THE STATE OF THE CALIFORNIA CURRENT, 2003–2004: A RARE "NORMAL" YEAR

RALF GOERICKE, ELIZABETH VENRICK, ARNOLD MANTYLA
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0218
rgoericke@ucsd.edu

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

ADRIANA HUYER, ROBERT L. SMITH, PATRICIA A. WHEELER
College of Oceanic and Atmospheric Science
Oregon State University
Corvallis, Oregon 97331-5503
ahuyer@coas.oregonstate.edu

RIAN HOOFF
Cooperative Institute of Marine Resource Studies
Oregon State University
Hatfield Marine Science Center
2030 SE Marine Science Drive
Newport, Oregon 97365

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

GILBERTO GAXIOLA-CASTRO
Departamento de Oceanografía Biológica
Centro de Investigación Científica y
Educación Superior de Ensenada
Apartado Postal 2732
22860 Ensenada, B.C., México

JOSÉ GÓMEZ-VALDES
Departamento de Oceanografía Física
Centro de Investigación Científica y
Educación Superior de Ensenada
Apartado Postal 2732
22860 Ensenada, B.C., México

BERTHA E. LAVANIEGOS
Departamento de Oceanografía Biológica
Centro de Investigación Científica y
Educación Superior de Ensenada
Apartado Postal 2732
22860 Ensenada, B.C., México
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0218

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

ABSTRACT

This report describes the state of the California Current System (CCS)—meteorological, physical, chemical, and biological—from January 2003 to the spring of 2004. The area covered in this report ranges from Oregon coastal waters to southern Baja California. Over the past year, most physical, chemical, and biological parameters were close to their climatological mean. Contributing to such "normal" conditions was the absence of a La Niña that had been expected after the previous year's El Niño. Noteworthy, however, are the cold and fresh anomalies in the upper 100–200 m that have been found over large areas of the CCS since 2002. Off Oregon these may have been responsible for increased productivity; off southern California these were associated with shallower nutriclines and subsurface chlorophyll maxima in the offshore areas. It is unclear if these anomalies are ephemeral or related to long-term changes in ocean climate. The effects of the hypothesized 1998 "regime shift" on the CCS are still difficult to discern, primarily because of other physical forcing varying on different time scales (e.g., El Niño/Southern Oscillation, ENSO, cycles; the "subarctic influence"; global warming). The resolution of many of these issues requires larger scale observations than are available now. Establishment of the Pacific Coast Ocean Observing System (PaCOOS) under the guidance of NOAA will be a crucial step toward achieving that goal.

INTRODUCTION

This is the eleventh in a series of annual reports summarizing the climatology, oceanography, and biology of the California Current System (CCS) between the springs of 2003 and 2004. This report is based on observations taken from Oregon to Baja California. The programs or institutions contributing to this report were the U.S. Global Ocean Ecosystem Dynamics Long-Term Observation Program (GLOBEC LTOP) working off Oregon, the Pacific Fisheries Environmental Laboratory (PFEL) providing basinwide and coastwide climatologies, the Point Reyes Bird Observatory (PRBO) working off central and southern California, the CalCOFI program working off southern California, and the Investigaciones Mexicanas de la Corriente de California program (IMECOCAL) working off Baja California.

Last year's "State of the California Current Report" (Venrick et al. 2003) described the development and demise of a minor El Niño event that peaked in the winter of 2002–2003. This event had only a small effect on the California Current. For example, off southern California phytoplankton biomass, primary production, and zooplankton displacement volumes were only slightly below their climatological averages (Venrick et al. 2003). A significant influence from the north during 2002–2003 was the intrusion of subarctic water into the CCS. These cold water and freshwater anomalies were evident all along the west coast of North America, from Vancouver

Island to San Diego. They were likely due to an intensification of the California Current flowing south and a weakening of the Davidson Current flowing north into the Gulf of Alaska (Freeland et al. 2003). Off Oregon, Wheeler et al. (2003) observed that higher nutrient concentrations, carried along by these "minty" water masses, stimulated primary production and increased standing stocks of phytoplankton biomass. Off southern California, few if any such patterns were observed, a likely effect of the El Niño (Bograd and Lynn 2003).

From 1999 until 2002, the CCS was dominated by cold sea-surface temperature (SST) anomalies, as reflected in negative values of the Pacific Decadal Oscillation index (PDO) (Mantua et al. 1997), which had been positive from the mid-1970s until 1998, the most recent warm period. During the recent cold period, dramatic changes in zooplankton community structure were observed in the California Current (Lavaniegos and Ohman 2003; Brinton and Townsend 2003; Peterson and Schwing 2003), suggesting that the CCS ecosystem had undergone a regime shift. However, it is questionable that this shift can be attributed to a phase shift of the PDO. Bond et al. (2003) have identified a new SST spatial pattern, now called the Victoria mode, that has replaced the dominance of the PDO since 1998 and contributed to the unusually cool state of the CCS during the recent cold period.

The expectations for the current year were the advent of a La Niña in the tropical Pacific, its manifestation in the CCS, and the return of the PDO to negative values. Instead, the last year was characterized by climatologically "normal" conditions on both basin and CCS scales, a rather unusual state since most climatological indexes have bimodal distributions. The one exception to "normality" is the continuation of cold and fresh anomalies associated with the CCS. This report describes the response of the CCS and its ecosystem to the larger scale physical forcing. We will use simple indicators of ecosystem state, such as concentrations of chlorophyll *a*, rates of primary production, and zooplankton displacement volume. Observations of avifauna community structure and production will be used as well; these integrate responses of the biological system to changing physical forcing (Veit et al. 1996; Hyrenbach and Veit 2003). It is hoped that this report will contribute to an understanding of the balance of forces responsible for the current state of the CCS.

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° x 2°) anomalies of SST and surface winds. The base period is 1968–96. Monthly upwelling indexes and their anomalies for the North American west coast (21–52°N) are calculated relative to 1948–67. The daily along-shore wind component and SST are from the NOAA National Data Buoy Center (NDBC). Values from six representative buoys from the CCS are plotted against the harmonic mean of each buoy.

The GLOBEC Long-Term Observation Program (LTOP) made interdisciplinary observations off Oregon 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; limited sampling of the NH line is continuing on an opportunistic basis. The NH line had been occupied regularly from 1961 to 1971, and long-term seasonal averages have been calculated from these historical data (Smith et al. 2001). The LTOP sampling along the NH line extends offshore to NH-85, 157 km from shore.

Hydrography, nutrients, chlorophyll, and zooplankton are measured along the inner portions of the NH line biweekly in the 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 nautical miles from shore, with depths ranging from 20 m to 95 m. Since 2001, sampling has been extended to 25 mi from shore (300 m water depth). Zooplankton are 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 individual carbon weight, then summing across stages and species. Total biomass of all copepod species is reported here.

This report covers observations made by the CalCOFI program between the summer of 2003 and the spring of 2004. Surveys, based on a fixed sampling grid (fig. 1), are conducted off southern California quarterly. The water column is routinely profiled to a depth of 500 m using conductivity, temperature, pressure, oxygen, fluorescence, and light transmission sensors. Water samples are retrieved from 12 to 20 depths, and salinity, dissolved oxygen, nutrients, and chlorophyll are determined. Standard (.505 mm mesh) oblique bongo tows are conducted to 210 m depth at each station. Sampling and analytical protocols followed are presented in data reports (e.g., SIO 2000) and on the CalCOFI website (http://www.calcofi.org). A census of avifauna is carried out during the daylight hours along the CalCOFI cruise track by personnel from the PRBO. The PRBO also assessed the reproductive performance of seabird populations at the Farallon Islands.

For each CalCOFI cruise, the average value of a prop-

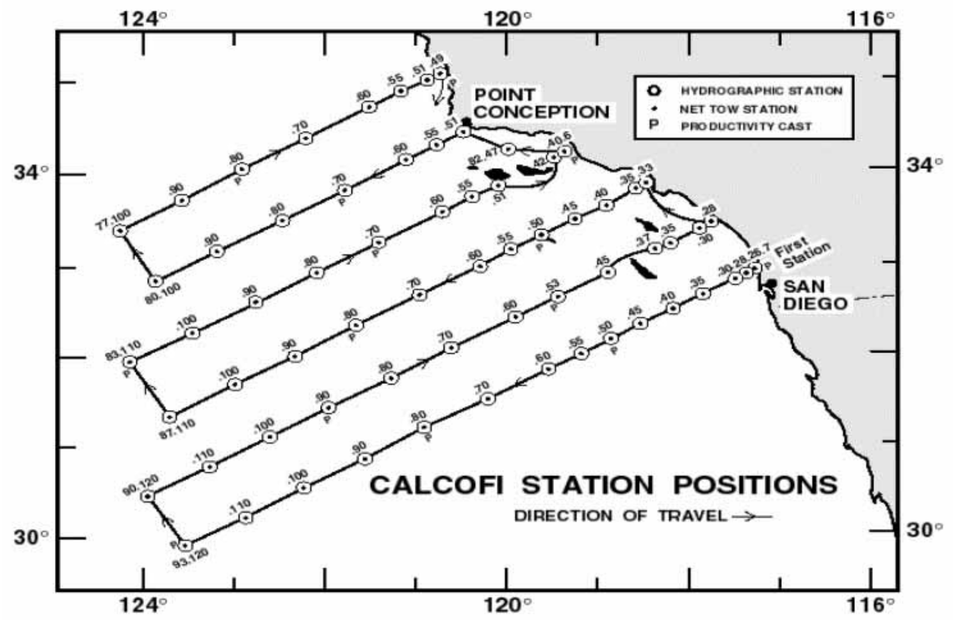

Figure 1. The standard CalCOFI station pattern. All 66 stations are occupied on most cruises. During the winter and spring cruises the pattern is extended north for observations of hydrographic properties and distributions of fish eggs.

erty was calculated, using data from all 66 standard CalCOFI stations (fig. 1); these are the CalCOFI region averages. A harmonic was fitted to the seasonal data from the last 20 years. Residuals from the harmonic are the anomalies of the parameter. The mixed-layer depth was assumed to be half way between those two depths where the temperature gradient reached values higher than 0.02 degrees per meter. For this analysis, the upper 12 m were excluded from the analysis to avoid including the diurnal thermocline in the analysis—that is, the slight or at times even large temperature increase in the upper 2–5 m that results from heating during the day and is typically eroded at night. This procedure will introduce a positive bias in calculation of the mixed-layer depth but will not affect the interpretation of the patterns, since the bias is consistent. A temperature-based mixed-layer depth was used for the analysis, since the density data were not yet available for all cruises at the time of analysis.

The data presented for the California Current off Baja California (IMECOCAL) were collected from April 2003 to February 2004 aboard of RV *Francisco de Ulloa* (fig. 2). The principal data collected at each IMECOCAL station include a CTD/Rosette cast to 1,000 m bottom, depth permitting, with sensors for pressure, temperature, salinity, and dissolved oxygen. Water samples for chlorophyll analyses were collected from CTD casts, using 5 l Niskin bottles. Macrozooplankton was sampled with bongo net tows from 200 m to the surface. Sampling methods and analyses are presented in greater detail in IMECOCAL data reports and on the web site (http://imecocal.cicese.mx).

BASINWIDE PATTERNS

While environmental conditions rarely appear as the climatological "average," recent atmosphere and ocean fields for the North Pacific closely resemble their long-term temporal means. Typically, spatially distinct regions display large anomalies of one sign associated with the ongoing climate event (e.g., El Niño, La Niña, or other climate regimes). A rapid reversal to an alternating anomaly pattern generally occurs as a new climate event develops. The resulting distribution of values for a variable is bimodal rather than normal; thus, the value at any location is rarely observed near its mean. It is even rarer to observe the greater North Pacific region at a near-neutral state.

Following the 2002–2003 tropical El Niño, SSTs in the equatorial Pacific have been near-average up to the present (spring of 2004) (NOAA CPC Climate Diagnostics Bulletin, http://www.cpc.ncep.noaa.gov). The equatorial ocean thermocline since early 2003 has been deeper than normal in the western Pacific and shallower than normal in the eastern Pacific, a pattern typically associated with La Niña. However, the atmospheric forcing and the indexes that represent it have been dominated by month-to-month variability associated with the intraseasonal Madden-Julian Oscillation (MJO). The relative strength of the MJO over the past year is due in part to the lack of any significant interannual ENSO development.

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). It became positive

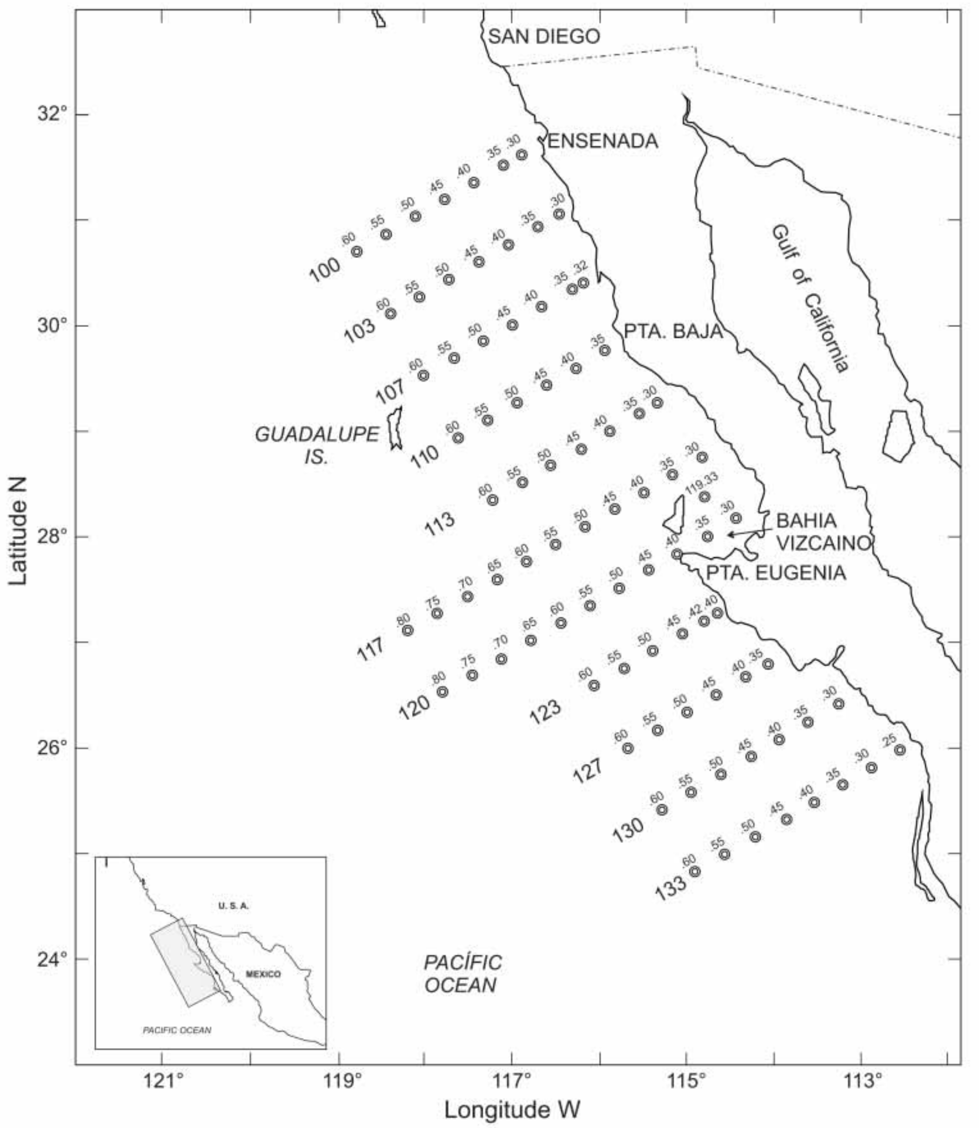

Figure 2. Standard IMECOCAL cruise pattern.

during the spring of 2002, indicating a weak-to-moderate El Niño, and has remained very slightly positive to the present. Enhanced intraseasonal variability has dominated the MEI during this time, and the spatial patterns of its individual components currently display a mixed signal with respect to ENSO. Current conditions in the tropical Pacific are similar to episodes during the late 1960s and late 1970s (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/mei.html).

In the second half of 2002, a positive SST anomaly developed in the North Pacific, concurrent with the El Niño warming in the tropical Pacific. Overlaying this warm North Pacific feature was a region of unusual northward winds. By late 2002, cool anomalies along the west coast of the continental United States were replaced by northward wind anomalies and warm SSTs at the peak of the El Niño. This coastal warming lagged the development of positive SST anomalies in the greater Northeast Pacific by several months. These anomalies have weakened since early 2003, but remain generally warmer than normal.

Most recently (September 2003–April 2004), virtually the entire North Pacific has exhibited weakly warm anomalies. The PDO (Mantua and Hare 2002), which characterizes decadal-scale variability in the spatial patterns of North Pacific SST, defines a warmer than normal CCS during its positive phase (http://tao.atmos.washington.edu/pdo/). After a period of negative PDO values following the hypothesized "regime shift" in 1998, the PDO has been positive since August 2002 (20 consecutive months at present) but only weakly so since the 2002–2003 El Niño. As stated above, changes in the

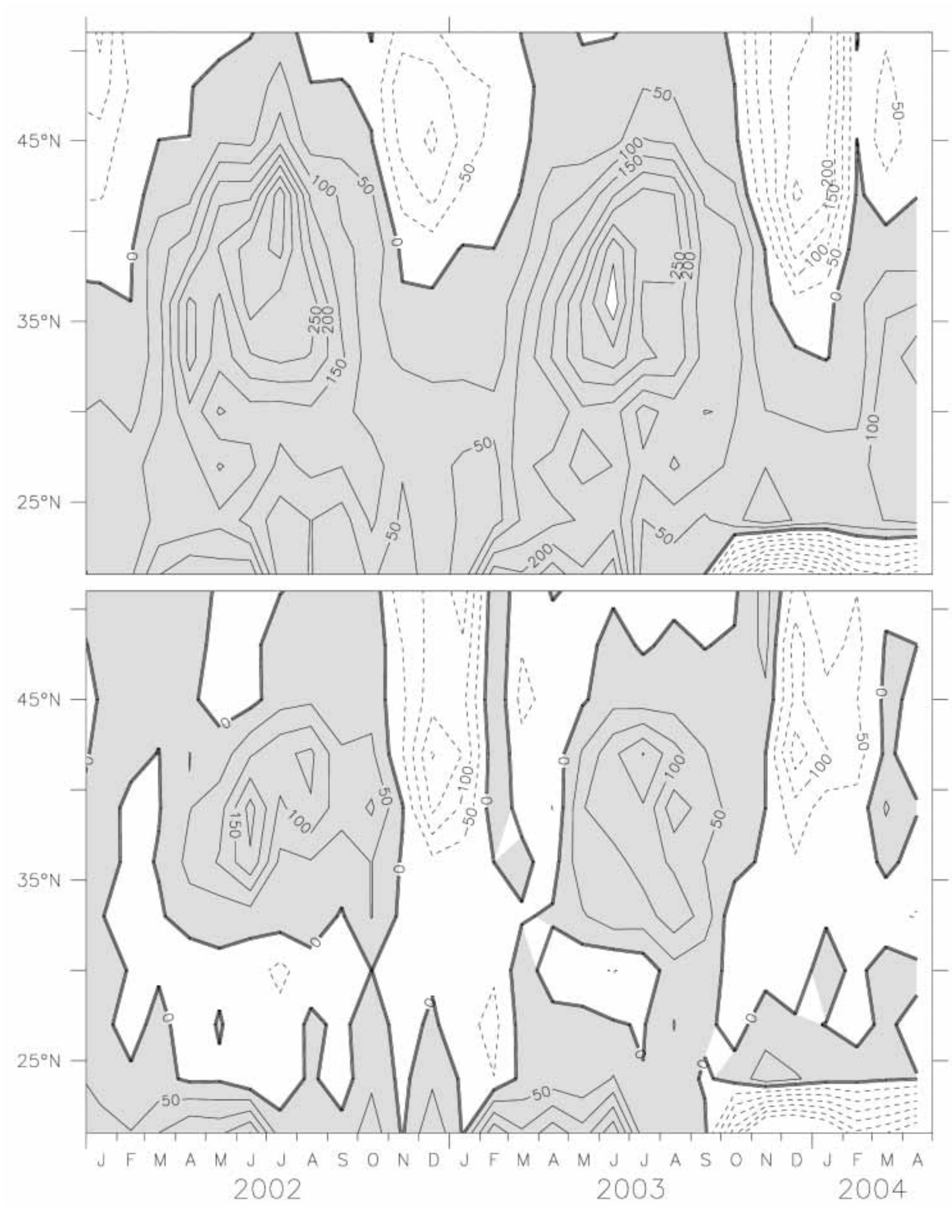

Figure 3. Monthly upwelling index (*upper panel*) and upwelling index anomaly (*lower panel*) for January 2002–April 2004. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m^3/s per 100 km of coastline.

