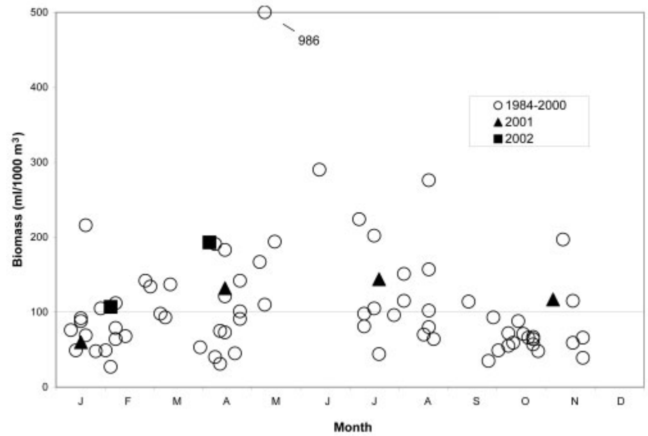

Figure 23. CalCOFI cruise mean macrozooplankton biomasses. Biomass values observed in 2001, 2002, and February 2003 compared with those observed since 1984.

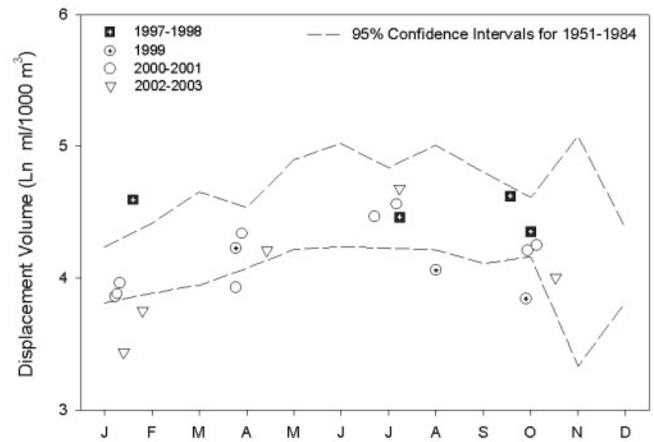

Figure 24. Mean macrozooplankton biomass of 21 IMECOCAL cruises from September 1997 to February 2003. Dashed lines indicate 95% confidence intervals for the historical mean of 1951–84 for the CalCOFI cruises in the region off Baja California. Data have been transformed to logarithms.

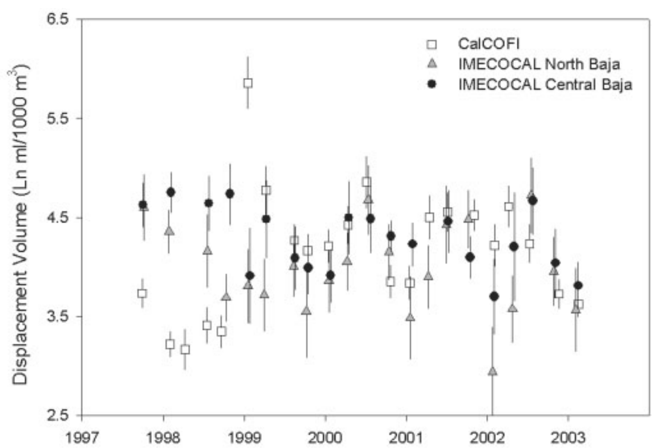

Figure 25. Mean macrozooplankton biomass in three regions of the California Current: Southern California (lines 80–93), northern Baja California (lines 100–110), and central Baja California (lines 113–133).

