THE STATE OF THE CALIFORNIA CURRENT, 2004–2005: STILL COOL?

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ABSTRACT

This report summarizes the recent state of the California Current System (CCS), primarily during the period of April 2004 to January 2005. The report is based on observations made between Oregon and Baja California by various ocean observing programs. The CCS was not forced by any coherent basin-wide processes during the observation period. The weak tropical El Niño of 2004 did not appear to have had a noticeable effect on the CCS. However, the CCS remains in a cold phase, a state it has had since the 1999 La Niña phase. Some biological parameters show a distinct response to this state, i.e. zooplankton biomass and its species richness, others display a mixed response such as the CCS avifauna and its productivity, and some do not show any response, such as phytoplankton biomass and Pacific sardine (*Sardinops sagax*) productivity. Over all, the state of the system remains "normal" with respect to its climatology. The unusual intrusion of cold and fresh subarctic water into the CCS is waning off Oregon but still noticeable off southern California and off Baja California. Because the CCS does not appear subject to coherent basin-wide forcing, the outlook for the CCS over the next years is uncertain

INTRODUCTION

This is the 12th in a series of annual reports since 1993 summarizing the climatology, oceanography, and biology of the California Current System (CCS). This report is based on observations taken between Oregon and Baja California between the spring of 2004 and 2005. The programs or institutions contributing to this report are the U.S. Global Ocean Ecosystem Dynamics Long-Term Observation Program (GLOBEC LTOP) working off Oregon, the Pacific Fisheries Environmental Laboratory (PFEL) providing basin- and coast-wide climatologies, the Point Reyes Bird Observatory (PRBO) working off Central and Southern California using seabirds as ecosystem indicators in the CCS, the Monterey Bay Aquarium Research Institute (MBARI) Monterey Ocean Time series and Observatory (MOTO), the NOAA Pacific Coastal Ocean Observing System (PaCOOS) program off Central California, the CalCOFI program working off Southern California, and the Investigaciones Mexicanas de la Corriente de California program (IMECOCAL) working off Baja California.

The most significant event affecting the CCS over the last decade was the switch of the sign 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. The switch of the PDO coincided with an extremely strong ENSO event, 1997/98. Initially, dramatic changes in zooplankton community structure were observed in the CCS during the cold period that began in 1999 (Brinton and Townsend 2003; Lavaniegos and Ohman 2003; Peterson and Schwing 2003) and were consistent with our expectations for such a cold period. Subsequently, however, climatic indices have gone bland. Sea surface temperature patterns in the North Pacific no longer resemble the canonical PDO warm or cold patterns; a newly "minted" ocean climate mode (Bond et al. 2003), called the Victoria mode, is no longer noticeable, and anomaly fields for most properties suggested that the North Pacific and the CCS had entered an unusual period of "normality" (Goericke et al. 2004). A tropical El Niño during this time period, observed in 2002/03, also failed to have a significant effect on the CCS (Venrick et al. 2003).

Nonetheless, the CCS did not cease to surprise us over the last five years. Most interesting was the intrusion of cold and fresh subarctic water masses into the CCS, which was first noticed off British Columbia and Oregon (Freeland et al. 2003) but quickly spread further south (Venrick et al. 2003; Goericke et al. 2004; Durazo et al. 2005). This intrusion was likely due to the weakening of the Davidson Current flowing into the Gulf of Alaska and the intensification of the California Current (Freeland et al. 2003; Wheeler et al. 2003). Last year, we speculated that this may have been driven by a spin-up of the central North Pacific gyre (Chavez et al. 2003; Goericke et al. 2004), either due to ephemeral changes in atmospheric forcing or due to changes in forcing associated with the recent shifts in climate indicators. Effects of this increased flow of subarctic water masses into the CCS region on the ecosystem were dramatic off Oregon (Wheeler et al. 2003), but likely obscured off California by the co-occurring 2002/03 El Niño (Bograd and Lynn 2003).

This report will focus on a description of the state of the CCS between the springs of 2004 and 2005, using simple descriptors such as hydrographic properties, flow-, temperature-, and salinity-fields, biological indicators such as biomass found at different trophic levels, and the distribution and abundance of indicator species. The relationships we hope to understand are the physical and chemical responses of the CCS to changes in the major indices of ocean climate and the consequent effects on the biomass and species composition of the ecosystem. Unlike recent years, there was no single climatological or environmental factor that clearly influenced a large portion of the CCS during 2004. Regional changes appeared to result from the waning of the subarctic intrusion (Venrick et al. 2003), which was confounded by anomalous warming in the north and superimposed on local influences.

DATA SETS AND METHODS

Basin- and Coast-Wide Analyses

Large-scale patterns are summarized from the National Center for Environmental Prediction Reanalysis fields (Kistler et al. 2001) and 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. Monthly upwelling indices and their anomalies for the North American west coast (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 CCS are plotted against the harmonic mean of each buoy.

Regional Analyses–Oregon

Regular sampling of the Newport Hydrographic (NH) line along 44.65°N by the GLOBEC Northeast Pacific Long-Term Observation Program (LTOP) ended in September 2003. Nevertheless, several sections were made along this line in 2004: in late summer (30 August–1 September) by GLOBEC LTOP and in spring (9–10 May), early summer (26–27 June), and fall (7–8 November) by the NOAA PaCOOS program. As in previous years, conductivity-temperature-depth (CTD) casts were made at 12 standard stations at locations between 3 and 157 km from shore. CTD casts sampled at least 90% of the water column over the continental shelf and upper slope and sampled to 500 m or 1000 m in deep water. Zooplankton are sampled with a 0.5 m net (0.2 mm mesh) towed vertically from 100 m to the surface or, in shallower water, from 3 m above 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 are reported here. Copepod species richness is calculated as the number of taxa present in a given sample. To de-trend seasonal signals of species richness, individual samples were first smoothed by converting to monthly averages and then calculated as monthly anomalies (i.e. climatological monthly mean subtracted from the year-specific monthly average).

Regional Analyses–Monterey Bay

Monterey Bay region time series consist of two moored telemetering buoys located in the Bay, hydrographic surveys of the Bay every three weeks, and quarterly surveys along CalCOFI lines 67 and 60 from the coast to station 90. Stations are sampled to near bottom or 1012 m where water depth permits. Parameters measured are similar to those for the CalCOFI program described below and methods are described in Chavez et al., 2002. Properties are mapped for each section and can be viewed at <www.mbari.org/bog/projects/secret/default.htm>.

Regional Analyses–CalCOFI

The CalCOFI program conducts quarterly surveys off Southern California, covering 66 stations (fig. 1);

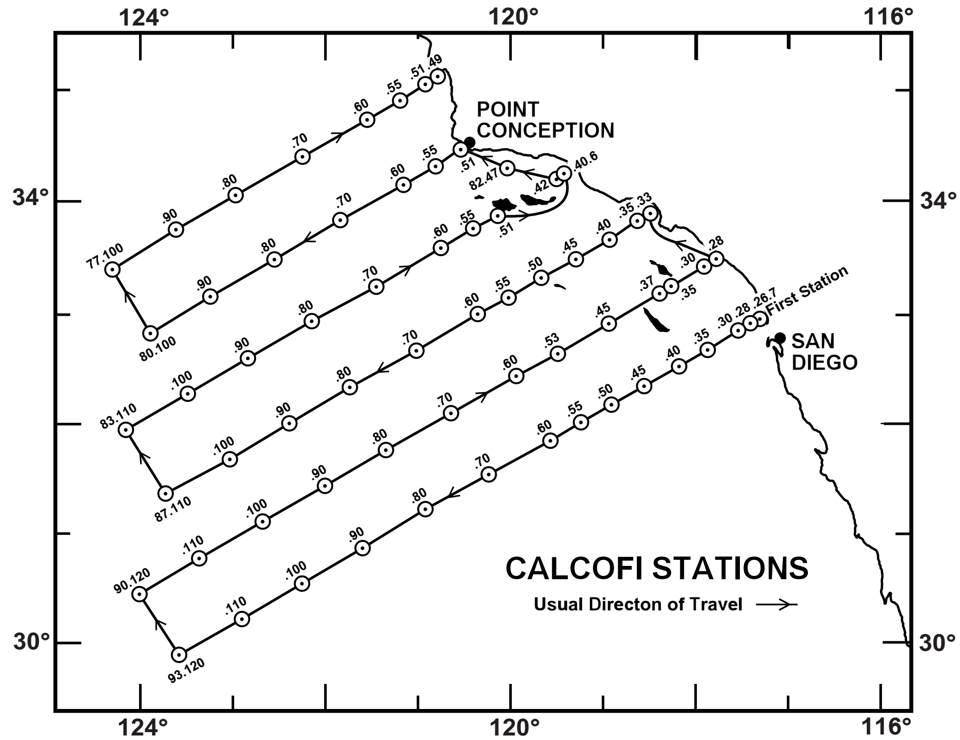


FIGURE 1

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.

results from surveys between April of 2004 and January 2005 are discussed here. Water column properties (conductivity, temperature, pressure, oxygen, fluorescence, and light transmission) were measured down to 525 m. Salinity, dissolved oxygen, nutrients, and chlorophyll are determined on 12 to 20 water samples collected throughout the water column. Standard (.505 mm mesh) oblique bongo tows are conducted to 210 m depth at each station, bottom depth permitting. Detailed descriptions of sampling and analytical protocols and data reports from past cruises are archived on the CalCOFI website (http://www.calcofi.org). Climatologies were calculated for various parameters; these are based on the 1984 to 2005 time period. Cruise averages were calculated for these parameters from individual station data. Anomalies were calculated as parameter value minus harmonic mean.

Regional Analyses–IMECOCAL

The IMECOCAL monitoring program began in autumn 1997, consisting of quarterly cruises surveying the area of a reduced CalCOFI grid of about 93 stations off Baja California, México (fig. 2). The core oceanographic data set collected at each station includes a CTD/Rosette cast to 1000 m depth, with sensors for pressure, temperature, salinity, dissolved oxygen, and fluorescence. Water samples from the upper 200 m are collected with 5 liter Niskin bottles at 0, 10, 20, 50, 100, 150, and 200 m depths to determine dissolved oxygen, phytoplankton pigments (chlorophyll *a* and phaeopigments), nutrients (NO3, NO2, PO4, SiO3), and primary production. IMECOCAL cruise schedules, data collection, methods, and analysis are fully described at <imecocal.cicese.mx>.

Avifauna

Systematic surveys of the distribution and abundance of marine birds have been made on CalCOFI cruises since spring of 1987 (Hyrenbach and Veit 2003). Personnel from the Point Reyes Bird Observatory (PRBO) Conservation Science conducted at-sea surveys during 2004. Additionally, PRBO has monitored the reproductive performance and diet of seabird populations breeding at the Farallon Islands (37°N, 123°W) since the early 1970s (Sydeman et al. 2001).

BASINWIDE PATTERNS

The SST anomaly patterns during the first three months of 2005 did not resemble any of the characteristic spatial patterns defined in previous analyses (i.e., the PDO, Mantua and Hare 2002; and the Victoria mode, Bond et al. 2003). A weak El Niño evolved in the tropical Pacific in 2004 (NOAA CPC Climate Diagnostics Bulletin, http://www.cpc.ncep.noaa.gov). The MEI (Multivariate ENSO Index, Wolter and Timlin 1998), which indicates El Niño conditions, has maintained pos-

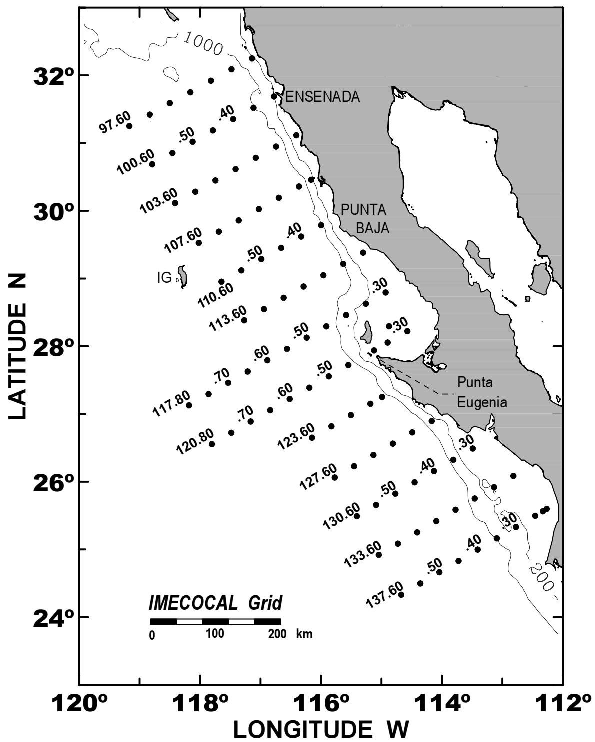


Figure 2. The standard IMECOCAL sampling grid. Solid dots represent the 93-station pattern (CalCOFI lines 100 to 137) occupied by the IMECOCAL program since 1997 (including line 97 for April surveys since 2003). Depth contours are in meters.

itive values since early 2002, although their magnitude has remained in the weak to moderate range. Associated with the 2004 event were warm upper ocean anomalies that developed in the central tropical Pacific (fig. 3). However, this warm anomaly did not propagate east to the South American coast, an evolution characteristic of El Niño, and, instead, cooler than normal SSTs prevailed along the South American coast throughout this event.

Despite the continuing signature of a weak El Niño, the atmospheric variability over the past two years has been dominated by the 60–90 day signal of the Madden-Julian Oscillation (MJO). The effect of the MJO is reflected in the extra-tropical North Pacific atmosphere and upper ocean anomalies as well, making it difficult to characterize any persistent long-term anomaly pattern. The predominant MJO forcing has also excited atmospheric variability at relatively short wavelengths (subocean basin), which may have contributed to the recent spatially complex and heterogeneous SST anomaly patterns. Patterns like the PDO are typically associated with much longer atmospheric wave patterns.

In the CCS, SST anomalies have been generally positive since early 2004. Although due to the strong MJO activity, a specific pattern did not persist for more than a few months. The anomaly maps in Figure 3 represent the predominant seasonal variability during the past year,

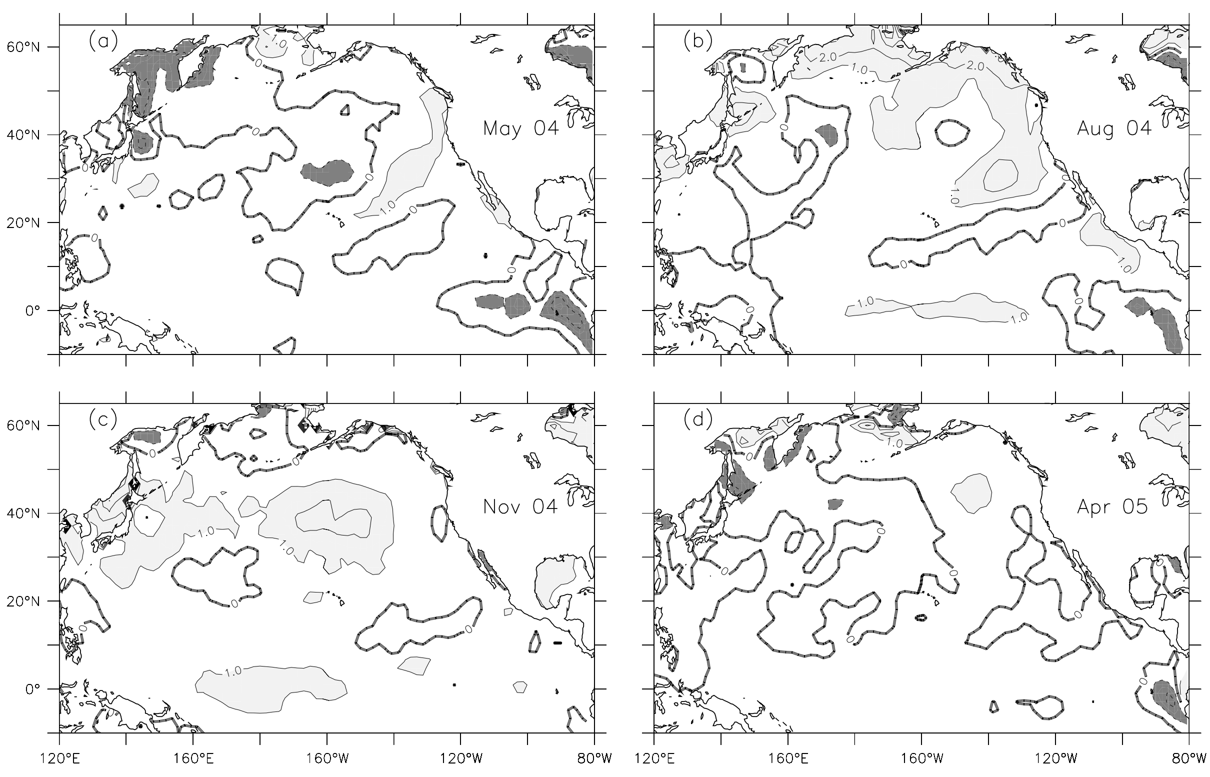


Figure 3. SST anomalies in the North Pacific Ocean for (a) May 2004, (b) August 2004, (c) November 2004, and (d) April 2005. Contour interval is 1.0°C. Positive (warm) anomalies are shaded light grey, and negative (cool) anomalies are shaded dark grey. SST climatology is 1968–96. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

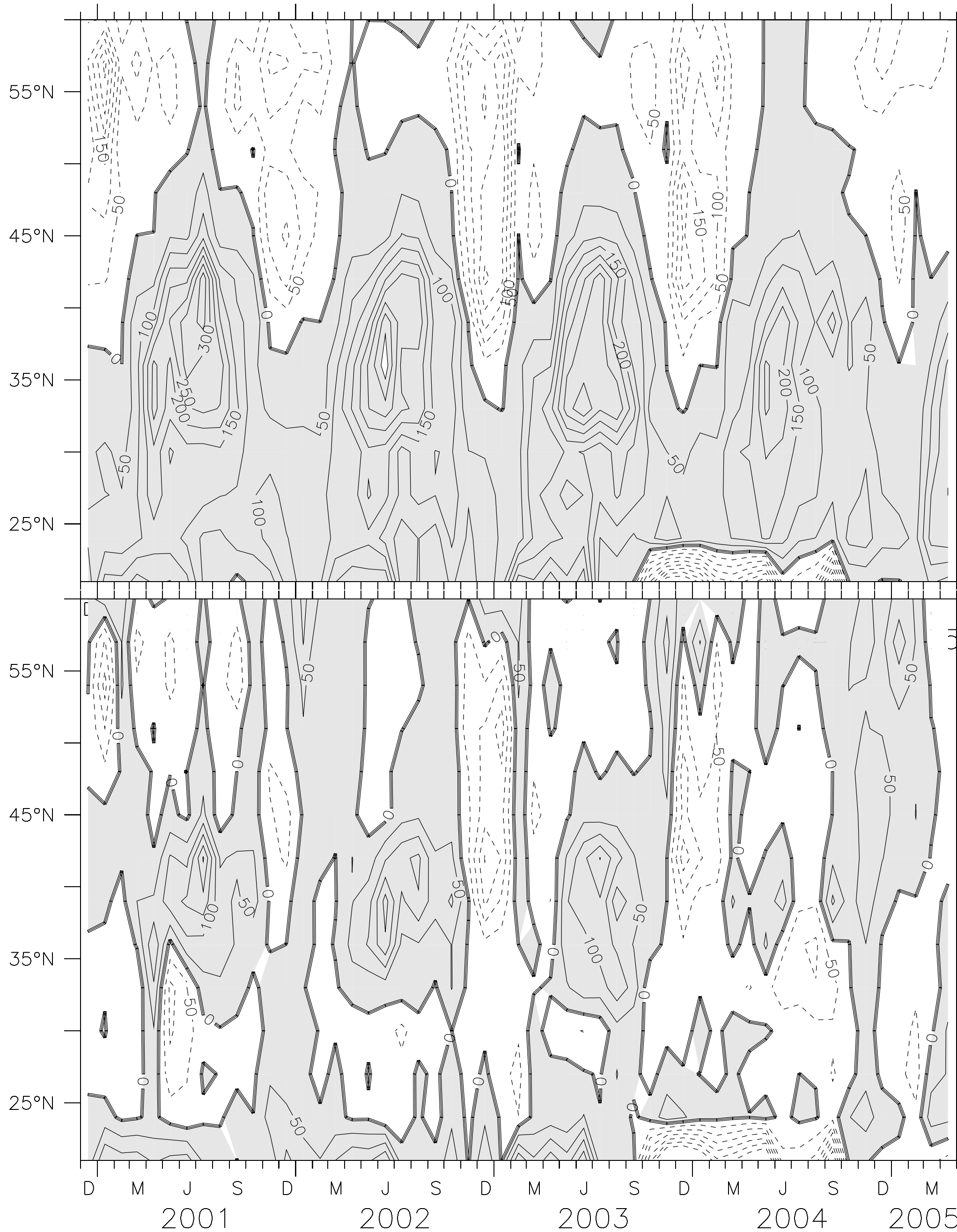


Figure 4. Monthly upwelling index (upper panel) and upwelling index anomaly (lower panel) for Jan. 2001–Apr. 2005. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m³/s per 100 km of coastline.

but the abrupt intra-seasonal shifts are unusual. SSTs were unusually warm in spring 2004, especially in the northern CCS. These anomalies peaked in summer, particularly in the northern Gulf of Alaska and Bering Sea, before declining in fall 2004. Most recently (spring 2005), surface waters of the CCS have remained anomalously warm. We believe this is due to anomalous regional winds, which are responsible for less upwelling at the coast and in the open ocean, and reduced mixing. However, the lack of temperature measurements at depth make it difficult to determine the cause of this long-term warm state or how likely it is to remain.