PDO since 1998 may not represent a shift to a negative (cool) PDO phase but rather a shift into the Victoria mode (Bond et al. 2003). This may have contributed to the unusually cool state of the CCS during that period. To confound the issue further, the recent generally weak warm SST pattern over the greater North Pacific resembles neither the PDO nor the Victoria modes (J. Overland, pers. comm.).

Just as the ongoing tropical and North Pacific atmospheric and ocean conditions have been very close to the long-term mean, most models project ENSO-neutral conditions over the next several months. The models reflect great uncertainty beyond summer 2004. With the lack of any appreciable ENSO activity expected in the near future, the prospects for confirming the presence and continuation of the cool and biologically productive West Coast climate regime (Peterson and Schwing 2003) are good.

COASTWIDE CONDITIONS

Monthly coastal upwelling indexes (Bakun 1973; Schwing et al. 1996) have indicated generally stronger than normal summertime upwelling in the CCS since 1998 (Hayward et al. 1999; Bograd et al. 2000; Durazo

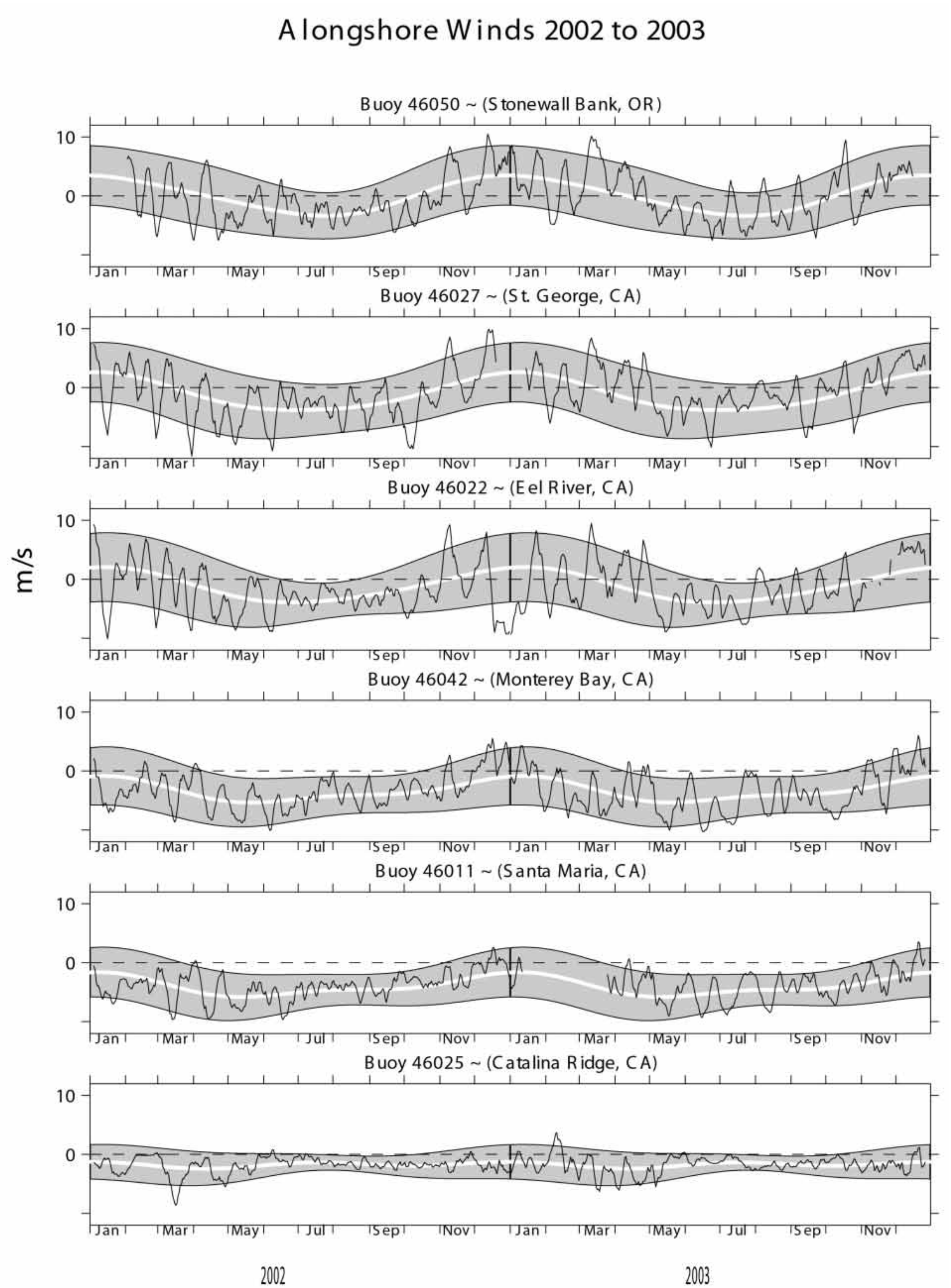

Figure 4. Time series of daily-averaged alongshore winds for January 2002–December 2003 at selected NOAA National Data Buoy Center coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a 7-day running mean. Data provided by NOAA NDBC.

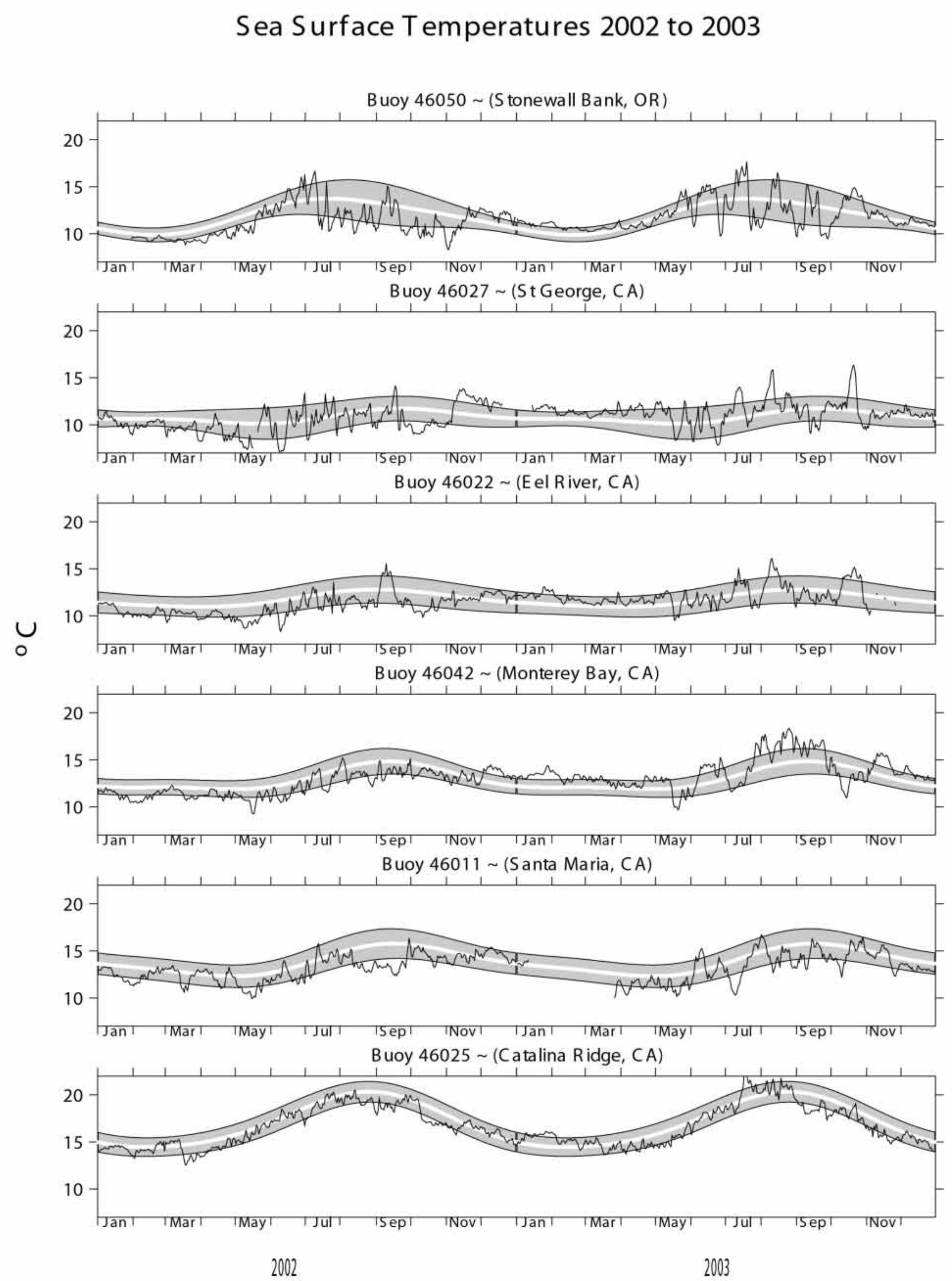

Figure 5. Time series of daily-averaged SST for January 2000–December 2001 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Data provided by NOAA NDBC.

et al. 2001; Schwing et al. 2002; Venrick et al. 2003). The normal cycle is for maximum upwelling in the summer, centered off California (shaded areas in upper panel of fig. 3), and downwelling in winter north of about 39°N. Winter 2002–2003 and 2003–2004 featured negative anomalies along the entire coast (white in lower panel of fig. 3), reflecting anomalously strong downwelling off northern California, Oregon, and Washington and very weak upwelling to the south. The 2002–2003 anomalies may have been influenced by the tropical El Niño event.

Summer upwelling was unusually strong throughout the CCS in 2003. The return to stronger than normal upwelling was particularly significant on the heels of the 2002–2003 El Niño, suggesting that this event had an ephemeral influence on conditions in the North Pacific and that the climate regime shift believed to have commenced in 1998 (Schwing and Moore 2000; Peterson and Schwing 2003) may be continuing. March 2004 upwelling anomalies were positive, but the most recent available indexes (April 2004) were slightly negative, reflecting the anomalies of the preceding winter. The strong summer upwelling of past years was not predicated by any clear signals in early spring, so we cannot speculate on the intensity of coastal upwelling in the next several months.

Winter 2002–2003 featured a very active intraseasonal pattern in the CCS, illustrated by a series of strong, approximately 30-day alongshore fluctuations in the NDBC coastal buoy winds (fig. 4). Winds were predominantly toward the north (positive) during winter and early spring of 2003 over most of the CCS. Summer 2003 winds were persistently to the south, indicating normal upwelling-favorable conditions in the northern CCS, but continued to be dominated by strong fluctuations or reversals in the alongshore winds on a roughly monthly scale. Note the greater amplitude of these monthly oscillations compared to summer 2002. This pattern is consistent with the intraseasonal variability in the tropical Pacific, which may have been affected by the MJO in recent months (March and April 2004).

The pattern of SSTs at the NDBC buoys (fig. 5) in the past several months reflects the pattern in alongshore winds. Regular intraseasonal fluctuations in SST exceeded 5°C (compared to the annual range of only 2–3°C). This pattern was particularly strong during the summer and fall of 2003 (again, compared to the previous summer). SSTs were unusually warm from November 2002 through April 2003, probably a response to the El Niño event. Unlike the winds, intraseasonal variability in CCS SST during the El Niño was relatively small, suggesting that the upper ocean was relatively well mixed. Seasonally averaged SSTs were close to the long-term mean in the northern portion of the CCS in 2003, but the southern CCS (buoys 46011 and 46025) was unseasonably cool since late spring. Preliminary data suggest that this pattern continued into early 2004.

Preliminary data from May 2004 revealed remarkably warm SSTs throughout much of the Northeast Pacific, with anomalies as high as 3–4°C in parts of the CCS. This represents a substantial increase from the previous few months. There is evidence to suggest, however, that these anomalies were confined to a relatively thin surface layer, perhaps driven by anomalous surface heat fluxes. Warm waters off the coast of Oregon were evident only within the upper few meters (Bill Peterson, pers. comm.).

REGIONAL STUDIES

Oregon Coast: GLOBEC LTOP Cruises

The long-term observation program (LTOP) of the U.S. GLOBEC Northeast Pacific Program that began seasonal sampling of the northern portion of the CCS in 1997 continued through most of 2003. During 2002, waters off central Oregon were subject to competing influences: a cooling influence from the subarctic Pacific and a warming influence from a weak or moderate El Niño in the equatorial Pacific (Venrick et al. 2003). Steric heights along the offshore portion of the NH line were above normal during much of 2003 (fig. 6); this may reflect influence from the 2002–2003 El Niño. Inshore steric heights were below normal in February 2003 when there was unusual winter coastal upwelling and above normal upwelling in early April after a month of very strong downwelling. Steric height values and anomalies (in dynamic centimeters) correspond directly to values and anomalies of sea surface elevation (in centimeters); offshore gradients of steric height are proportional to the alongshore component geostrophic surface current. Thus Figure 6 suggests the inshore current was more southward than normal in February and July but weaker than normal in early April.

NH line sections in 2003 (fig. 7) show the usual strong seasonal cycle in the upper 200 m of the ocean: in the winter, deep mixed layers and weak horizontal gradients, and in the summer, very strong stratification associated with the Columbia River plume. The strong summer tilt of the main pycnocline is also normal, with subsurface temperature decreasing and salinity increasing toward shore. The early April 2003 section clearly shows the influence of strong March downwelling, with very little stratification above 60 m offshore, and a lens of very fresh water (from local runoff) adjacent to the coast (fig. 7b).

Each NH line section contains positive temperature anomalies that differ from the seasonal average by more

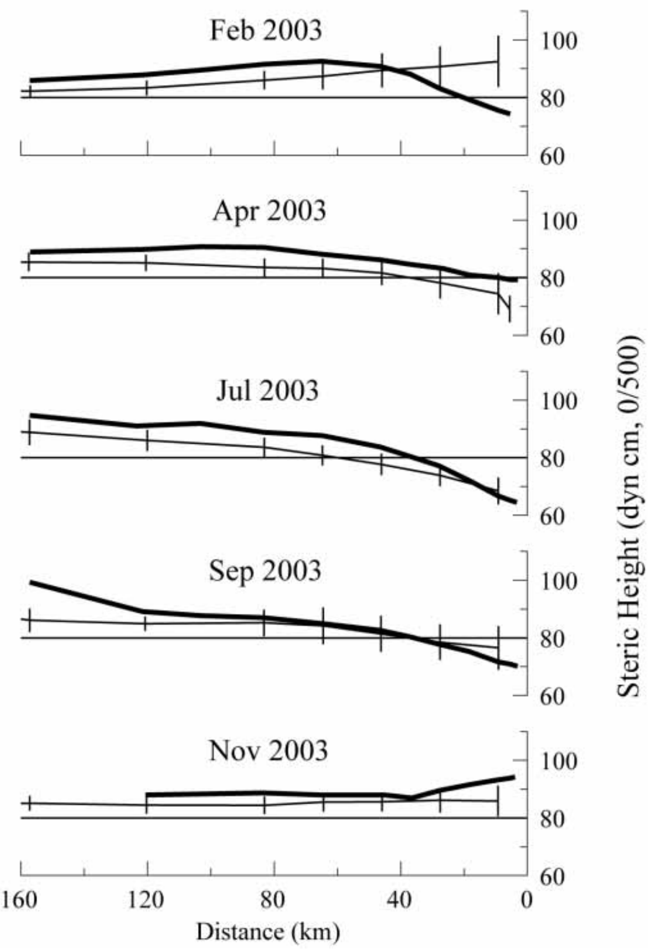

Figure 6. Steric height profiles of the sea surface relative to 500 dbar along the NH line at 44.65°N since April 2002 (heavy line) shown with the long-term (1961–71) seasonal or monthly average from Smith et al. (2001). Vertical bars indicate 1 standard deviation above and below the average. Values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976).

than 1 standard deviation (fig. 8); in the first half of the year these anomalies were strongest in the top 100 m. Each section (except in early April) also contains significant negative temperature anomalies at a depth of about 100 m, and within the permanent halocline (compare figs. 7b and 8). These negative anomalies suggest the 2002 subarctic intrusion (Freeland et al. 2003; Huyer 2003; Wheeler et al. 2003) lingered through 2003; temperature and salinity diagrams for the shelf-break station (NH-25) confirm this impression (fig. 9). In July 2003, the cool halocline anomaly was present along the entire section: in the salinity range of S = 33–33.8, temperatures were still about 0.5°C lower than they had been in July 2001, though not as low as in July 2002. Peak amplitudes in July 2003 occurred near 124.5°W over the outer shelf.

Regional surveys were made in April, July, and September 2003. As in recent years (Schwing et al. 2002; Venrick et al. 2003), surface temperatures were nearly homogeneous in April 2003 (fig. 10a), though there was equatorward flow near the coast (fig. 10b). A narrow wedge of low salinity water lay adjacent to the coast (fig. 10c), indicating recent downwelling and coastal trapping of local runoff. By July 2003, there were strong surface temperature gradients: inshore waters were 6–7°C colder than offshore waters (fig. 10a). Geostrophic flow at the surface, relative to 500 dbar, was equatorward except on the southeast flank of Heceta Bank (fig. 10b), and low-salinity Columbia River plume waters (S < 32.5) covered all but the inshore portion of the northern sections (fig. 10c). In late September, zonal gradients of surface temperature had weakened, the southward current had migrated offshore, and there seemed to be some eddies both north and south of Cape Blanco that were not resolved by our survey. Low-salinity Columbia River plume waters (S < 32.5) covered the offshore portion of each section. Winds had continued to be favorable for upwelling through most of September, and this continued upwelling is reflected in the cold, dense waters observed in the coastal strip at the end of September (fig. 10a,c).

