THE STATE OF THE CALIFORNIA CURRENT, 2007–2008: LA NIÑA CONDITIONS AND THEIR EFFECTS ON THE ECOSYSTEM

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ABSTRACT

The state of the California Current system (CCS) between Oregon and Baja California is summarized in this report, covering spring of 2007 to winter/spring 2008. The 2006–07 period began with moderate El Niño conditions which decayed rapidly in early 2007. By summer 2007, a moderate-to-strong La Niña had developed. The North Pacific sea surface temperature (SST) anomalies displayed a negative pattern of Pacific Decadal Oscillation with below-normal SSTs in the California Current and Gulf of Alaska consistent with this pattern. The region experienced anomalously strong southward coastal winds, leading to positive anomalies of the West Coast upwelling index, in strong contrast with 2005. The 2007 upwelling season also began early (in contrast to delayed onset in 2005 and 2006) and remained unseasonably strong through May. The cumulative upwelling for the 2007 season was greater than normal in the southern portion of the California Current system. Despite the La Niña conditions, nitrate and chlorophyll concentrations off Oregon were about average in 2007. On the other hand, copepod biomass rebounded strongly in 2006 after the exceptionally low biomass in 2005, and copepod species richness in 2006 was low, also indicating transport of sub-arctic water into the northern California Current in 2006–07, which is relatively productive but low in diversity.

Anomalously high salinities at 200 m depth were also observed during CalCOFI and IMECOCAL cruises off southern and Baja California. In the CalCOFI area, where there has been a general trend toward a deepening mixed layer, the mixed layer responded to this year's La Niña conditions by shoaling. Nitrate (but not silicate and phosphate) concentrations in the mixed layer were anomalously high, but chlorophyll concentrations were about average, except for spring 2007, which was one of the lowest values on record. Spring chlorophyll *a* concentrations are notably variable during La Niñas. In the northern California Current, forage fish and predatory fish abundance remained low in 2007. In the southern California Current, Pacific sardine (*Sardinops sagax*) larval abundance was relatively high and distributed in relation to the inner edge of the California Current and the edge of an eddy. Northern anchovy (*Engraulis mordax*) larvae were relatively low in abundance, apparently related to a large downwelling feature. Reproductive success of all six seabirds monitored on Farallon Island was recovering slowly this year, following the previous two disastrous seasons. However, cluster analysis indicated that reproductive success is still relatively low. The cold-water planktivorous auklets (*Ptychoramphus aleuticus*) continued to be found at high densities in southern waters.

Overall, the transition in 2007 to La Niña conditions appeared to contribute to average to above average pro-