COASTWIDE CONDITIONS

Monthly coastal upwelling indices (Bakun 1973; Schwing et al. 1996) support the contention that upwelling winds in the CCS have been unusually weak in the past year (fig. 4). The evolution of upwelling index

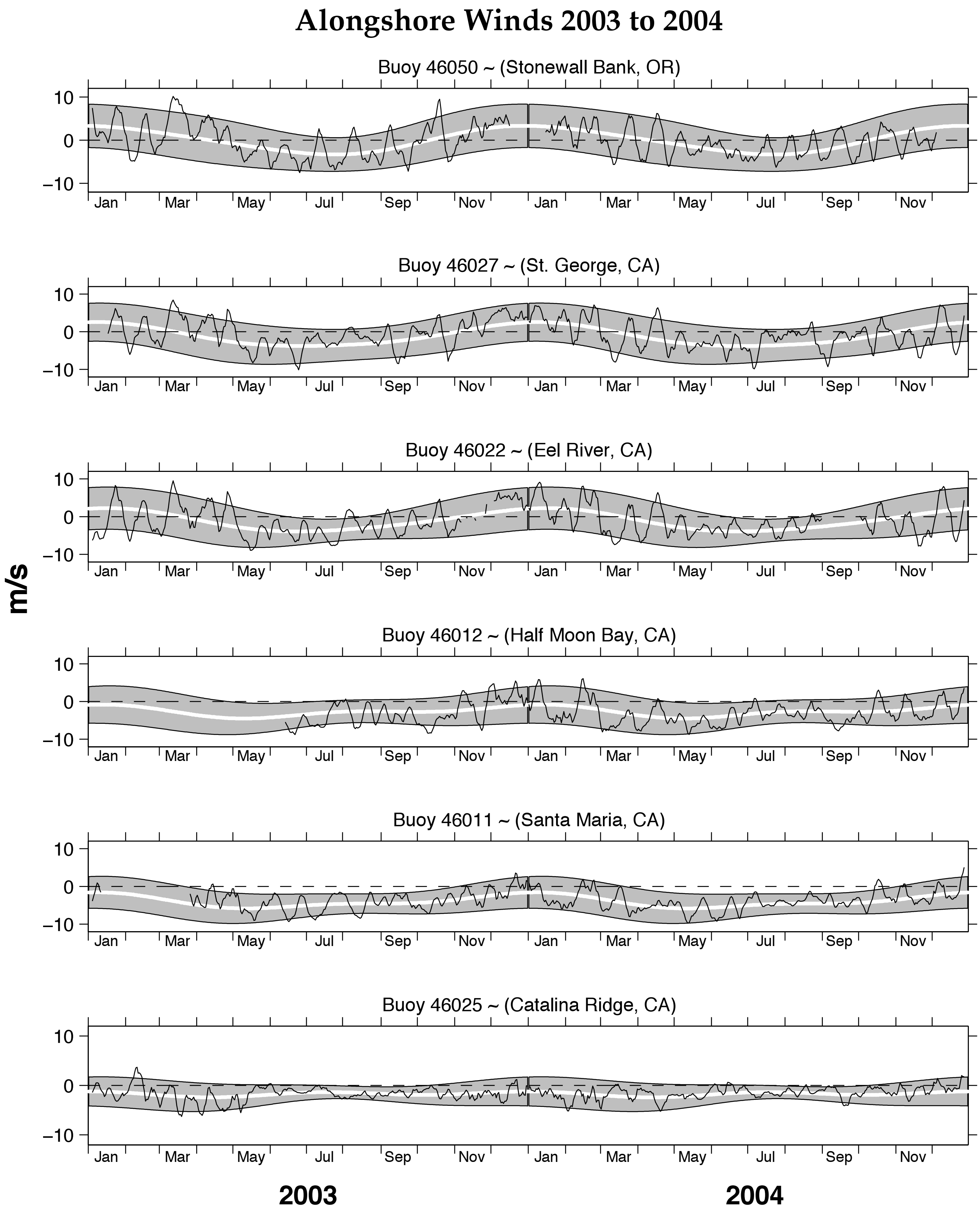


Figure 5. Time series of daily-averaged alongshore winds for Jan. 2003–Dec. 2004 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a 7-day running mean. Data provided by NOAA NDBC.

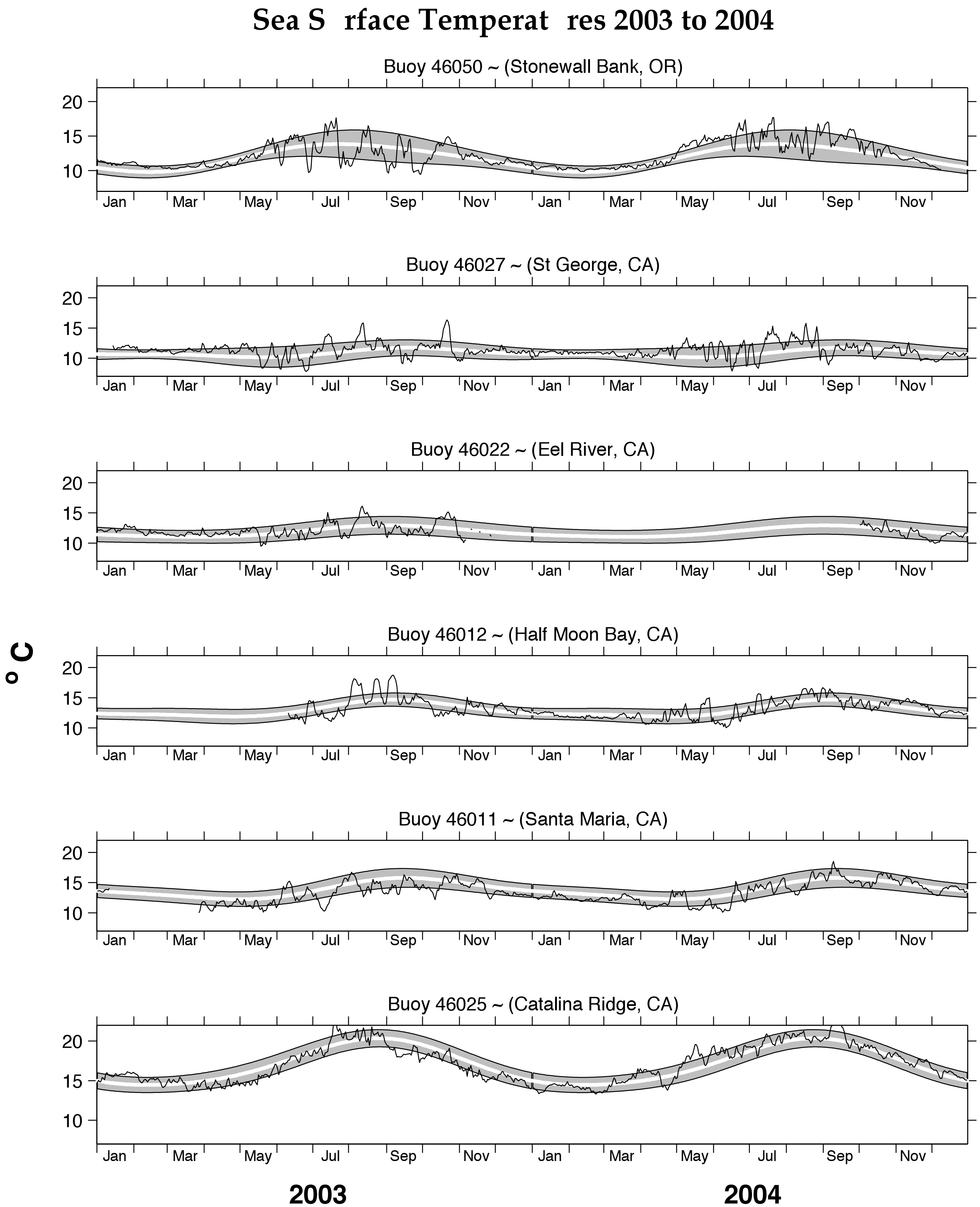


Figure 6. Time series of daily-averaged SST for Jan. 2003–Dec. 2004 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Data provided by NOAA NDBC.

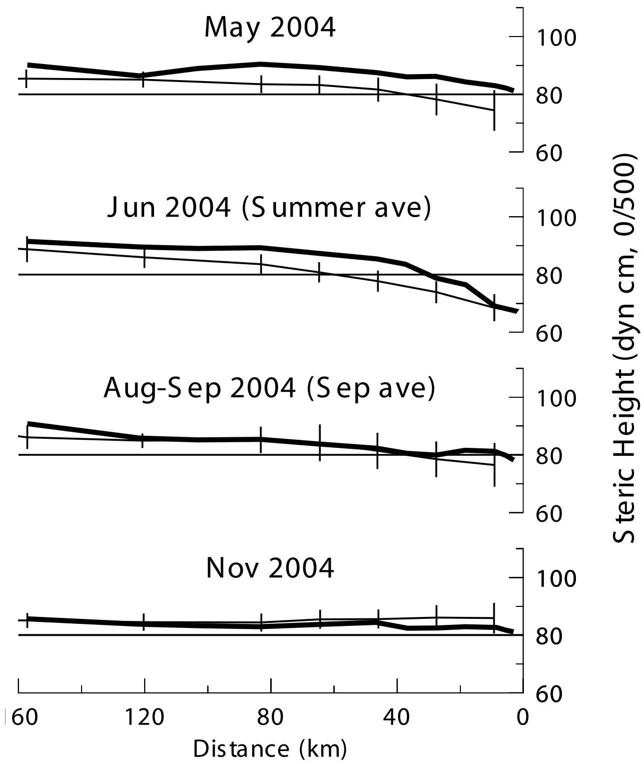


Figure 7. Offshore profiles of steric height (geopotential anomaly, surface relative to 500 dbar, J/kg) along the NH-line. Each panel shows the 2004 values and the corresponding historical (1961–71) average with plus/minus one standard deviation (Smith et al. 2001). Values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976).

anomalies (weakly negative in summer 2004 to weakly positive in fall) matches the large-scale SST anomalies (fig. 3). The period 2004–05 differs from recent years. Since 1999, the CCS has featured winters with weak upwelling, followed by anomalously strong summer upwelling (Hayward et al. 1999; Bograd et al. 2000; Durazo et al. 2001; Schwing et al. 2002; Venrick et al. 2003; Goericke et al. 2004). In the past year, the summer of 2004 featured negative upwelling index values (weak upwelling) and positive anomalies in late fall and winter. Negative anomalies continued through spring 2005 over much of the West Coast. Not until July 2005 (not shown) did strong upwelling return to the northern CCS, while weaker than normal upwelling continued farther south. Significant biological effects, including increased seabird mortality throughout the region[1], appeared to be associated with this unusually late transition to upwelling.

The predominance of strong intraseasonal variability in the CCS is illustrated by a series of ca. 30-day, alongshore fluctuations in the National Data Buoy Center (NDBC) coastal buoy winds (fig. 5). These strong fluctuations or reversals in the alongshore winds were observed throughout the 2003–04 period, particularly in the northern CCS. The contrast between the 2003 and 2004 upwelling seasons is also clear. Summer 2003 winds were persistently to the south, indicating normal upwelling-favorable conditions in the northern CCS. In summer 2004, however, weaker equatorward winds prevailed. Stronger upwelling-favorable winds did not return until unusually late in the year, around October-November. A similar late transition to upwelling-favorable conditions occurred in 2005.

This anomalous wind forcing is reflected in the SST time series from the NDBC buoys (fig. 6). The intraseasonal oscillations in alongshore winds in summer and fall 2003 resulted in strong fluctuations in SST, with changes sometimes exceeding 5°C over the course of a few days. Winter temperatures showed much smaller fluctuations and were near climatological values throughout the CCS. Unseasonably warm SSTs prevailed in summer 2004, especially in the northern CCS. But the anomalously strong southward winds in late fall led to a rapid cooling of SST to near climatological levels. Upper ocean temperatures appeared to be very warm in early spring 2005 (not shown), but there has been no apparent surface ocean teleconnection with the tropical Pacific.

REGIONAL STUDIES

Oregon Coast: GLOBEC LTOP and NOAA PaCOOS Cruises

Monthly anomalies of the PFEL coastal upwelling index at 45°N, 125°W were negative from April through August 2004 (fig. 4), indicating that equatorward winds were weaker than normal through most of the upwelling season. September winds were near normal. Monthly anomalies for October and especially November were positive, indicating more upwelling and less downwelling than normal during these months. Weaker-than-average spring and summer upwelling is consistent with higher-than-average steric heights in May and June (fig. 7) and with the end-of-August values being about the same as the September average. Steric height values for November were close to normal.

Temperature sections (fig. 8) show isotherms tilting up toward the coast as normal in spring and summer, though not as steeply as usual. Surface waters were especially warm in May when inshore temperatures were more than four standard deviations above the historical average for that month (fig. 9). In November, temperatures were near normal (fig. 9).

Salinity sections (fig. 10) were similar to those observed in 2003 (Goericke et al. 2004), except that the spring and summer cruises showed fresher inshore surface waters; this inshore position of the Columbia River Plume is consistent with weaker upwelling, i.e., with weaker southward winds.

[1]B. Sydeman, pers. comm.

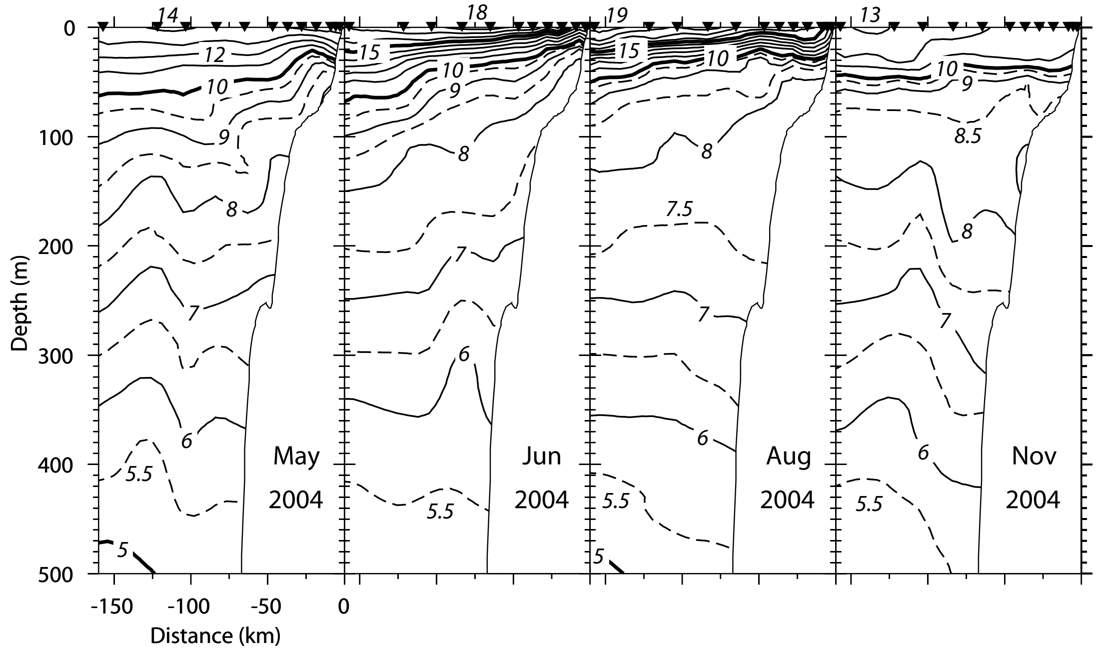


Figure 8. Temperature along the NH-line: 9–10 May, 26–27 June, 30 August–1 September, and 7–8 November 2004.

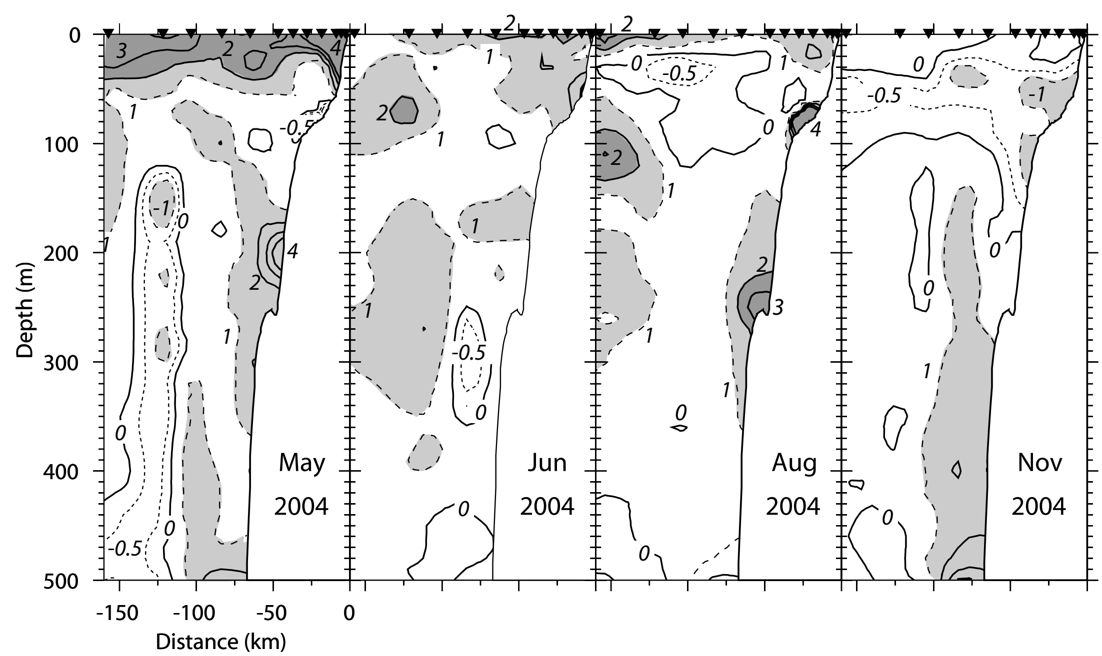


Figure 9. Normalized temperature anomalies along the NH-line, obtained by subtracting the historical monthly or seasonal average (for May, summer, September, fall) and dividing the difference by the corresponding standard deviation. (Historical values were calculated by Smith et al. 2001).

An unusually cold, nutrient-rich halocline indicating enhanced subarctic influence was present along this line in the summer of 2002 (Freeland et al. 2003; Wheeler et al. 2003). Remnants of this cold halocline anomaly were still (or again) present in summer 2003 (Goericke et al., 2004). T-S diagrams (fig. 11) for the shelf-break station NH-25 show that the halocline was not significantly colder than normal in the summer of 2004. The period of enhanced subarctic influence has apparently ended in this region. The warm (spicy) anomaly on the 25.6 kg m^{-3} isopycnal in late August likely results from local subduction of previously upwelled surface water that was exposed to solar heating. The cool, fresh (minty) anomaly in and above the halocline (S < 33.8 psu) in

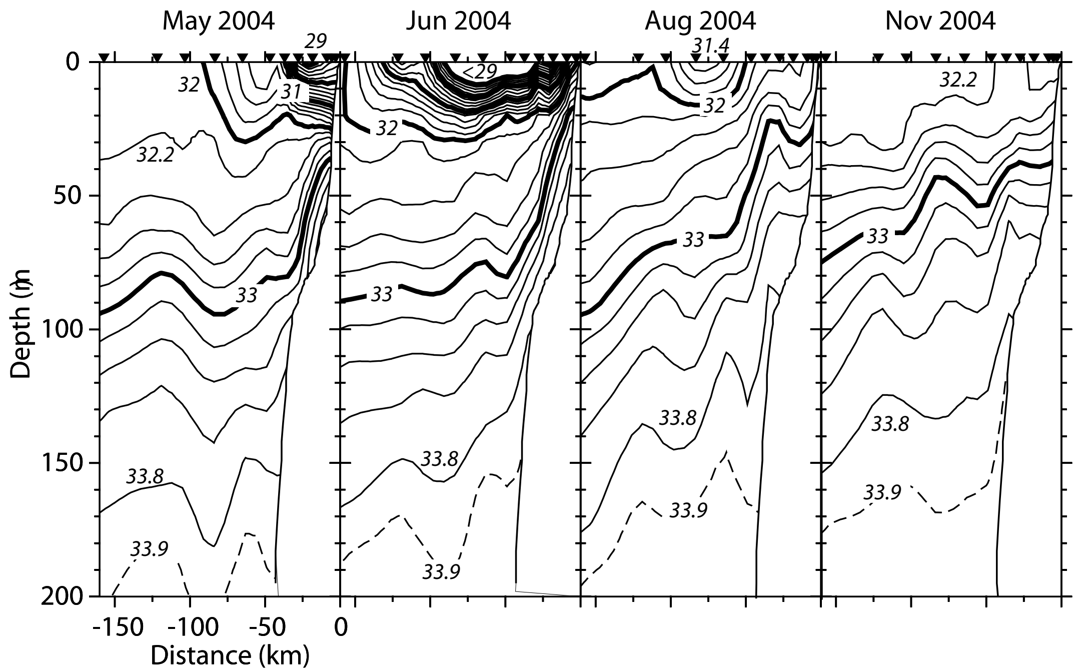


Figure 10. Salinity along the NH-line: 9–10 May, 26–27 June, 30 August–1 September, and 7–8 November 2004.

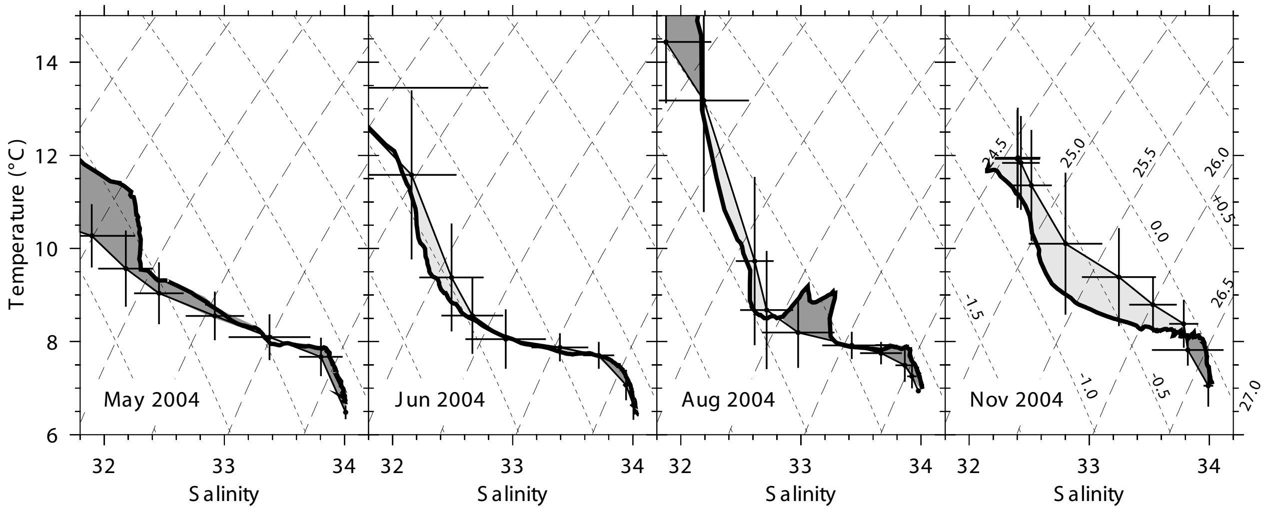


Figure 11. T-S diagrams for the shelf-break station (NH-25). Continuous curves represent CTD casts for 2004 sections; dots with bars represent 1961–71 seasonal averages and standard deviations (Smith et al. 2001).

November is likely due to the stronger-than-normal upwelling (or weaker downwelling) during autumn, which would cause the southward surface current to persist longer than normal.

Central California

Oceanographic conditions in Monterey Bay indicated that surface temperature, salinity, and nitrate were close to the 15-year mean (fig. 12). The positive anomaly of total phytoplankton biomass (chlorophyll) observed during 2004 was greater than any previous years, probably due to weaker-than-normal northwesterly winds (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/gifs/p10.gif), which reduce advective loss of phytoplankton from Monterey Bay. Positive productivity anomalies remained high but were only about one-third of the 2002–03 levels. Positive chlorophyll and productivity anomalies have now been observed continuously since 1999.