Southern California Bight: CalCOFI Cruises

Overview. The CalCOFI program is based on quarterly surveys of the CCS off Southern California (CalCOFI region). Such quarterly observations can be biased. To determine such a bias we compared SST derived from AVHRR and MODIS for the 66 CalCOFI stations with mixed-layer temperatures measured at the 66 stations during the quarterly surveys. Patterns of temperature anomalies are very similar (fig. 11a,b), demonstrating that our quarterly surveys are sufficient to delineate effects of the major climatological events, such as ENSO cycles, on ocean climate. The cruise-based climatology (symbols in fig. 11C) shows only a little bias—such as the timing of the spring temperature minimum relative to the climatology based on the remotely sensed data (line in fig. 11C). The slight overall positive bias in the ship-based data, ~0.2°C, is surprising because one would expect ship-based mixed-layer data to be lower than satellite-derived SST, since ship-based observations include periods of cloud cover.

Mixed-layer temperature anomalies of the CalCOFI region (fig. 11B) have been close to zero over the last year. The difference between satellite-derived SST and ship-based mixed-layer temperature anomalies over the last year (fig. 11A versus 11B) is surprising, and the cause is unknown. As described previously (Venrick et al. 2003), the response of mixed-layer temperatures to the recent El Niño differed dramatically from the response to the 1997–98 event; during the peak of the recent El Niño, only weak positive anomalies were observed

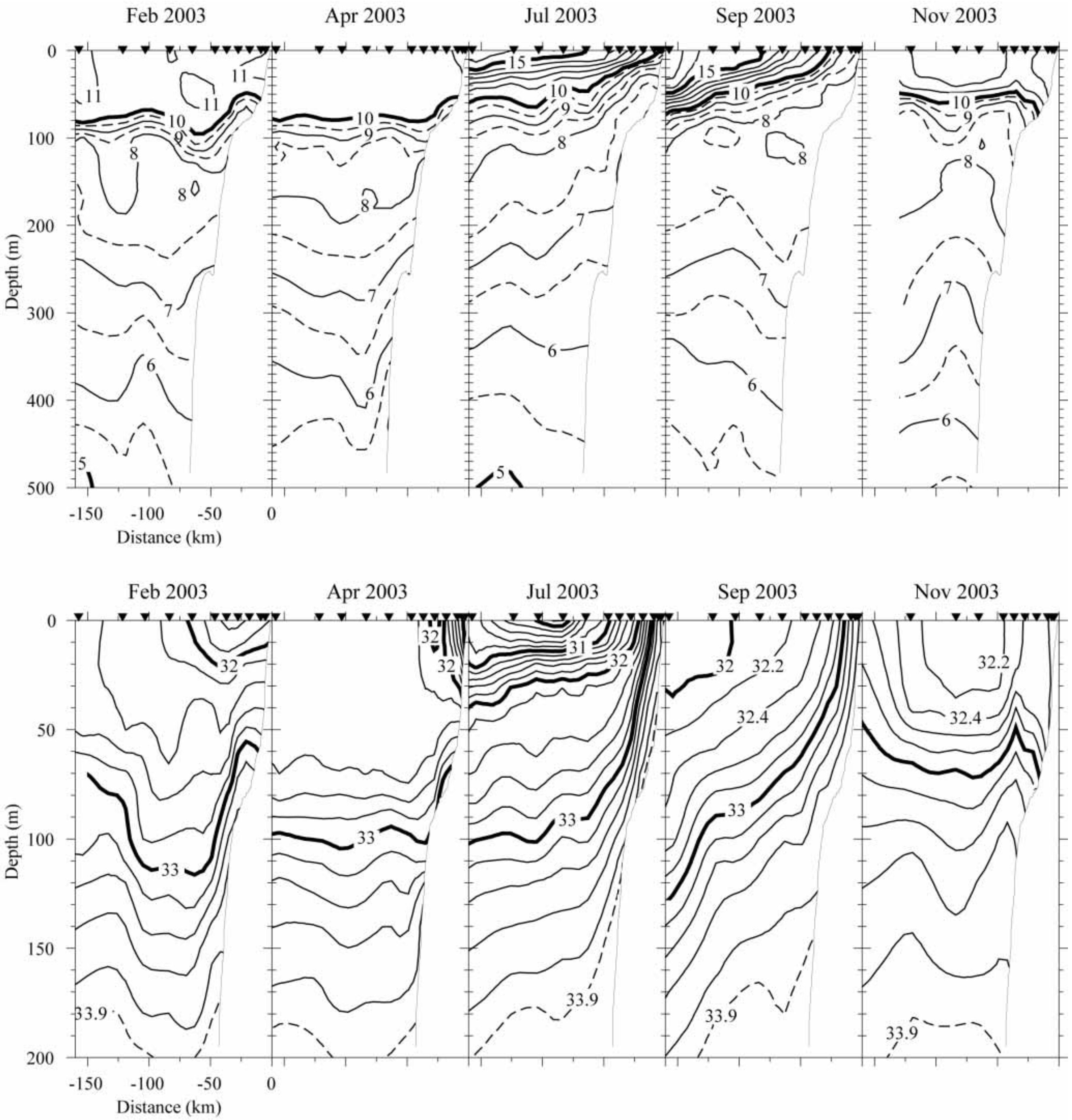

Figure 7. Temperature (*top*) and salinity (*bottom*) along the NH line at 44.65°N in 2003. Triangles on upper edges indicate the location of CTD stations.

(fig. 11B). Mixed-layer temperature anomalies have been close to zero since then; a La Niña did not develop.

Mixed-layer salinities have been dropping below long-term averages since the beginning of 2002, and this trend continued during 2003 (fig. 12). The average anomaly over the last year was −0.28. The salinity anomaly is found in most areas of the CalCOFI region (fig. 13). It is strongest at the edge of the Central Gyre (lines 90–93, stations 100–120, fig. 13A), slightly less in the region of the California Current (lines 83–90, stations 70–90, fig. 13B) and still noticeable in the coastal waters off Central California (lines 77–80, stations 60 and inshore, fig. 13C). In April 2004 the salinity anomaly was found between the surface and 100–150 m. The freshening of the CCS began in most regions in 2001 as a subsurface feature (Huyer 2003; Bograd and Lynn 2003) that has

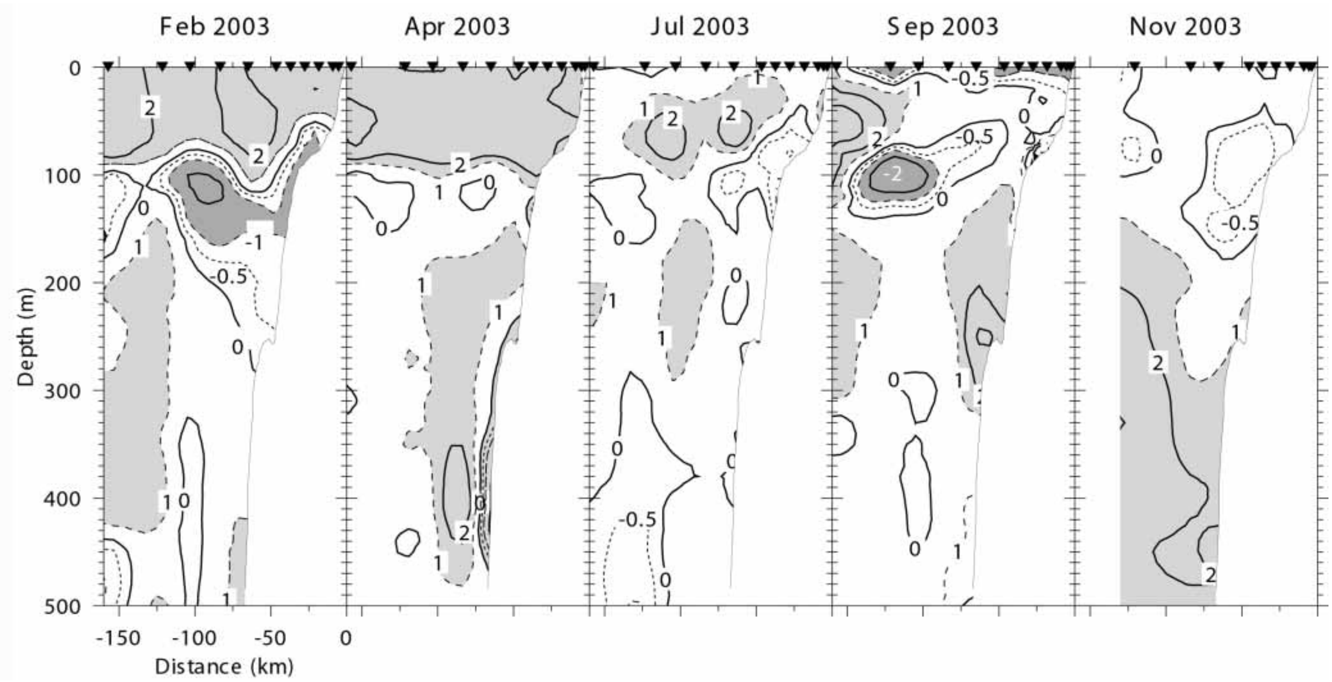

Figure 8. Normalized temperature anomalies for the NH line at 44.65°N. Positive (negative) anomalies indicate that present values are warmer (colder) than the historical (1961–71) seasonal or monthly averages. Values greater than 1 (2, 3) are significant at the 90% (95%, 99%) level.

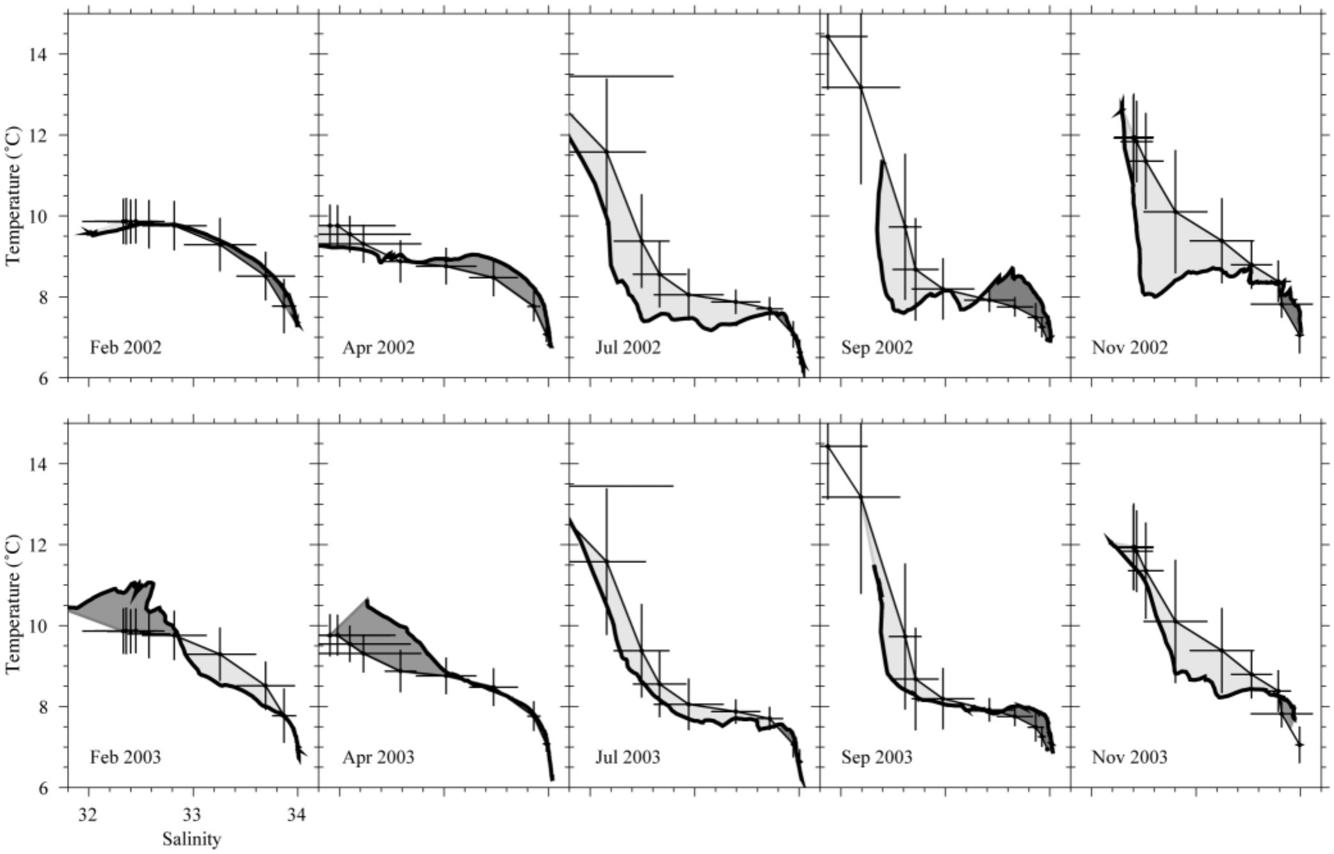

Figure 9. T-S diagrams for the shelf-break station (NH-25), comparing data from 2002 (*top row*) and 2003 (*bottom row*). Bold curves represent recent CTD casts; thin curves represent historical (1961–71) seasonal averages with cross-bars indicating plus and minus 1 standard deviation at standard sampling depths (Smith et al. 2001). Areas between the recent T-S curves (*bold*) and the historical-average T-S curves (*thin*) are shaded to emphasize the difference between warm, salty anomalies (*dark gray*) and cool, fresh anomalies (*light gray*).

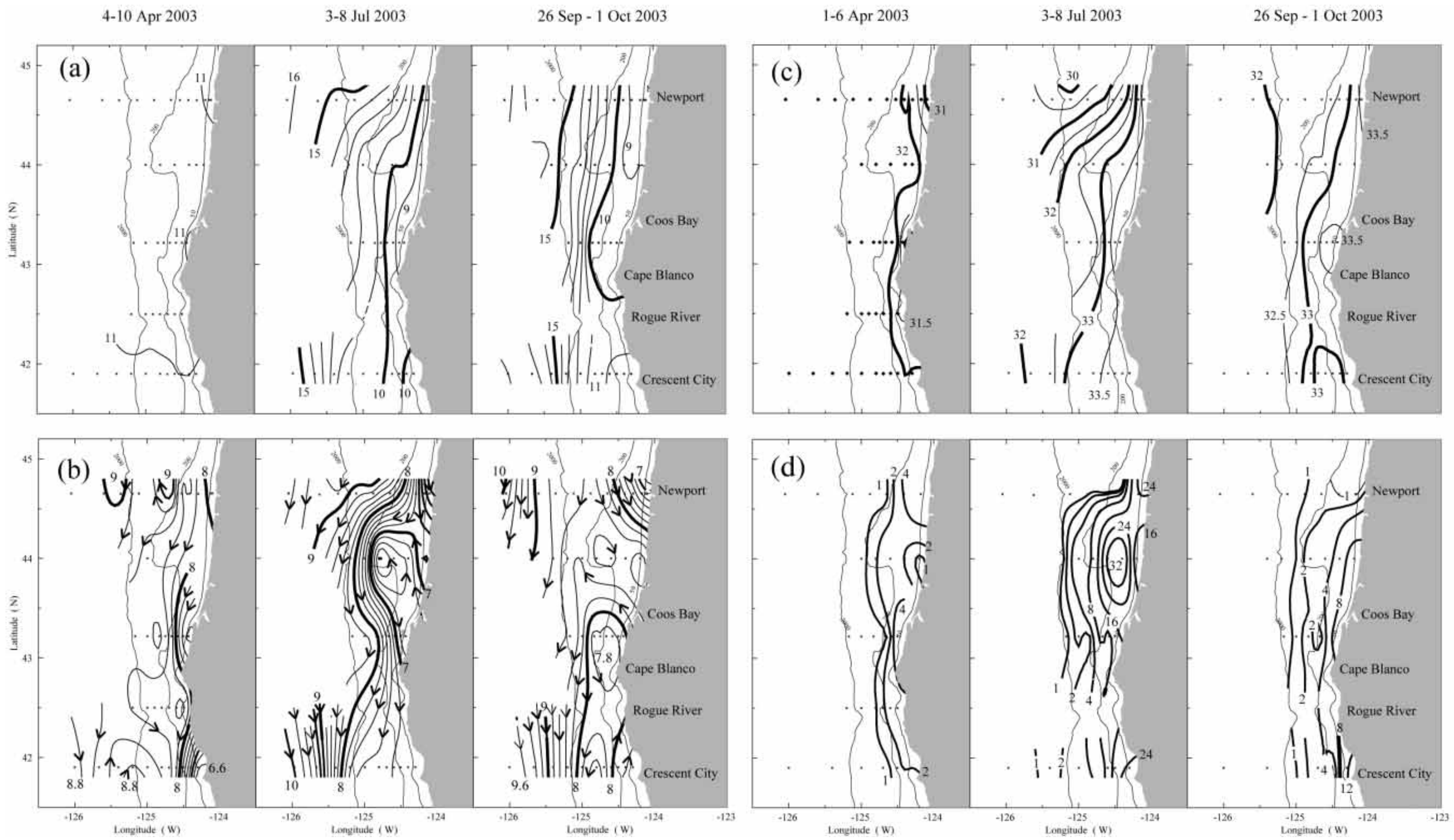

Figure 10. Spatial patterns for GLOBEC LTOP cruises: (*a*) 10 m temperature, (*b*) geopotential anomaly (J/kg) of the sea surface relative to 500 dbar, (*c*) 10 m salinity, and (*d*) 10 m chlorophyll (μg/L).

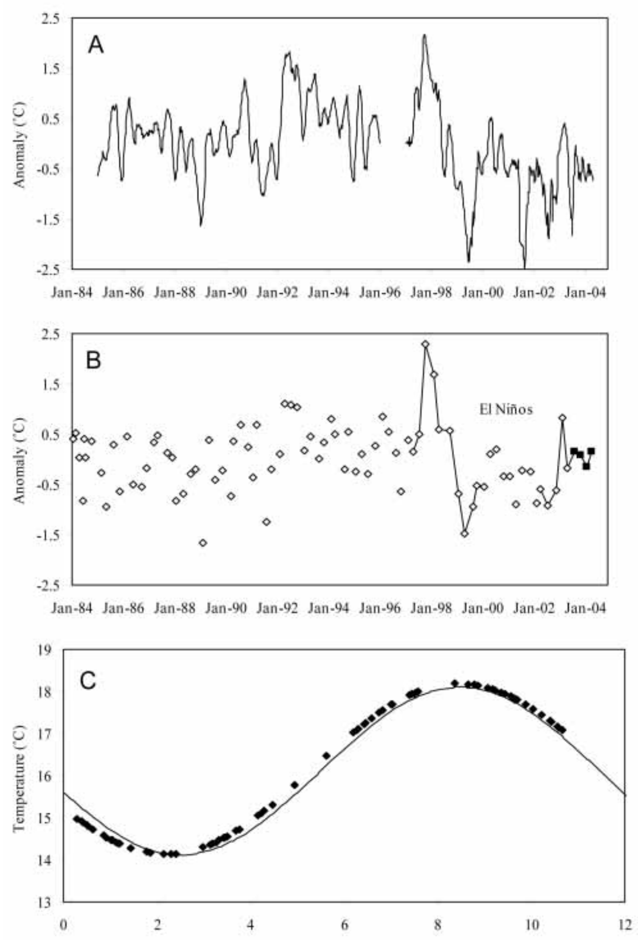

Figure 11. Average SST anomalies for the 66 standard CalCOFI stations calculated from (*A*) weekly AVHRR or MODIS data and (*B*) observation made on the quarterly CalCOFI cruises. Anomalies are calculated relative to the time period 1985–2004. Prominent in the time series are the effects of the 1997–98 El Niño and the subsequent La Niña. The 2002–2003 El Niño is only weakly expressed. (*C*) A comparison of harmonics calculated from CalCOFI cruise data (*symbols*) and weekly AVHRR or MODIS data (*line*).