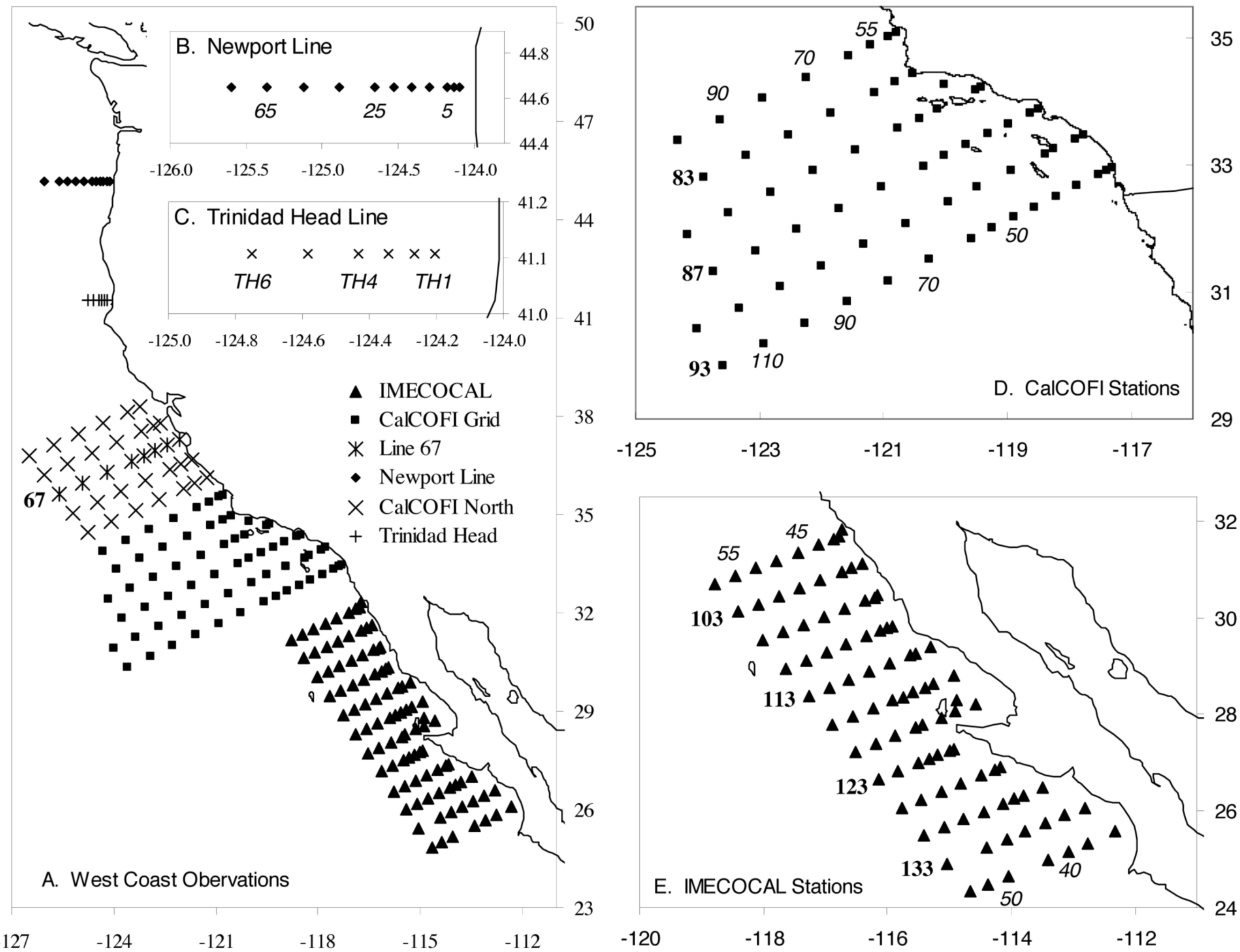

Figure 1. Location of stations where observations were made for this year's report. Observational lines are labeled using bold numbers positioned west of the line terminus; stations are labeled using numbers in italics immediately below or above the respective stations. Line and station numbers for the IMECOCAL and CalCOFI programs are following the CalCOFI line and station nomenclature. The IMECOCAL program covers all lines out to station 60, i.e., the westernmost station on any IMECOCAL line is 60. The CalCOFI program is covering lines 93 and 90 out to station 120, lines 87 and 83 to station 110 and lines 80 and 77 to lines 100. The Newport Line station names designate distance (nm) from shore. The 66 standard CalCOFI stations (black squares in A) are occupied on all cruises, weather permitting. During the winter and spring cruises the pattern is extended north for observations of hydrographic properties and distributions of fish eggs and larvae (crosses). The Monterey Bay Aquarium Research Institute monitors conditions in Monterey Bay triweekly and, with the Naval Postgraduate School and UCSC, occupies CaCOFI lines 67 and 60 westward to station 90 quarterly. The Newport line is covered biweekly out to St. 25 and occasionally farther offshore. The Trinidad Head line is covered monthly. The Newport line is covered biweekly out to St. 25 and occasionally farther offshore.

ductivity in the California Current, but the physical, chemical, and biological (phytoplankton, zooplankton, fish, and seabird) indices of productivity were far from consistent.