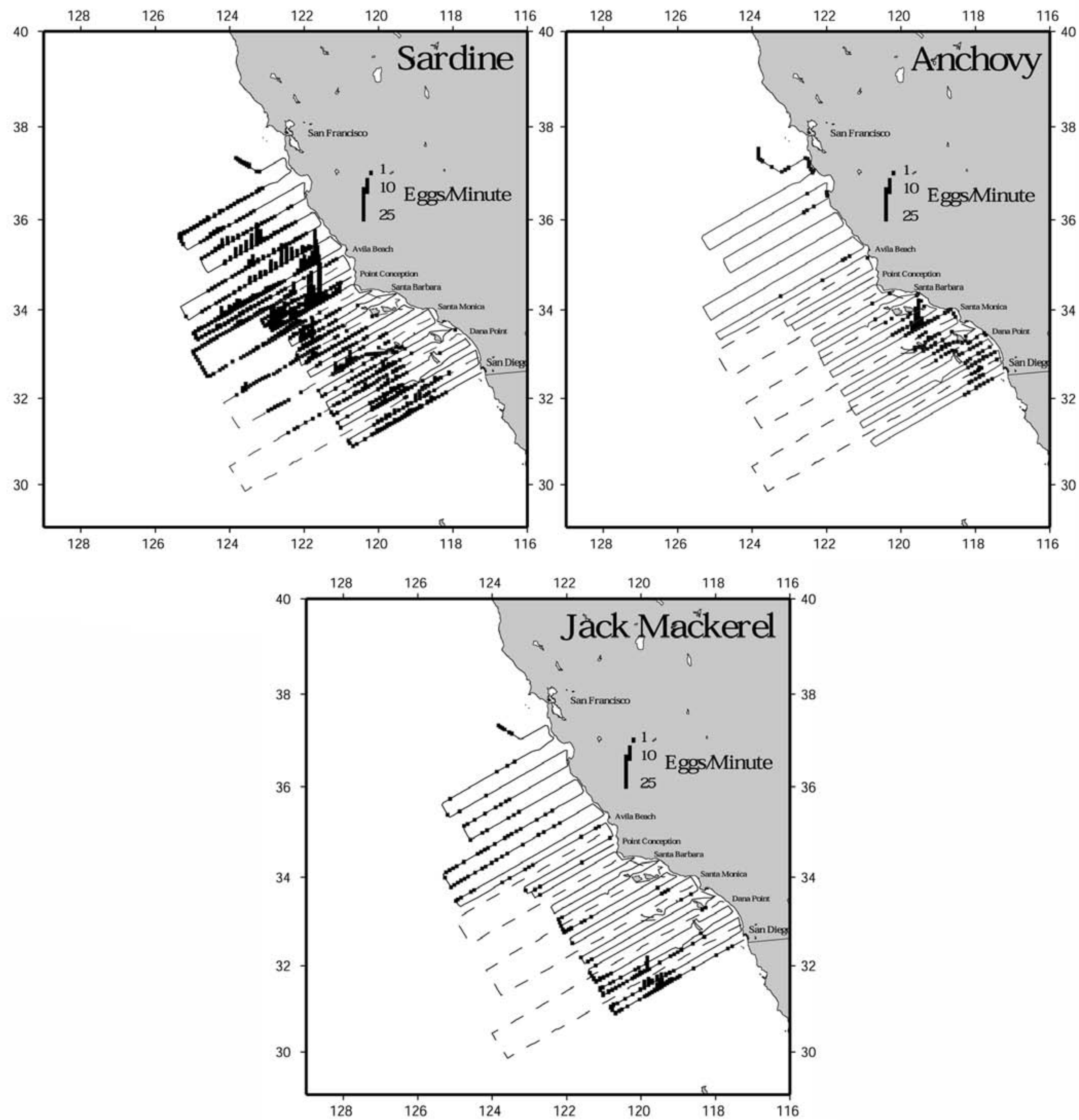

Figure 26. Rate of occurrence of eggs of Pacific sardine (*Sardinops sagax*), northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*) sampled with the continuous underway fish egg sampler (CUFES) in April-May 2003. Dashed line represents RV *New Horizon* cruise; solid line represents RV *David Starr Jordan* cruise. One egg per minute corresponds to approximately 1.4 eggs per cubic meter.

Avifauna

In this report we describe observations of marine bird populations collected during 2002–2003 and compare these observations to data from the CalCOFI and PRBO time series. Our objective is to assess the response of marine bird communities off the west coast of North America to the 2002–2003 El Niño event and to interpret these short-term fluctuations within the context of the hypothesized 1998–99 shift to a cold-water regime (Bograd et al. 2000; Durazo et al. 2001; Schwing et al. 2002a). Observations of marine bird populations provide information on the response of upper-trophic preda-