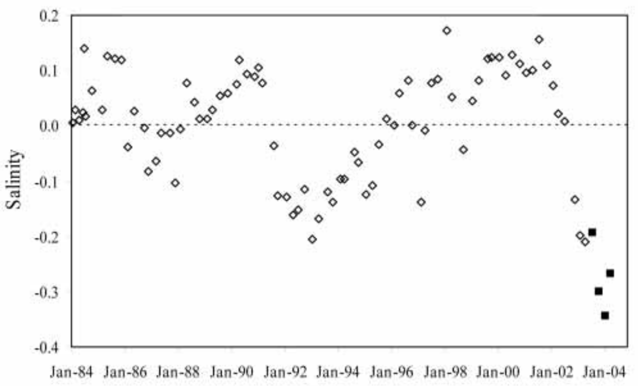

Figure 12. Cruise averages for mixed-layer salinity anomalies for the 66 standard CalCOFI stations. Solid symbols represent data from the last four cruises.

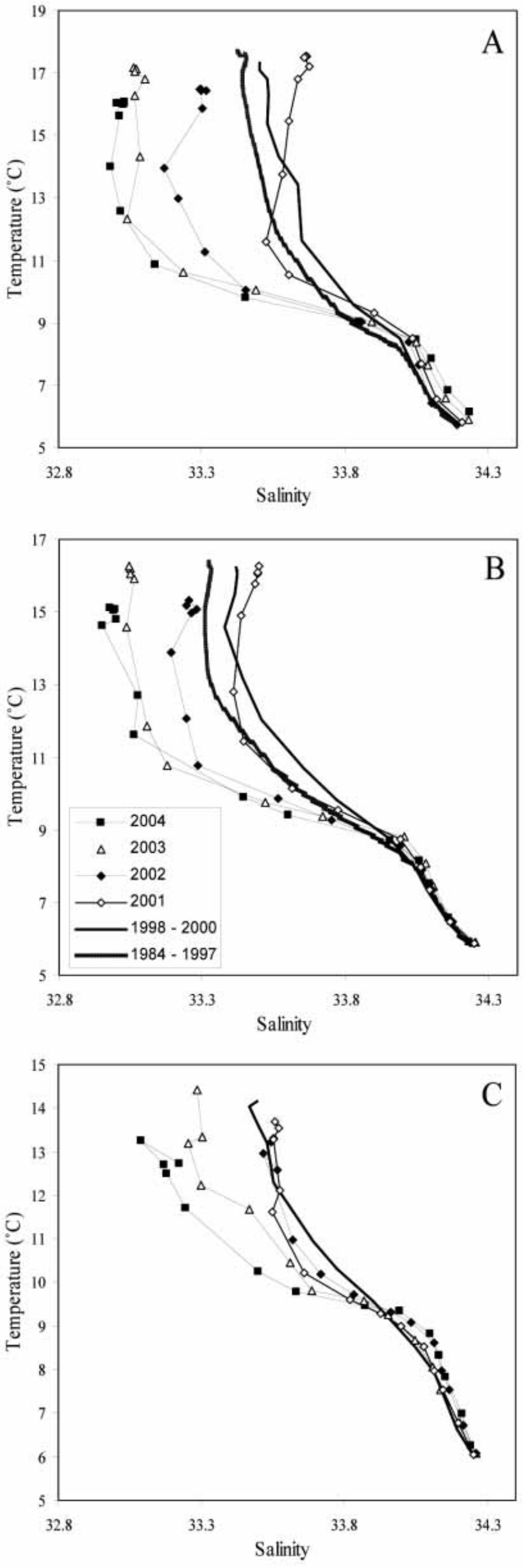

Figure 13. T-S lines for three representative areas of the CalCOFI region. (*A*) The edge of the central gyre (lines 90–93, stations 100–120), (*B*) the California Current region (lines 83–90, stations 70–90), and (*C*) the coastal areas in the north (lines 77–80, stations 60 and inshore). Each data point represents the average T-S characteristic of one standard depth level for the specified time period, such as the year 2002. Note that values for 2004 are based only on the winter and spring cruises.

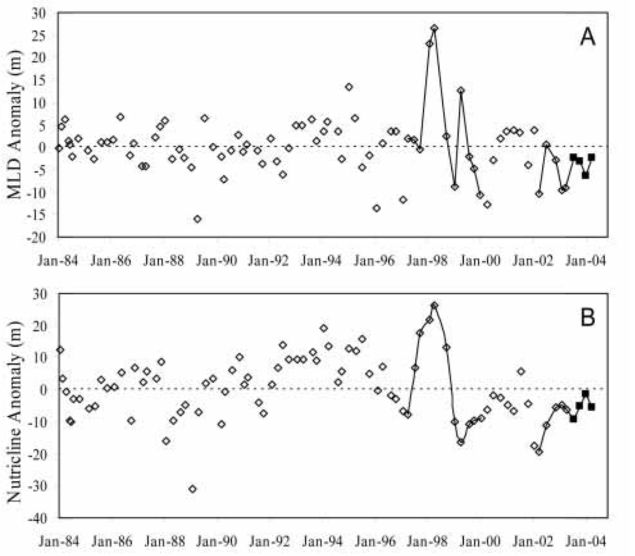

Figure 14. CalCOFI region anomalies for (*A*) mixed-layer depth and (*B*) nutricline depth. Data are derived from all 66 standard CalCOFI stations. Open symbols represent the period 1984 to the spring of 2003. Solid symbols represent data from the last four cruises. The two recent El Niño events are emphasized (*symbols connected with lines*) for a better comparison of the two events. Included in both events are data following the El Niño; for the 1997 event this represents the La Niña; for the 2002 event this represents the period of neutral anomalies.

intensified over the years and has been manifest at the surface for the last 2 years. Thermoclines are shallower in the California Current and, in particular, in regions west of the current

Mixed-layer depths during the last year were significantly below the long-term average (fig. 14A). Large excursions of mixed-layer depths, as were observed during the 1997–98 ENSO cycle, were not observed over the last 2 years. It is noteworthy that mixed-layer depths, so far, did not covary with the PDO cycle; mixed-layer depths for 1984–97 and 2000–2004 were, respectively, 34 ±11 m and 32 ±10 m. Nutricline depth (fig. 14B) over the last year showed a very similar pattern: values were smaller than long-term averages and were not noticeably affected by the recent ENSO cycle. Nutricline depth, however, reflects the PDO cycle, in contrast to mixed-layer depths.

CalCOFI Cruise 0307 (17–31 July 2003). This cruise did not occupy the usual outer-most stations on the four southern lines due to ship time constraints (fig. 15). However, the cruise did cross the main offshore California Current jet.

The surface currents showed features that are often seen during the summer: a strong southward California Current on the outer part of the region and a strong northward flow along the coast. This coastal surface countercurrent was not present on the spring cruise (0304). The currents appeared to be faster than usual. The cyclonic Southern California Eddy was present along the outer Channel Islands, and an anticyclonic loop and eddy was seen in the center of the region, between lines 83 and 90. This anticyclonic current loop persisted over the next 6 months and was more intense during the winter.

There was considerable variability in the near-surface temperature patterns due to the shallow seasonal thermocline with its strong near-surface temperature gradients and to the effects of the circulation in tilting the thermocline. The coolest water was found in the center of the Southern California Eddy, produced by the doming of the thermocline in the middle of the cyclonic eddy (“cold-core” eddy). A typical patch of warm surface water occurred between the coast and the Channel Islands, but there was much colder water immediately below. The northern edge of the anticyclonic current loop in the middle of the pattern carried warmer water eastward along lines 83 and 87.

The chlorophyll *a* patterns were similar to those seen on many previous summer cruises. The highest concentrations occurred in the Southern California Eddy, between the two opposing flows. The high chlorophylls were not an advective feature from the central California upwelling zones but occurred where the thermocline (and nutricline) was shallowest as a result of the geostrophic adjustment to the flow field. The depth of the chlorophyll maximum layer (not shown) showed a similar shoaling.

An anomalously high oxygen inversion (140% of normal) was seen at station 83.90, at a density of $\sigma_t = 26.375$ and a depth of 225 m. This feature was deeper than the usual near-surface oxygen maximum that commonly appears in summer and fall cruises and may not have been produced by local photosynthesis. A map of characteristics on this density surface shows this density at temperatures of 8.6–9.2°C and a salinity near 34.0—characteristics that are close to those of upwelling waters off the central California coast. Nitrate was also lower at the high oxygen anomaly station, suggesting a photosynthetic origin, most likely at the coastal upwelling areas. Upwelling is strongest there during spring to early summer, and the coastal upwelled water originates from as deep as 200 m where the initial oxygen levels are less than 2 ml/l and nitrate levels are around 30 µM. While dense upwelled water is in the photic zone, photosynthesis increases the oxygen concentration while reducing nutrient concentration. When upwelling winds subside, the inshore water may sink back down to its original density depth, but with altered chemical characteristics. The recently upwelled water may be subducted beneath lighter water offshore, embedded in either offshore “squirts” or eddies that drift away from the coast and southward into the California Current. The oxygen anomaly seen on this cruise was clearly in the main flow

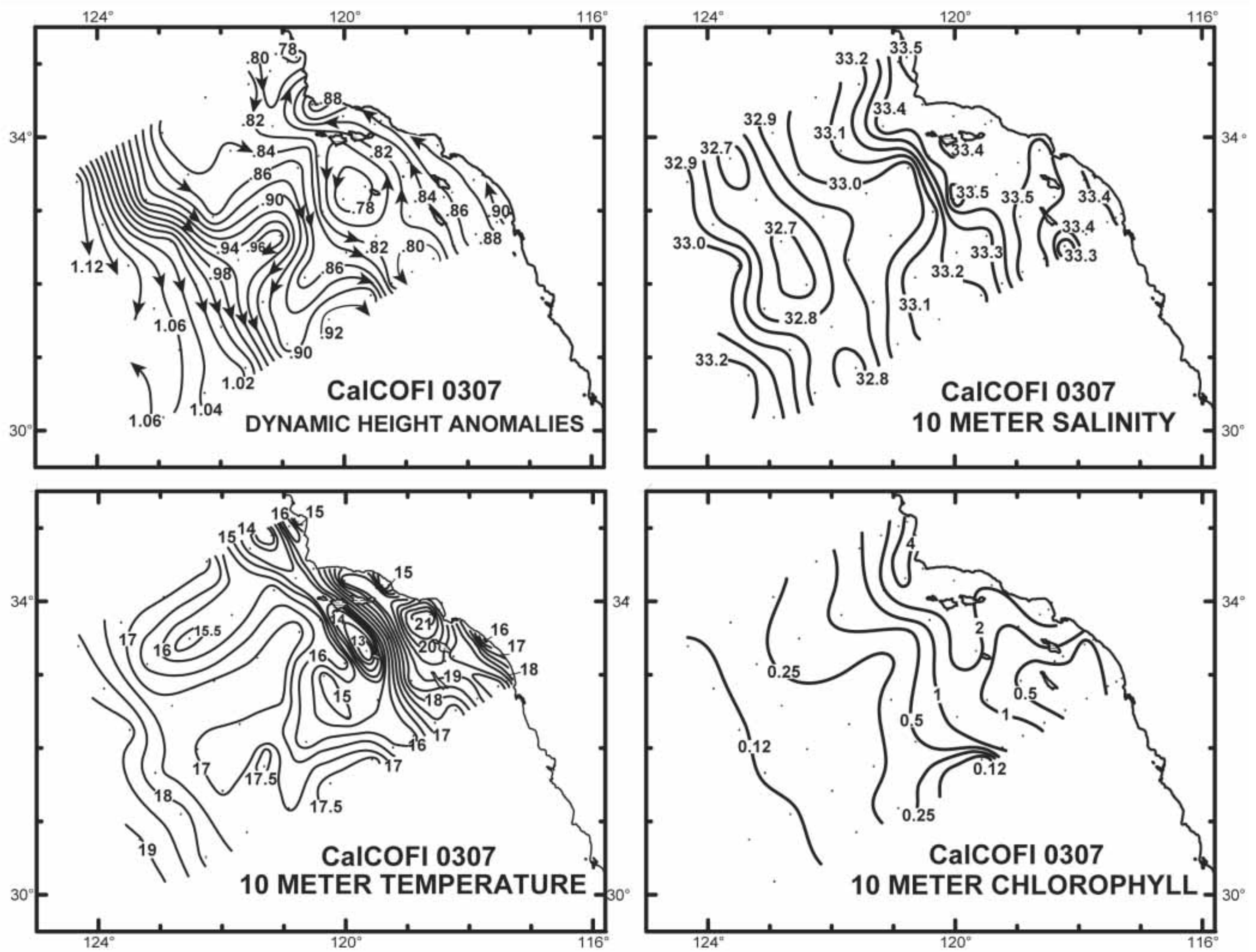

Figure 15. Spatial patterns for CalCOFI cruise 0307 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

of the California Current; a similar feature seen on CalCOFI cruise 8508 was in a cyclonic eddy.

CalCOFI Cruise 0310 (20 Oct.–4 Nov. 2003). The surface current map still shows some features that were seen during the summer (fig. 16). The onshore and offshore loop was still present, although shifted slightly further offshore. A cyclonic eddy had developed in the middle of lines 77 and 80. The Southern California Eddy was still present, with northward flow close to the coast. The cyclonic loop that was previously seen on lines 90 and 93, centered on stations 70 and 80, pinched off to form a cold core cyclonic eddy further offshore, centered on stations 100 and 110.

The cruise mean 10 m temperature anomaly was slightly warmer than normal, but there were also large areas down the middle of the pattern and around the Channel Islands that were cooler than normal. The 10 m salinities were all lower than normal, continuing a trend toward increasingly lower cruise mean 10 m salinities. The lowest salinities entered the pattern from the northwest corner, along with the California Current jet.

Surface chlorophylls were extremely high on the first station off Del Mar (93.26.7) as a result of a persistent red tide bloom (*Lingulodinium polyedra*) near the coast. The highest chlorophyll, > 60 µg/l, was measured at a depth of 3 m, and the dissolved oxygen was also extremely high: 11.1 ml/l, or 213% saturation. Elsewhere, the chlorophyll patterns appeared typical for a fall cruise, generally low, and with a deep chlorophyll maximum layer.

CalCOFI Cruise 0401 (5–20 Jan. 2004). The anticyclonic current loop that was present on the last two cruises intensified and penetrated farther toward the coast on this cruise (fig. 17). The cyclonic eddy that appeared at the middle of the northern two lines last fall was still strong and carried low salinity water from the northwest corner all the way around the eddy to just off of Point

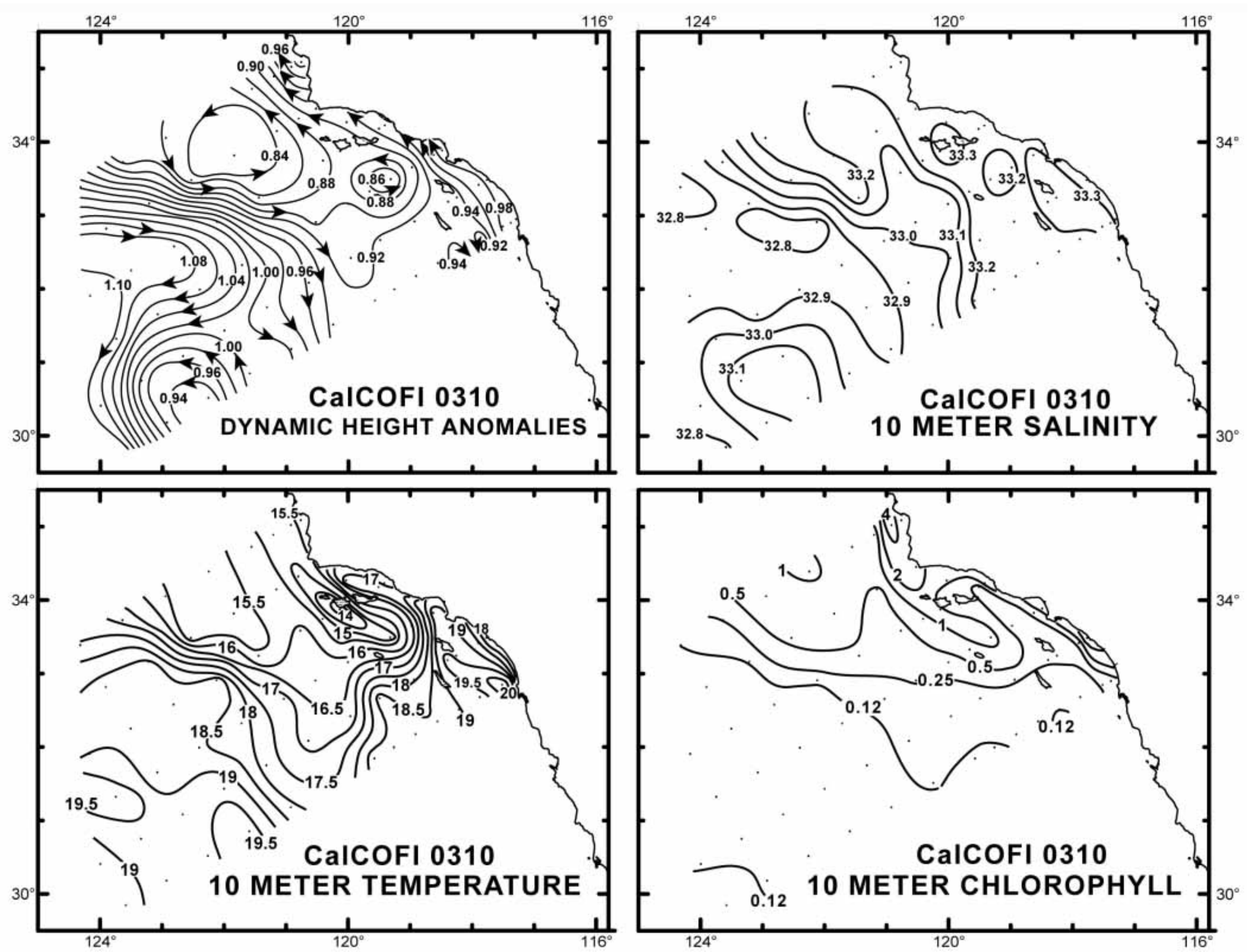

Figure 16. Spatial patterns for CalCOFI cruise 0310 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

Conception. The coastal surface countercurrent, strong in October, nearly disappeared in January.

The 10 m salinities continued the recent trend toward lower salinities. A comparison of the surface current and the salinity maps indicates that the salinity patterns were primarily due to advection. The 10 m temperatures remained slightly warmer than usual; warm water was seen in the warm-core clockwise current loop just to the south of the low-salinity water.

The 10 m chlorophyll *a* was highest in the Santa Barbara basin, somewhat higher than usually seen on winter cruises. Lower values were associated with the warm-water anticyclonic current loop.