INTRODUCTION

This report summarizes the climatology, oceanography, and biology of the California Current system (CCS) between the spring of 2007 and the spring of 2008. It is based on observations taken between Oregon and Baja California. Participating programs or institutions include the NOAA Fisheries Pacific Fisheries Environmental Laboratory (PFEL) providing basin- and coast-wide climatologies, the NOAA Fisheries Stock Assessment Improvement Program working off Oregon, the Point Reyes Bird Observatory (PRBO) studying seabirds 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, and a collaborative effort between the NOAA Fisheries Southwest Fishery Science Center Fisheries Ecology Division and Humboldt State University to collect ocean observations off northern California. The stations regularly occupied by these programs are shown in Figure 1. The objective of this report is to describe the state of the CCS over the last year, to compare this to long-term conditions, and to relate changes of the state of the ecosystem to forcing by climate. In a report of this nature it is not possible to provide all substantiating data for each statement, and the reader is encouraged to seek more detailed analyses in other more narrowly focused publications.

Over the last decade the north Pacific Ocean has been in a cool phase characterized by negative or neutral values of the Pacific Decadal Oscillation (PDO) index and associated large negative sea surface temperature (SST) anomalies throughout the California Current system. The ecosystem responded to this forcing (Bograd et al. 2000; Peterson and Schwing 2003) with increased zooplankton production and, at times, dramatic shifts in community structure (Brinton and Townsend 2003; Lavaniegos and Ohman 2003). A weak equatorial El Niño/Southern Oscillation (ENSO) event in 2002–03 had only small effects on the California Current system (Venrick et al. 2003). Over the last four years regional or local forcing dominated hydrographic properties and the ecosystem's response. Notable events during this time period were the late onset of upwelling off Oregon and central California in 2005 and 2006 (Petersen et al. 2006; Goericke et al. 2007), with dramatic consequences for the ecosystem, e.g., the almost zero reproductive success of some seabird species on the Farallon Islands (Sydeman et al. 2006; Goericke et al. 2007). The intrusion of cold and fresh waters into the upper 200 m of the CCS, which lasted from 2003 to 2007, had dramatic effects on nutrients and concentrations of chlorophyll *a* off Oregon but only moderate effects on hydrographic properties and negligible effects on the ecosystem off southern California and Baja California (Venrick et al. 2003).

It is important to determine to what extent the CCS is affected by global climate change. Even though it is in most cases not possible to attribute regional long-term changes, such as changes of SST or changes of deep hydrographic properties in the different areas (e.g., the CalCOFI study region, Goericke et al. 2007) to global climate changes, disproving this hypothesis is equally difficult. Nevertheless, we need to view data with global climate change in mind and ask how changes in key system variables—temperature, nutrient supply rates, atmospheric forcing—will affect ecosystem structure and function.

During the time this report covers, i.e., the year 2007 and the winter and spring of 2008, the north Pacific Ocean experienced strong La Niña conditions that dominated forcing throughout the CCS (see below). This report will focus on describing the response of the CCS to this forcing. In particular we will discuss how the ecosystem responded to the cooling of the surface ocean during this period and contrast it with other similar events, the 1988–89 La Niña that occurred during a period of positive PDO index values, and the extended 1999–2000 La Niña that coincided with the transition of the CCS into a cold phase.

DATA SETS AND METHODS

Large-Scale 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° x 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 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.

Regional Analyses—Oregon

Regular sampling of the Newport Hydrographic (NH) line along 44.65°N continues on a biweekly basis along the inner portions of the line, at seven stations ranging from 1 to 25 nautical miles from shore. Methods and measurements are the same as listed in last year's report (Peterson et al. 2006).

Since 1998, pelagic forage and predatory fish have been sampled every ten nights from mid-April through mid-July. Four stations are occupied along each of two transects off the Columbia River and southern Washington. At each station, a 30 minute pelagic rope trawl is towed between the surface and 20 m. Additional details may be found in last year's report.

Regional Analyses—Northern California

An ocean observing effort has been recently established by NOAA's National Marine Fisheries Service (NMFS) in cooperation with Humboldt State University. Data are collected at roughly monthly intervals along the Trinidad Head line (41°31.5'N), which consists of six stations along a transect extending approximately 50 km due west from Trinidad Head (fig. 1). At each station, a conductivity-temperature-depth (CTD) cast to 150 m (or as limited by bathymetry) is performed to collect data on temperature (T), salinity (S), dissolved oxygen, fluorescence, and transmissivity. Plankton are sampled by (1) an oblique tow from a maximum of 100 m depth with a 70 cm bongo frame fitted with dyed 505 µm and 335 µm mesh nets, and (2) a vertical haul of a PairoVET frame, fitted with 153 µm mesh from a maximum depth of 70 m. Flow-through instruments are used to sample near-surface T, S, fluorescence, and turbidity continuously along the ship's track. Since November 2007, all operations have been conducted at night.