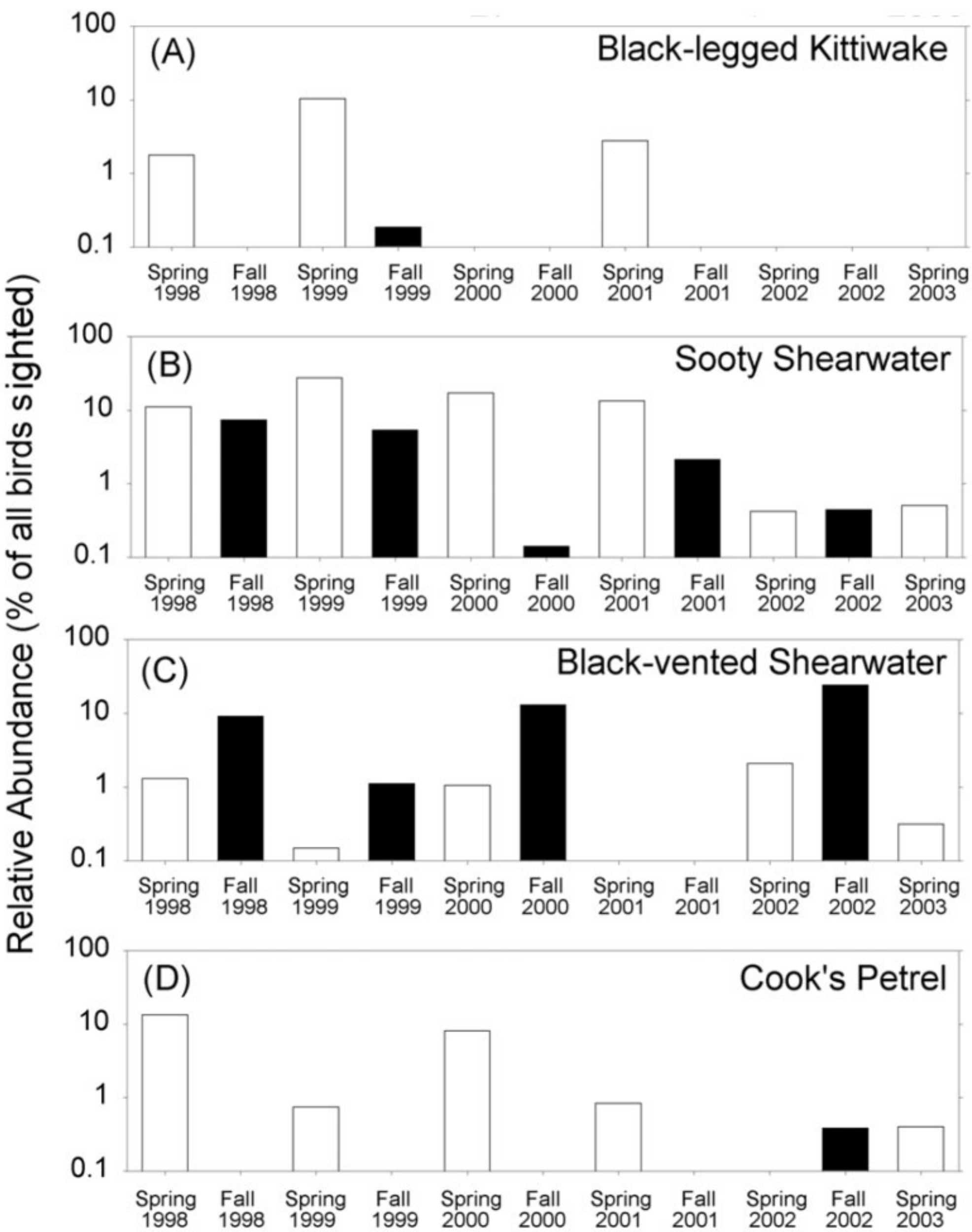

Figure 27. Relative abundance of four indicator seabirds with an affinity for distinct water temperature and biogeographic domains: (*a*) and (*b*) subarctic/cold water taxa, (*c*) and (*d*) subtropical/warm-water taxa. Importance was computed by dividing the number of individuals of a given species by the total number of seabirds sighted during each cruise. The white histograms depict spring cruises, and the black, fall cruises.

tors to interannual and longer-term oceanographic variability. Previous CalCOFI observations have documented fluctuations in seabird community structure in response to changes in the physical and biological properties of the California Current system (Veit et al. 1996; Hyrenbach and Veit 2003). Colony-based studies of seabird diet, demography, and population dynamics underscore the conclusions of at-sea surveys. These time series have revealed that locally breeding bird populations are sensitive to shifts in ocean productivity and prey availability over short (interannual) and long (decadal) temporal scales (Ainley et al. 1995; Sydeman et al. 2001; Abraham and Sydeman, in press).

To examine short-term (interannual) fluctuations in the composition of marine bird communities at sea, we describe changes in the relative abundance of four species with different water mass preferences and biogeographic affinities (fig. 27). The subtropical black-vented shearwater (*Puffinus opisthomelas*) shifts its distribution northward into the CalCOFI study area in the fall, particularly during warm-water years. The Cook's petrel (*Pterodroma cooki*) is a pelagic spring-summer visitor that moves shoreward during warm-water periods and has increased significantly in abundance off southern California between 1987 and 1998. The once numerically dominant cold-water species, the sooty shearwater (*Puffinus griseus*), is a spring-fall visitor that has declined by 74% between 1987 and 1998. Finally, the black-legged kittiwake (*Rissa tridactyla*) is a subarctic winter visitor that becomes more numerous during cold-water years, particularly in spring (Lynn et al. 1998; Hayward et al. 1999; Hyrenbach and Veit 2003).

Surveys of marine bird communities at sea between the fall of 1998 and the spring of 2003 failed to detect clear and persistent signals of a shift to a cold-water regime. After the transition from one of the strongest El Niño events in the twentieth century to La Niña conditions in the summer and fall of 1998, 1999 was characterized by a prolonged period of cool water and enhanced upwelling along the west coast of North America (Hayward et al. 1999; Bograd et al. 2000; Schwing et al. 2000). The two cold-water indicators (black-legged kittiwake and sooty shearwater) occurred off southern California in high numbers during 1999. The kittiwake reached its highest relative abundance (approximately 10% of all birds sighted) in the spring of 1999, when the sooty shearwater accounted for over 27% of all birds observed (fig. 27a,b). Interestingly, the kittiwake was also observed in the fall of 1999, a period when the subtropical black-vented shearwater had almost completely vanished from the region (fig. 27c).