Oceanographic conditions along line 67 (out to station 90) also remained close to the climatological mean for data collected since 1997. Figure 13 shows results for

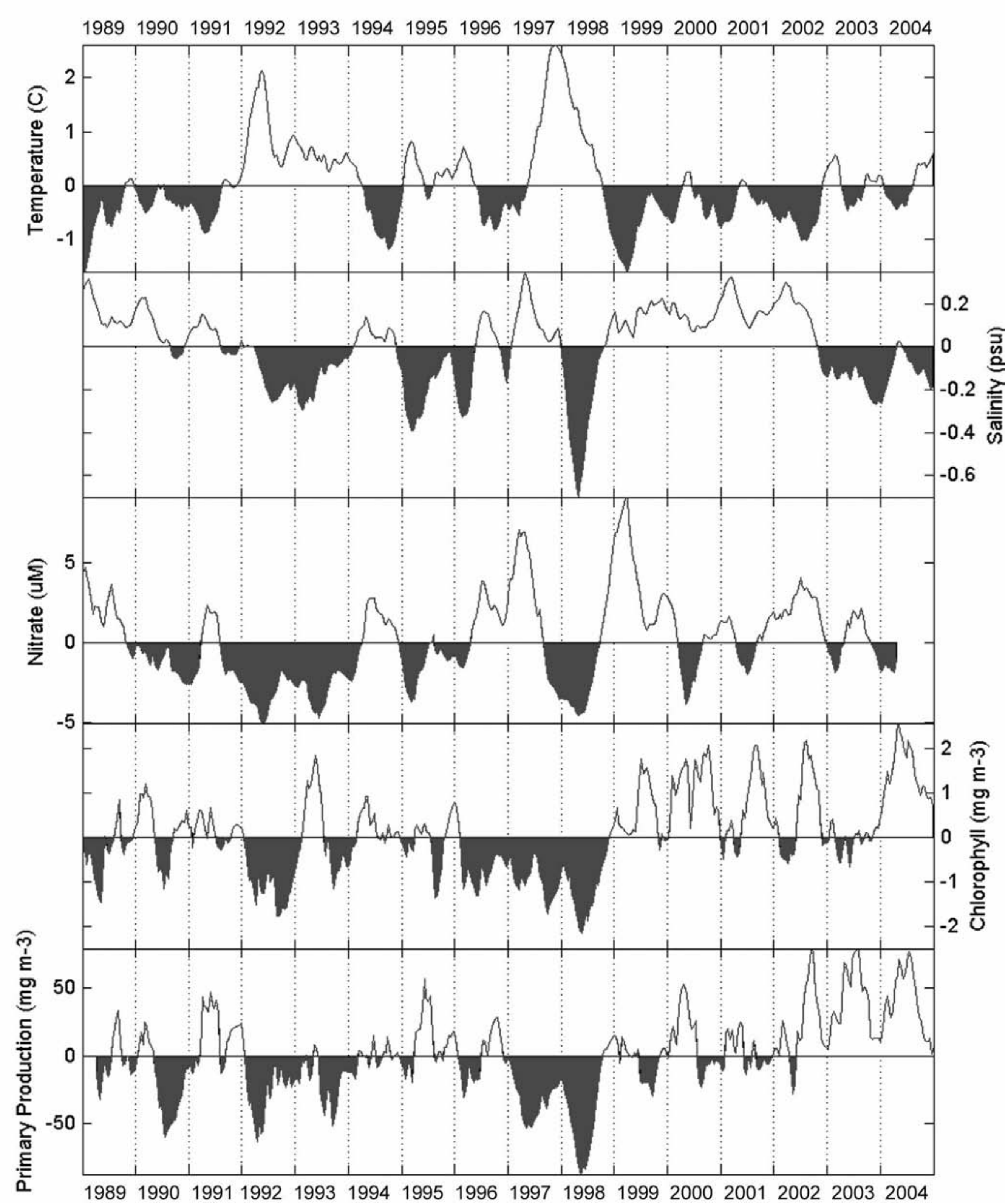


Figure 12. Anomaly plot of sea surface temperature, salinity, nitrate, chlorophyll, and primary production collected as part of the Monterey Ocean Timeseries Observatory (MOTO) program maintained by MBARI. Temperature, salinity, and nitrate were near-normal in 2004, but chlorophyll and primary production were high. As part of MOTO, three to four stations in Monterey Bay and the contiguous waters of the California Current System are sampled every three weeks. The data from all stations are averaged and the averages used to calculate a mean annual cycle. The annual mean cycle is subtracted from a smoothed time series of the data and the anomalies presented in the figure.

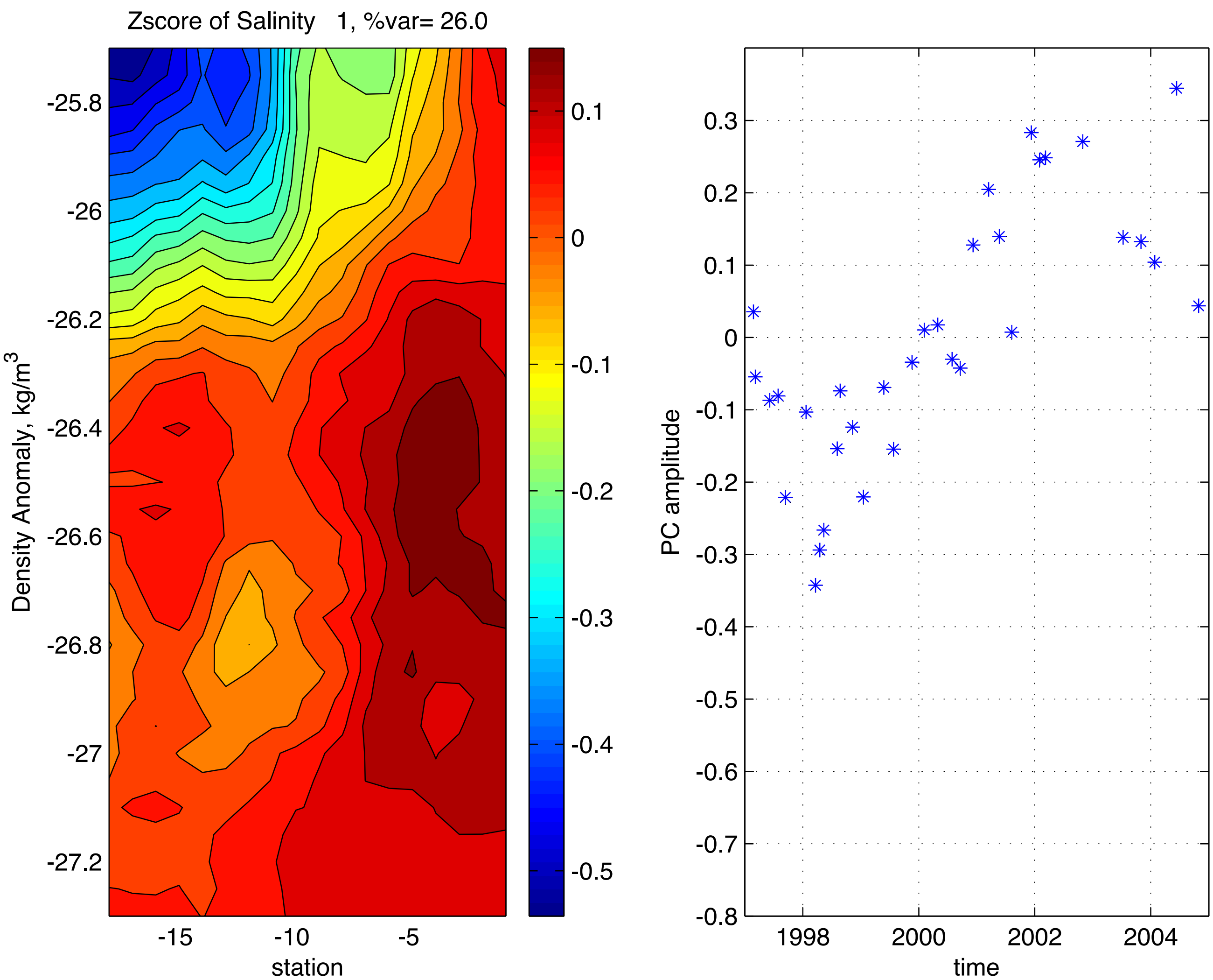


Figure 13. CalCOFI line 67 CTD sections. First principal component for salinity on density anomaly surfaces . (left) Z-score, C.I. = 0.1. (right) PC time series.

a principal component analysis of salinity on density surfaces ranging from 25.75 to 27.25 kg/m³ for hydrographic sections that were started in 1997. The z-score has positive values associated with regions dominated by poleward flow of equatorial waters and negative values offshore for waters lighter than 26.2 kg/m³ (also near 26.8 kg/m³) associated with equatorward flowing subarctic (North Pacific Intermediate) waters. The first principal component accounted for 26% of the variance and steadily increased from −0.3 in 1998 to 0.3 in 2002 in a manner consistent with a decrease in salinity of subarctic waters and an increase in salinity of equatorial waters. Subsequent to 2003, this pattern appeared to reverse. The mean temperature-salinity relationship for the October 2004 section indicated that the halocline waters had warmed and the thermostad beneath the halocline was saltier than normal.

In October 2004, line 60 was occupied as well as line 67 (fig. 14). Poleward flow immediately adjacent to the shelf was observed on both transects and is reflected in the downwelling of deeper isotherms toward the coast and higher salinities over the upper slope. The strongest circulation feature observed was associated with an anticyclonic eddy, or meander, of the inshore edge of the California Current (CC) centered at the southwest corner of the grid (about 300 km from Moss Landing). Surface temperatures at this location exceeded 17°C and salinities were less than 33. The inshore edge of the anticyclonic CC feature was located about 200 km from Moss Landing and marked by vertical isohalines, in the upper 100 m, and strong convergence. Upper level currents of about 0.7 m/s were directed offshore along line 67 inshore of the front. On the offshore side of the front, currents were directed southward at about 0.4 m/s. The fresh (S < 33) waters above 100 m continued along line 60 to within 40 km of the Gulf of the Farallones (700 km from Moss Landing), gradually cooling to 15°C.

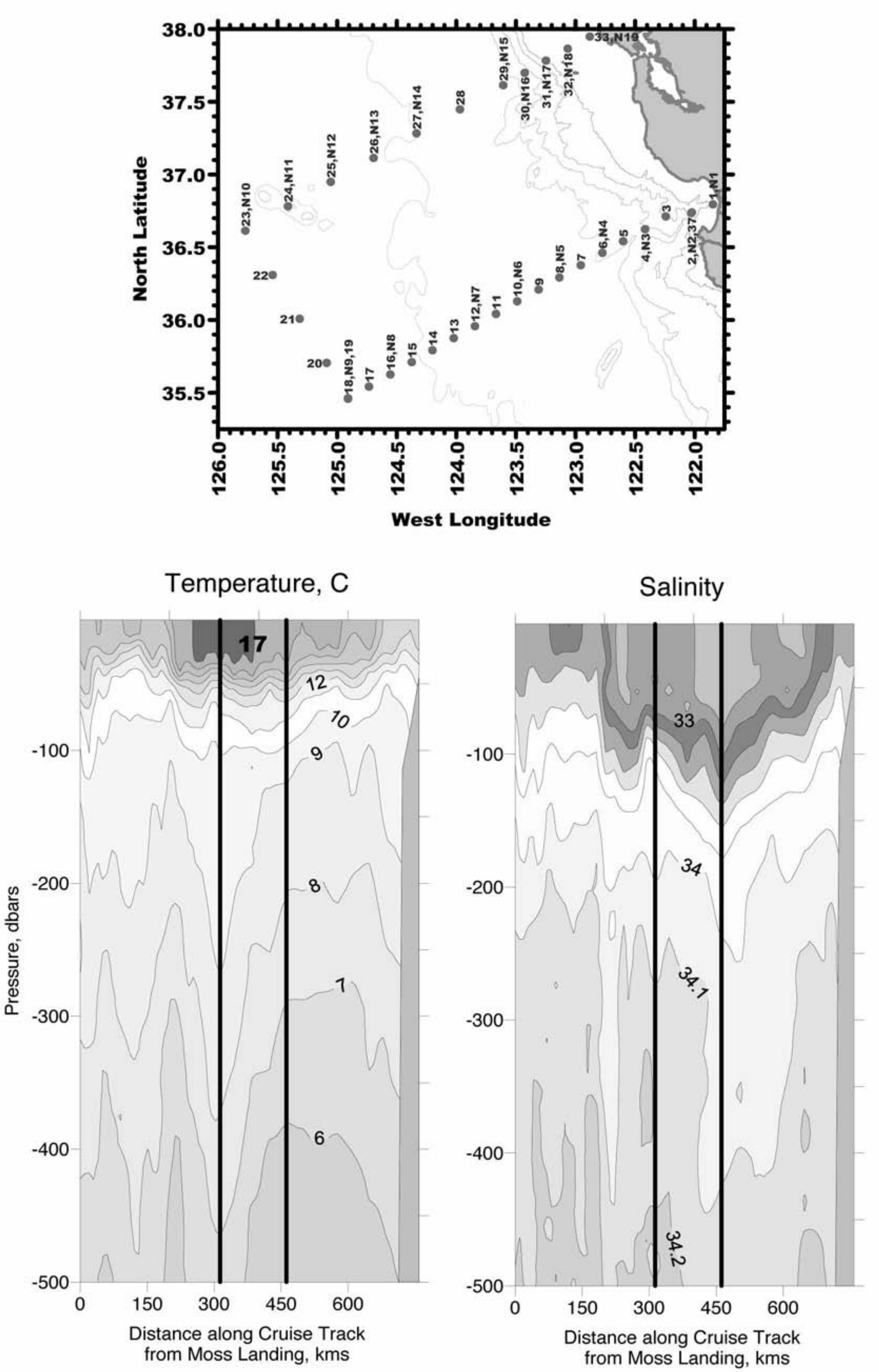


Figure 14. October 2004 Central California CalCOFI Cruise. (upper) Station pattern. (lower) Temperature and salinity plotted clockwise around the cruise track from Moss Landing (left) to Point Reyes (right). (lower left) Temperature, C.I. = 1°C. (lower right) Salinity, C.I. = 0.2 for S > 34, 0.1 otherwise.

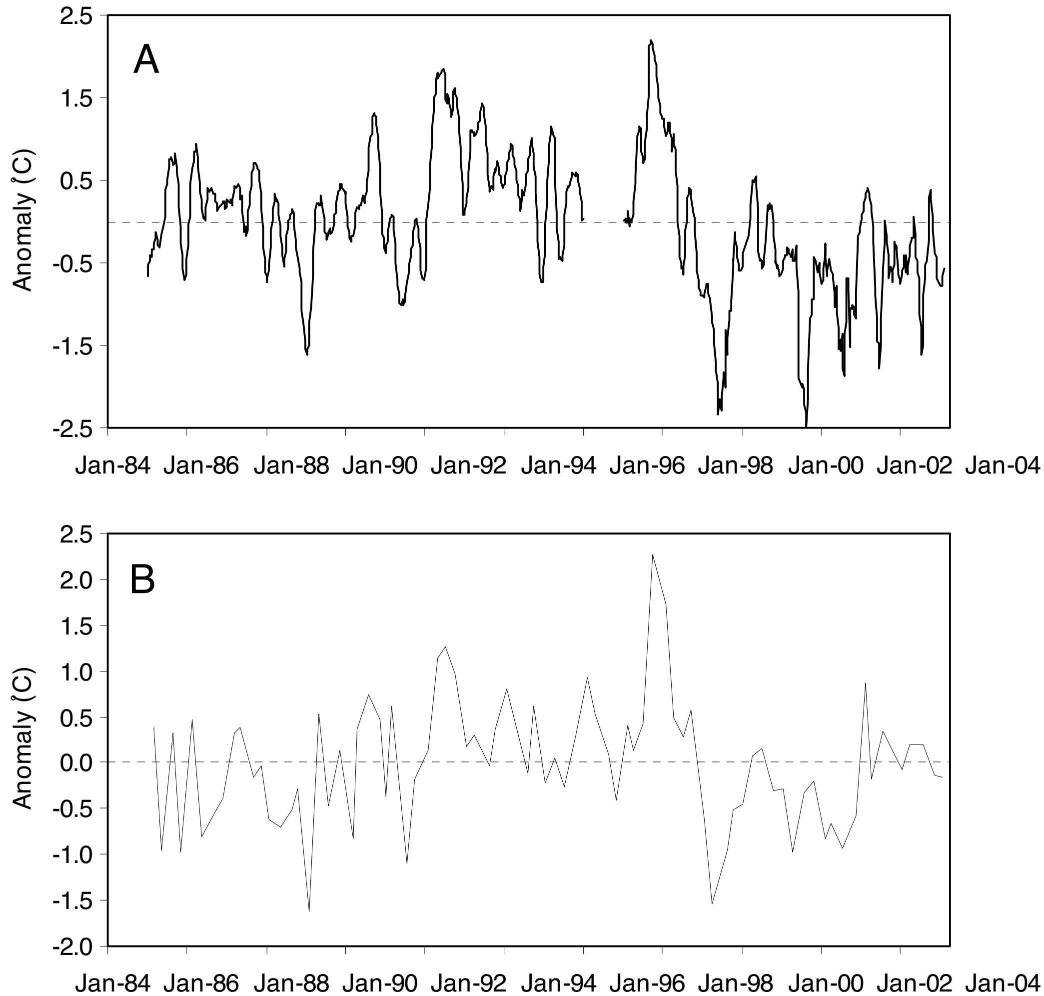


Figure 15. Average SST anomalies for the 66 standard CalCOFI stations calculated from (a) weekly AVHRR or MODIS data and (b) observations made on the quarterly CalCOFI cruises. Anomalies are calculated relative to the time period 1985 to 2004.

The deep-reaching character of the CC meander is indicated by the "V" shape of the isotherms which extended to pressures greater than 1000 dbars directly under the 17°C surface warm pool (300 km from Moss Landing). Along line 60, beginning at a distance of 450 km from Moss Landing, isopycnals below 200 dbar continued to rise toward the coast to within a distance of 30–60 km from the slope. The upward slope toward the coast indicates equatorward flow and was also marked by S = 34.1 waters extending to pressures of 400 dbar. Note that these waters were also found along line 67 directly under the surface front noted above at a distance of 200 km from Moss Landing.

Southern California Bight: CalCOFI Survey Cruises

Overview: Over the last year, CalCOFI conducted the usual four cruises in April, July, November of 2004, and January of 2005. Results from these cruises will be presented here and contrasted with those from previous years and compared to the climatologies. Average remotely sensed SST (SST_{MODIS}; fig. 15a) at the 66 standard CalCOFI stations were similar to average in situ SST measured at the stations ($SST_{CalCOFI}$; fig. 15b). Anomalies of $SST_{CalCOFI}$ over the last year were close to zero; in contrast, anomalies of SST_{MODIS} were 0.5°C below normal, suggesting that the quarterly sampling introduced some bias. This is supported by the similar average temperatures for the differing base periods—SST_{MODIS}: 85–05 and $SST_{CalCOFI}$: 84–05 (16.09 and 16.16°, respectively).

Mixed layer depths (MLD) during the last year were slightly below the long-term average (fig. 16a), similar to values observed since 2002. ML temperature anomalies (fig. 16b) were virtually identical to $SST_{CalCOFI}$ anomalies. Annual averages of these have been close to zero after a period of negative values from 1999 to 2002.

ML salinities continue to be abnormally low (fig. 16c).

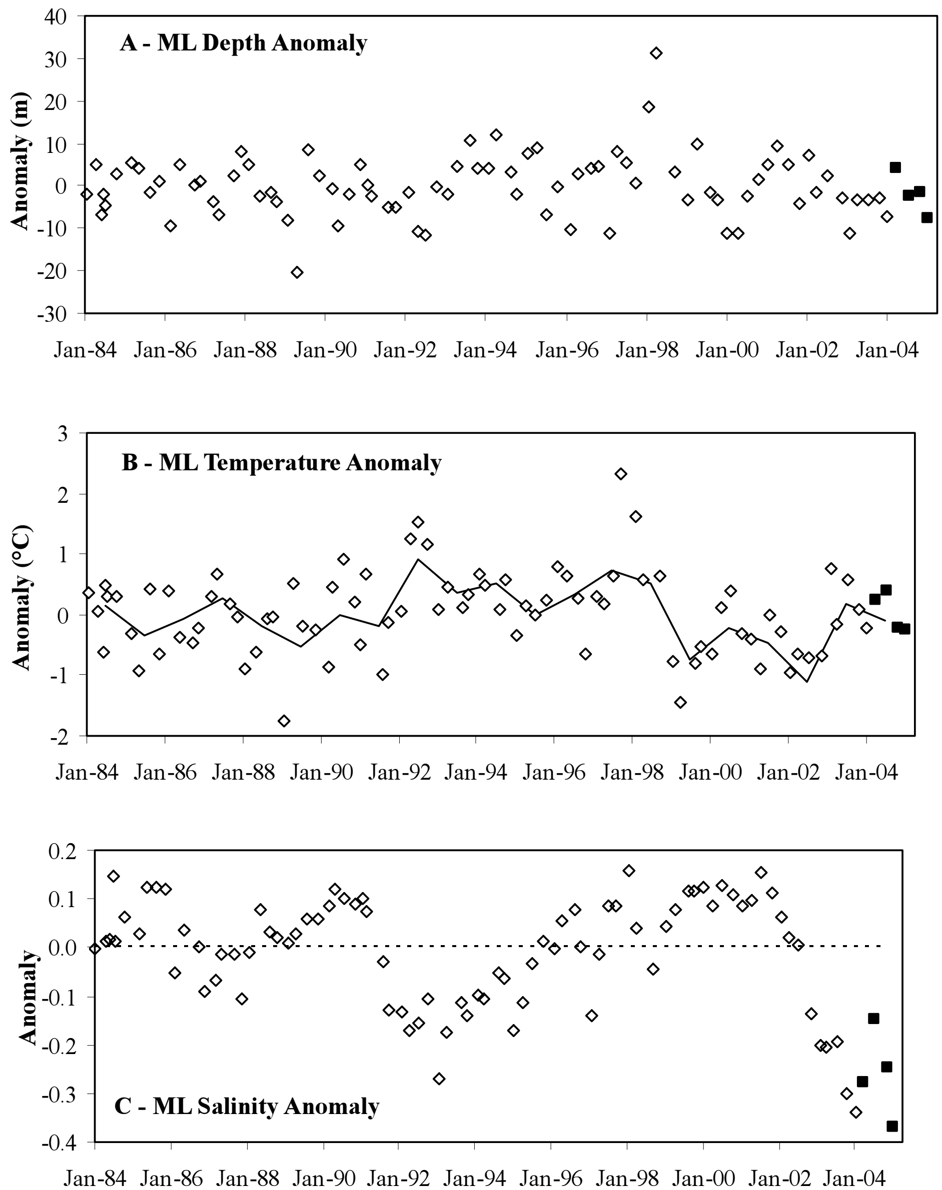
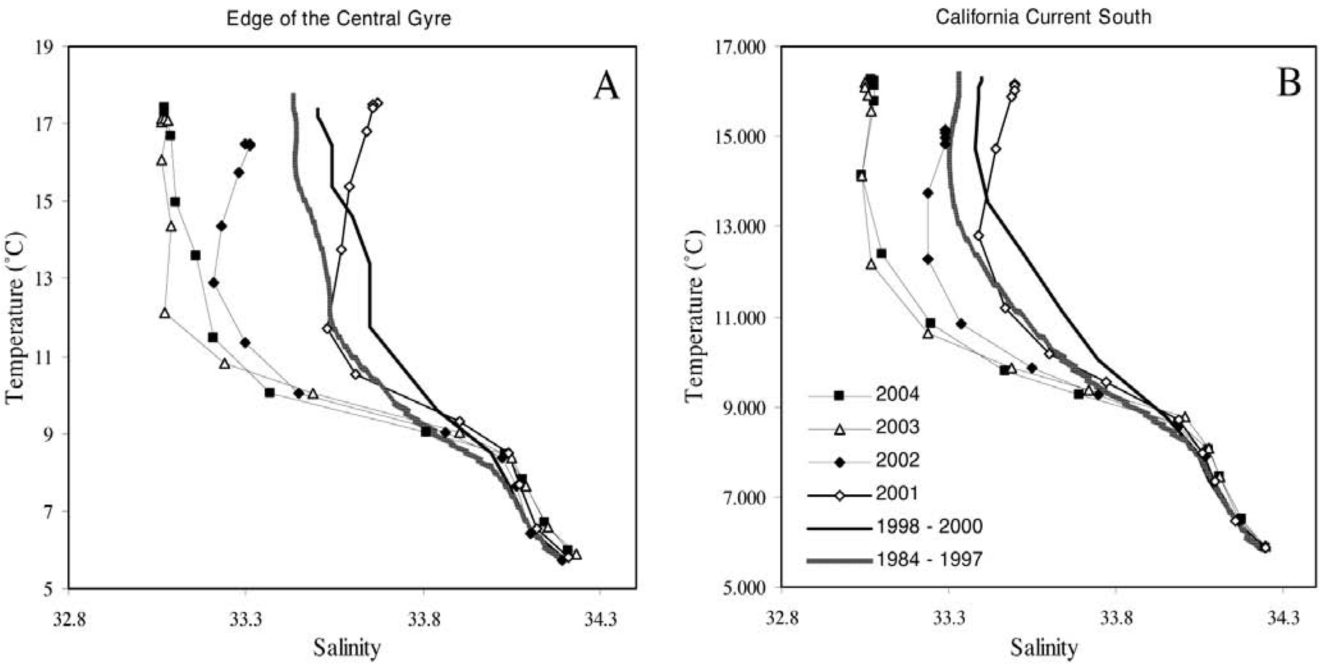


Figure 16. CalCOFI region anomalies for (a) mixed layer depth (MLD), (b) mixed layer temperature, and (c) mixed layer salinity. Data are derived from all 66 standard CalCOFI stations (fig. 1). Open symbols are for the period 1984 to spring of 2003. Data from the last four cruises are plotted as solid symbols. Annual averages in panel (b) are indicated with a solid line.