CalCOFI Cruise 0404 (23 Mar.–8 Apr. 2004). The surface current patterns (fig. 18) were markedly different from those seen on the last cruise. The large northern cyclonic eddy was gone, as was the big loop that was present in the southern part of the pattern. The new pattern showed two bands of strong southward flow, quite similar to what was seen during the spring of 2003. The Southern California Eddy was present but centered around the northern Channel Islands.

The lowest 10 m salinities appeared in the northwest corner of the pattern, where the offshore California Current jet also entered the pattern. Highest salinities occurred in the cold newly upwelled water just north of Point Conception. Although the cruise-mean 10 m salinity anomaly was still below normal, the steady decrease in salinity seen over the last nine cruises was reversed slightly (fig. 12). The 10 m temperatures were cool in the upwelled water, as well as in the inshore edge of the current jet present around stations 55 and 70 on most of the lines. Warmer water was seen in the southeast corner of the pattern where there was a clockwise current loop. Cruise-mean temperature anomalies were slightly warmer than normal. High values for 10 m chlorophyll *a* were present in the cold-water regions; warm-water areas had low values.

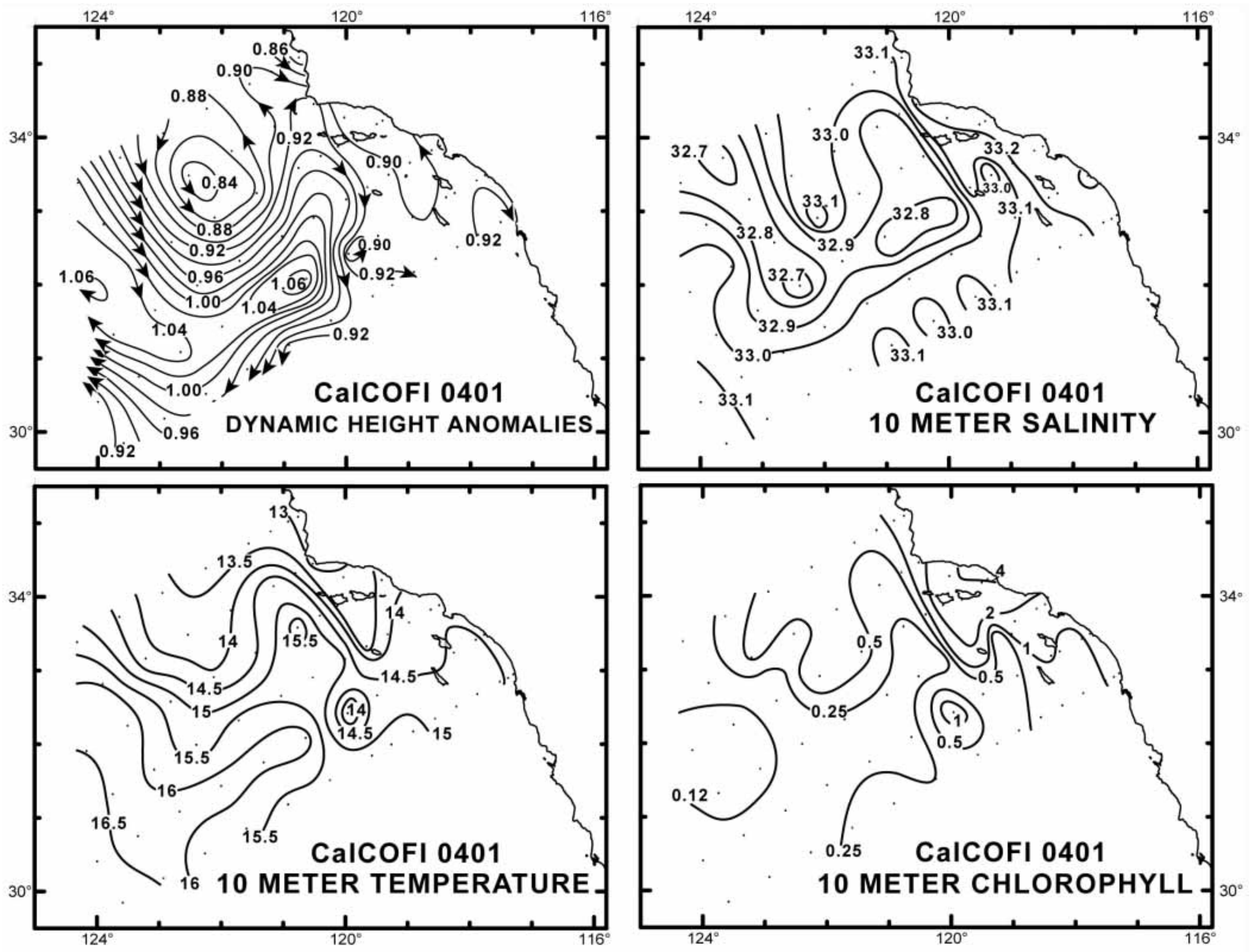

Figure 17. Spatial patterns for CalCOFI cruise 0401 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*. Data used for these plots are still preliminary.

IMECOCAL Cruises off Baja California

IMECOCAL Cruise 0304 (3–24 Apr. 2003). In April 2003, the typical spring pattern of strong southward flow of the California Current was observed (fig. 19). Isotherms parallel to the coast are consistent with this circulation pattern, showing the cool-water characteristic of coastal upwelling (fig. 20). The higher temperature was associated with the large anticyclonic eddy in the offshore central part of the area. A core of low salinity occupies almost the entire region (fig. 21). In the coastal region, the isohalines were parallel to the coast, and lightly saltier water was present, a pattern compatible with coastal upwelling. High inshore chlorophyll concentrations (> 4 mg m^{-3}) occurred at the upwelling centers, mainly off Punta Colonet (line 103), San Quintin (line 107), and Punta Canoas (line 113) (fig. 22). Chlorophyll values diminished immediately offshore to ~0.2 mg m^{-3}. Near-surface chlorophyll had a similar pattern but with values 50% lower than those reported for January 2003 (Venrick et al. 2003), when subarctic water was strongly affecting the region.

IMECOCAL Cruise 0307 (7–29 July 2003). The California Current was split into two jets during July 2003, one offshore and straight, and the other meandering between the coast and seaward (fig. 19). These meanders were apparently generating those eddies observed on lines 110 and 113. These eddies retained the cold and fresh water of the California Current (figs. 20 and 21). Saltier, warmer waters were found off Central Baja California. A strong thermal front was observed in the southeast edge of the area. The salinity in the upper few hundred meters of the region was anomalously low—reaching, for example, values of −0.3 near the surface along line 120 (fig. 23). However, negative temperature anomalies were not associated with these salinity anomalies. The spatial distribution of chlorophyll during the summer was similar to the spring pattern but with lower inshore concentrations in the northern IMECOCAL re-

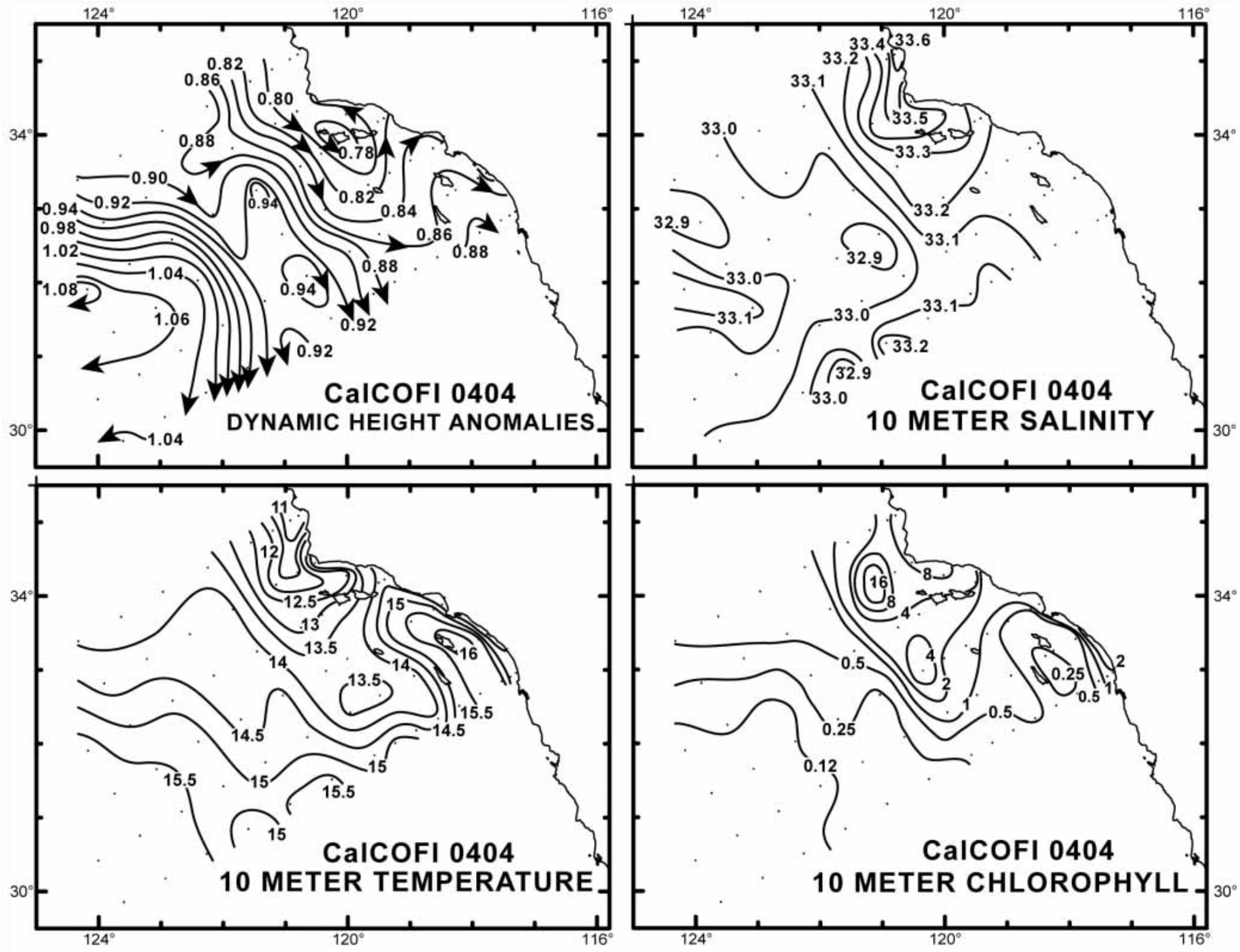

Figure 18. Spatial patterns for CalCOFI cruise 0404 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*. Data used for these plots are still preliminary.

gion (fig. 22). We detected only two inshore zones of high values, one between Ensenada and Punta Baja in the northern sampled lines, and one off Punta Abreojos (line 127) in the southern sampled lines, both areas where coastal upwelling occurs during the spring and summer. Some small areas of high chlorophyll, observed offshore, appear to be related to the meandering of the current.

IMECOCAL Cruise 0310 (10–31 Oct. 2003). In October 2003, a small cyclonic eddy off Ensenada (lines 100 and 103) altered the main flow of the California Current (fig. 19). From the northwest, a separate cool flow meanders toward the equator until line 127 (figs. 19 and 20), reversing impelled by the counterflow of warm and more saline water at the central offshore stations (fig. 21). South of Punta San Hipólito (27°N) the isotherms and isohalines were aligned in a strong gradient perpendicular to the coast. During autumn, the chlorophyll continued the decreasing trend, but the spatial patterns common to spring and summer remain unchanged (fig. 22). The higher levels (> 1.0 mg m^{-3}) at inshore locations follow the reinforcement of the equatorward circulation.

IMECOCAL Cruise 0401 (30 Jan.–20 Feb. 2004). In January 2004, the California Current was split into two jets off Ensenada. The California Current off Punta Baja (lines 110 and 113) was greatly distorted by a large seaward meander (fig. 19). Negative salinity anomalies were observed throughout the region; for example, salinity anomalies along line 120 reached values of up to −0.5 (fig. 23). These salinity anomalies did not correspond to negative temperature anomalies; these were only found along the coast out to station 120.60 (fig. 23), unusual for this time of the year. Subtropical water was compressed in the other half of the area, forming a thermohaline front affected by upwelling near the coast. Chlorophyll levels increased during winter along the coast (> 2.0 mg m^{-3}), maintaining the spatial pattern observed in the seasons described before (fig. 22).

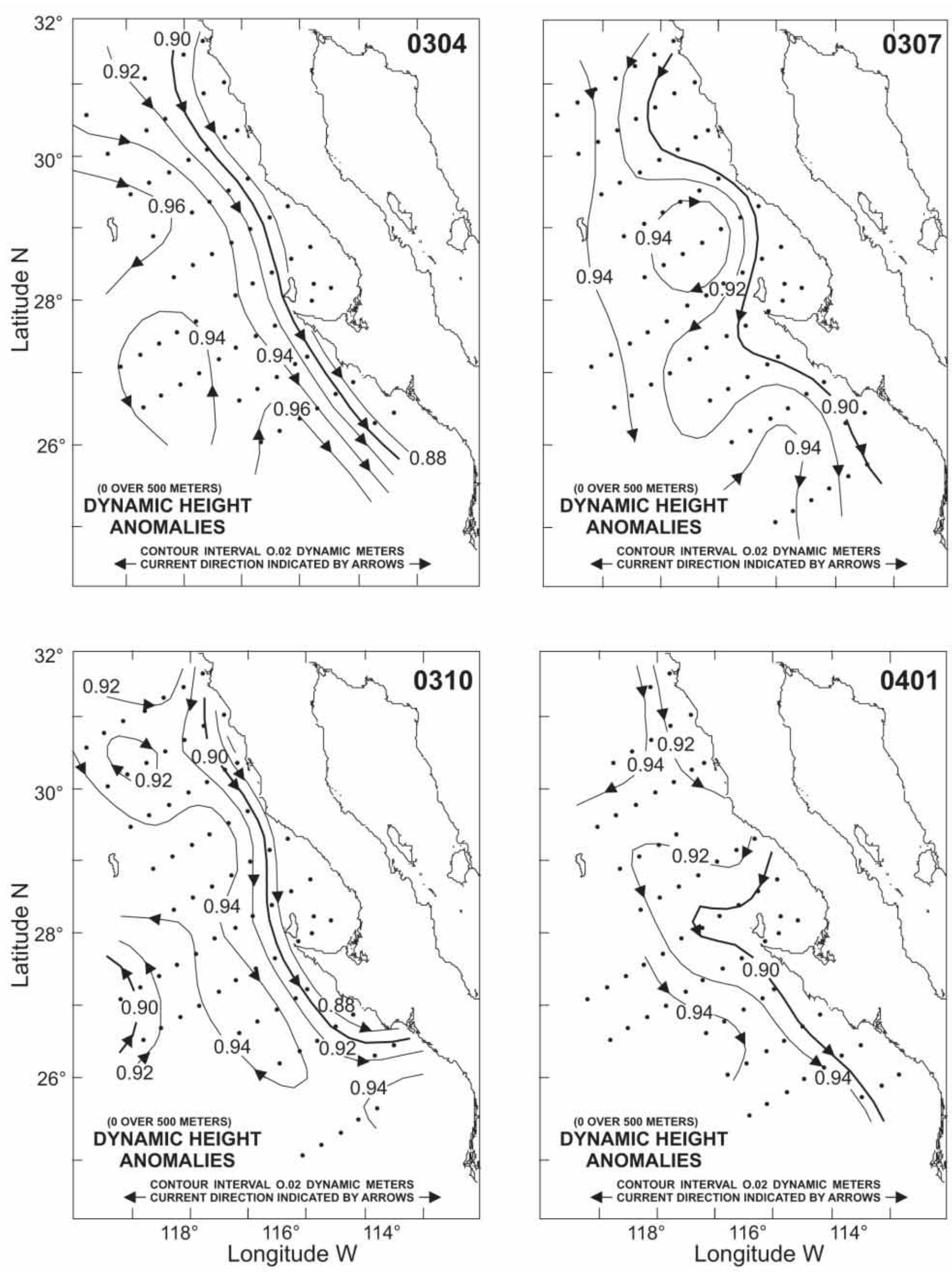

Figure 19. Spatial patterns of upper-ocean geostrophic flow estimated from 0/500 dbar dynamic height anomalies for IMECOCAL cruises: 0304 (3–24 April 2003), 0307 (7–29 July 2003), 0310 (10–31 October 2003), and 0401 (30 January–20 February 2004).

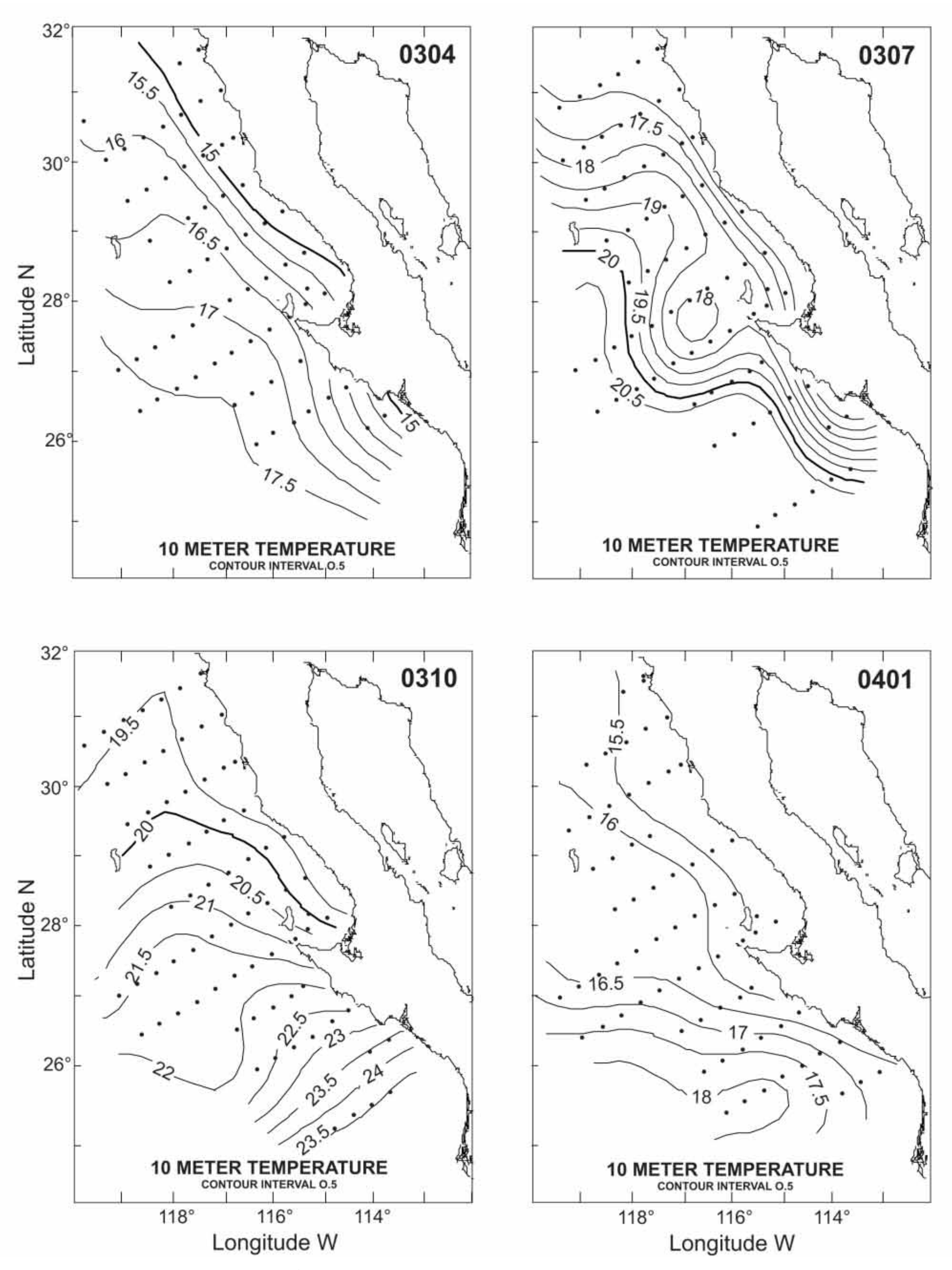

Figure 20. Spatial patterns of 10 m temperature (°C) for IMECOCAL cruises: 0304 (3–24 April 2003), 0307 (7–29 July 2003), 0310 (10–31 October 2003), and 0401 (30 January–20 February 2004).