However, during the spring cruise of 2000, we observed no kittiwakes and fewer sooty shearwaters compared with their relative contribution during 1999 (fig. 27a,b). Additionally, there was a rebound in the importance of the two warm-water species, to levels similar to those observed during the spring of 1998 (fig. 27c,d). The return to a warm-water avifauna was particularly evident in the fall of 2000. At this time, the black-vented and the sooty shearwater accounted for 13% and $< 1\%$ of all the birds sighted, respectively (fig. 27b,c).

During 2001 and 2002, persistent moderate to strong (1–4°C) negative SST anomalies were observed off the west coast of North America (El Niño Watch January 2001–December 2002 advisories, http://coastwatch.pfel.noaa.gov/elnino.html) (fig. 4). Once more, the avifauna responded to these new oceanographic conditions, and a shift toward a cold-water community was evident by spring 2001. At this time, the combined relative contribution of the two warm-water indicators declined to $< 1\%$ of all the birds sighted, whereas the importance of the sooty shearwater and the kittiwake increased but remained below the number observed during 1999 (fig. 27a,b). The fall cruise revealed a bird community dominated by phalaropes (*Phalaropus* spp.) and devoid of warm-water indicators (fig. 27c,d).

Starting in the fall of 2002, positive temperature anomalies developed offshore (west of 125°W; fig. 4). Subsequently, anomalously warm water (1–2°C) was apparent along the southern California coast and off Oregon and central California starting in December 2002 (fig. 4; El Niño Watch January 2002–March 2003 advisories, http://coastwatch.pfel.noaa.gov/elnino.html). The fall CalCOFI cruise revealed a large northward incursion of the subtropical black-vented shearwater, which accounted for ~25% of sightings (fig. 27c). The other warm-water indicator, the Cook's petrel, was also observed in large numbers at this time, when it reached the highest fall-time relative abundance since 1997. Notably, conditions during spring 2003 were indicative of a transitional community with both warm-water and cold-water indicator species present but numerically dominated by phalaropes and other spring migrants.

In contrast to the fluctuating seabird communities at sea, marine birds at the Farallon Islands, central California (37°N), revealed record high reproductive success in 2002 (fig. 28). In particular, mean annual productivity reached the highest value in the entire 30+ year time series for the Cassin's auklet (*Ptychoramphus aleuticus*), 1.18 chicks fledged per breeding pair; pelagic cormorant (*Phalacrocorax pelagicus*), 2.59 chicks fledged per breeding pair; and pigeon guillemot (*Cepphus columba*), 1.46 chicks fledged per breeding pair. In fact, when all six breeding species are considered, 2002 represents the fourth consecutive year of positive seabird anomalies. Notably, this period of high and sustained Farallon seabird productivity started after the hypothesized regime shift of 1998–99 (tab. 2).

To further consider whether seabird demography is indicative of a new cold-water regime, we compared annual seabird productivity values during the warm-water (1990–98) and cold-water (1999–2002) periods before and after the 1998–99 regime shift (tab. 2). The seabird productivity data from 2002 supports the preliminary evidence of enhanced seabird productivity after 1998 (see also Durazo et al. 2001; Schwing et al. 2002a). In particular, the breeding-success data revealed significant increases in the productivity of four species (Cassin's auklet, pelagic cormorant, pigeon guillemot, and rhinoceros auklet [*Cerorhinca monocerata*]), and the marginally significant ($0.10 < p < 0.05$) increase in the reproductive success of the Brandt's cormorant (*Phalacrocorax penicillatus*). For the common murre (*Uria aalge*), we did not detect a significant increase in productivity starting in 1999.

In order to evaluate the impact of the developing 2002–2003 El Niño on seabird productivity patterns we reanalyzed a hierarchical clustering analysis of the seabird productivity data between 1990 and 2001, including data

TABLE 2
Comparison of the Productivity of Six Seabird Species Breeding at the Farallon Islands (off Central California), in Conjunction with the 1998–99 Regime Shift

	Productivity (chicks fledged/pair)				
Seabird species	1990–98	1999–2002	Proportional change (%)	Mann-Whitney U	*p* value
Brandt's cormorant	1.38 (±0.93)	2.17 (±0.20)	+57	6	0.064
Cassin's auklet	0.62 (±0.24)	0.97 (±0.17)	+56	2	**0.013**
Common murre	0.66 (±0.27)	0.81 (±0.02)	+22	14	0.531
Pelagic cormorant	0.54 (±0.64)	1.84 (±0.69)	+239	2	**0.013**
Pigeon guillemot	0.54 (±0.38)	1.28 (±0.15)	+138	2	**0.013**
Rhinoceros auklet	0.48 (±0.16)	0.63 (±0.02)	+32	4.5	**0.037**

Note: Numbers in parentheses are mean standard deviation. The proportional change in seabird productivity was quantified as PC = 100% * [(after) − (before) / (before)]. Positive and negative PC values indicate increasing and decreasing productivity, respectively. Boldfacing denotes statistical significance.