Average anomalies of these, 0.26 over the last year, were similar to those observed during the prior year (0.26). These anomalies are found throughout the CalCOFI region (e.g. fig. 17). Anomalies over the last two years were largest at the edge of the Central Gyre, becoming weaker, but still distinct, in the inshore areas (fig. 17). These anomalies are confined to the mixed layer and the seasonal thermocline.

0404 (23 Mar.–8 Apr. 2004; fig. 18). Preliminary data for this cruise were presented in last year's report (Goericke et al. 2004). The surface current patterns during April, as indicated by the dynamic height anomaly map, show two separate bands of strong southward flow, much like those seen during the spring of 2003 (Venrick et al. 2003). The strong flow starting at the northwest corner of the map was the main core of the California Current Jet, as revealed by the low salinity water that is commonly associated with the fastest part of the current. The other strong southward current band closer to shore was adjacent to the strong upwelling zone north of Point Conception. The upwelling is revealed by the cool temperatures and relatively high salinity seen near Point Conception. The cruise mean 10 m temperature was slightly warmer than normal. Near-surface



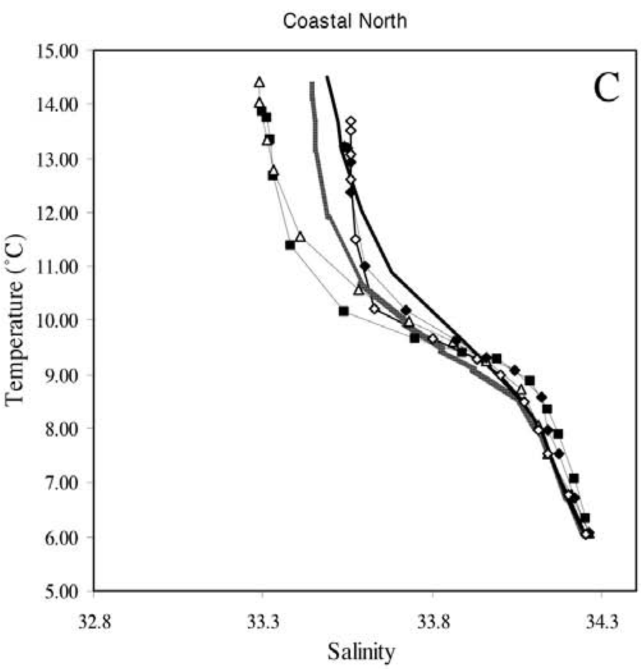


Figure 17. TS lines for three representative areas of the CalCOFI region. (a) The edge of the central gyre (line 90–93, stations 100–120). (b) The California Current region (line 83–90, stations 70–90). (c) the coastal areas in the north (line 77–80, stations 60 and inshore). Each data point represents the average TS characteristic of one standard depth level for the specified time period, e.g. the year 2002.

chlorophyll-*a* concentrations were also very high near the nutrient rich upwelled water. Offshore of the main California Current Jet, chlorophyll *a* was quite low, as usual. The Southern California Eddy was small at this time and was confined to the area around the northern Channel Islands.

0407 (13–28 Jul. 2004; fig. 19). The California Current Jet seen far offshore in the spring (0404) cruise had split into two branches by summer time with an anticyclonic eddy embedded between the two flows. The cyclonic Southern California Eddy had expanded in size and was centered offshore of the Channel Islands, with northward coastal flow up to the Santa Barbara Basin. Low 10 m salinity was associated with the main California Current Jet, and high saltiness occurred in the shoreward portion of the cruise pattern. Overall, however, the cruise mean 10 m salinity remained well below normal.

The temperature at 10 m was high both in the offshore regions and in the southeast corner of the pattern, between San Diego and the Channel Islands. Cool temperatures were seen extending southward from Point

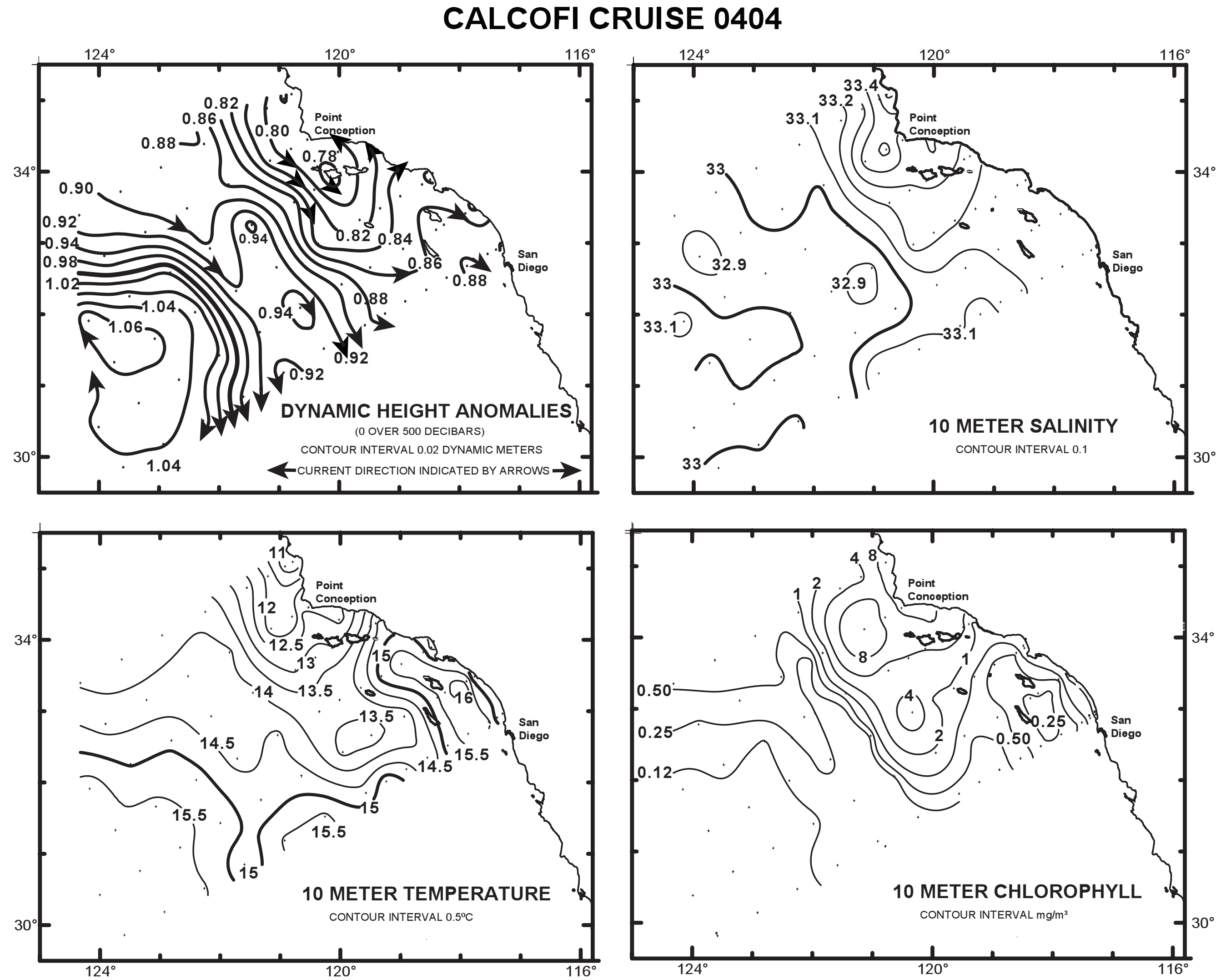


Figure 18. Spatial patterns for CalCOFI cruise 0404, including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

Conception, all the way through the cruise pattern, and located just inshore of the strong southward flow. Elevated salinities were found in the same zone. Together, these are indications of upwelling, corroborated by measurements taken at station 83.51, next to Santa Rosa Island, with surface oxygen saturation of only 88% and nitrate concentrations of 7.8 µm.

Surface chlorophyll *a* was unusually high for a summer cruise, especially around Point Conception, in the Santa Barbara Basin, and on the shallow shelf stations close to shore. The dissolved oxygen saturations on the shelf stations (between lines 83 and 93) were highly over-saturated, ranging from 120 to 148%, which indicates an accumulation of oxygen from an ongoing phytoplankton bloom.

0411 (13–28 Jul. 2004; fig. 20). Strong southward surface flow on this fall cruise was found between stations 90 and 100 on all six station lines, with little variation or meandering. An arc of relatively strong northward flow was seen along the coast to beyond Point Conception. Flows were weak over the middle of the pattern. The lowest 10 m salinities were observed in the core of the California Current Jet, where salinity anomalies were −0.5. The 10 m temperature anomaly was lowest near Point Conception, but the overall cruise mean was slightly warmer than normal, although the California Current Jet carried water that was slightly cooler than normal.

Chlorophyll-*a* concentrations at 10 m were elevated near Point Conception, otherwise, they were generally low, as is typical for an autumn cruise. Observed shelf station dissolved oxygen saturation was closer to the normal over-saturation levels (105%).

0501 (4–20 Jan. 2005; fig. 21). Some features of the

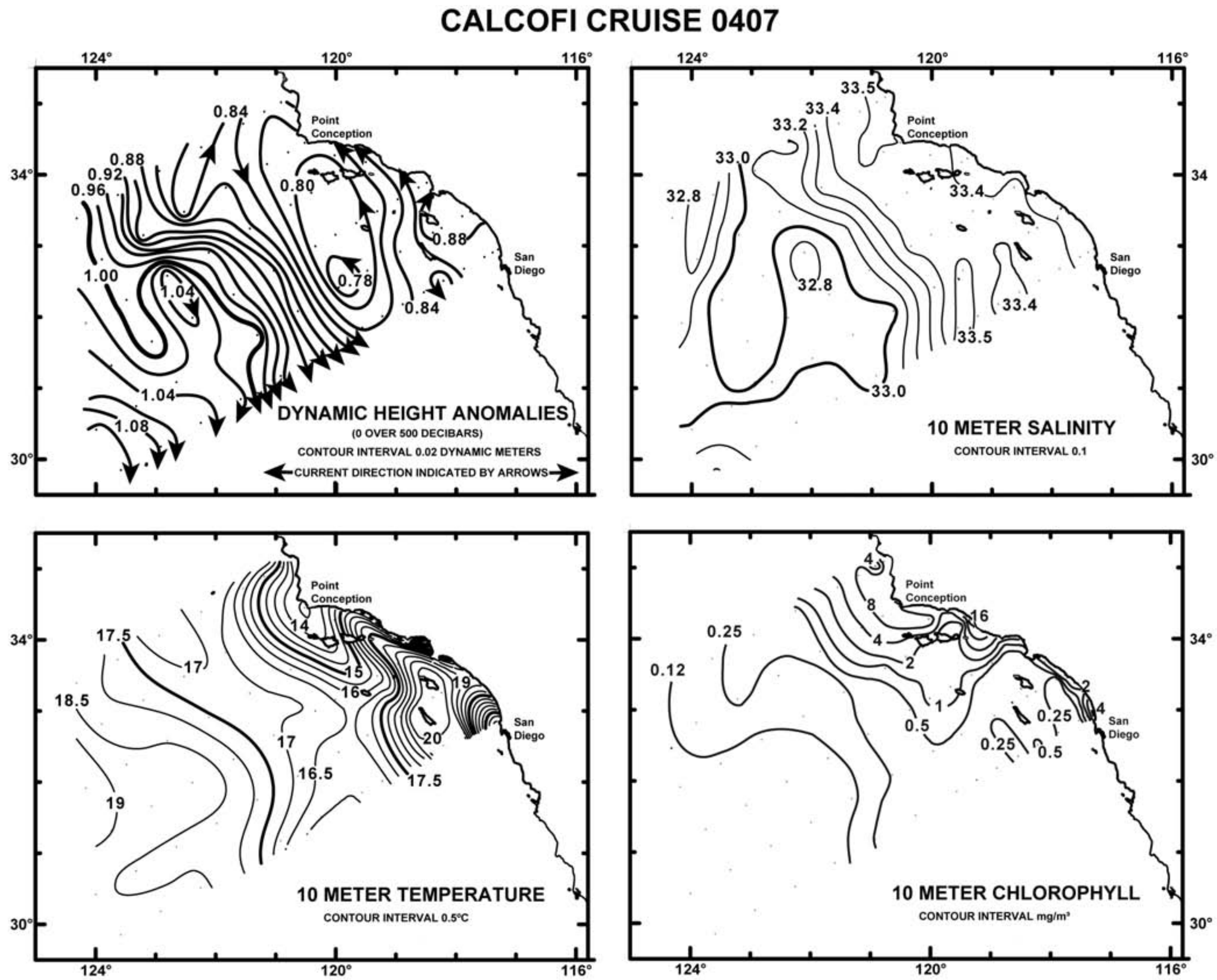


Figure 19. Spatial patterns for CalCOFI cruise 0407, including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll-*a*.

surface flow patterns for the 0501 winter cruise were similar to those of cruise 0411: the California Current Jet was still strong, located at the outer edge of the cruise pattern, and the northward coastal flow had intensified. However, other features appeared that were more like the flow seen in last year's winter cruise (0401): an eddy centered on station 80.70 and a large current loop penetrating shoreward along line 90.

Low salinities were seen in the offshore jet and in the shoreward current loop along line 90. There was considerable rainfall in Southern California this winter with significant runoff. This was probably responsible for the low surface salinities observed in the near-shore areas. Shipboard observers also noted high turbidity and suspended material in the upper meter at some stations. The 10 m temperatures were slightly above average for the cruise, especially at the eastern half of the pattern, but stations in the California Current Jet were slightly cooler than normal.

Over most of the pattern, chlorophyll *a* at 10 m was quite low, and surface dissolved oxygen was at equilibrium with the atmosphere with saturation values around 99 to 101%. Both patterns are typical of winter. A few stations were slightly under-saturated either due to winter convective overturn or upwelling at some stations.

Station 90.28 showed some unusual characteristics resulting from local runoff. The surface salinity was very low, 28.4, and the nutrient profile had an "inverted" shape with the highest nutrients appearing in the surface, low-salinity layer and lower nutrients below. Surface chlorophyll *a* was relatively high at this station, and the dissolved oxygen was over-saturated by 26%.

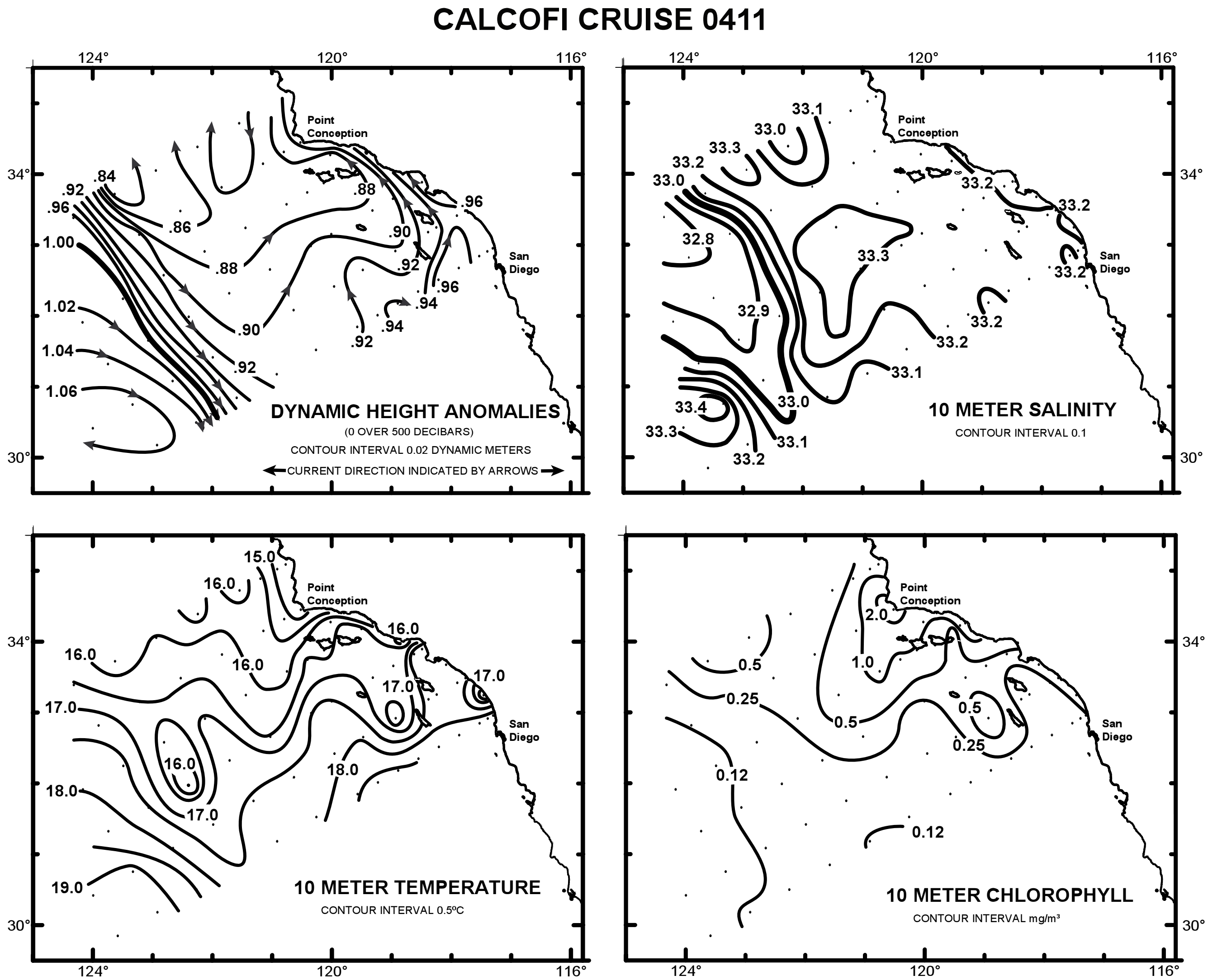


Figure 20. Spatial patterns for CalCOFI cruise 0411, including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll-*a*.

IMECOCAL Survey Cruises off Baja California

The IMECOCAL program surveyed the CCS off Baja California during April, July, October 2004, and January 2005. During all four cruises, upper ocean salinities (σ_t < 25.5) were significantly lower than climatological means (fig. 22), patterns similar to those observed off Baja California during the weak El Niño of 2002–03 (Durazo et al. 2005) and off Southern California during 2002 to 2004 (Goericke et al. 2004). These upper layer salinity anomalies were first evident in 2002/03 in the upper thermocline (σ_t < 24.5) and later expanded further (σ_t < 25.5). These anomalies were still evident in January 2005 (fig. 22). SST anomalies were only positive during the winter and spring of 2004 (cruises 0301 and 0304, respectively).

0404 (15 Apr.–7 May 2004; fig. 23). The dynamic height anomalies during the spring showed the CC as a very uniform band close to the coast flowing SSE. The current entered the survey region both from the northernmost section and from the northwest. Near shore, low temperatures and relatively high values of chlorophyll *a* suggest upwelling, with maximum chlorophyll-*a* concentrations inside Bahía Vizcaíno and south of Punta Eugenia. Relatively low salinities were found throughout the survey area. The core of the CC closely followed the salinity minimum of 33.2. Salinities above the σ_t < 25.5 surface were lower than the climatological mean (fig. 22).