Regional Analyses—Central California

CTD sections extending offshore from Monterey Bay to a distance of 315 km (CalCOFI Line 67) have been carried out quarterly since 1997. CTD station spacing is 10 nm and the water column is sampled to a depth of 1000 m.

Regional Analyses—CalCOFI

Results are presented as contour maps of properties, and as time series of cruise averages over all 66 stations or as anomalies with respect to the 1984–2007 time series. The mixed-layer (ML) depth is calculated using a density criterion and set either to 12 m or to the halfway point between the two sampling depths where the sigma-theta gradient first reaches values larger than 0.002/m, whichever is larger. The 12 m cutoff avoids including the diurnal thermocline in the analysis. This procedure will introduce a positive bias in calculation of the ML depth but, because the bias is consistent, it will not affect the interpretation of patterns. The nitracline depth is defined as the depth where concentrations of nitrate reach values of 1 μM, calculated from measurements at discrete depths using linear interpolation. Mesozooplankton displacement volumes for individual stations were log-transformed and then averaged over all stations.

Regional Analyses—IMECOCAL

The IMECOCAL monitoring program began in autumn 1997, consisting of quarterly cruises surveying 93 stations off Baja California, México (fig. 1). 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 L Niskin bottles at 0, 10, 20, 50, 100, 150, and 200 m depths to determine dissolved oxygen, chlorophyll *a*, nutrients (NO_3, NO_2, PO_4, SiO_3), and primary production. IMECOCAL cruises schedules, data collection, methods, and analysis are fully described at http://imecocal.cicese.mx.

Remote Sensing

We used satellite-detected monthly mean composite of chlorophyll *a* concentration as a proxy for phytoplankton concentration. While ocean color measurements of chlorophyll *a* in coastal waters are affected by interference from other optically active substances, such as detrital material, dissolved organic substances, and suspended sediments, and some blooms are missed by satellite sensors due to cloud cover, the monthly mean composite of chlorophyll *a* is a robust index of water quality and corresponds to the combined effects of chlorophyll *a* and other optically active substances. We use our archive of full resolution chlorophyll *a* data merged from all available ocean color sensors (http://spg.ucsd.edu/Satellite_Projects/Full_res_sat_time_series_California/Full_res_sat_time_series_California.htm) to find the annual maximum monthly chlorophyll *a* for each pixel. We interpret the time series of the annual maxima as a change in bloom magnitude. We then used the Sen slope estimator to detect trends and their significance in bloom magnitude.

Fish Egg Surveys off California

The planned 2007 survey consisted of three legs: Leg 1, the regular CalCOFI survey, and Legs 2 and 3, the daily egg production method (DEPM) survey. Leg 1 (27 March–12 April) was to occupy six CalCOFI lines (93.3–76.7). Leg 2 (13–20 April) was to occupy six lines northward from line 91.7 out to station 70. Leg 3 (20 April–1 May) was to occupy four CalCOFI lines (73.3–63.3) off central California. Due to equipment problems and weather conditions, Leg 1 ended on 19 April with five CalCOFI lines from 93.3 to 80.0 occupied. Leg 2 from 19–23 April covered three lines from line 91.7 out to station 70 and ended at Port San Luis. Leg 3, from 23 April–1 May, occupied three lines: 76.7, 66.7, and 63.3 due to weather conditions. Thus, the RV *David Starr Jordan* cruise (27 March–1 May) occupied 11 lines (93.3–63.3) out of 17 planned lines; lines were 37 or 74 km apart (fig. 1). Bongo samples were taken at all CalCOFI stations except line 63.3. During Leg 1, CalVET tows were taken only at regular CalCOFI survey stations. During Legs 2 and 3, CalVET tows were taken at 7.4 km intervals on each line after the egg density from each of two consecutive CUFES samples exceeded 1 egg/min and CalVET tows were stopped after the egg density from each of two consecutive continuous underway fish egg sampler (CUFES) samples was less than 1 egg/min (Lo et al. 2005).