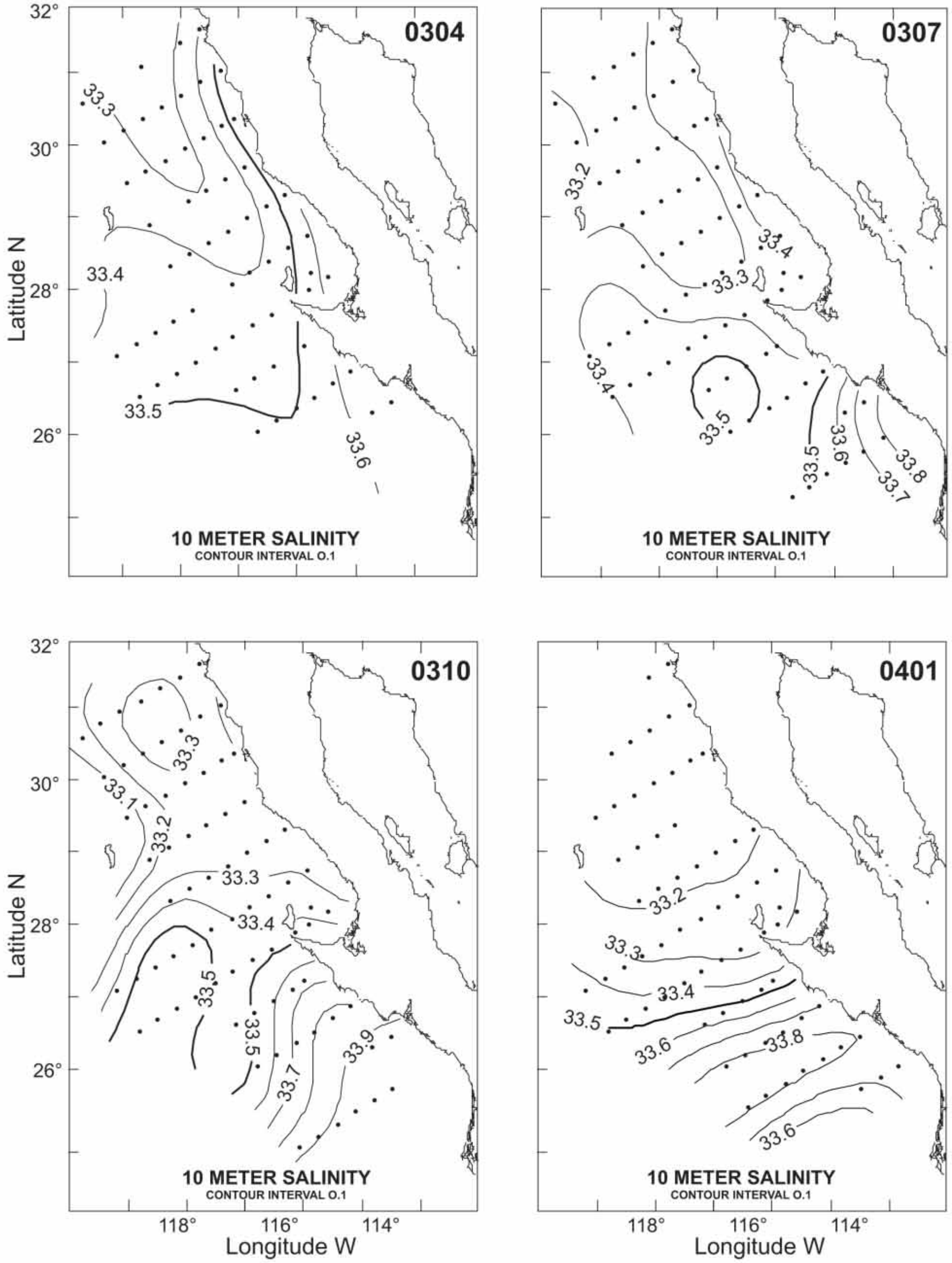

Figure 21. Spatial patterns of 10 m salinity for IMECOCAL cruises: 0304 (3–24 April 2003), 0307 (7–29 July 2003), 0310 (10–31 October 2003), and 0401 (30 January–20 February 2004).

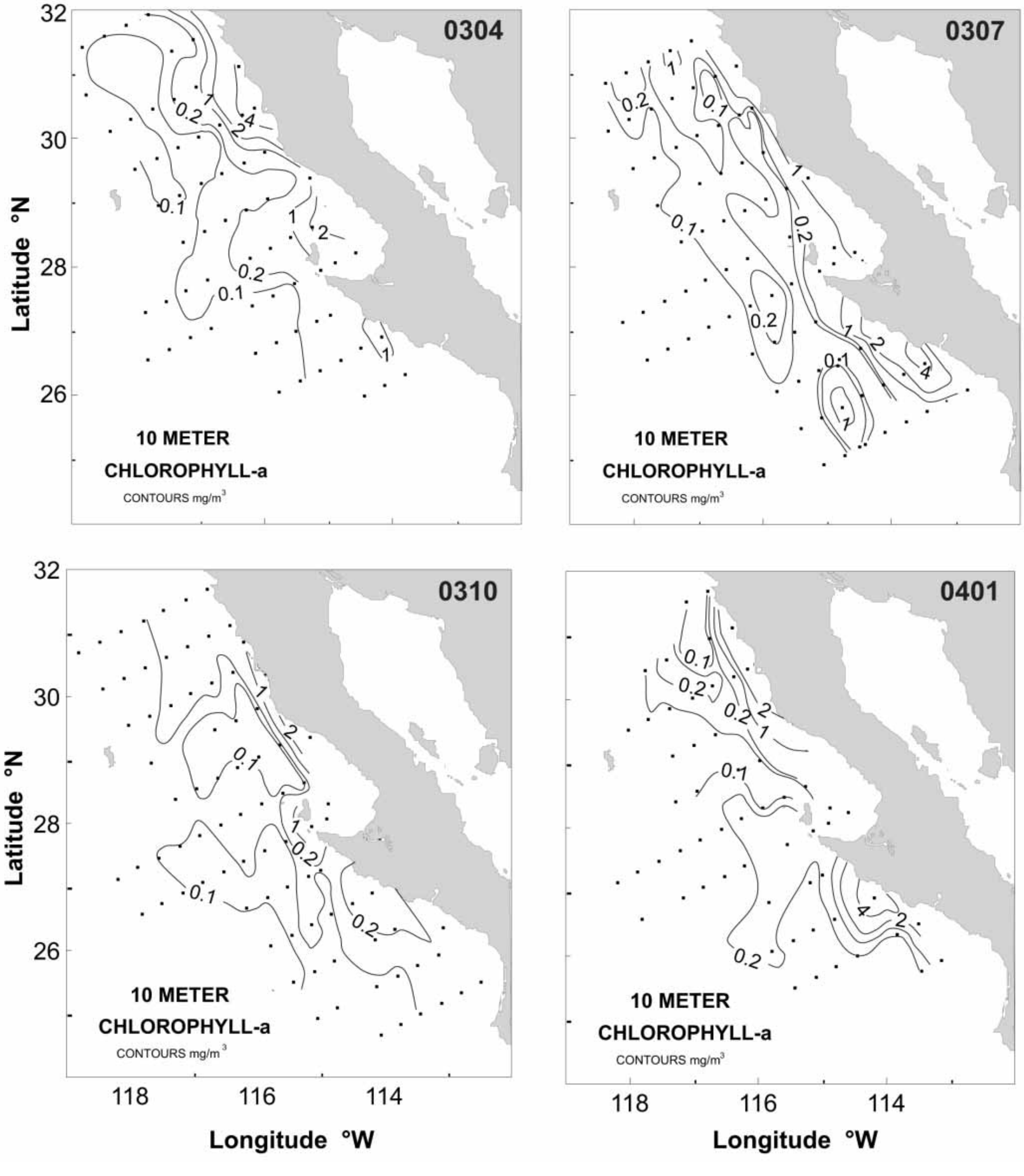

Figure 22. Spatial patterns of 10 m chlorophyll *a* for IMECOCAL cruises: 0304 (3–24 April 2003), 0307 (7–29 July 2003), 0310 (10–30 October 2003), and 0401 (30 January–20 February 2004).

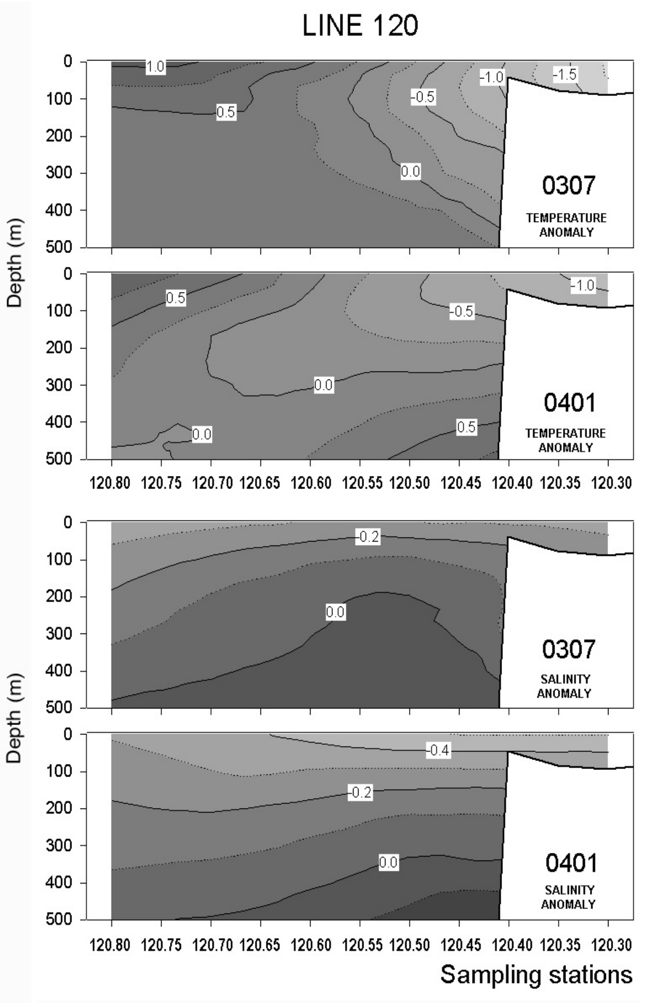

Figure 23. Temperature and salinity anomalies along line 120 for cruises 0307 and 0401. Anomalies were calculated relative to the 1950–78 time period (Lynn et al. 1982).

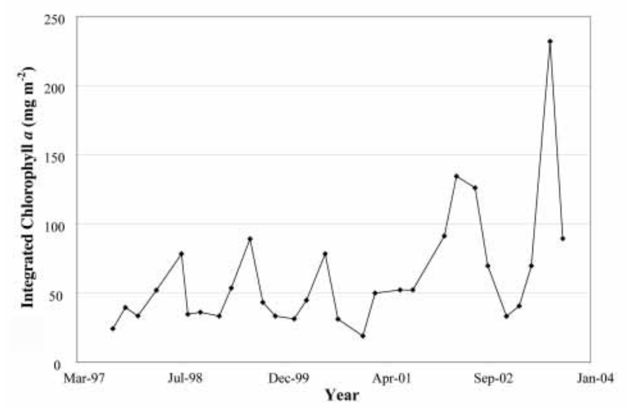

Figure 24. Time series of GLOBEC data showing mean integrated chlorophyll *a* averaged over all four lines (adapted from Wheeler et al. 2003).

BIOLOGICAL PATTERNS

Macronutrients, Chlorophyll *a*, and Primary Production

Oregon. Chlorophyll *a* concentrations in April 2003 (fig. 10d) were much lower than in April 2002, presumably because of the strong downwelling in March 2003 resulting from the persistent northward winds observed at Stonewall Bank and Point St. George (fig. 4). Chlorophyll concentrations in July 2003 were very high, exceeding 16 µg/l at one or more stations on each section. At the end of September, most of the inner shelf still had values > 4 µg/l. These high values for chlorophyll may reflect the persisting influence of subarctic waters (Wheeler et al. 2003); at densities corresponding to the permanent pycnocline and upper nutricline, subarctic waters have higher concentrations of phosphate (and other nutrients) than subtropic waters of the same density (Reid 1997). Time series of mean vertically integrated chlorophyll (fig. 24) suggest that summer phytoplankton biomass doubled from 2000 to 2003. Whether and to what extent these enriched conditions will persist through 2004 remains to be seen.

CalCOFI. Average concentrations of nitrate and phosphate in the mixed layer were close to their climatological averages during the observation period (fig. 25A,B). Mixed-layer concentrations of both macronutrients appear to be unaffected by the phase of the PDO. The shallow nutriclines observed off southern California since 2000 (fig. 14B) did not affect concentrations of the two macronutrients. Mixed-layer concentrations of both macronutrients were first negatively and then positively affected during the 1997–2000 ENSO cycle (solid lines in fig. 25A,B). In contrast, no significant response was observed for either macronutrient during the recent El Niño; concentrations remained close to their climatological means between the spring of 2002 and the present. Mixed-layer concentrations of silicate have been significantly below their climatological average since the beginning of 2003 (fig. 25C), a time period coinciding with the decline of mixed-layer salinities. This general trend would have masked an effect of the recent ENSO cycle on mixed-layer concentrations of silicate.

Mixed-layer concentrations of chlorophyll *a* were above the climatological mean throughout the last year (fig. 26A). Anomalies for mixed-layer chlorophyll *a* over the last two El Niños were surprisingly similar; anomalies were slightly below zero during both events (fig. 26A). However, it is not possible to unambiguously ascribe the patterns to the effects of the El Niño because of the large variability of mixed-layer chlorophyll *a* over the last two decades. Mixed-layer chlorophyll *a* differed significantly between periods of positive (1984–96) and negative (2000–2002) values for the PDO. Ascribing this difference to physical forcing associated with PDO phase changes is, again, difficult, not only because of the ap-

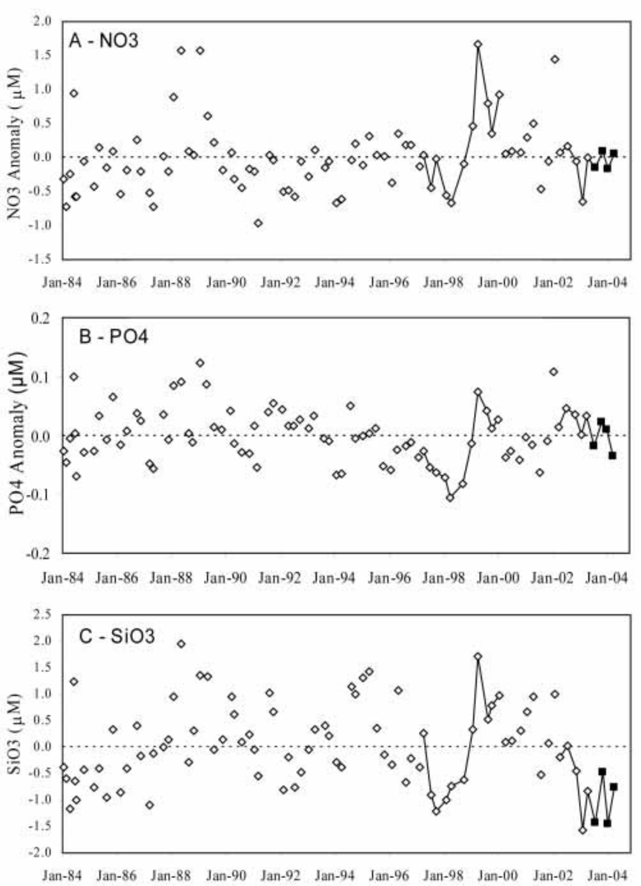

Figure 25. CalCOFI region anomalies for concentrations of (*A*) nitrate, (*B*) phosphate, and (*C*) silicate in the mixed layer. Data are derived from all 66 standard CalCOFI stations. Open symbols represent the period 1984 to spring 2003. Solid symbols represent data from the last four cruises.

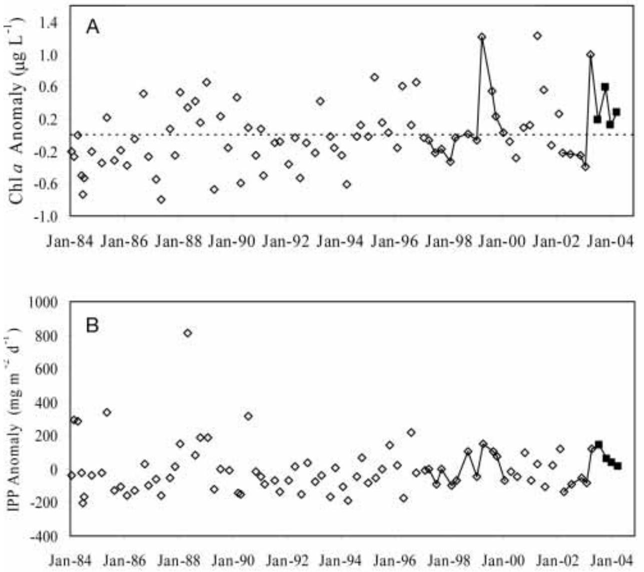

Figure 26. CalCOFI region anomalies for concentrations of (*A*) mixed-layer chlorophyll *a* concentrations and (*B*) integrated primary production (IPP). Open symbols represent the period 1984 to spring 2003. Solid symbols represent data from the last four cruises.

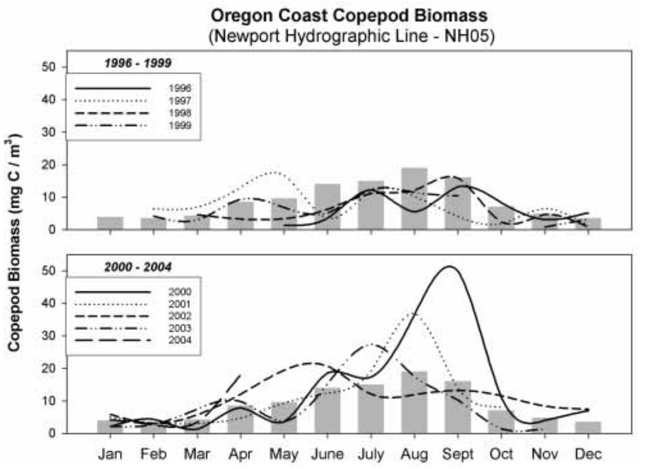

Figure 27. Seasonal and interannual patterns of copepod biomass at NH05 (60 m depth) of the NH line (45°N) compared to the 8-year climatological mean (*shaded bars*). The upper (lower) panel reveals data from 1996 to 1999 (2000 to 2004).

parent trend of increasing chlorophyll *a* over the time period 1984–96 but also because of the continuing positive chlorophyll a anomalies over the last year, even though the PDO is near neutral.