0407 (9–29 Jul. 2004; fig. 24). Dynamic height anomalies during July 2004 suggest that the CC entered the survey region between lines 100 and 103 in the form of a clockwise meander, left the survey region, reentered the region at 27 to 28°N, meandered and flowed southward close to the coast. Lower coastal temperatures sug-

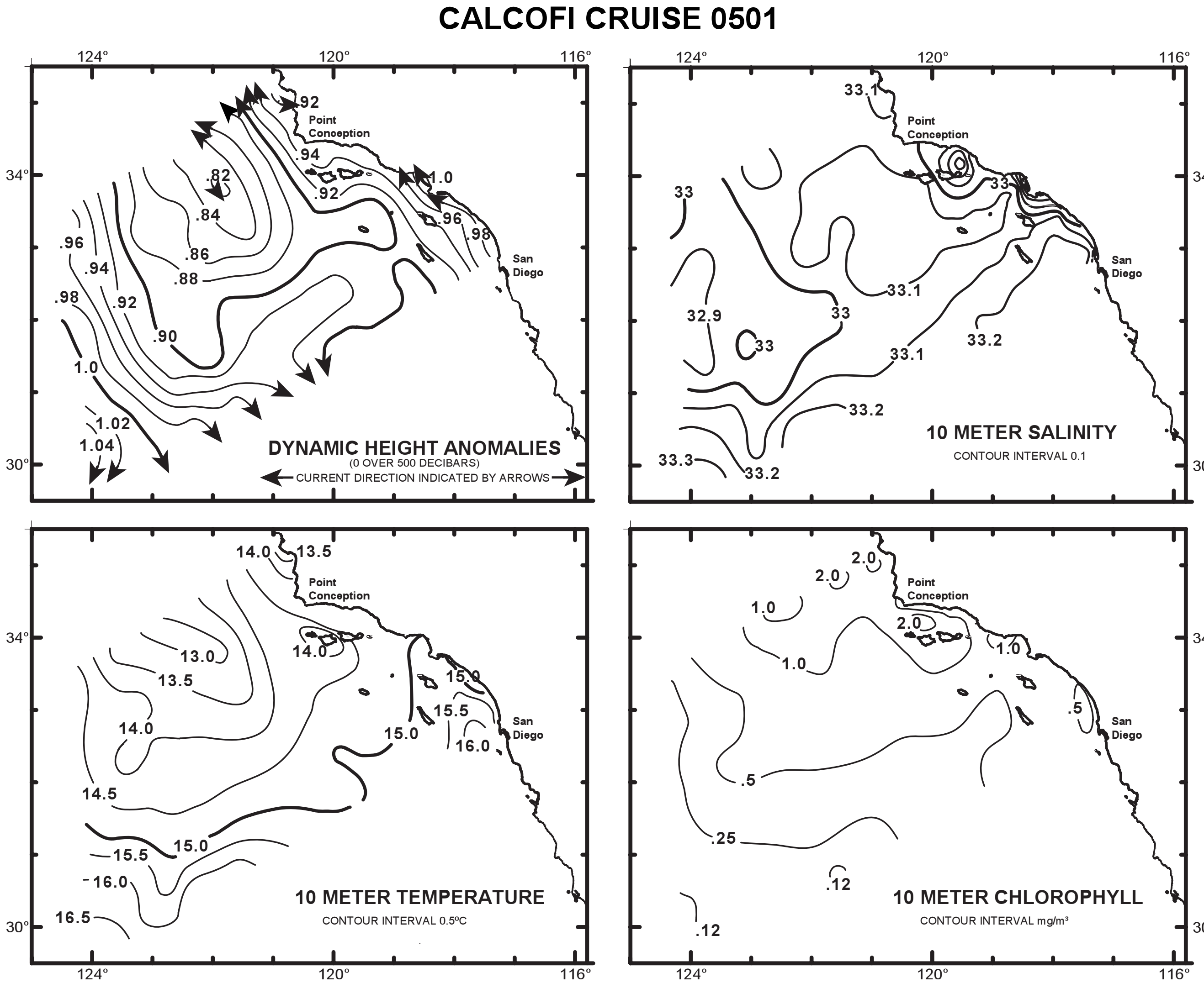


Figure 21. Spatial patterns for CalCOFI cruise 0501 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll-*a*.

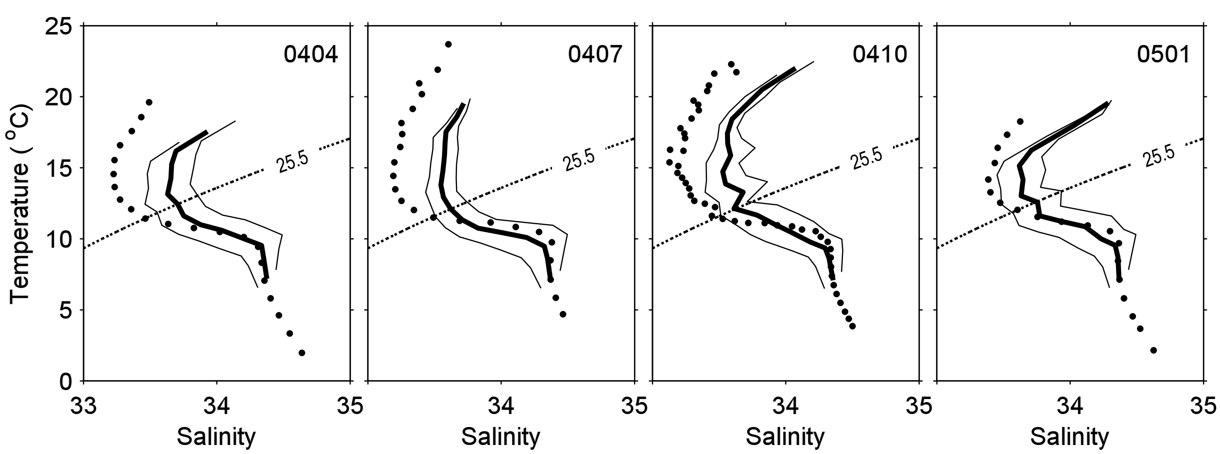


Figure 22. Temperature-salinity diagrams for the spring, summer, and fall 2004 and winter 2005 data collected in the IMECOCAL grid. Bold continuous line represents the climatological mean computed at standard depths from historical (1948–78) and recent (1997–2004) data sets, from 0 to 500 m. Continuous thin lines depict one standard deviation along the salinity axis. Heavy dots indicate the mean temperature-salinity for each cruise. Both cruise and climatological mean profiles were obtained using the same stations on each case. Thin dotted line marks the $\sigma t = 25.5$ isopycnal contour.

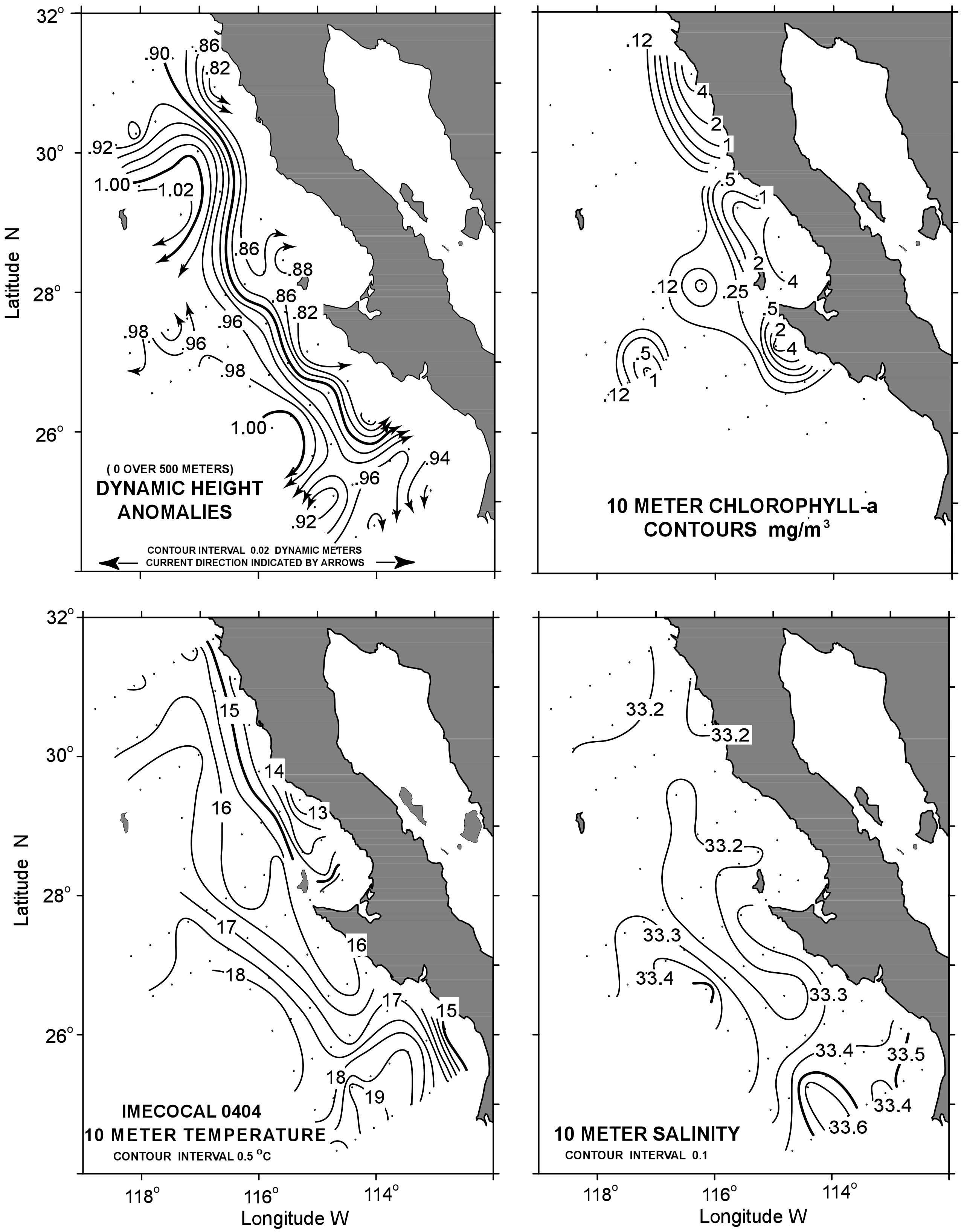


Figure 23. Spatial pattern for the IMECOCAL cruise 0404 (15 Apr.–7 May 2004) including upper ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll, 10 m temperature, and 10 m salinity. Full data of chlorophyll-*a* are not available for this cruise because some stations were missed due to bad weather.

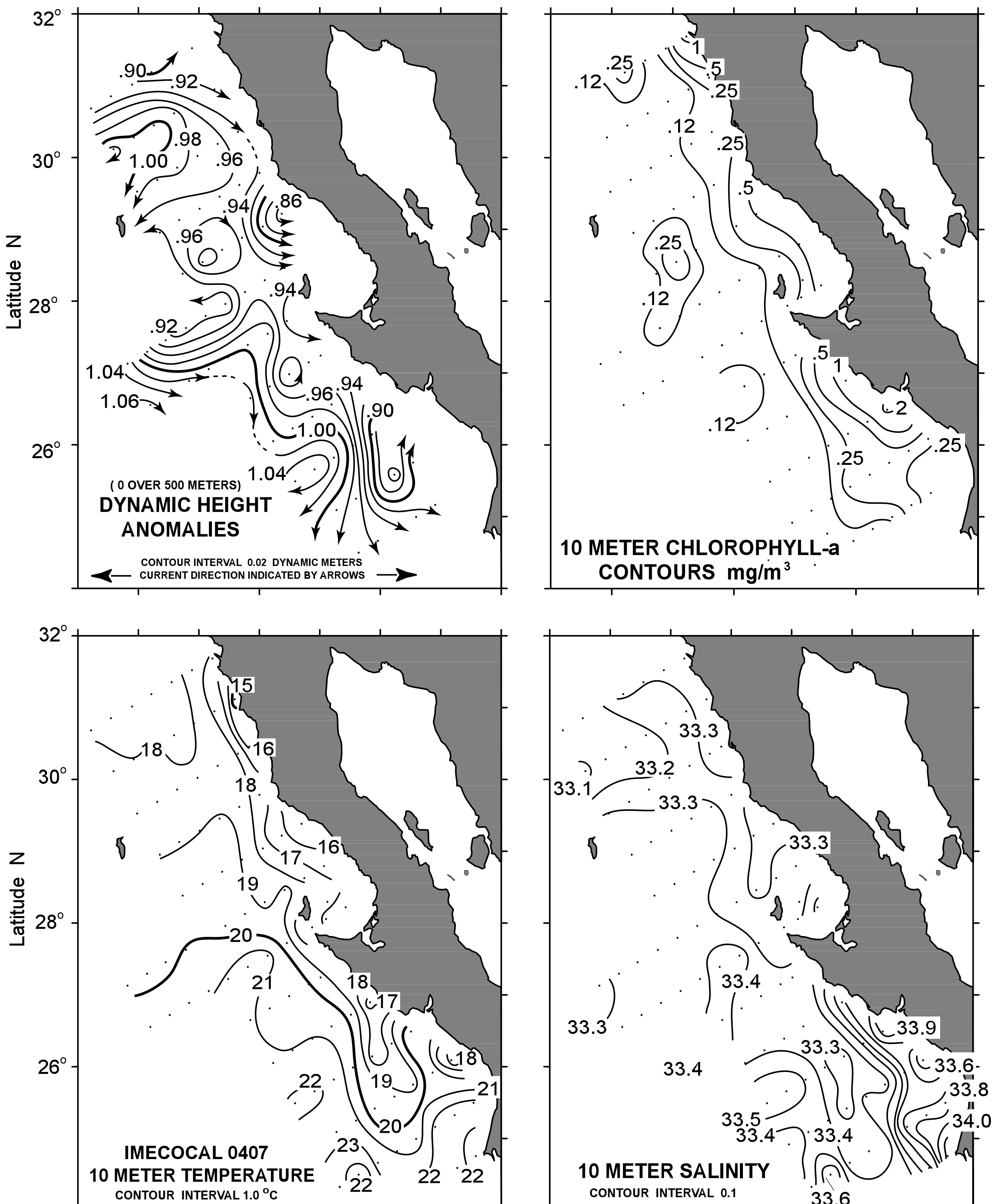


Figure 24. Spatial pattern for the IMECOCAL cruise 0407 (9–29 Jul. 2004), including upper ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

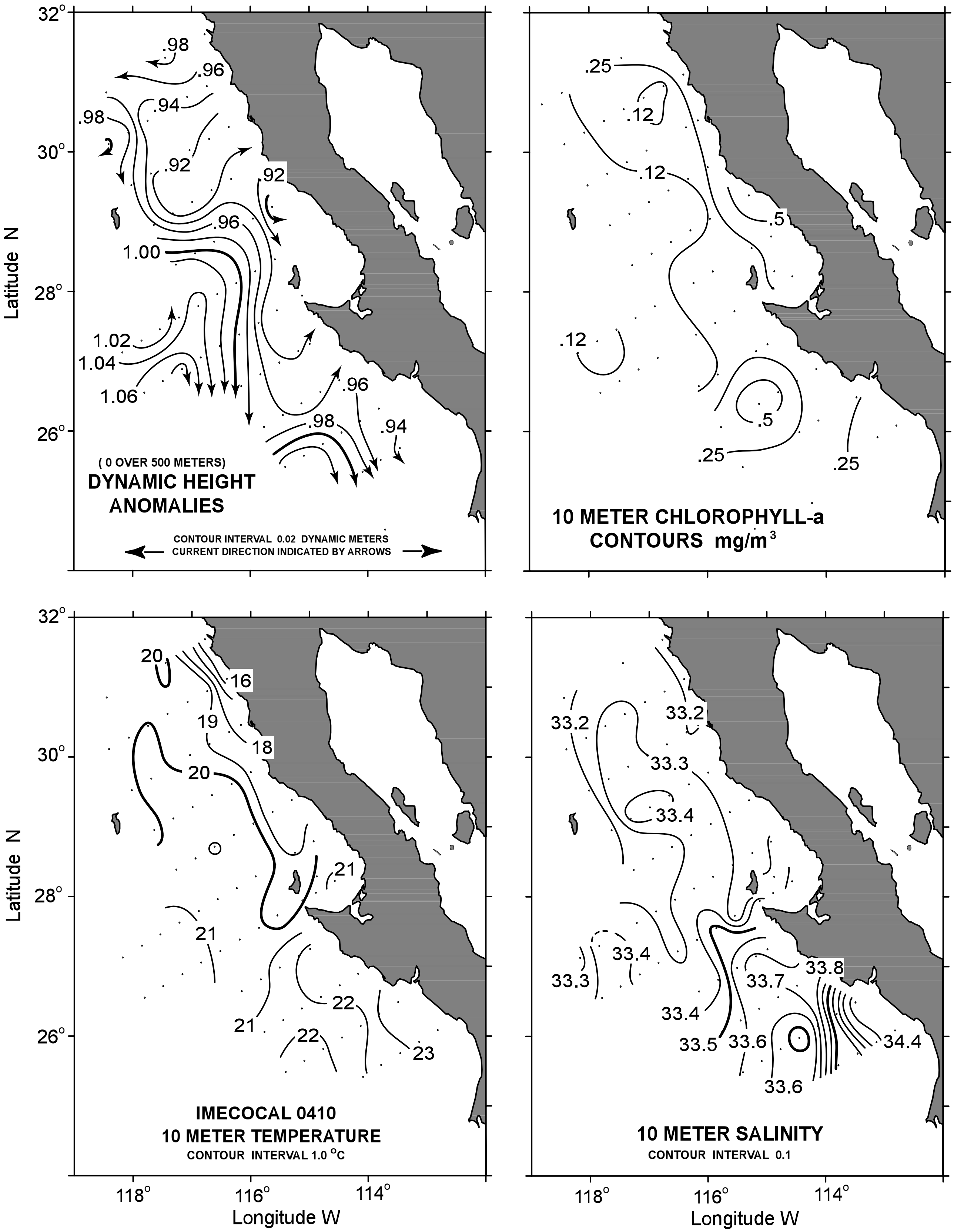


Figure 25. Spatial pattern for the IMECOCAL cruise 0410 (9–28 Oct. 2004), including upper ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

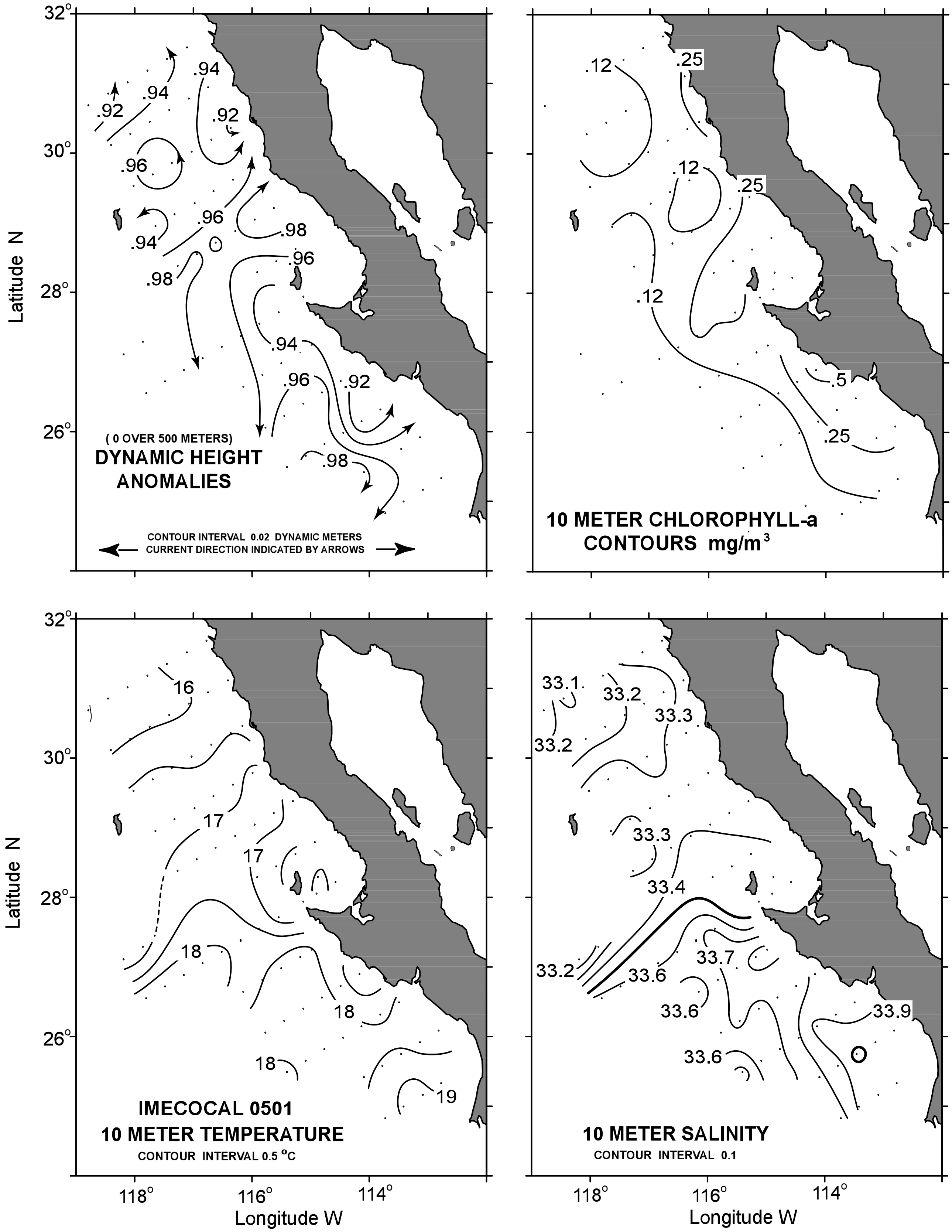


Figure 26. Spatial pattern for the IMECOCAL cruise 0501 (21 Jan.–11 Feb. 2005), including upper ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

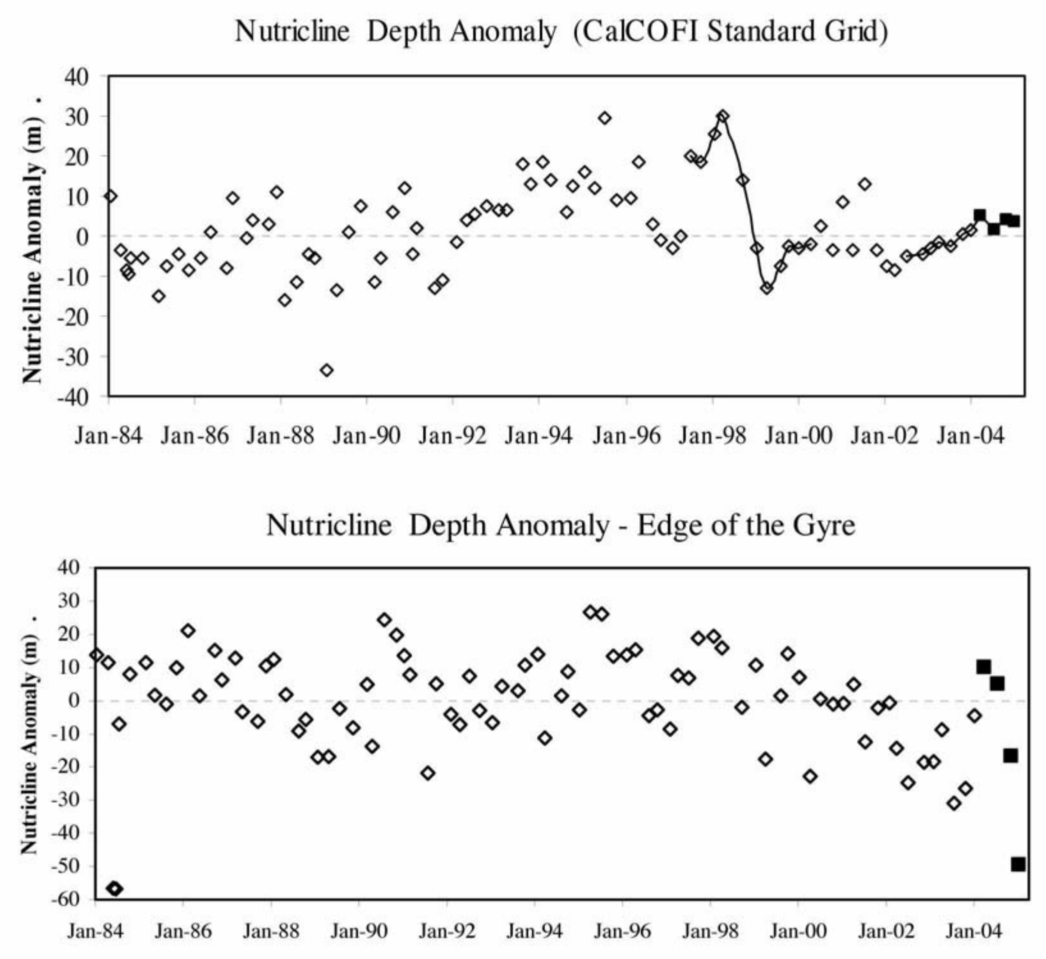


Figure 27. CalCOFI region anomalies for nutricline depth. (a) CalCOFI area anomalies, (b) anomalies for the edge of the central gyre (Line 90–93, Stations 100–120). Data and symbol codes are the same as those in Figure 16.

gest upwelling, mainly south of the coastal promontories, Ensenada to Colonet (30.5–31°N), Punta Baja (29°N), and Punta Eugenia (27°N). Surface salinities were near uniform in the northern portion of the region but showed large gradients south of Punta Eugenia. Higher salinities near the coast suggest a poleward flow of water from the south. Lower than normal salinities were observed above the σ_t = 25.5 surface, consistent with observations made during the previous cruise. Concentrations of chlorophyll-*a* were very low over most of the survey region (<0.25 µg/L), with the exception of upwelling centers along the coast south of Punta Eugenia (>1 µg/L).