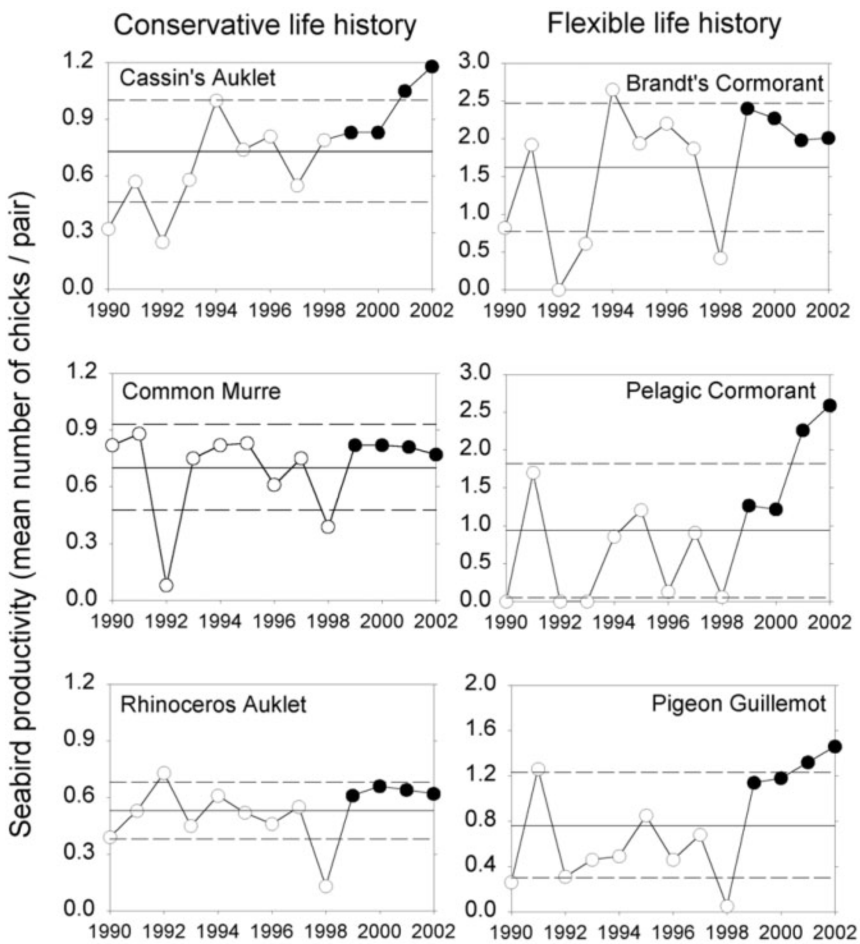

Figure 28. Anomalies of productivity for six seabird species breeding at southeastern Farallon Island (central California). Solid horizontal lines represent long-term averages (1990–2002); hatched lines represent the variability (mean ±SD); solid dots highlight productivity anomalies after the hypothesized regime shift during the winter of 1999.

from the 2002 breeding season. The previous analysis revealed three distinct clusters of years, corresponding to time periods of high, intermediate, and low productivity, respectively (Schwing et al. 2002a). The reanalysis indicated that 2002 was somewhat of a peculiar year between the intermediate productivity (2 years: 1994 and 1996) and the high productivity (6 years: 1999–2001, as well as 1991, 1995, and 1997) clusters. Interestingly, while three species yielded the highest productivity values in the time series, the reproductive success of the common murre declined slightly to 0.77 chicks fledged per breeding pair (fig. 28). This is within the normal range of variation found for this species.