Depth-integrated rates of primary production (IPP) during the observation period (average 435 ±157 mg-C m^{-2} half-day^{-1}) were within the normal range (388 ±190 mg-C m^{-2} half-day^{-1}; fig. 26B). Patterns of IPP are too variable to detect patterns in response to interannual physical forcing.

Macrozooplankton

Oregon. Seasonal and interannual cycles of copepod biomass at NH-05 of the NH line off Oregon (44°40'N, water depth 60 m), together with an 8-year climatology, are shown in fig. 27. 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 often observed in August or September, near the end of the upwelling season. These observations are consistent with a loss of biomass 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.

Copepod biomass was relatively constant for the first 4 years of the 8-year time series (fig. 27) but showed a dramatic increase (up to 200%) after the "regime shift" of 1998–99. Averaged over the May–September time period, biomass for the first 4 years of our sampling was approximately 10 mg carbon per cubic meter (8.8 m^3 in 1996, 10.3 m^3 in 1997, 10.5 m^3 in 1998, and 10.4 m^3 during the upwelling season of 1999). Although a climate shift seems to have occurred in 1999 (Peterson et al. 2002; Peterson and Schwing 2003), not until summer 2000 were significant changes in biomass observed. During 2000, copepod biomass averaged 25.5 mg carbon per cubic meter and remained high through 2001 (21.5 mg carbon per cubic meter).

During 1996 and 1997, and during the 1997–98 El Niño, copepod biomass was low, and species with southern and offshore affinities were unusually abundant in coastal waters (Mackas et al. 2005). This group includes *Mesocalanus tenuicornis*, *Paracalanus parvus*, *Ctenocalanus vanus*, *Clausocalanus pergens*, *Clausocalnanus arcuicornis*, and *Clausocalanus parapergens*. This condition suggests that, at least during the 3-year period 1996–98, reduced coastal upwelling and low biomass characterized shelf waters of the northern California Current. However, following the onset of cool, La Niña-like conditions in 2000, copepod biomass doubled, and positive anomalies in the abundance of northern (cold-water) copepod species were observed off Newport (and off Vancouver Island; Mackas et al. 2001). The dominant members of this group include species that dominate the waters of the Bering Sea shelf, coastal Gulf of Alaska, British Columbia coastal waters, and the Washington-Oregon coastal upwelling zone—*Pseudocalanus mimus*, *Acartia longiremis*, and *Calanus marshallae*. These indicators of "cold-water" conditions were common during the May-September upwelling seasons of 2000 and 2001, as well as the early part of 2002 (Mackas et al. 2005).

Similarly, 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 (Feinberg and Peterson 2003). Marine survival of salmon stocks also showed a dramatic increase (Logerwell et al. 2003), contributing to near-record return rates of adult Chinook salmon not observed since the high-productivity years of the 1960s and 1970s.

Since 2002, however, trends in copepod biomass off the coast of Oregon suggest a high degree of variability that complicates a simple characterization based on interdecadal fluctuations of cool-water versus warm-water regimes. Greater-than-average copepod biomass was observed throughout the spring of 2002, only to be followed by a substantial decrease beginning in late June (fig. 27). This anomalous progression of events has been attributed to enhanced subarctic influence on shelf waters along the west coast (Huyer et al. 2003). The 2003 upwelling season was characterized by the onset of positive (warm) anomalies of PDO and MEI climate indexes, as well as greater-than-average biomass of southern/offshore copepod species. Although the seasonally integrated mean of total copepod biomass for 2003 was near the 8-year climatological mean (14.7 mg carbon per cubic meter), this was largely the result of an earlier-than-normal peak during mid-July, which had significantly declined by late August (fig. 27).

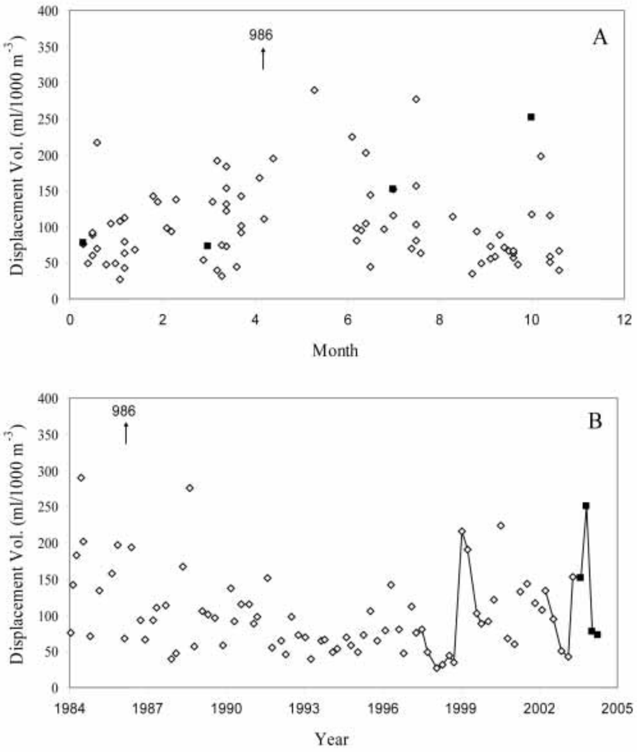

Figure 28. CalCOFI cruise mean macrozooplankton displacement volumes plotted against the month of the year (*A*) and the year (*B*). Open symbols represent the period 1984 to spring 2003. Solid symbols represent data from the last four cruises.

At the time of this writing (May 2004), the upwelling season of 2004 can be characterized by a high biomass of northern copepod species, but with continued high diversity (though low abundance) of offshore warm-water copepod species.

CalCOFI. Macrozooplankton displacement volumes during the observation period were close to the climatological mean, except for October 2003 (fig. 28A). Patterns of zooplankton displacement observed over the last ENSO cycle are surprisingly similar to the pattern observed during the previous cycle, 1997–2000 (fig. 28), including a post-El Niño bloom that is difficult to explain because the system did not enter a La Niña phase. Taken at face value, these patterns suggest that macrozooplankton biomass was affected by the recent ENSO event. This interpretation is tenuous since the recent change of the PDO phase coincided with the 1997–2000 ENSO event. It is similarly difficult to attribute the difference in zooplankton biomass between the pre- and the post-PDO phase change—for example, 1990–96 and 2000–2004—to the PDO phase change because the short period of positive PDO (1999–2004) includes not just an ENSO event; zooplankton biomass during the negative phase (1984–96) also had a significant downward

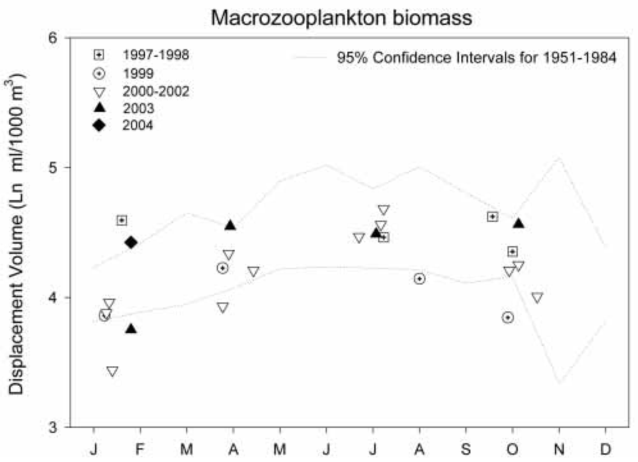

Figure 29. Mean macrozooplankton biomass for 25 IMECOCAL cruises from September 1997 to February 2004. Dotted lines indicate 95% confidence intervals for the historic mean of 1951–84 for the CalCOFI cruises in the region off Baja California. Data have been transformed to logarithms.

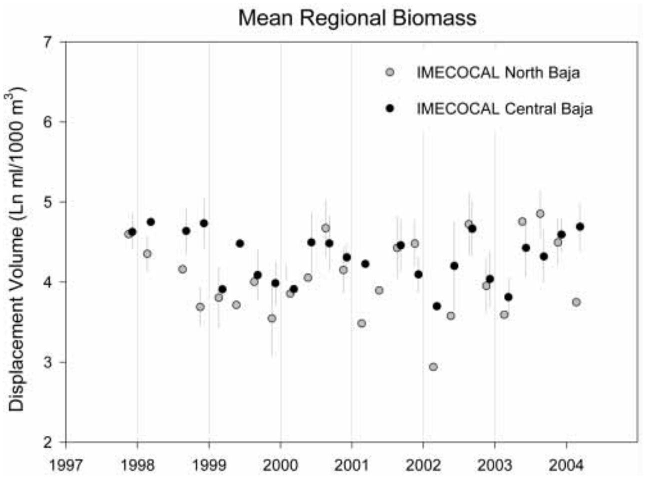

Figure 30. Mean macrozooplankton biomass in two regions of the California Current: northern Baja California (lines 100–110) and central Baja California (lines 113–133).

trend. This trend is driven by the extremely low zooplankton abundances during 1992–95. Thus, rather than looking for an effect of PDO phases on zooplankton displacement volume, one might want to ask why displacement volumes were so low during 1992–95. It is possible that these low displacement value are related to the consistently positive values of the MEI during the same period.

IMECOCAL. From April 2003 to February 2004 zooplankton biomass (i.e., displacement volumes) off Baja California was consistently high—a typical seasonal abundance cycle was not observed (fig. 29). The highest springtime values of biomass over the 1997–2004 time series were observed during the spring of 2003. Biomass during the summer of 2003 was typical for the season. Off Baja California, zooplankton biomass is usually highest during the summer and decreases in the fall. During 2003, in contrast, biomass in the region was high during the fall, similar to what was observed during the El Niño fall of 1997, despite the remarkable differences in hydrographic conditions (Lavaniegos et al. 2002). Winter is the season of lowest biomass in the region, and a sequence of extremely low values has been observed between 1999 and 2003. The winter of 2004 broke that sequence with a strong rebound, close to the mean biomass of the El Niño winter of 1998. Compared to CalCOFI data from that region collected from 1951 to 1984, the mean biomass of three of the analyzed cruises (0304, 0310, and 0401) fell in the upper limit of the 95% confidence interval (fig. 29).

Latitudinal variability in zooplankton biomass is high along the IMECOCAL area. The region from the U.S. border south to Punta Baja (lines 100–110) is characterized by low values during some periods, such as between October 1997 and April 1999, compared to the region covered by lines 113–133 (fig. 30). During other periods, however, such as July 1999 to October 2000, seasonal changes in biomass in both regions were coherent and similar to those observed in the CalCOFI region (fig. 28). Furthermore, two consecutive years (2001 and 2002) showed high regional variability in winter and spring. From October 2002 to October 2003 the three regions again showed similar trends, broken in winter 2004, with the biomass from southern California to northern Baja California being lower than off central Baja California.

Avifauna

Observations of marine bird populations provide information on the response of upper-trophic level predators to interannual and longer-term oceanographic variability. This perspective complements time series of physical variables (e.g., atmospheric pressure, upwelling indexes, thermocline depth) and lower trophic-level ecosystem constituents (e.g., phytoplankton, zooplankton, fish eggs, and larvae). CalCOFI cruises have provided the opportunity for systematic surveys of the distribution and abundance of marine birds and mammals in relation to oceanographic conditions off southern California since 1987.

The Point Reyes Bird Observatory (PRBO) Marine Ecology Division has monitored the reproductive performance and diet of seabird populations breeding at the Farallon Islands (37°N, 123°W) since the early 1970s. These time series have revealed that locally breeding bird populations are sensitive to shifts in ocean climate and prey availability over short (interannual) and long (decadal) temporal scales (Sydeman et al. 2001; Abraham and Sydeman 2004). In this report we compare at-sea and colony-based observations of marine bird populations collected during 2003–2004 with data from the CalCOFI and PRBO time series. Our objective is to quantify the interannual variability in marine bird community structure and productivity off the west coast of North America since the 1998–99 transition into a cold-water regime (Bograd et al. 2000; Durazo et al. 2001; Schwing et al. 2002; Peterson and Schwing 2003; Venrick et al. 2003).

We describe changes in seabird communities during spring and fall CalCOFI cruises after the winter of 1999. To place these observations in a broader context, we also include in this analysis observations from cruises during a period of warm-water (El Niño: fall 1997 and spring 1998) and cold-water (La Niña: fall 1998 and spring 1999) anomalies. During spring and fall, the avifauna is especially affected by incursions of warm-water and cold-water taxa. We focus, in particular, on four indicator species with different water-mass preferences and biogeographic affinities to illustrate short-term (interannual) fluctuations in the composition of marine bird communities. The subtropical black-vented shearwater (*Puffinus opisthomelas*) shifts its distribution northward into the CalCOFI study area during warm-water years. The Cook's petrel (*Pterodroma cooki*) is an offshore spring-summer visitor that moves shoreward during warm-water periods; its abundance increased significantly off southern California from 1987 to 1998. The numerically dominant cold-water species, the sooty shearwater (*Puffinus griseus*), is a spring–fall visitor whose abundance declined by about 74% from 1987 to 1998. Finally, the black-legged kittiwake (*Rissa tridactyla*) is a subarctic winter visitor from Alaska that becomes more numerous during cold-water years, particularly in spring (Lynn et al. 1998; Hayward et al. 1999; Hyrenbach and Veit 2003; Venrick et al. 2003).

During the fall cruise of 2003, the avifauna was dominated by phalaropes (Red, *Phalaropus fulicaria*, and Red-necked, *P. lobatus*) and western gulls (*Larus occidentalis*), which accounted for over 39% and 19%, respectively, of all birds sighted. No kittiwakes were observed within the study area, and the sooty shearwater contributed only 6% of all birds recorded. Similarly, the subtropical black-vented shearwater accounted for only 4% of all birds sighted, and few Cook's petrels were recorded within the CalCOFI survey grid at this time. Overall, the avifauna during the fall 2003 cruise consisted of a mixture of subtropical and subarctic taxa, without compelling evidence of incursions by warm-water or cold-water visitors. This mixed community structure was consistent with the concurrent pattern of simultaneous positive (+1.5°C) and negative (−1.5°C) SST anomalies off southern California at that time (El Niño Watch Advisory, October 2003, http://coastwatch.pfel.noaa.gov/cgi-bin/elNiño.cgi).

These intermediate oceanographic conditions, with low-amplitude temperature anomalies and a slightly positive MEI suggestive of weak El Niño conditions (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/mei.html), prevailed from the summer of 2003 to the spring of 2004. By April 2004, the avifauna was dominated by endemic western and California (*L. californicus*) gulls, accounting for 28% and 11%, respectively, of all birds sighted. The kittiwakes were not recorded for a third consecutive year, and the sooty shearwaters, accounting for less than 1% of all the birds recorded, were also virtually absent. Though the black-vented shearwater and the Cook's petrel were present in very low numbers within the study area, there was evidence of northward shifts in range by other warm-water species. In particular, the black storm-petrel (*Oceanodroma melania*), a subtropical species known to expand its range into the CalCOFI region during El Niño events, occurred off southern California at this time (Lynn et al. 1998; Hyrenbach and Veit 2003).

To characterize the patterns observed during 2003–2004 in a broader context, we addressed interannual variability in seabird community structure after the 1998–99 regime shift. We considered all the species sighted during at-sea surveys and used cluster analysis to identify groups of years with similar community structure. We considered fall and spring cruises separately and included observations from an El Niño (fall 1997, spring 1998) and a la Niña (fall 1998, spring 1999) event as "outgroups" to better resolve the year-to-year variability.

The community structure of the avifauna observed during the fall of 2003 was similar to that documented during previous fall cruises after the 1998–1999 regime shift (fig. 31). The hierarchical clustering revealed only one cluster containing all cruises (1999–2003) except for the El Niño (1997) and the La Niña (1998) periods. Three of these years (1999, 2001, and 2003) were characterized by a mixed community structure with low levels (< 10% of all birds sighted) of warm-water and cold-water indicators. The two other years in this cluster (2000 and 2002) were characterized by a stronger subtropical influence, with substantial black-vented shearwater incursions (> 10% of all birds) and low sooty shearwater abundance (< 1% of all birds). These results underscore the mixed nature of CCS seabird communities in the last few years, without clear numerical dominance of warm-water or cold-water taxa (Venrick et al. 2003).

The hierarchical grouping revealed two distinct clusters of spring cruises (fig. 32). The first cluster, comprising 3 years (2002, 2003, and 2004), was characterized by intermediate community structure, with low levels of cold-water and warm-water indicators. In particular, it is noteworthy that the black-legged kittiwake, a subarctic species that accounted for over 10% of all birds sighted in spring 1999, has not been observed off southern California during the last three spring cruises.

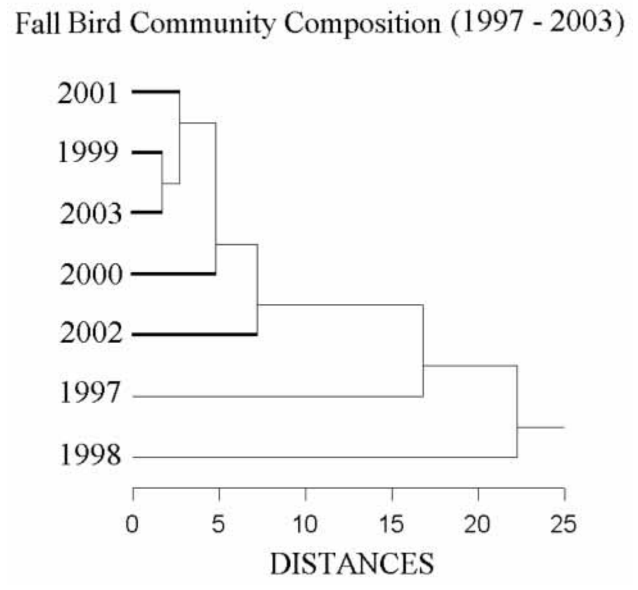

Figure 31. Cluster tree of marine bird community structure at-sea off southern California during fall CalCOFI cruises (1997–2003). The euclidean distances are based on the hierarchical clustering technique, with the median linkage algorithm. The thick lines identify years in the same cluster.