Ichthyoplankton and Oceanography

We related hydrographic features observed in data collected on the spring 2007 CalCOFI cruise to the spatial pattern in larval fish and squid. We described the spatial pattern of larval Pacific sardine, northern anchovy, and squid (*Loligo opalescens*), and small zooplankton displacement volume in terms of the spring 2007 anomaly from the median value at each station sampled during March through May from 1985 to 2007. We used the median anomaly because the distribution of larvae is highly right-skewed. Larval distributions were contoured using kriging with covariance parameters for the variance and range determined by fitting semi-variogram models to the spring 2007 anomalies. Although there was considerable anisotropy in the variograms, we used the values from the omnidirectional models because the along-transect direction contained the most data and dominated the omnidirectional model. Sardine variograms were fit by an exponential model, the zooplankton were fit to a linear model, but both the anchovy and squid presented non-classical patterns due to their extreme patchiness.

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–Conservation Science (PRBO) conducted at-sea surveys during 2006. 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).

To investigate the responses of planktivorous auklets to inter-annual oceanographic variability in the CCS, we related local colony-based (reproductive success) and at-sea (summer abundance) responses to five monthly environmental data sets indicative of oceanographic conditions in the eastern north Pacific Ocean: large-scale variability associated with the Pacific Decadal Oscillation (PDO) and the El Niño/Southern Oscillation Index (ENSO) indices, and regional indices of coastal upwelling at three reference sites (39°N, 36°N, 33°N), to provide complete spatial coverage of the study area. Because previous studies of the diet and productivity of seabird species breeding at southeast Farallon Island have documented lagged responses to local (e.g., upwelling intensity) and remote (e.g., ENSO variability) oceanographic conditions (Ainley et al. 1993, 1995), we included antecedent environmental conditions as explanatory variables in our analysis. To account for the time lags between changes in basin-wide/regional oceanographic conditions and local seabird responses, we considered three distinct time periods: late winter (January–February); early spring (March–April); and late spring (May–June). We used Systat 11.0 (© 2002 SYSTAT Software Inc.) to examine the relationship between the abundance and productivity of planktivorous auklets and 15 environmental variables using Principal Component analysis (PCA).

LARGE-SCALE PATTERNS

Moderate El Niño conditions in the tropical Pacific Ocean decayed rapidly in early 2007 to generally neutral conditions by early spring. A moderate-to-strong La Niña (NOAA CPC Climate Diagnostics Bulletin) developed during the late summer (fig. 2) and sea surface temperature (SST) anomalies in the tropical Pacific Ocean east of the Date Line exceeded –2°C by fall 2007 (fig. 3B). The NOAA CPC Oceanic NINO Index (ONI) during Dec–Jan–Feb 2008 indicates that the La Niña was the strongest since 2000, while the multivariate ENSO index (MEI) (Wolter and Timlin, 1998) was the lowest Jan-Feb MEI value since 1976 (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/). SST anomalies displayed the typical horseshoe pattern of La Niña through fall/winter 2007, continuing into early 2008 (fig. 3C, D). This pattern included below-normal SSTs in the California Current and Gulf of Alaska, and strong above-normal SSTs north of the Bering Strait.