Also, we evaluated changes in the chick diet compo-

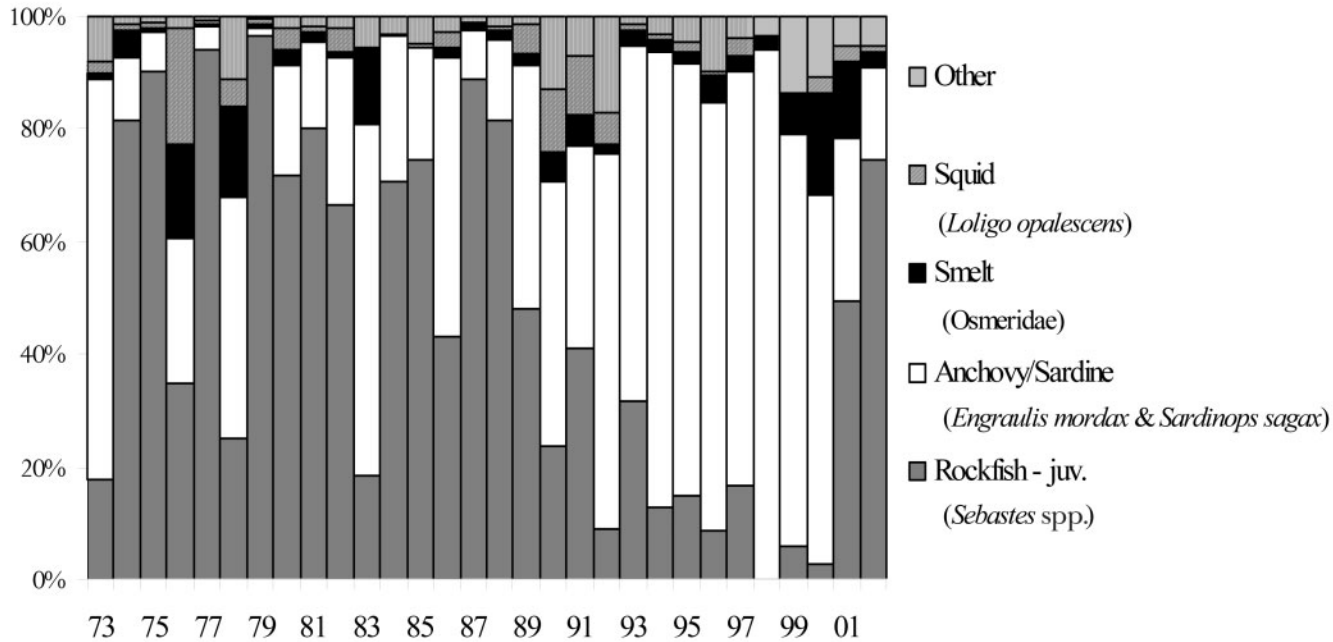

Figure 29. Interannual diet composition of common murre chicks at SE Farallon Island (central California, 1973–2002), based on the number of prey items of each species consumed. The "other" category includes Pacific butterfish (*Peprilus simillimus*), juvenile salmon (*Oncorhynchus* spp.), flatfishes (*Bothidae* and *Pleuronectidae*), juvenile lingcod (*Ophiodon elongatus*), señorita (*Oxyjulis californica*), and other fish species comprising less than 5% of the diet in any given year.

sition for the common murre from 1973 to 2002 (fig. 29). These data are indicative of a decline in the take of rockfish (*Sebastes* spp., mostly *Sebastes jordani*) by murres and other breeding seabird species after 1989 (Sydeman et al. 2001). However, starting in 2001 and continuing in 2002, there was an increase in the proportion of rockfish in the murre diet. In 2002, approximately 74% of the chick diet was composed of juvenile rockfish, a level comparable to those observed in 1987–88. The murre diet is indicative of changes in the abundance of young-of-the-year (i.e., 0-age-class) rockfish in the Gulf of the Farallons and adjacent waters (Sydeman et al. 2001). Indeed, midwater trawl surveys conducted by NOAA Fisheries in the vicinity of the Farallon Islands in 2002 documented an increase in juvenile rockfish abundance over the preceding years,[3] thereby corroborating the conclusions drawn from the study of diets of breeding seabirds.

Together these results strongly suggest that the Farallon Island ecosystem has responded to the 1998–99 regime shift, with four consecutive years of elevated seabird productivity across the board, and the recovery of one of the bird's primary prey resources, juvenile rockfish. It is worth noting, however, that seabird reproductive success during the 2002 breeding season appeared intermediate between the conditions characteristic of high and intermediate productivity years (Schwing et al. 2002a). Namely, while some species reached the highest productivity levels recorded to date, others declined slightly (fig. 28). We note that the sooty shearwater, a transequatorial migrant that dominated the avifauna in the late 1980s, has yet to recover. Modeling studies of prey consumption and energetic requirements may provide insights into the shearwater's numerical response to changing ocean climate and prey availability in the California Current system.

Colony-based and at-sea observations during 2002–2003 have provided additional evidence that marine birds respond to short-term (interannual) and longer-term (decadal) changes in the conditions of the California Current system. However, locally breeding populations and at-sea communities differ in the magnitude and persistence of their responses.

DISCUSSION

Three large-scale events claimed the attention of West Coast oceanographers between April 2002 and April 2003: the anomalous intrusion of subarctic water, the predicted El Niño, and the possible interdecadal climate shift in 1998–99. All of these interacted in some way or another, and interpreting the various signals is not certain.

The anomalous intrusion of cold, fresh water was clearly seen from the Gulf of Alaska to the latitude of southern California. It was not evident from the IMECOCAL surveys. It may have lost its unique characteristics by these latitudes or occurred offshore of the survey area. The intrusion was characterized by elevated nutri-

[3]Mills, K. L., S. R. Ralston, T. Laidig, and W. J. Sydeman. Functional response curves and the use of top predator diet as indicators of pelagic juvenile rockfish (*Sebastes* spp.) abundance in the California Current system. (manuscript)

ent levels and upwelling of these waters off Oregon and northern California and resulted in enhanced chlorophyll concentrations. A similar impact further south was not noticed. The effects of this intrusion were opposite those of the predicted El Niño and appeared to dominate conditions, at least in the northern portion of the region. As of the most recent cruises (April 2003) the feature was still present off Oregon and Southern California. Further development and dissipation of this cold, fresh anomaly will be closely followed.

The effects of the El Niño that developed in the California Current system last winter were short-lived and modest by most standards. The event was marked by increased SSTs throughout the region in late winter, but these rapidly cooled in the spring. The influence of El Niño was most clearly seen in the biological characteristics. Chlorophyll concentrations were reduced in February 2003 in the CalCOFI region (fig. 22). Macrozooplankton volumes were low in February 2003 in both CalCOFI and IMECOCAL regions (fig. 25).