0410 (9–28 Oct. 2004; fig. 25). Low gradients of dynamic height anomalies north of 29°N suggest that the core of the CC was located west of the sampling area. The CC core appears to have entered the survey region at the northwestern corner and meandered southward roughly along stations 60 to latitude 29°N. South of this latitude, it flowed closer to shore. South of Punta Eugenia, the CC core was displaced offshore by water of southern origin (S > 33.6). With the exception of the coastal region south of Ensenada, where upwelling may have occurred, 10 m temperatures were relatively high throughout the study domain, although these were near the seasonal mean (fig. 22). 10 m salinities were relatively uniform and low north of 28°N, but had strong gradients and higher values south of 28°N. Near surface waters (σ_t < 25.5) were found fresher than the mean. Chlorophyll-*a* concentrations were very low throughout the survey region.

0501 (21 Jan.–11 Feb. 2005; fig. 26). Gradients of dynamic height anomalies north of 28°N during January–February 2005 were small and suggested flow towards the coast between lines 100 and 103 and lines 110 and 113. South of 28°N, flows toward the south appeared more organized although dynamic height gradients were small. Chlorophyll-*a* concentrations were relatively low. Temperature contours followed those of dynamic height, i.e., an east-west orientation. Salinity contours were generally perpendicular to the coast, with a latitudinal gradient of ΔS ~1 along the north and south extremes of

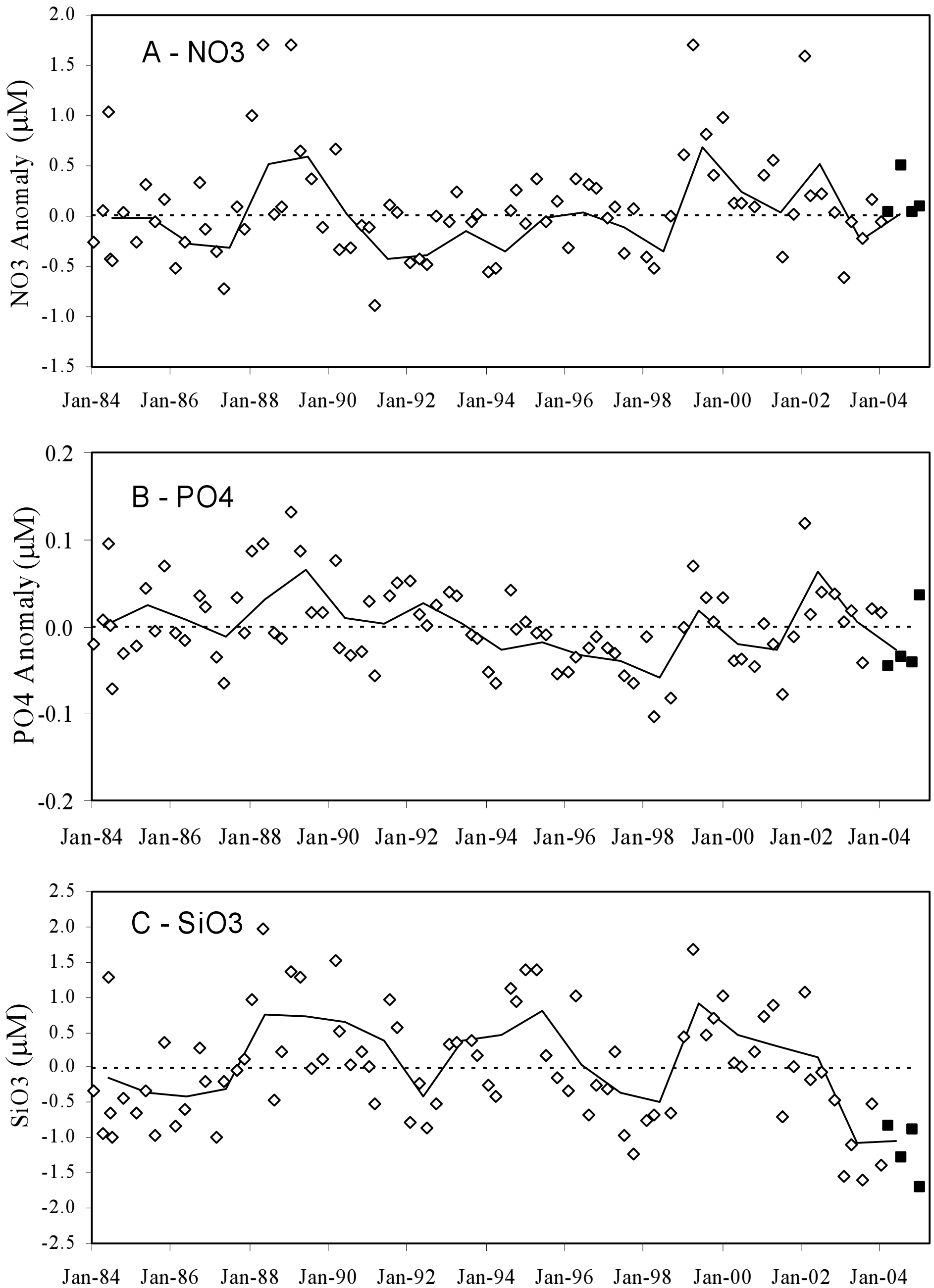


Figure 28. CalCOFI region anomalies for concentrations of (a) nitrate, (b) phosphate, and (c) silicate in the mixed layer. Data and symbol codes are the same as those in Figure 16.

the survey region. For this cruise, the T-S diagram indicates near-normal temperatures but lower than the mean salinities (fig. 22).

BIOLOGICAL PATTERNS AND PROCESSES

Macronutrients and Chlorophyll *a*

Oregon: The 2002–03 enhanced subarctic influence coincided with a significant increase in phytoplankton biomass (Wheeler et al. 2003). In July 2002, July 2003, September 2002, and September 2003, values of spatially-averaged, vertically-integrated chlorophyll in this region were 126, 232, 70, and 89 mg m^{-2}, respectively (Goericke et al. 2004). In contrast, the value for late August 2004 (the only cruise for which we have recent data) is 43 mg m^{-2}, which is similar to the September values observed in earlier LTOP years (1998–2001). This reduction in phytoplankton biomass seems to confirm that the period of enhanced subarctic influence has ended.

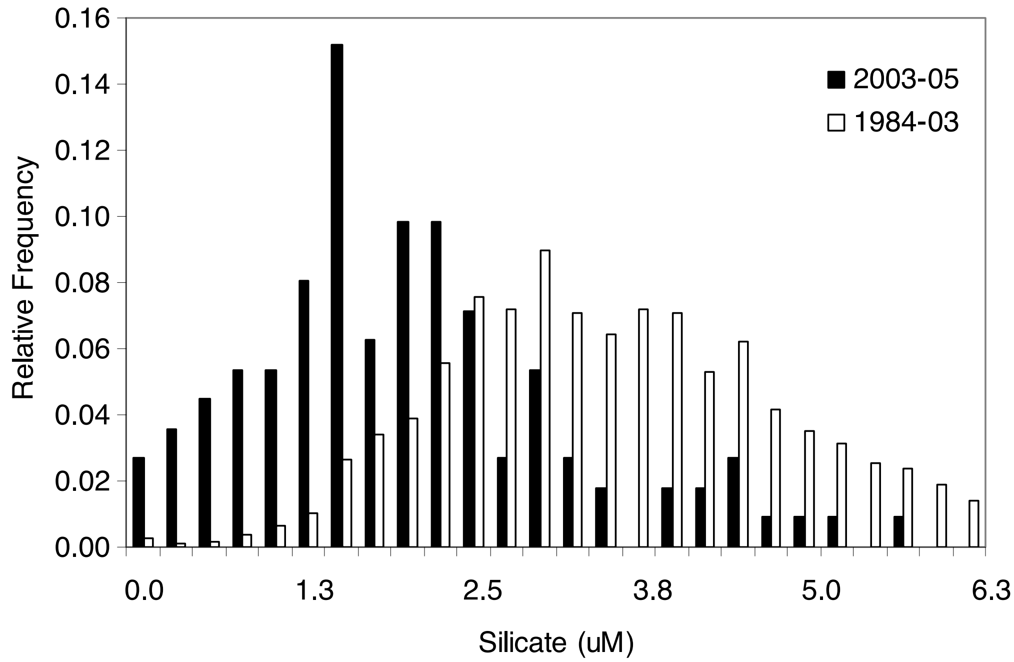


Figure 29. Normalized ML silicate concentration frequencies for CalCOFI stations with nitrate concentrations larger than 0.3 μM.

CalCOFI: Nutricline depth anomalies for the whole CalCOFI region were close to zero over the last year (fig. 27a), similar to the previous year. This pattern, however, was not seen throughout the CalCOFI area; large negative nutricline anomalies—i.e. nutriclines shallower than normal—were observed in the offshore regions in the fall and winter (fig. 27b). Mixed layer (ML) nitrate and phosphate anomalies were variable but, when averaged over the year, close to zero (fig. 28a, b). Silicate anomalies observed over the last two years are the lowest on record (fig. 28c). These large negative silicate anomalies coincided with the large negative salinity anomalies, suggesting that the former, too, are directly or indirectly related to the possible increased transport of subarctic waters into the CalCOFI area. These changes in silicate concentrations may affect diatom growth. The half saturation constant for silicate uptake by most diatoms is in the range of 2 to 3 μM. Prior to 2003, only 9% of all stations with ML nitrate concentrations larger than 0.3 μM had silicate concentrations <2.5 μM (i.e. were likely to be limited by silica rather than nitrate), but after 2003, 52% of all stations were in that category (fig. 29). For comparison, during 1984 to 1987, when silicate concentrations were also consistently below their climatological average, this value was 19%. These data imply that the likelihood that diatom growth was limited in recent years by the availability of silicate increased by about a factor of five.

Last year the Santa Barbara Basin (SBB) was in an unusual state as well. The basin is surrounded by a sill; its deeper regions are isolated from the surrounding ocean. It flushes only intermittently. At these times, cold, oxygen- and nitrate-rich waters replace the older oxygen- and nitrate-depleted waters. Oxygen concentrations in the Santa Barbara Basin often reach suboxic levels (fig. 30a), initiating denitrification. During 2004, nitrate dropped below values of 15 μM, the lowest observed since measurements began in 1984 (fig. 30b). In January 2005 values were less than 1 μM. Concentrations of nitrite, which had previously always been less than 0.2 μM, reached values of 2.9 μM in July 2004 (fig. 30c). Rates of nitrate consumption at the bottom of the basin over the last 18 months were 0.060 μm day^{-1}. This value is similar to those previously observed, 0.058 ± 0.016 μm day^{-1} ($n = 10$). However, previously denitrification occurred continuously only over periods of 3 to 6 months, interrupted by partial or complete flushing of the basin. These data suggest that the drawdown of nitrate in the basin is simply due to changing hydrographic forcing of the basin. However, the dramatic increase in concentrations of nitrite at the bottom of the basin (fig. 30c) suggests that a consequence of this hydrographic forcing was a change in some biogeochemical processes within the basin.

The annual average of the CalCOFI-domain chlorophyll *a* was close to the 1999–2003 average value. Values observed during the spring were not as high as those observed during some previous years since 1998. This, however, may have been a function of the timing of the cruise. The standing stocks observed during the sum-

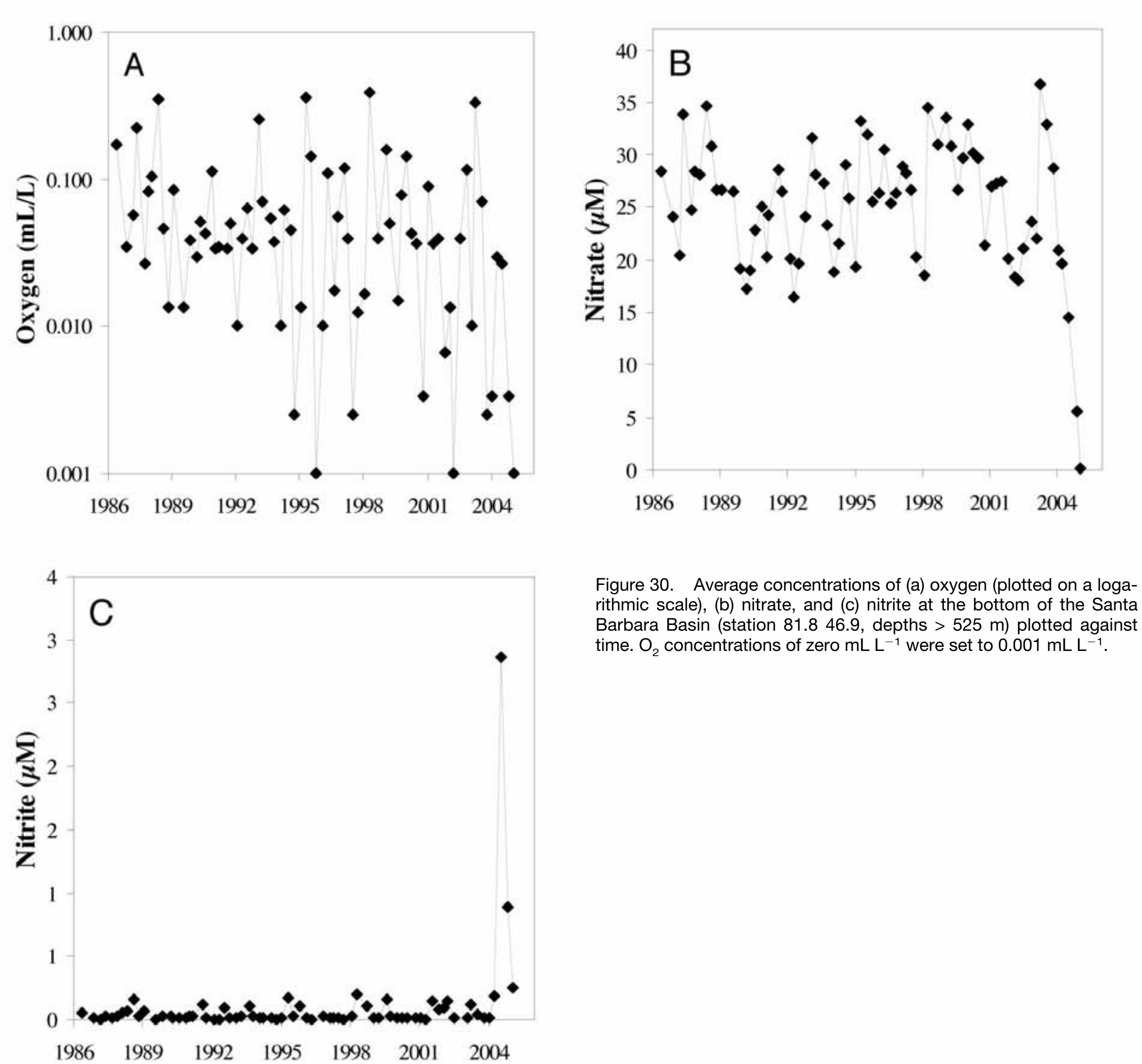


Figure 30. Average concentrations of (a) oxygen (plotted on a logarithmic scale), (b) nitrate, and (c) nitrite at the bottom of the Santa Barbara Basin (station 81.8 46.9, depths > 525 m) plotted against time. O_2 concentrations of zero mL L^{-1} were set to 0.001 mL L^{-1}.

mer were unusually high (fig. 31). In the offshore areas, the depth of the chlorophyll-*a* maximum had returned to a depth of ~100 m after two years at ~ 80 m (fig. 32a). The area of the CC is still characterized by slightly higher concentrations (fig. 32b) compared to the historical averages.

Macrozooplankton

Oregon: Inter-annual patterns of copepod biomass at the NH05 sampling station off Oregon (44°40'N; water depth 60 m) are shown in fig. 33. These seasonally integrated measures (May–Sept. average) of total copepod biomass indicate that 2004 was comparable to the preceding three years. The 2001–04 time period appeared to remain at a relatively stable state compared to either the lower levels observed during 1996–99 or the highly productive upwelling season of 2000. However, temporal resolution provided by bi-weekly sampling and species-specific data products provide evidence that suggests significant variability over the past four years.

Compared to observations during previous years, 2004 had substantial intra-annual variability in total copepod biomass, with some notable departures from the climatological mean (fig. 34). Rather than observing a late summer peak in copepod biomass, our sampling showed three events with high biomass values; the highest in May, and then two of a lesser magnitude in early July and early August. By early September, biomass showed a significant decrease, at least one month earlier than the "normal" fall transition, similar to patterns observed during 2003 (Goericke et al. 2004).

Anomalies in species-specific abundances have proven useful for relating the prevalence of copepod taxa with contrasting biogeographical affinities to inter-annual variability in ocean conditions (Mackas et al. 2001; Peterson

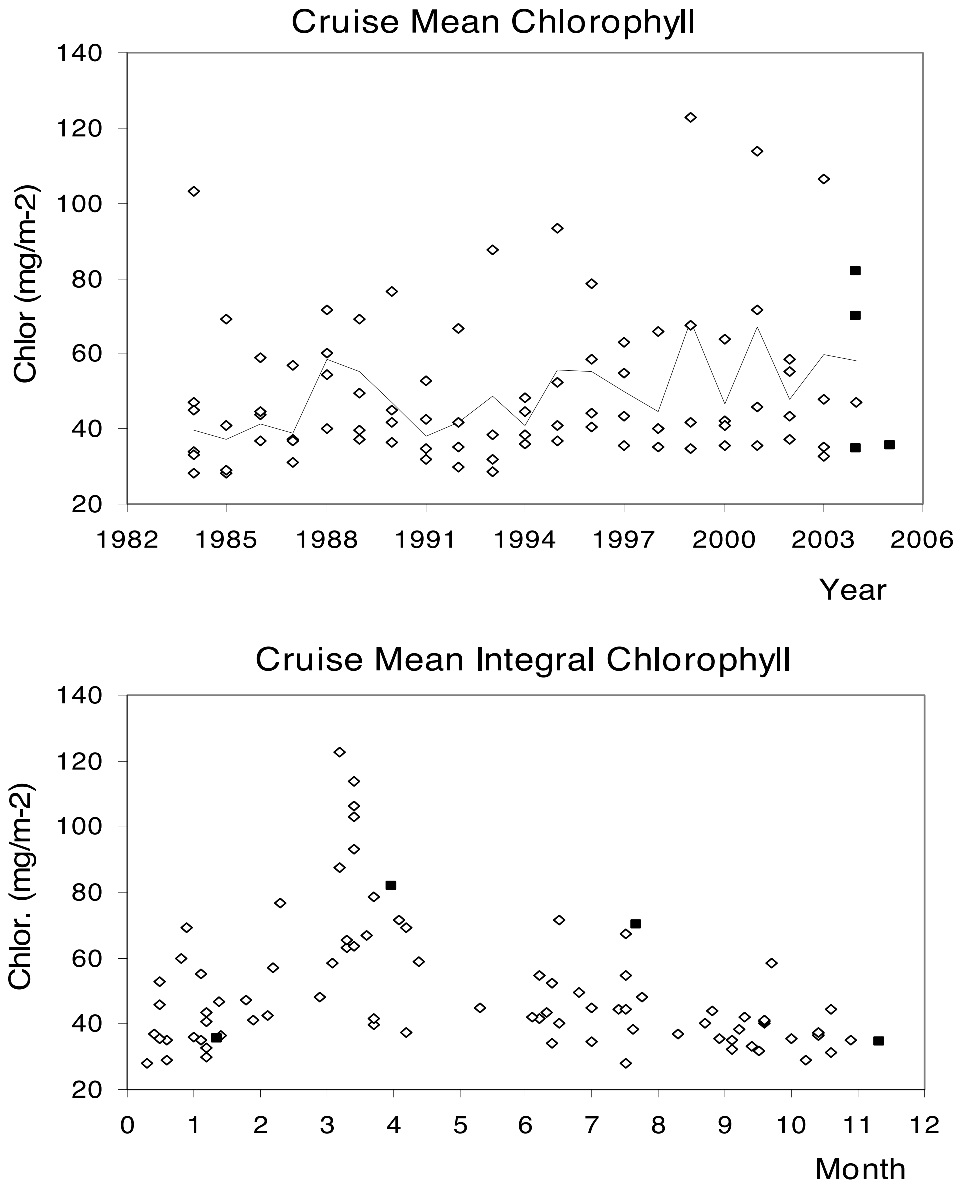


Figure 31. CalCOFI region chlorophyll-*a* standing stocks (mg per m^2). (a) plotted against time and (b) against the month (note that the 31st of January has a value of 1).

and Schwing 2003; Mackas et al. 2004). Prior to 1997, and particularly during the 1997–98 El Niño, copepod biomass was low and species with southern and off-shore affinities showed anomalously high abundances in coastal waters (Mackas et al. 2004). This group includes *Mesocalanus tenuicornis*, *Paracalanus parvus*, *Ctenocalanus vanus*, *Clausocalanus pergens*, *Clausocalnanus arcuicornis*, and *Clausocalanus parapergens*. This suggests that at least during the three-year period 1996–98, reduced coastal upwelling and low productivity characterized shelf waters of the northern CCS. 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 abundant 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 season of 2000, 2001, and early portions of 2002 (Mackas et al. 2004). During 2003 and 2004, however, the biomasses of both warm water and cold water taxa were moderately high.