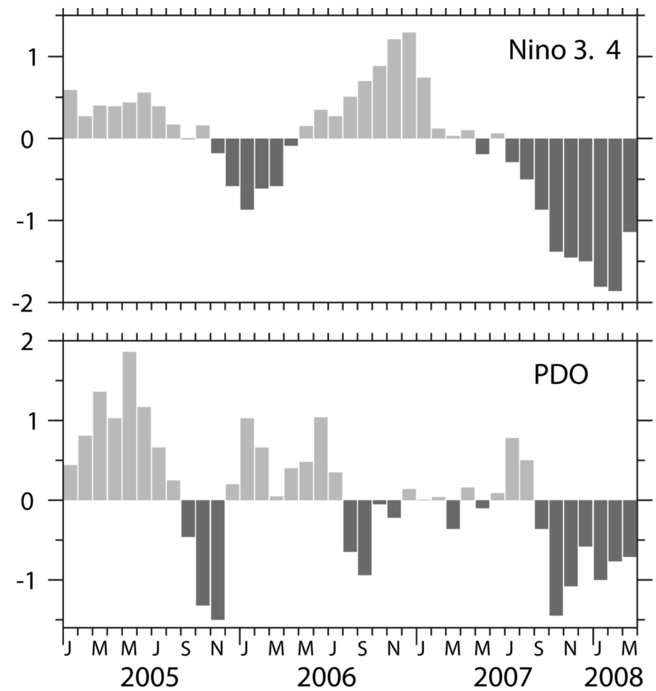

Figure 2. Time series of monthly anomalies of Niño 3.4 (top) and the Pacific Decadal Oscillation index (bottom) for January 2005 to March 2008.

During the same period, the north Pacific Ocean SST anomalies displayed a negative pattern of Pacific Decadal Oscillation (fig. 2) with below-normal SSTs in the California Current and Gulf of Alaska (fig. 3C, D). The positive SST anomalies that have occurred each boreal summer since 2002 north of the Bering Strait reached the highest value of about 2.5°C in 2007. The associated global ocean was much cooler than in 2006, especially in the equatorial Pacific Ocean, northeast Pacific and north Atlantic Ocean, but much warmer in the Arctic. Details on month-to-month and interannual global ocean climate variability can be found at CPC's "Monthly Ocean Briefing" archive (http://www.cpc.ncep.noaa.gov/products/GODAS).