The most apparent response to this El Niño event in our biological data appeared in seabird communities at sea. The avifauna has shifted from year to year in response to transient warming and cooling periods since the spring of 1998, with a series of short-term incursions of subarctic taxa and subtropical species (fig. 27). Starting in the second half of 2002, we observed changes in seabird communities that were consistent with the onset of El Niño conditions. By the fall of that year, the avifauna was dominated by warm-water indicators, like the black-vented shearwater (fig. 27c). The northward incursions of subtropical species were particularly apparent during the spring of 2003, when brown boobies (*Sula leucogaster*), black storm-petrels (*Oceanodroma melania*), and least storm-petrels (*O. microsoma*) were recorded off southern California. Large numbers of these species have not been observed within the CalCOFI study area since the 1997–98 El Niño event (Hyrenbach and Veit 2003).

This was the first winter in five years with warm surface waters in the California Current system (fig. 4). The rapid breakdown of El Niño conditions in our waters and the evidence for a La Niña to develop next year strengthen the possibility that an interdecadal climate shift took place in 1998–99. Of the biological data under consideration in this report, the avifauna provide the strongest evidence for a corresponding "regime shift." Because seabird populations integrate the variability in oceanographic conditions during the breeding season, productivity metrics respond strongly to interannual changes in ocean conditions and prey availability (Ainley et al. 1995; Sydeman et al. 2001). The productivity data from the Farallon Islands indicate that locally breeding seabird populations have undergone four consecutive years of elevated reproductive success across the board (fig. 28). This change in seabird productivity suggests that breeding populations have benefited from enhanced upwelling and ocean productivity after the 1998–99 regime shift (tab. 2). Nevertheless, we have yet to observe the recovery of the sooty shearwater, a transequatorial migrant that dominated the avifauna in the late 1980s, in response to the switch to a cold-water period. Modeling studies of prey consumption and energetic requirements may provide insights into the shearwater numerical response to changing ocean climate and prey availability in the California Current system.

Additional at-sea and colony-based observations are needed to fully characterize and understand the response of marine bird populations to ocean climate variability in the California Current system. As with all ecosystem components, we are faced with the challenge of reconciling range shifts with local population changes in productivity and mortality.

The evolution of the La Niña conditions currently developing in the tropical Pacific Ocean (NOAA Climate Prediction Center, ENSO Diagnostic Discussion, http://www.cpc.ncep.noaa.gov) will set the stage for 2004. Understanding the coupling of high-frequency (i.e., ENSO) and low-frequency (i.e., PDO) environmental variability will require continued time series of physical and biological properties. Once more, the dynamic nature of the California Current system underscores the value of prolonged time series when interpreting short-term and long-term changes in marine ecosystems (McGowan 1990).

ACKNOWLEDGMENTS

Nearly all of the data discussed here was collected the hard way and would not have been collected at all without the seagoing scientists and technicians who spent long, cold, wet hours doing so, or the ships' captains and crews who took us where we needed to go and kept us safe. We are indebted to them all. Christine Abraham and Peggy Yen (PRBO) compiled the seabird productivity and at-sea data, respectively. Pete Warzybok and Russell Bradley (PRBO) supervised collection of Farallon seabird data in 2002. Phaedra Green-Jessen and Mark Pickett assisted PFEL in preparing figures.

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APPENDIX

This appendix contains a selection of e-mail correspondence concerning an anomolous intrusion of subarctic waters. Correspondence is among Jane Huyer (Oregon State University), Curtis Collins (Navy Postgraduate School), Ronald Lynn (Southwest Fisheries Science Center/National Marine Fisheries Service), Howard Freeland, Frank Whitney (Institute of Ocean Sciences), Steven Bograd (Pacific Fisheries Environmental Laboratory/NMFS), and Arnold Mantyla (SIO). Correspondence was edited lightly for brevity and clarity.

——-Original Message——-
From: Jane Huyer
Sent: Monday, 05 Aug, 2002 11:55 AM
Subject: cold halocline off Oregon
Colleagues,

Attached is a postscript file containing a set of three T-S diagrams for our standard station NH-25 that is 25 nm west of Newport, Oregon. The remarkable conclusion is that the halocline (S between 32.4 and 33.8) observed off central Oregon on 9–10 July 2002 is nearly one degree Celsius lower this year than it has been in the three previous summers. It is at the lower limit of halocline temperatures in all of our previous observations including the cold years (1972 and 1973) of the Coastal Upwelling Experiments CUE-1 and CUE-2. In the salinity range of 33.0 to 33.6, the halocline is colder than we have ever observed at this location.

This permanent halocline provides most or all of the water that upwells along the coast of central Oregon. The cold halocline extends offshore at least to NH-85, the most offshore of our standard stations, 85 nm west of Newport. Since this water is both fresher and colder than normal, we do not (and would not expect to) see anomalous values of steric height. These T-S diagrams indicate stronger subarctic influence than normal, suggesting either increased advection from the north, or that the subarctic source was colder than normal.

We are wondering if any of you have seen similar anomalies elsewhere off the west coast of North America.