Hooff and Peterson[2] (submitted) have used biodiversity measures to characterize inter-annual variability in

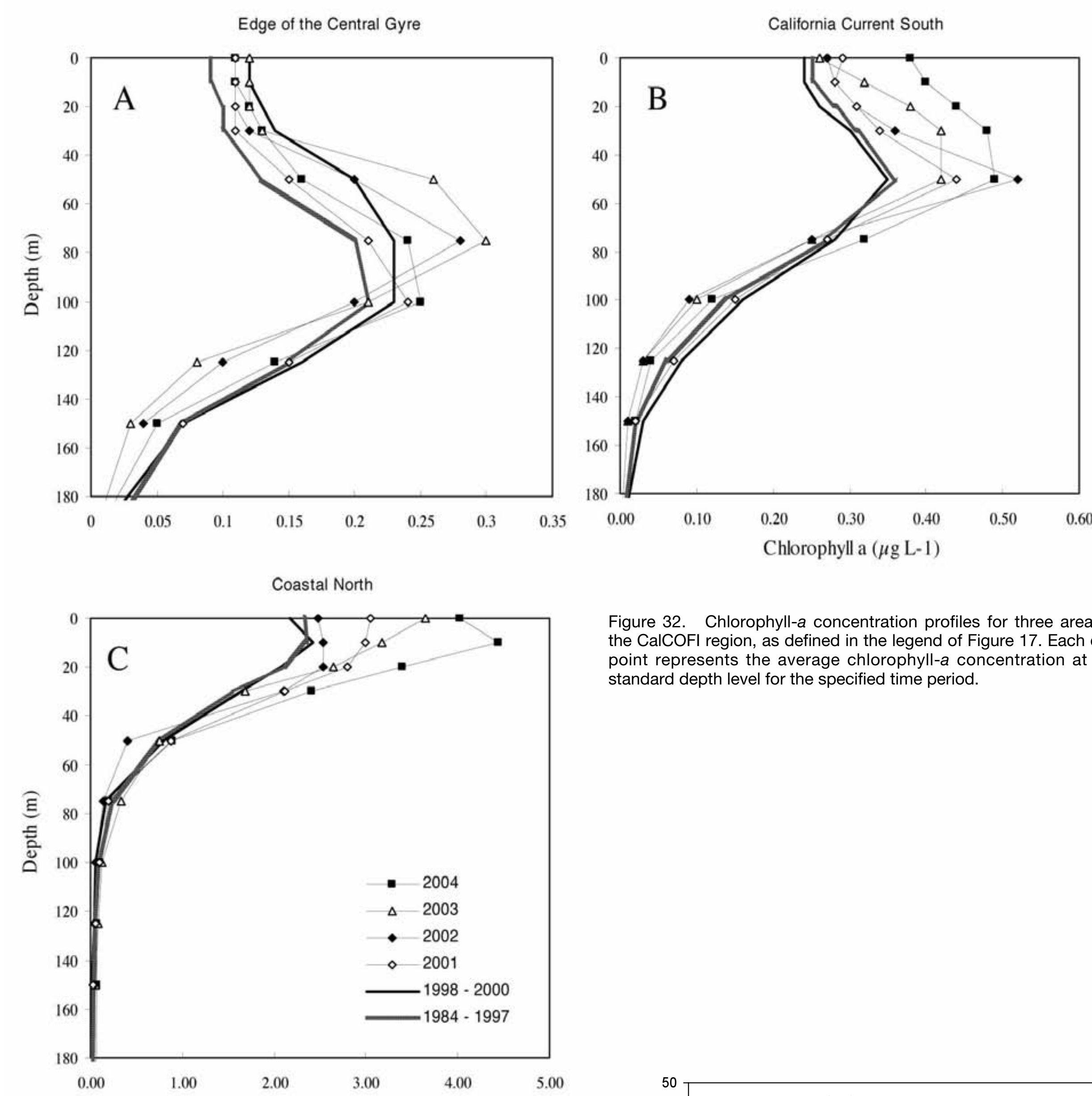


Figure 32. Chlorophyll-*a* concentration profiles for three areas of the CalCOFI region, as defined in the legend of Figure 17. Each data point represents the average chlorophyll-*a* concentration at one standard depth level for the specified time period.

copepod community composition and its relationship to recent changes in ocean conditions. Figure 35 compares seasonally detrended monthly anomalies of species richness with basinwide climatological indices (i.e. MEI and PDO). In general, copepod biodiversity increases during El Niño events, largely due to an increase of warm-water taxa of southern and/or offshore origins (Keister and Peterson 2003). A dramatic shift from anomalously high to anomalously low biodiversity levels is apparent in late 1998, following the strong El Niño event. Low biodiversity persisted for approximately two years after this shift. However, since 2000, levels have gradually increased. As indicated by the strong correspondence with the MEI and PDO, these recent changes appear to be related to regional or basinwide processes influencing

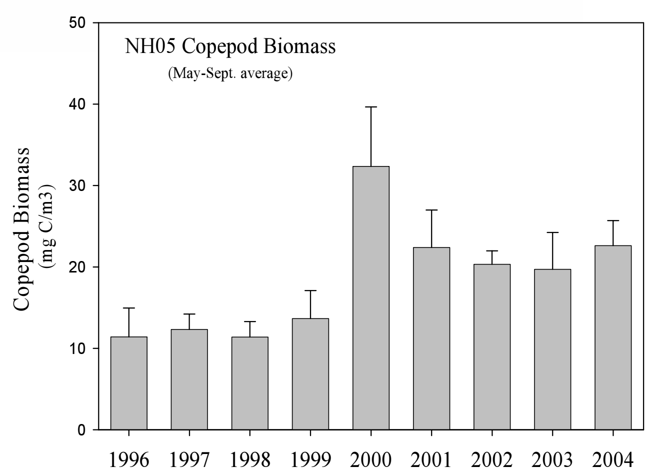


Figure 33. Inter-annual patterns of total copepod biomass (May–Sept. average ± standard error) at station NH05 of the Newport Hydrographic line (45°N, 60 m depth) for 1996 to 2004.

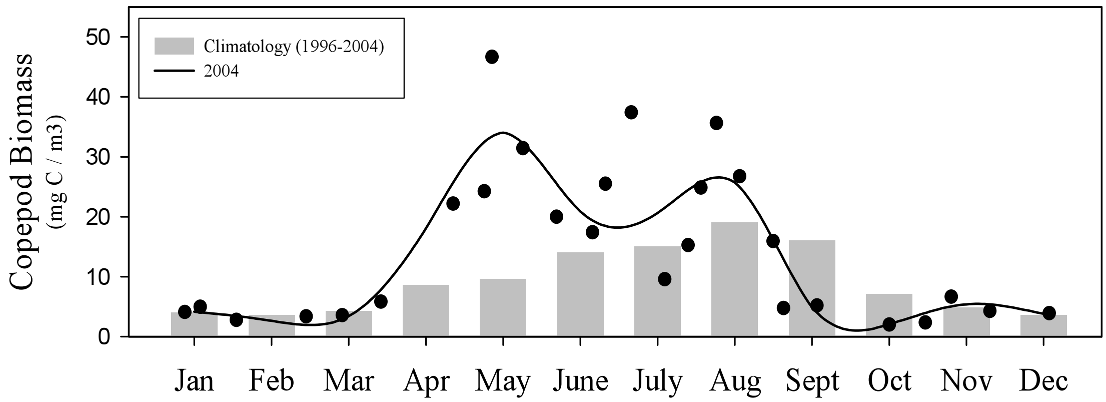


Figure 34. Total copepod biomass at station NH05 based on monthly averaged (line) and individual samples (scatter) compared to the 9-year monthly climatology (bars).

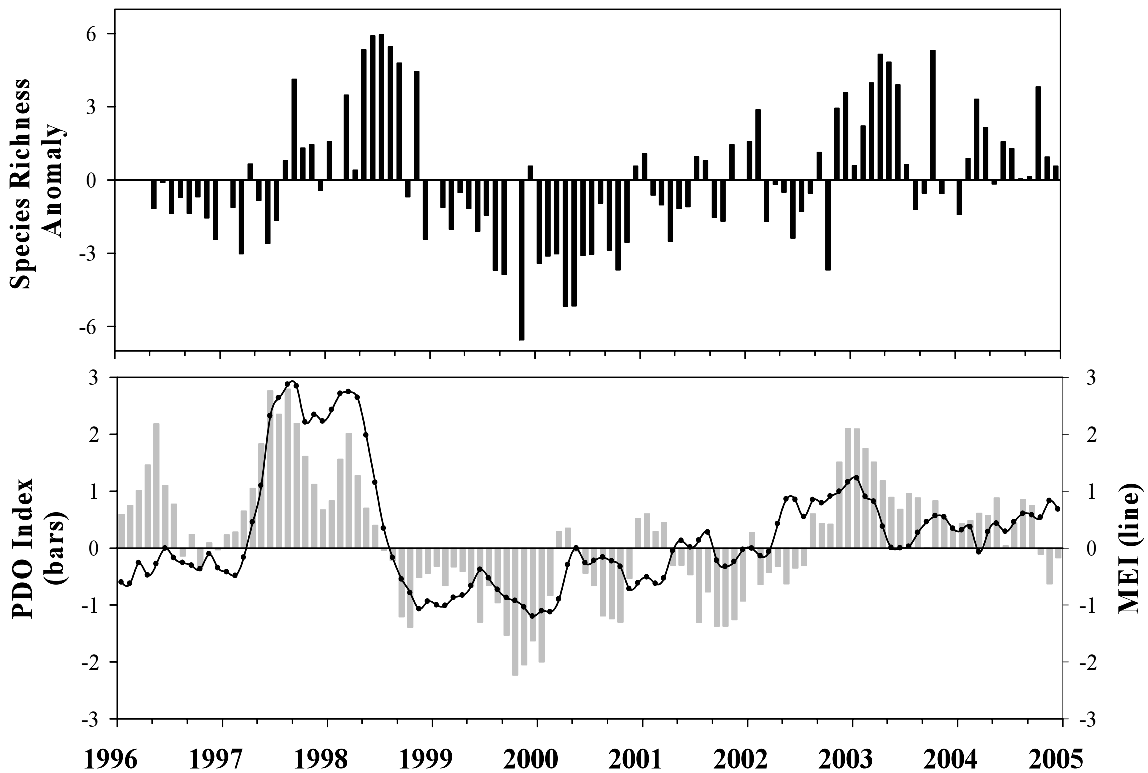


Figure 35. Seasonally de-trended monthly anomalies of copepod species richness at station NH05 off the Oregon coast (a), and monthly values of the MEI (line) and PDO (bar). For any given month, a negative value means fewer species than "normal" for that month; positive values indicate more species than normal. The presence of fewer species than normal is usually associated with cold waters; more species with warmer waters.

transport dynamics off the Oregon Coast. Biodiversity during the years 2003 and 2004 (and through the summer 2005) continues to be high and tracks recent changes in the PDO and MEI from negative to positive values. This suggests that the northern CCS has been under the influence of ocean conditions that are similar to an El Niño event, yet there has been no equatorial El Niño forcing. Another interesting aspect of the summers of 2003 and 2004 is the high abundances of two subtropical neritic copepods, *A. tonsa* and *C. anglicus*. Other details related to relationships between biodiversity, PDO and MEI are presented in Hooff and Peterson[2].

CalCOFI: Macrozooplankton displacement volumes during the observation period (86 ml/1000 m^3) were close to the climatological mean (113 ml/1000 m^3, 1984 to 2005 base period) and the mean for the 2000 to 2003 time period (fig. 36). Clearly, zooplankton bio-

[2]Hooff, R.C. and W.T. Peterson. Submitted. Increased copepod biodiversity as an indicator of recent changes in climate and ocean conditions in the northern California Current ecosystem. Limnol. Oceanogr.

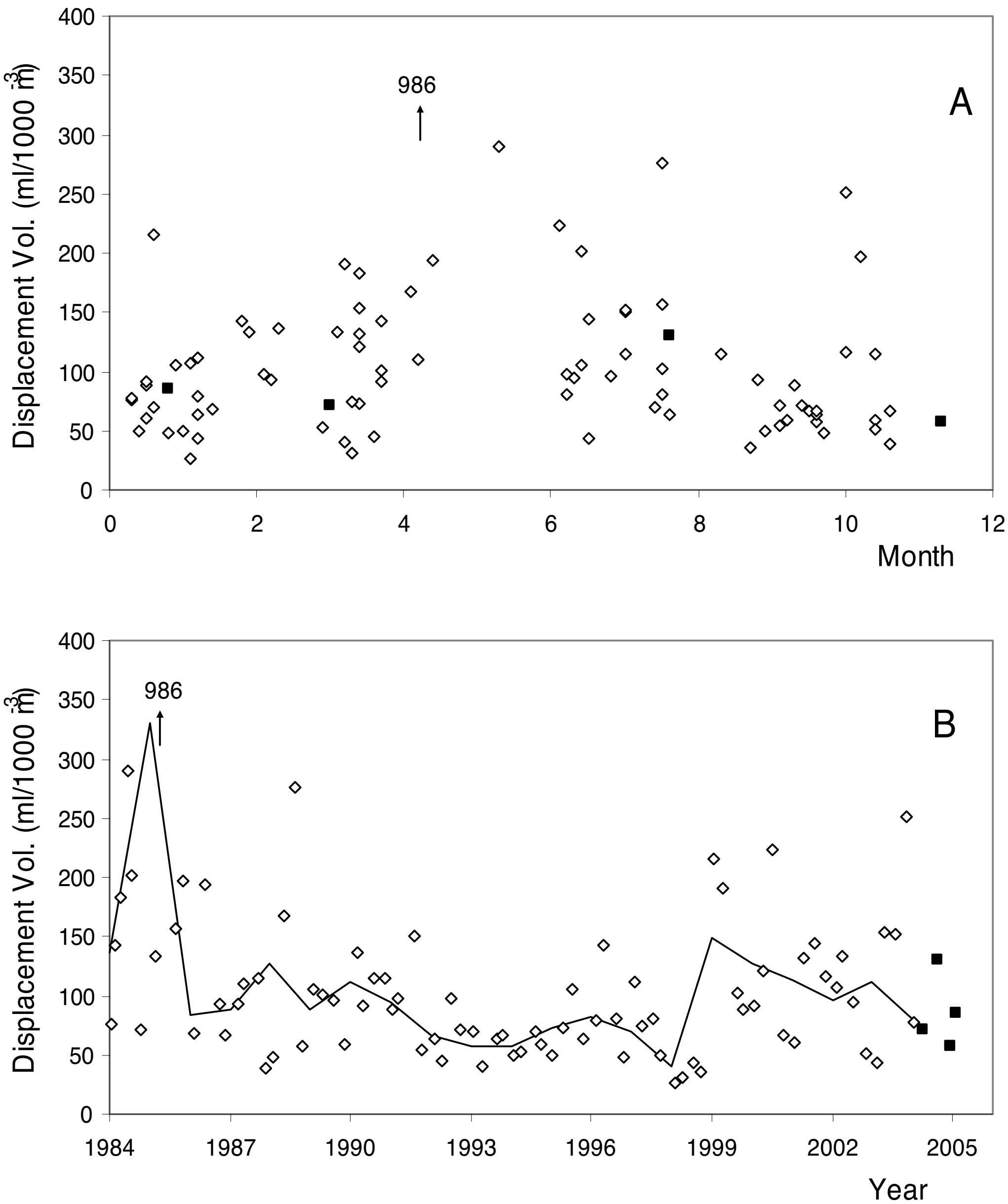


Figure 36. CalCOFI cruise mean macrozooplankton displacement volumes plotted against the month of the year (a) and the year (b). Data and symbol codes are the same as those in Figure 16.

mass has recovered from the dramatic decline of the 1990s. So far, no clear trends in zooplankton biomass since 2000 have emerged, making it difficult to relate changes in zooplankton biomass to climate indicators.

Fish Spawning

CalCOFI: In the spring of 2003, sardine, anchovy, and jack mackerel eggs were quite abundant compared to other recent spring values (fig. 37). Sardine eggs were most abundant between Santa Barbara and Monterey Bay, although they were also found along the southern and northernmost lines. Anchovy eggs, much less abundant than sardine eggs, were confined to the Southern California Bight. Jack mackerel eggs were offshore of the sardine eggs, with relatively little overlap, similar to previous years. The spatial distribution of sardine eggs in the spring of 2004 differed from previous years; very few eggs were found near and south of Point Conception. Most were found between Avila Beach and San Francisco. As the survey stopped at San Francisco, it was unclear whether the distribution of sardine eggs continued north of CalCOFI line 60. Again, in spring, 2004, anchovy eggs were found in the Southern California Bight, and jack mackerel eggs were found more offshore than anchovy eggs. Both anchovy eggs and jack mackerel eggs dominated the area south of Avila Beach. Overall, sar-

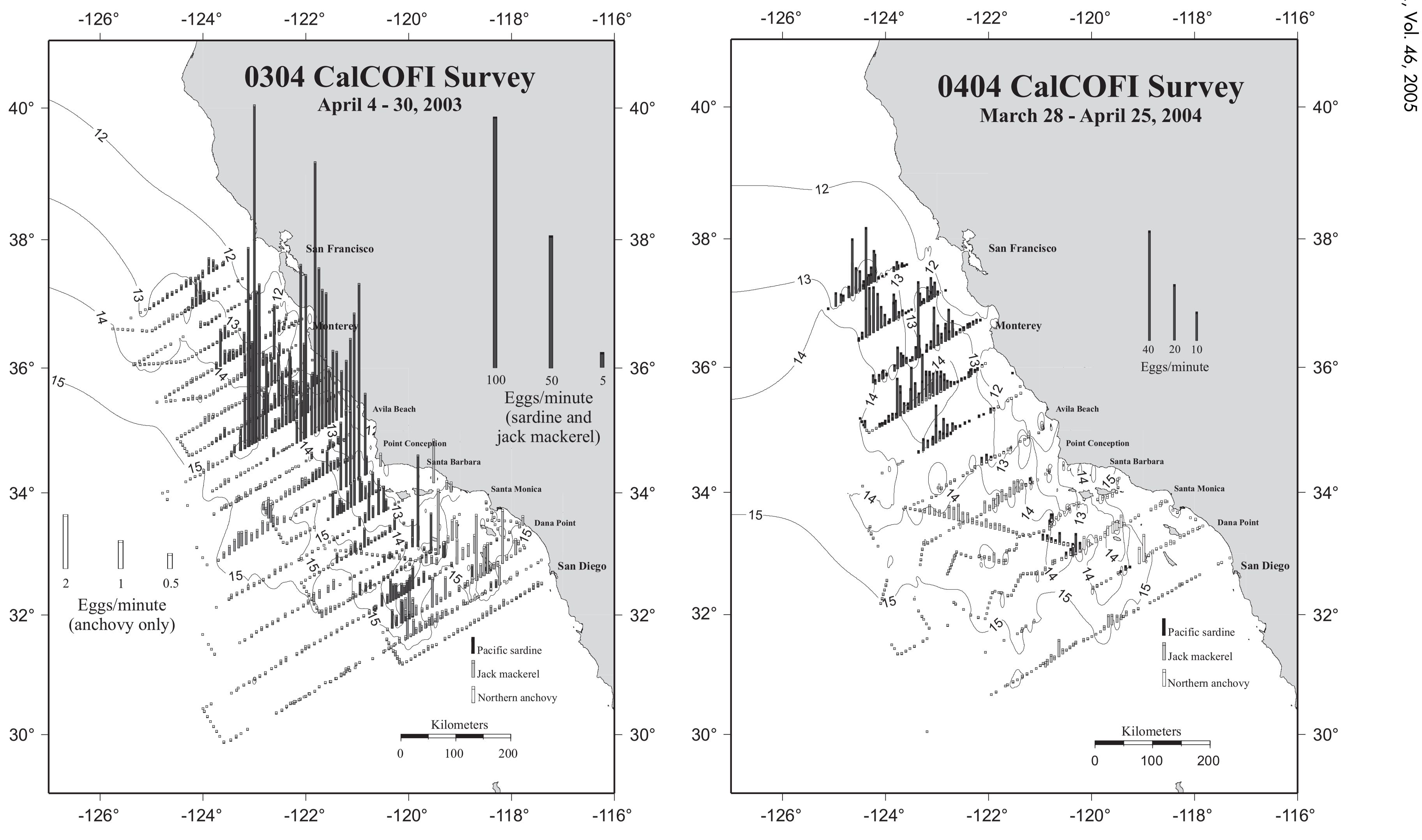


Figure 37. Rate of occurrence of eggs of Pacific sardine (*Sardinops sagax*), northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*) sampled with the continuous underway fish egg sampler (CUFES) and sea surface temperatures in March–April 2003 and April 2004. One egg per minute corresponds to approximately four eggs per cubic meter

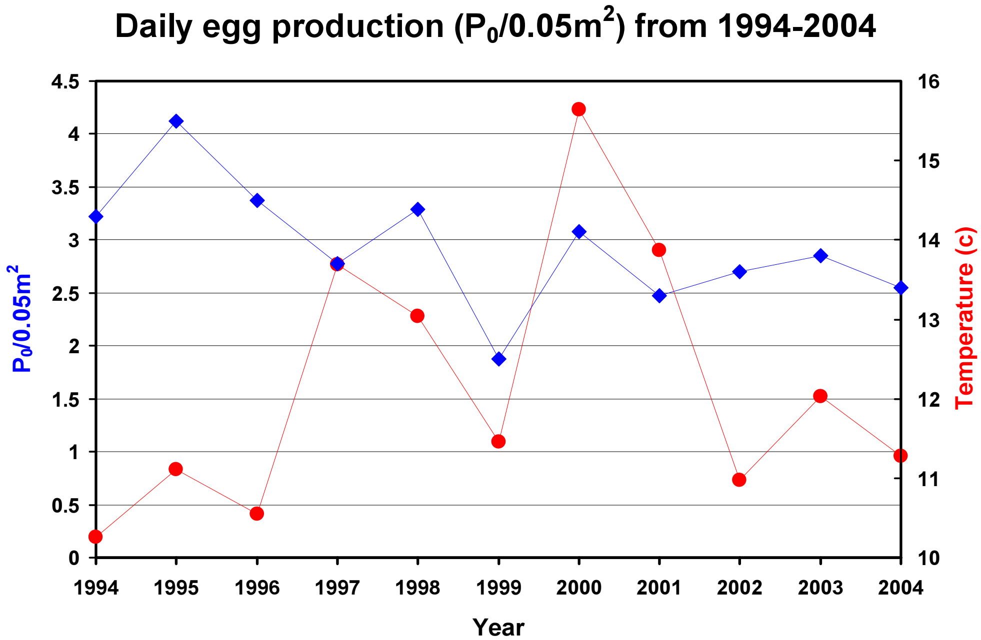


Figure 38. Daily egg production per 0.05 m^{-2} of Pacific sardine (circle) and average sea surface temperature (°C) (diamond) during March–April CalCOFI cruises from 1994–2004.

dine eggs were far more abundant than anchovy or jack mackerel eggs. Peak abundances observed in 2004 were similar to 2002 and less than 2003. During both 2002 and 2003, sardine eggs were found in the 12–14°C SST zone. In contrast, in 2004 few sardine eggs were found in the 12–14°C zone. Possible explanations for these observations are either a low spawning population or low spawning rates. Without adult samples taken in the low-density area, it is difficult to ascertain the causes of low sardine egg concentrations south of Point Conception in 2004. (For more information, see http://swfsc.nmfs.noaa.gov/FRD/CalCOFI/currentcruise/sardmaps.htm).

The spawning biomass of Pacific sardine is a fishery-independent population index, and it is useful to see how spawning was related to SST in the past years based on CalCOFI surveys. The spawning biomass of Pacific sardine is positively related to the daily egg production in particular if the number of oocytes per biomass weight remains constant (Lo et al. this volume). The relationship between the daily egg production per 0.05 m^2 and the average SST (°C) during 1994–2004 indicated that in most years the relative peaks in egg production coincided with elevated SST; exceptions are the years 1997 and 2002 (fig. 38). The observed relationship is consistent with the assertion that high temperature is favorable for the Pacific sardine (Jacobs and MacCall 1995).