The current La Niña was preconditioned with neg-

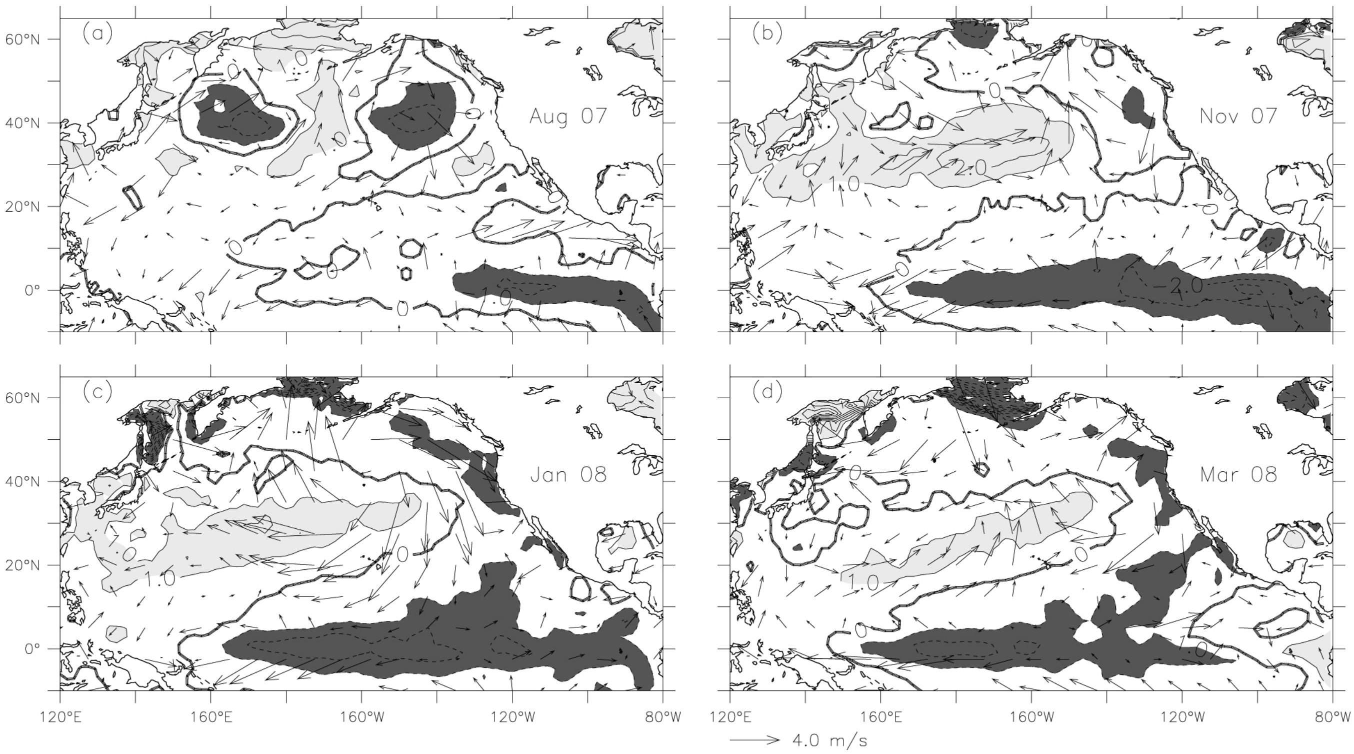

Figure 3. Anomalies of surface wind velocity and sea surface temperature (SST) in the north Pacific Ocean, for (A) August 2007, (B) November 2007, (C) January 2008, and (D) March 2008. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative (cool) SST anomalies are shaded. Wind climatology period is 1968–96. SST climatology period is 1950–79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

ative ocean heat content anomalies in the equatorial eastern Pacific Ocean in spring 2007. When seasonal trade winds intensified in summer 2007, negative subsurface temperature anomalies shoaled to the surface through entrainment at the bottom of the mixed layer, and were then advected westward. Negative SST anomalies first appeared in the far eastern equatorial Pacific and were then displaced westward. La Niña peaked during January–February 2008, and then weakened substantially during March 2008, coincident with a significant reduction of ocean heat content anomalies. The upward trend of the negative SST anomalies near the west coast of South America since mid-December 2007 was related to the westward expansion of westerly wind anomalies in the far eastern Pacific. Recent strengthening of the westerly wind anomalies pushed SSTs off South America to +1°C in March 2008. This westward expansion of negative SST anomalies and development of positive SST anomalies in the eastern Pacific also occurred during the 1999–2000 La Niña.

While the overall circulation in the Pacific in recent months was typical of La Niña, the pattern has been modulated by considerable intraseasonal Madden-Julian Oscillation (MJO) activity, which is characterized by 30–60 day variability in the tropics. Intraseasonal activity was evident in the northeast Pacific throughout much of 2007, with moderate-to-strong MJO activity from November to mid-February 2008 influencing, at times, the region through atmospheric teleconnections. This is illustrated by considerable month-to-month variability on sub-ocean basin scales (fig. 3). Month-to-month SST anomaly changes in the north Pacific have been controlled locally by a combination of surface air-sea heat fluxes and Ekman transport and pumping (open ocean upwelling).

MJO-related winds can significantly affect surface and subsurface conditions across the tropical Pacific. Strong easterly wind anomalies associated with the mid-December 2006 MJO episode led to an oceanic upwelling Kelvin wave that reduced positive ocean heat content anomalies and contributed significantly to the demise of the 2006 El Niño. In early summer 2007, MJO-related westerly wind bursts in the western tropical Pacific reduced negative heat content anomalies. Moderate-to-strong MJO activity from November to mid-February 2008 forced a series of Kelvin waves. The downwelling Kelvin wave episode initiated in January 2008 led to a propagation of positive heat content anomalies across the tropical Pacific, and contributed to a sudden weakening of the La Niña in March 2008. The MJO role in the concurrent warming near the west coast of South America is the subject of further analysis.