From: Curtis Collins
Sent: Wed, 07 Aug, 2002 10:48 AM
Jane,

I don't think that we have seen these kinds of changes in the coastal area yet. The change that we have seen that is probably related to what you are seeing is offshore in the "California Current" area. Beginning last December, the subducted surface waters showed a pronounced salinity minimum, with values as low as 31.8 or so. The subduction might be related to the low temperatures that you are seeing.

From: Frank Whitney
Date: Wed, 7 Aug 2002 15:37:16
Jane:

I see colder halocline temperatures also off the southern BC coast. I quickly checked back to 1989 and find this is the coolest water we have seen in spring over the past decade. Line P data for these years is on our web site,

http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/linepdata/default.htm

but not quite yet for July 2002. Also, nitrate levels (vs. salinity) are higher in this water, a distinct marker of subarctic rather than subtropical waters.

Just preparing to head out on Line P again. I'll be looking for this feature as we head offshore.

To: Ron Lynn
Date: Thu, 08 Aug 2002 15:52:59 -0700
From: Arnold Mantyla

That's a neat plot from Adriana, it looks like the type of T/S curve that you see much further north, so it looks like a stronger influx from the subarctic.

On our last CalCOFI [cruise], we had 2 stations on line 80 (90 and 80) that had a lower than usual salinity minimum, about 32.75 at about 12 degrees or a little less.

neat!

Date: Wed, 07 Aug 2002 13:47:34
From: Ron Lynn
Jane,

The crew on the July CalCOFI survey say that temperatures were, for the most part, a quarter to a half degree C below the ltm over a broad area. Some response was expected from the unusually strong upwelling off central CA. See the El Niño Watch, http://cwatchwc.ucsd.edu/cgi-bin/elnino.cgi.

From: Howard Freeland
Date: Wed, 07 Aug 2002 19:05:03

I pulled all of the files in the Institute of Ocean Sciences data library from station MP3 observed in June or July [deleting duplicates close in time]. The attached TS plot on a gif file shows the result. Clearly the observations this year are outside of all previous experience.

From: "Collins, Curtis"
Date: 13 Aug 2002 21:09:39. 0329 (UTC)

Here is a T/S plot for a station at the entrance to Monterey Bay. There are no effects yet at this inshore station from the cooling of the halocline off Oregon. Regards.

Date: Thu, 15 Aug 2002 17:23:13
From: Steven Bograd
Hi Jane et al.,

Following up on Ron Lynn's plot, I am attaching a PDF showing a T-S scatter for CalCOFI station 80.90, all summer (Jul-Sep) profiles for 1984–99 (bottles), and July 2002 marked green. This is clearly a well-confined feature (seen only at stations 80 and 90 on line 80, and between 60–90 m), although it's remarkable that it shows up clear to Line P.

We know 80.90 also had an anomalously high O2 content at this depth as well. Perhaps we should check with Reggie Durazo and the IMECOCAL lines?

From: Howard Freeland
Date: Fri, 16 Aug 2002 13:57:54
I think the pictures from Steven Bograd and Ron Lynn are remarkable. They are very similar to what we have seen on line P and Jane is seeing off Newport. The big question in my mind is, why is it not being seen in the MBARI data?

Date: Fri, 16 Aug 2002 11:07:11
From: Jane Huyer
Howard et al.,
I'm pretty sure that Curt's data from the Monterey area is too close to the coast for the phenomenon to be manifest there. Steve Bograd's CalCOFI station 80.90 lies about 300 km offshore. This fits my conceptual image of the California Current lying near shore off Washington and Oregon, migrating offshore between Cape Blanco (at 43°N) and Point Reyes (at 38°N), and lying offshore off central and southern California.

For a "typical best example" of shape of California Current, you might want to take a look at 15-m drogued drifter trajectories at:

http://diana.coas.oregonstate.edu/drift/recent/fixes-2001-07.html

Further examples can be found at http://ltop.coas.oregonstate.edu

Date: Mon, 19 Aug 2002 07:58:13
From: Ron Lynn
Not mentioned before are the two CalCOFI stations (80.70 & 80.100) that lie either side of the low-salinity plug. They have a definite high salinity bias from 75 to 150 or 200 m. Does that show up elsewhere?

From: Howard Freeland
Date: Mon, 19 Aug 2002 11:12:09
Along Line-P there seemed to be a low-salinity anomaly associated with the low-temperature anomaly. I think it is evident in these two anomaly plots.

From: Frank Whitney
Date: Tue, 20 Aug 2002 11:26:08
Marie Robert has plotted July line-P data (Howard previously plotted T anomaly) for T, S, and sigma-t anomalies. Results show that waters underlying the mixed layer (salinity 32.6–33.9) in the southern Gulf of Alaska are distinctly cold, fresh, and light. As I pointed out earlier, these waters are relatively LOW in oxygen (not high as might be expected for cold waters) and high in nutrient at our shelf station (P4) compared with data collected in the past decade. This indicates that we are seeing waters of stronger subarctic character off the BC coast.

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