Avifauna

This report focuses on spring and summer observations of marine bird populations made on CalCOFI cruises and on studies of diet and reproductive performance carried out on the Farallon Islands, which are located on the edge of the continental shelf west of San Francisco. We focus on the spring–summer period since this is a sensitive phase in the seabird seasonal cycle of breeding effort and migration (Schwing et al. 2000; Sydeman et al. 2001). Figures 39 and 40 extend past observations through 2004.

The most unusual single avifaunal event of this past year was the extremely poor breeding success of Cassin's auklet (*Ptychoramphus aleuticus*) on the Farallon Islands. There is also evidence that this species did not attempt breeding on the Channel Islands in 2004[3]. One inference is that zooplankton prey (the euphausiids *Euphausia pacifica* and *Thysanoessa spinifera*) may have been unavailable in 2004. Such reproductive failure was unprecedented since monitoring of these populations began in the mid-1980s and will be followed closely.

Our long-term objective is to characterize the response of the avifauna to the 1998 transition from a warm- to a cold-water regime (Schwing et al. 2002; Peterson and Schwing 2003; Venrick et al. 2003). To do so, we compare seabird abundance, diet, and productivity during the years 2000 to 2003 with those of 1990 to 1997. The avifauna of the CCS is influenced by northward incursions of subtropical species during warm-water periods and by the southward movement of subarctic species during cold-water periods (Hayward et al. 1999; Hyrenbach and Veit 2003; Venrick et al. 2003). To illustrate interannual and longer-term fluctuations in

[3]P. Martin, Channel Island National Park, pers. comm.

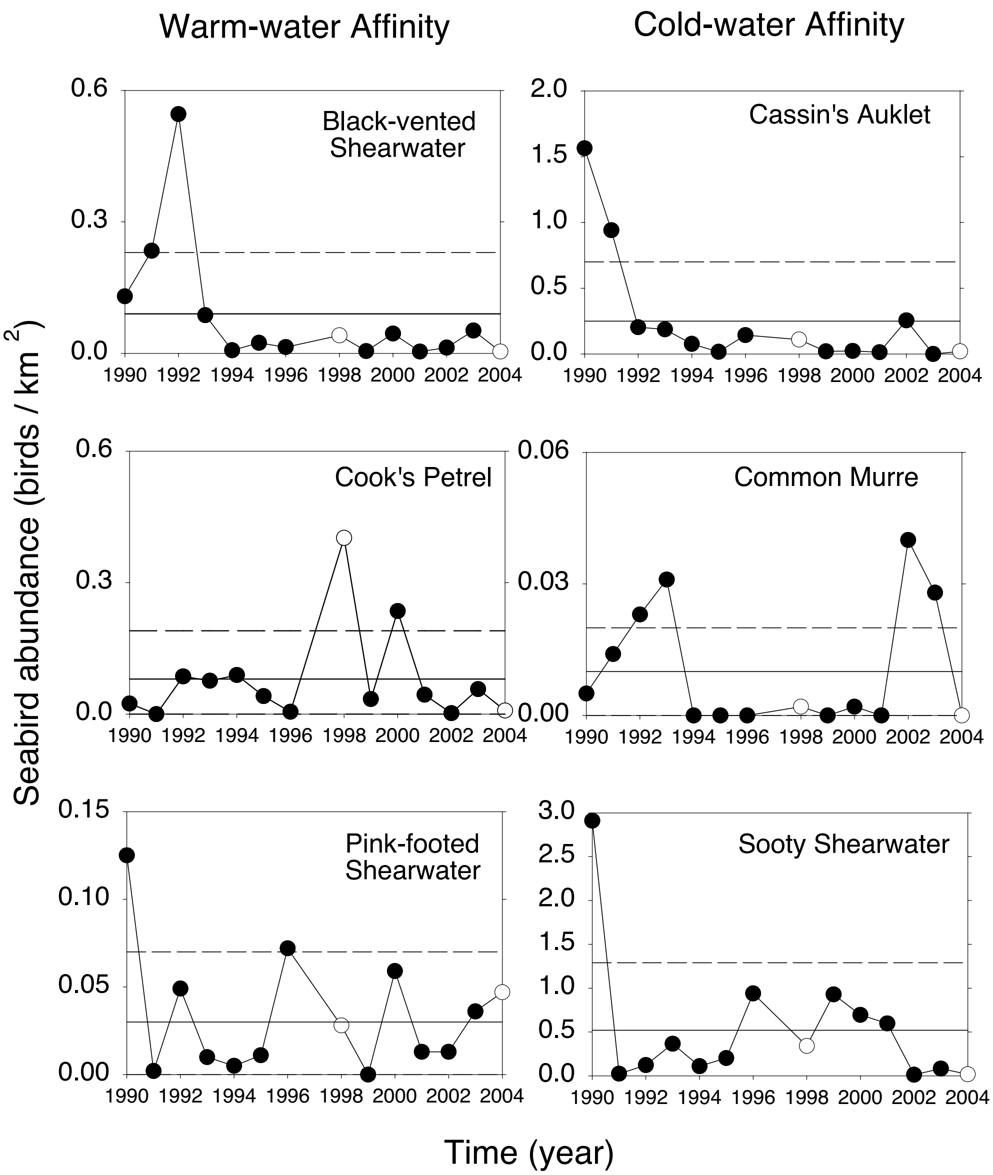


Figure 39. Anomalies of at-sea abundance of six seabird species with different water temperature affinities. The long-term averages (1990–2004) are depicted by the solid horizontal lines; the hatched lines illustrate the variability (mean ± 2 S.D.). Filled circles highlight abundance values during the base periods before (1990–97) and after (1999–2003) the regime shift during the winter of 1999. Note: there were no at-sea surveys in the spring of 1997.

the composition of marine bird communities, we focus on six indicator species with different water mass preferences and biogeographic affinities. We considered three subtropical species, which breed south of the CalCOFI study area and have an affinity for warm-water conditions. The pink-footed shearwater (*Puffinus creatopus*) occurs off southern California waters between spring and fall and becomes most numerous after El Niño events (Hyrenbach and Veit 2003). The Cook's petrel (*Pterodroma cookii*) also occurs off southern California during spring–fall and reaches the highest densities during periods of warm-water anomalies (Hayward et al. 1999). Large numbers of black-vented shearwaters (*Puffinus opisthomelas*) enter the CalCOFI study area in fall, especially during El Niño events, and remain in the area over winter and spring (Hayward et al. 1999; Hyrenbach and Veit 2003). We also considered three subarctic species with an affinity for cold-water conditions (Hyrenbach and Veit 2003). The sooty shearwater (*P. griseus*), a spring–summer–fall visitor from the southern hemisphere, and two locally breeding species: the planktivorous Cassin's auklet, and the piscivorous common murre (*Uria aalge*).

No significant temporal trends were detected for the pelagic densities of the indicator species. Only the subtropical black-vented shearwater showed a marginally significant decline of 84% (p = 0.088) between 1990–

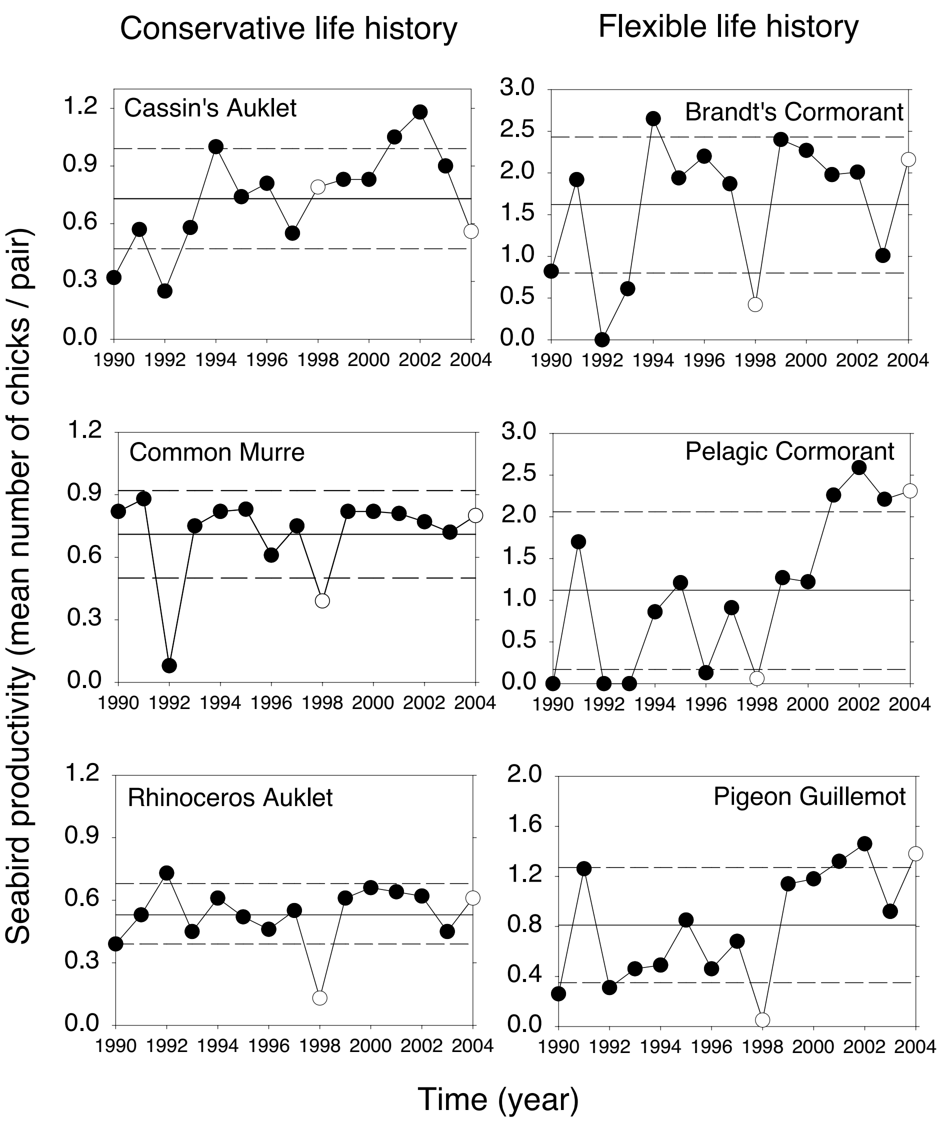


Figure 40. Anomalies of productivity for six seabird species breeding at SE Farallon Island (central California). The long-term averages (1990–2004) are depicted by the solid horizontal lines; the hatched lines illustrate the variability (mean ± 2 S.D.). Filled circles highlight abundance values during the base periods before (1990–97) and after (1999–2003) the regime shift during the winter of 1999.

TABLE 1

Comparison of the abundance of six indicator species within the CalCOFI survey grid (southern California), in conjunction with the 1998–99 regime shift. The proportional change in seabird productivity was quantified as PC = 100% * [(after) – (before)/(before)]. Positive and negative PC values are indicative of increasing and decreasing productivity respectively. For each species, the biogeographic affinity (ST: subtropical, SA: sub-arctic) and breeding status in the California Current (B: breeding, NB: non-breeding) are shown.

		Abundance (birds/km^2)				
		(mean ± SD)				
Seabird Species	Life History	(1990–97)	(1999–2003)	Proportional Change (%)	Mann-Whitney U	*p* Value
Black-vented Shearwater	NB–ST	0.15 ± 0.19	0.02 ± 0.02	–83.95	28	0.088
Pink-footed Shearwater	NB–ST	0.04 ± 0.05	0.02 ± 0.02	–37.61	18	0.935
Cook's Petrel	NB–ST	0.05 ± 0.04	0.07 ± 0.09	+62.88	16	0.808
Cassin's Auklet	B–SA	0.45 ± 0.58	0.06 ± 0.11	–86.11	27	0.123
Common Murre	B–SA	0.01 ± 0.01	0.01 ± 0.02	+34.88	16	0.801
Sooty Shearwater	NB–SA	0.67 ± 1.04	0.46 ± 0.40	–30.63	19	0.808

TABLE 2
Comparison of the productivity of six seabird species breeding at the Farallon Islands (central California), in conjunction with the 1998–99 regime shift. The proportional change in seabird productivity was quantified as PC = 100% * [(after) – (before)/(before)]. Positive and negative PC values are indicative of increasing and decreasing productivity respectively. Bold font denote statistical significance at the alpha = 0.05 level. For each species, the reproductive strategy (F: flexible, C: conservative) and the diet (P: piscivore, Z: zooplanktivore) are shown.

	Productivity (chicks fledged/pair)					
		(mean ± SD)				
Seabird Species	Life History	(1990–97)	(1999–2003)	Proportional Change (%)	Mann-Whitney U	*p* Value
Brandt's Cormorant	F–P	1.50 ± 0.91	1.93 ± 0.55	+28.83	17	0.463
Pelagic Cormorant	F–P	0.60 ± 0.66	1.91 ± 0.62	+217.67	2	**0.006**
Pigeon Guillemot	F–P	0.60 ± 0.33	1.20 ± 0.20	+101.93	3	**0.009**
Cassin's Auklet	C–Z	0.60 ± 0.25	0.96 ± 0.15	+59.00	8.5	0.062
Common Murre	C–P	0.69 ± 0.26	0.79 ± 0.04	+13.79	25.5	0.686
Rhinoceros Auklet	C–P	0.53 ± 0.11	0.60 ± 0.08	+12.45	12.5	0.180

97 and 1999–2003 (tab. 1). This warm-water indicator occurred in large numbers off southern California during 1990–93, during a protracted warm-water period (Chavez 1996; Trenberth and Hoar 1997), and declined thereafter (tab. 1). The two other warm-water indicators (Cook's petrel and pink-footed shearwater) varied substantially from year to year and did not show a consistent response to the 1998–99 regime shift (tab. 1). Cook's petrel occurred at "average" levels during the 1992–95 warm-water period and was most numerous during the 1997–98 El Niño (fig. 39). The abundance of the pink-footed shearwater has increased significantly in the CalCOFI study area over the long-term when all four seasons are considered (1987–98) (Hyrenbach and Veit 2003), but its spring-time abundance was highly variable and the decline after the 1998–99 regime shift was not statistically significant (tab. 1).

Nor did the at-sea densities of the three cold-water indicators show a significant response to the 1998–99 regime shift (tab. 1). Sooty shearwater numbers declined from a maximum in 1990, remained low during the protracted 1992–95 warm-water period, and rebounded slightly during 1996–97 and 1999–2001 (fig. 39). When all seasons are considered, however, this species has declined significantly over the long-term (1987–98) (Hyrenbach and Veit 2003). Likewise, the Cassin's auklet declined by an order of magnitude early on and remained at low densities after 1992, rebounding only slightly in 2002 after the onset of cold-water conditions. The common murre showed a different response, with anomalously high densities at the beginning (1992–93) and the end (2002–03) of the time series. The murre was present in very low average densities (<0.01 birds km^{-2}) during spring-time cruises, both before and after the 1998–99 regime shift (tab 1). However, population-level responses of auklets and murres to changes in environmental conditions and reproductive success occur with a three- to five-year lag, due to the age of reproductive maturity in these species (Pyle 2001)[4], so it may still be premature to expect their pelagic abundances to clearly reflect a regime shift.

Because seabird reproductive success depends directly upon oceanographic conditions and prey availability during breeding season, we expect an immediate response of seabird productivity to recent oceanographic changes (Sydeman et al. 2001). The productivity of marine bird populations breeding at the Farallon Island (fig. 40) increased during 1999–2002 (Venrick et al. 2003). After declines in most species during the 2003 El Niño (Goericke et al. 2004), most species—except the planktivorous Cassin's auklet—returned to high productivity levels in 2004. Over the long-term, we documented statistically significant changes in productivity for two of the six species monitored (tab. 2). These two are piscivores; one is neritic and one benthic (pelagic cormorant and pigeon guillemot). They more than doubled their productivity after the 1998–99 regime shift (tab. 2). The Brandt's cormorant, whose productivity can be decoupled from that of the other piscivores (Sydeman et al. 2001), did not experience a long-term increase in productivity. The increased productivity of the three locally-breeding species with more conservative life histories (one-egg clutches) was not significant (tab. 2).

The enhanced productivity of locally-breeding piscivores (pelagic cormorant and the pigeon guillemot) has taken place during a return of juvenile rockfish (*Sebastes* spp.) as a major prey constituent for seabirds (Miller and Sydeman 2004). After a period of very low average (0.15 + 0.12% S.D.) rockfish in the murre chick diet (1990–2000), this item increased substantially to over half of the diet (0.58 + 0.14% S.D.) during the last few years (2001–03). These values are comparable to those observed between 1973 and 1989 in the CCS (0.63 + 0.2 % S.D.) (fig. 41).

[4]Point Reyes Bird Observatory, unpub. data.

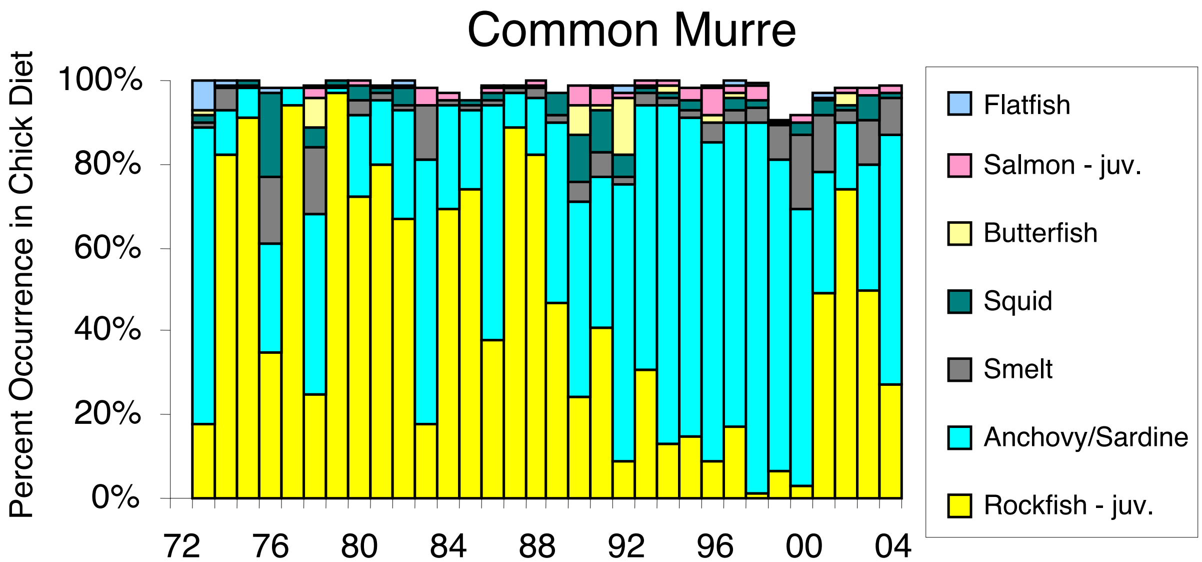


Figure 41. Inter-annual diet composition of common murre chicks at SE Farallon Island (central California, 1973–2004), based on the number of prey items of each species consumed. Other dietary items include Pacific butterfish (*Peprilus simillimus*), juvenile salmon (*Oncorhynchus* spp.), flatfishes (*Bothidae* and *Pleuronectidae*) juvenile lingcod (*Ophiodon elongatus*), señorita (*Oxyjulis californica*), and other fish species comprising less than 5% of the diet in any year.

DISCUSSION

The focus of this discussion is the state of the California Current System (CCS) in relation to leading indicators of climate and the effect of the subarctic water on the system. The weak tropical El Niño of 2004 did not appear to have a noticeable effect on the CCS. Hydrographic effects failed to propagate to the coast of South America. Unrecognized effects via atmospheric teleconnections can not be ruled out; some of the recent warm SST anomalies may have been associated with atmospheric anomalies related to the tropics. However, variations of physical or biological indicators—mixed layer depths, temperature anomalies, biomass of zooplankton or avifauna—over the last year do not suggest that these were forced by an ENSO event (see also Goericke et al. 2004).

The Evolution and Effects of the Subarctic Influence

One of the more unusual phenomena over the past few years was the large-scale intrusion of cold and fresh (minty) subarctic water into the CCS. This was first noticed off British Columbia and Oregon (Freeland et al. 2003), but quickly spread further south (Venrick et al. 2003; Goericke et al. 2004; Durazo et al. 2005). Off Oregon it appeared to wane over the last year—salinity anomalies in the upper thermocline were returning to normal. In contrast, in the CalCOFI and IMECOCAL region 2004 salinity anomalies continued strong (figs. 16, 17). The intrusion of the minty water into the CalCOFI region and the associated uplift of the seasonal thermocline in the offshore areas (figs. 17, 27) had a significant effect on the location of the chlorophyll maximum in the offshore areas (fig. 32). It remains to be seen if the strong silicate anomaly off southern California (fig. 28c) is related to the intrusion of the subarctic water. Historical hydrographic data from CalCOFI suggest that alternating periods of cool-fresh and warm-salty waters have affected the CCS in the past, although the recent anomalies are the strongest on record. Broad changes in the gyre-scale circulation in the northeast Pacific, possibly related to regime-scale variability, could lead to increased transport of subarctic waters into—and enhanced equatorward transport within—the CC.

The Evolution of the Post-1998 Cold Phase

The change in the sign of the PDO after the El Niño of 1998 was dramatic. Even though current climatologies no longer support the characterization of the state of the North Pacific as a negative PDO phase, patterns of SST in the CCS support the contention that the system is still in a slightly cool phase (figs. 12, 15). Biological properties also suggest that at least some regions underwent significant changes in 1998 and have remained in this new state. These include copepod biomass and community species richness off Oregon (fig. 33, 35), chlorophyll-*a* in Monterey Bay (fig. 12), and zooplankton biomass in the CalCOFI region (fig. 36). Other properties, however, appear unaffected by changes in ocean climate indices. For example, annually-averaged chlorophyll-*a* in the CalCOFI region appears to have increased since the 1980s but defies more detailed analysis due to the large variability in the data. Similarly, daily egg production of the Pacific sardine (fig. 38) did not appear to respond to the 1998 regime shift.

Avifaunal evidence for a long-term switch to cold-water conditions in 1999 is mixed. The colony-based data revealed an increase of piscivore productivity in 2004 after a decline in 2003, continuing a trend observed during the previous four cold-years (1999–2002) (Schwing et al. 2002). Even though this demographic response is statistically significant for only two of the six species monitored at the Farallon Islands, this result suggests that breeding seabird populations continue to benefit from the transition into a cold-water regime of enhanced upwelling and prey availability. The Farallon Island productivity data suggest the possibility of a subsequent increase in the abundance of avifauna at-sea, but this did not occur. The pelagic abundances of both cold-water and warm-water indicators showed changes, but there were no significant trends indicative of a regime shift to cold water conditions after 1998–99 (tab. 1). Indeed, changes were inconsistent with the environmental affinities, with one warm-water species increasing in recent abundance and one cold-water species decreasing.

In summary, it appears that the CCS is currently in a cold phase, but many biological parameters and some physical parameters did not respond consistently to this change in phase that occurred in 1998. This suggests that the forcing of the system associated with this change in phase was weak and was in many instances overpowered by other forcing occurring on interannual scales, i.e. ENSO cycles, variations in the transport of the CC, etc. As a consequence, we will not speculate on the evolution of the system during the coming year.

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These reports would be impossible without the dedicated work of the ship crews and the technical groups that collect and process the data, often under adverse conditions.

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