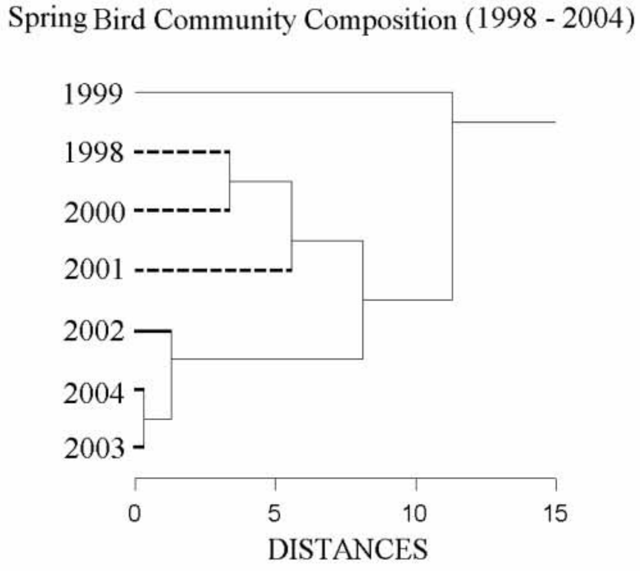

Figure 32. Cluster tree of marine bird community structure at-sea off southern California during spring CalCOFI cruises (1998–2004). The euclidean distances are based on the hierarchical clustering technique, with the median linkage algorithm. The dashed lines and the continuous thick lines identify years in the two different clusters.

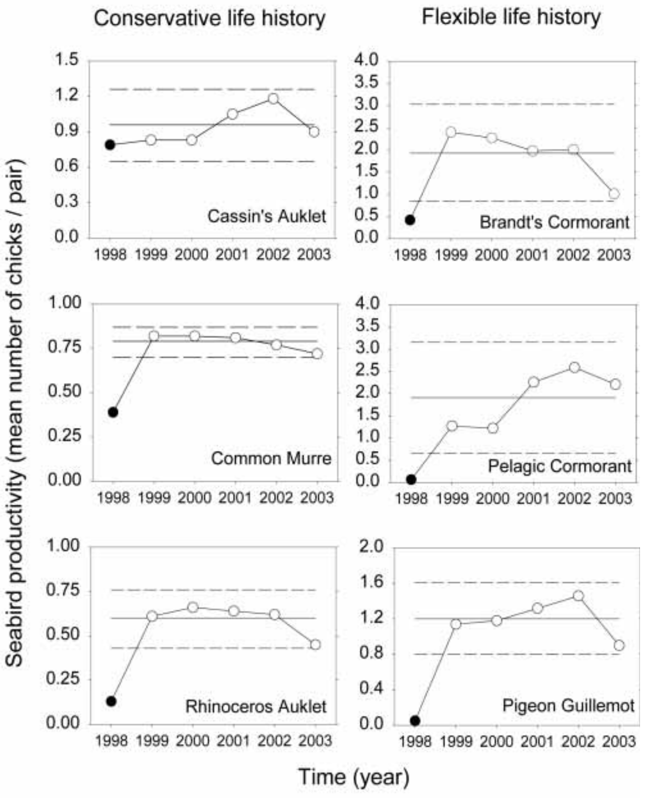

Figure 33. Anomalies of productivity for six seabird species breeding at Southeast Farallon Island (off central California). Solid horizontal lines indicate the long-term averages (1990–2002); hatched lines indicate the variability (mean ±2 SD). Solid circles highlight productivity values during the 1998 El Niño.

Similarly, the sooty shearwater has remained at low levels (< 1% of all birds) during the last three spring cruises (Venrick et al. 2003). The second cluster, comprising 3 years (1998, 2000, and 2001), was characterized by a slightly higher presence of sooty shearwaters (> 10% of all birds sighted) and intermediate levels of Cook's petrels. These results suggest that, in spite of transient incursions of warm-water species (2000 and 2001) similar to those during the 1998 El Niño event, springtime seabird communities off southern California from 1999 to 2004 have remained intermediate between a subtropical and a subarctic avifauna (Venrick et al. 2003).

Observations of marine bird populations breeding at the Farallon Islands, on the edge of the continental shelf west of San Francisco, revealed a widespread decrease in productivity during 2003, after record high reproductive performance during the previous year (Venrick et al. 2003). When we considered three species with conservative life histories (Cassin's auklet, *Ptychoramphus aleuticus*; common murre, *Uria aalge*; rhinoceros auklet; *Cerorhinca monocerata*) and three species with flexible ones (Brandt's cormorant, *Phalacrocorax penicillatus*; pigeon guillemot, *Cepphus columba*; pelagic cormorant, *P. pelagicus*), the mean number of chicks produced per breeding pair declined across the board in 2003 (tab. 1; fig. 33). Nevertheless, the mean species-specific productivity remained significantly higher after the hypothesized regime shift (1999–2003) than during the preceding warm-water period (1990–98) (Wilcoxon paired test, $Z = 2.201$, $n = 6$ species, $p = 0.028$).

TABLE 1
Productivity of Six Seabird Species Breeding at the Southeast Farallon Island (Central California), Before (1990–98) and After (1999–2003) the 1998–99 Regime Shift

	Productivity (chicks fledged per pair)		
Seabird species	Average, 1990-98 (mean +S.D.)	Average, 1999-2003 (mean +S.D.)	Proportional, 2002 vs. 2003 (% change)
Brandt's cormorant	1.38 ±0.93	1.93 ±0.55	−49.75
Cassin's auklet	0.62 ±0.24	0.96 ±0.15	−23.73
Common murre	0.66 ±0.27	0.79 ±0.04	−6.49
Pelagic cormorant	0.54 ±0.64	1.91 ±0.62	−14.67
Pigeon guillemot	0.54 ±0.38	1.20 ±0.20	−36.99
Rhinoceros auklet	0.48 ±0.16	0.60 ±0.08	−27.42

Note: The proportional change in seabird productivity from 2002 to 2003 is quantified as PC = 100% * [(2003 value) − (2002 value) / (2002 value)]. Positive and negative PC values indicate increasing and decreasing productivity, respectively.

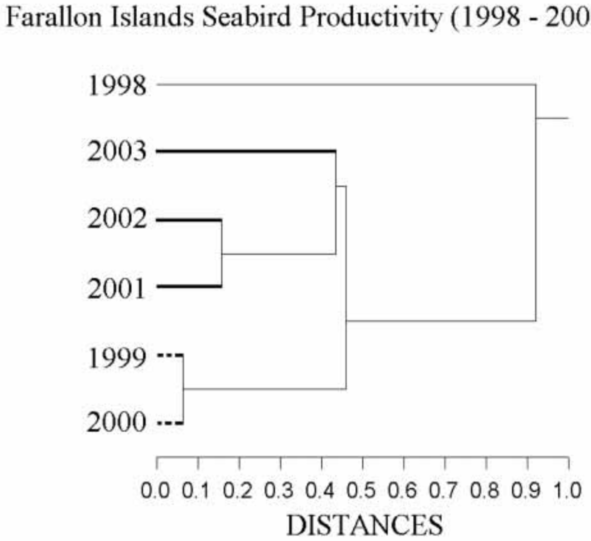

Figure 34. Cluster trees of marine bird productivity (mean number of chicks produced per breeding pair) for six species breeding at Southeast Farallon Island from 1998 to 2003. The euclidean distances are based on a hierarchical clustering technique, with the median linkage algorithm. The dashed lines and continuous thick lines identify years in the two different clusters.

Hierarchical clustering of the productivity data revealed two clusters of years after the 1998–99 regime shift: one containing two early years (1999 and 2000), and the other including the three subsequent years (2001, 2002, and 2003) (fig. 34). After the pervasive increase in reproductive performance during 1999 and 2000, the six monitored species behaved differently. A clear dichotomy was apparent in 2001. The reproductive success of three species (the planktivorous Cassin's auklet and the piscivorous pelagic cormorant and pigeon guillemot) soared, surpassing their long-term (1990–2002) average values by 1 standard deviation, and continued to increase in 2002. Conversely, the productivity of the three other piscivorous species (Brandt's cormorant, common murre, and rhinoceros auklet) declined in 2001 and leveled off or continued to decrease in 2002 (Venrick et al. 2003).

DISCUSSION

The state of the CCS over the last few years was potentially affected by three distinct factors: the change from a warm PDO phase over to the Victoria mode, the equatorial ENSO event, and the intrusion of subarctic waters into the system. Over the last year, the state of the system, when viewed from different perspectives, has been near neutral. This is also true for the whole North Pacific Basin.

ENSO Events

A La Niña phase of the recent ENSO event was undetectable in the equatorial Pacific. The climatological anomalies derived from observations made in the CCS, such as temperature, mixed-layer depth, and nutricline depth fields, have been near zero over the last year. Upwelling anomalies along the cost were little affected by the last El Niño (fig. 3). Anomalies of macronutrient concentrations in the CalCOFI region were either near zero (nitrate or phosphate) or displayed a pattern that was not affected by the ENSO event (silicate, fig. 25).

Temporal changes of the plankton and avifauna, relative to the recent ENSO event, differed greatly among different groups of organism and localities. Off Oregon, a large increase in phytoplankton biomass has been observed over the last 2–3 years, a signal clearly unrelated to the recent ENSO event and potentially masking its more subtle effects on the ecosystem. Zooplankton biomass off Oregon has been significantly larger over the last 4 years as well, when compared to the previous 4 years, with interannual variability masking effects that could be attributed to the recent ENSO event. Off southern California, temporal patterns of mixed-layer chlorophyll *a* and zooplankton biomass anomalies were very similar during the ENSO events of 1997 and 2002. The similarity of the patterns is disconcerting considering that the two ENSO events differed not only dramatically in strength, the latter having hardly any effect on the physical state of the CCS, but also in the development of a La Niña phase. Zooplankton biomass off Baja California covaried with zooplankton biomass off southern California only during the most recent ENSO event, not during the event beginning in 1997, suggesting that these patterns were not necessarily forced by the El Niño events.

The avifauna in the CalCOFI region was not affected substantially by the recent ENSO event. The spring seabird communities from 2002 to 2004 were virtually indistinguishable, that is, they were not affected by the recent ENSO cycle. The patterns observed during the fall are not that clear cut; however, the seabird communities of 2002 and 2003 were distinctly different from the ENSO-affected communities of 1997 and 1998. Despite a widespread decline in the productivity of seabird populations breeding off central California in 2003, annual reproductive success (number of chicks produced per breeding pair) at the Farallon Islands remained considerably higher than during the 1998 El Niño episode.

As has been concluded previously (Venrick et al. 2003), the data available for the CCS show that the recent El Niño had only a small to moderate effect on the CCS. Since a La Niña did not develop in the equatorial Pacific, La Niña-like conditions in the CCS were not expected. Thus, the similarity of some biological patterns off southern California with those observed during previous complete El Niño–La Niña cycles must be related to physical forcing other than ENSO.

Subarctic Influence on the CCS

There was enhanced subarctic influence on the California Current in 2002 (e.g., Freeland et al. 2003; Bograd and Lynn 2003). The CCS has strong subarctic characteristics: it is the only subtropical eastern boundary current in which salinity increases monotonically with depth. North of Point Conception, normal advection of cool, low-salinity, nutrient-rich subarctic waters enhances the productivity associated with coastal and offshore upwelling that is driven by the alongshore winds and by positive wind-stress curl, but this advective influence was stronger than usual in the late winter and spring of 2002 (Strub and James 2003; Barth 2003; Kosro 2003). This enhancement was apparently not related to either the MEI or the PDO but nevertheless resulted from anomalous winds over the northern North Pacific (Murphree et al. 2003). The anomalous wind field shows that both the Aleutian Low *and* the North Pacific High were stronger than normal in 2002. Bond et al. (2003) suggests that this pattern is orthogonal to the PDO. In any case, the oceanic effects of such a large-scale climatic anomaly are likely to persist for at least a year or two, since oceanic advection is so much slower than atmospheric advection. Thus, it is not surprising that anomalously cool, nutrient-enriched waters and high biomass were observed throughout the California Current region in 2003.

Off Oregon, cool, fresh, and likely nutrient-rich subarctic waters were observed intermittently over the last year, with anomalies strongest in the upper halocline. Anomalies observed in 2002 were stronger than those observed in 2003. Off southern California, the anomalies are now found in most areas of the CalCOFI region (fig. 13). These were first evident during 2001 and 2002 (Venrick et al. 2003) as subsurface anomalies at offshore stations but have since spread to the surface and to stations along the coast. The anomalies still tend to be strongest at the offshore stations, where conditions since 2003 have not changed much, but these have intensified over the last year at the inshore stations. Associated with the change in water masses, particularly at the offshore stations, was a shallowing of the seasonal thermocline and the nutricline. In contrast to the salinity data, which suggest a massive change in the upper 100-150 m of the system (fig. 13), climatologies of other water-column properties do not show such large anomalies over the last 2–3 years, with the exception of silicate. This contrast may not be that surprising when considering that properties such as salinity are strongly affected by advective forcing into the region, whereas properties such as SST are strongly affected by local atmospheric forcing. The expected effect of this subarctic influence on the ecosystem is an enrichment (Wheeler et al. 2003). The dramatic changes in phytoplankton biomass off Oregon over the last year are a likely consequence of this effect. Off southern California, much less dramatic domainwide changes in ecosystem properties were noticed over the last 2 years. However, a slight positive anomaly in mixed-layer chlorophyll *a* was observed, a likely consequence of this enhanced subarctic influence. More dramatic changes in ecosystem structure are evident in the offshore areas where the depth of the chlorophyll-maximum has changed over the last years from approximately 100 m to 80 m (data not shown). This ~20 m change corresponds to a 30 m change in the depth of the nutricline in that region. Negative temperature anomalies were found throughout the region off Baja California. However, these were not associated with negative temperature anomalies. These observations suggest that this region too has experienced an increased influence of subarctic waters (Lavaniegos et al. 2003; Durazo et al. submitted).

The State of the CCS after the 1998 Regime Shift

The state of the California Current system changed dramatically in 1998–99 (Chavez et al. 2003; Lavaniegos and Ohman 2003; Brinton and Townsend 2003; Peterson and Schwing 2003). It was hypothesized that this change represented a "regime shift" associated with a change in the sign of the PDO, and it was anticipated that the system would remain in this state for a long time. Recent studies, however, have shown that patterns of SST anomalies over the North Pacific since 1998 do not resemble those characteristic of a cool phase of the PDO (Bond et al. 2003). Rather, the North Pacific until 2003 was characterized by cool anomalies in the CCS but warmer conditions in the subarctic Pacific (Bond et al. 2003), a pattern called the Victoria mode. However, as stated above, conditions at present do not appear to be representative of either the PDO or Victoria modes. Indeed, the PDO has been slightly positive the last 2 years after a period of negative values since 1998.

Temperature anomalies in the CCS, which had responded dramatically to the 1998 climate shift, have been neutral over the last 2 years (e.g., fig. 11B). Off Oregon, dramatic changes in ecosystem structure have been observed since 1999, during which the recent trend for enhanced summer upwelling is associated with an overall increase in ocean production for this region, including primary production, and more plankton, small bait fish, and salmon in the Pacific Northwest. Off southern California mixed-layer concentrations of chlorophyll *a* have been significantly higher since 1998. However, ascribing these differences to physical forcing associated with a recent climate shift is not possible because of the possible trend of increasing mixed-layer chlorophyll *a* concentrations over the last two decades (fig. 26A). Anomalies of primary production off southern California were close to climatological means during either phase of the PDO. Zooplankton displacement volumes have been significantly higher during the last 5 years compared to the previous 5 years, 1992–97. Unfortunately, time series based on data collected off Baja California are too short, but compared to the CalCOFI data collected in the region from 1950 to 1978 they indicate a lag in the response to increased zooplankton biomass until 2000.

Surveys of marine bird communities at sea have failed to detect clear avifaunal signals suggestive of a transition into a persistent cold-water regime in the California Current since the winter of 1999. The "mixed" nature of the avifauna since the 1998–99 regime shift is underscored by the hierarchical clustering analyses of fall and spring cruise data (figs. 31 and 32). The seabird communities documented during recent fall cruises differ from the avifauna observed during 1997 and 1998 (Lynn et al. 1998; Hayward et al. 1999; Venrick et al. 2003). Similarly, in spite of episodic incursions of warm-water species (2000 and 2001), the springtime seabird community structure during the last 5 years (2000–2004) has remained intermediate between a subtropical and a subarctic avifauna (Lynn et al. 1998; Venrick et al. 2003). Thus, we conclude that the composition of seabird communities reflected the struggle for dominance by subarctic and subtropical influences in the CCS.

Because seabirds integrate the variability in oceanographic conditions and prey resources during the breeding season, we expected a strong response of the Farallon productivity indexes to recent year-to-year oceanographic variability (Ainley et al. 1995; Sydeman et al. 2001). Indeed, the diet and demography of seabirds are the population-level attributes most sensitive to fluctuations in the marine environment and prey availability (Montevecchi 1993). In spite of widespread declines in productivity across all six species monitored in 2003 (fig. 33), which we interpret as a response to El Niño conditions, the average values after the regime shift (1999–2003) remain much higher than those observed during 1990–98, when the ocean off central California was considerably warmer (tab. 1). This result suggests that breeding seabird populations continue to benefit from the transition into a cold-water regime of enhanced upwelling and prey availability. This has been reflected in the return of juvenile rockfish (*Sebastes* spp.) as a major prey item in the diet of the piscivorous species (Venrick et al. 2003; Mills et al., in press; Miller and Sydeman 2004); in the increase in the take of *Thysanoessa spinifera*, the larger bodied coastal euphausiid in this region, by planktivorous auklets (Abraham and Sydeman 2004); and in an offshore shift in the distribution of breeding common murre (May–June) in the Gulf of the Farallones from 1996–97 to 2001–2002, reversing an onshore trend previously described during the preceding warming period (1985–94) (Oedekoven et al. 2001; Yen et al. 2004).

CONCLUSION

Climatologically, the past year has been near neutral, both on basin and CCS scales. However, much of the data discussed here, particularly that collected off Oregon, support the hypothesis that the CCS is still in a state of higher ecological productivity that began in late 1998 (Peterson and Schwing 2003). It is unclear, however, if the observed changes were driven by changing physical forcing associated with the 1998 shift or by other factors. Increased phytoplankton biomass off Oregon, for example, may have been driven by the stronger subarctic influence. Indeed, this stronger subarctic influence is the most interesting phenomenon currently occurring in the CCS. Freeland et al. (2003) suggests that stronger subarctic influence is merely the result of a combination of stochastic processes—that is, coincidence, in which case it would be expected not to persist for longer periods of time. However, it is also possible that the enhanced southward transport of the California Current associated with the increased subarctic influence reflects a spin up of the entire Subtropical Gyre following the 1998 regime shift, in which case it can be expected to affect the CCS over a longer period.

The evolution of the current neutral oceanographic conditions in the tropical Pacific Ocean over the next months remains unclear as well, with forecasts ranging from neutral to full-fledged El Niño conditions beginning in the summer of 2004. Yet, because none of the forecasts indicate that a La Niña event will develop during 2004, we can anticipate neutral or warm-water conditions in the next 3–6 months (Climate Prediction Center ENSO Diagnostic Discussion, http://www.cpc.ncep.noaa.gov). On a longer time scale, the continued strengthening of the PDO index, which has remained slightly positive since August 2002, may indicate a developing shift back into a warm-water regime (http://jisao.washington.edu/pdo/PDO.latest). This uncertainty will set the stage for 2005.

The onset of an El Niño event would represent a great natural experiment to quantify the ecosystem response to a transient warm-water period, superimposed on a potentially longer-term cold-water regime. Additionally, a transition back into a warm-water regime would provide an excellent opportunity to contrast the behavior of the CCS during a warm-cold and a cold-warm transition. The ability to monitor and interpret these future fluctuations in the CCS depends on the existence of long-term time series of the physical, chemical, and biological ecosystem constituents (McGowan 1990).

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