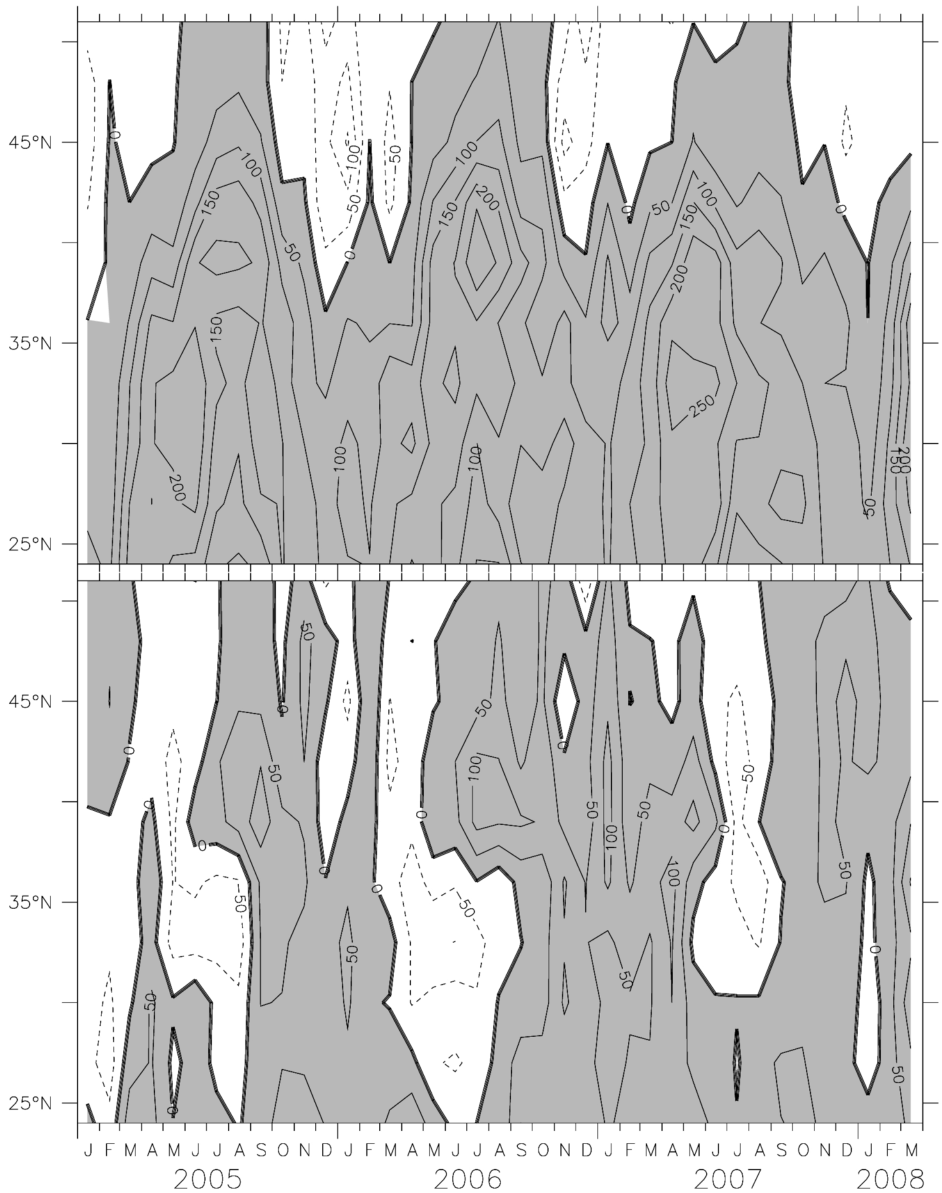

Figure 4. Monthly coastal upwelling index (top) and coastal upwelling index anomaly (bottom) for January 2005–March 2008. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m³/s per 100 km of coastline.

The effect of this large-scale pattern on the California Current has been anomalously strong southward coastal winds and stronger than normal coastal upwelling along the West Coast (fig. 4) for most of the year. Strong anticyclonic (clockwise) wind anomalies near the western coast of North America favored coastal upwelling and reduced SST. With the exception of a brief period of negative anomaly (weaker than normal upwelling) in summer 2007, West Coast upwelling index anomalies have been positive since late summer 2006. Wind anomaly patterns in early 2008 reflect anomalously strong high pressure over the northeast Pacific (fig. 3C, D) and very high upwelling (fig. 4). The frequency of relaxation events was higher in summer 2007, roughly 2–4 weeks compared to monthly in most years (fig. 6). This may have influenced recruitment of nearshore species (cf. Farrell et al. 1991). These unusual regional conditions since summer 2007 have occurred during a period of tropical La Niña and negative PDO (fig. 2), both of which are typically associated with an unseasonably cool California Current.

The delayed onset of seasonal upwelling in spring 2005 (fig. 5) and 2006 (Schwing et al. 2006) has been blamed for poor ocean conditions and biological pro-

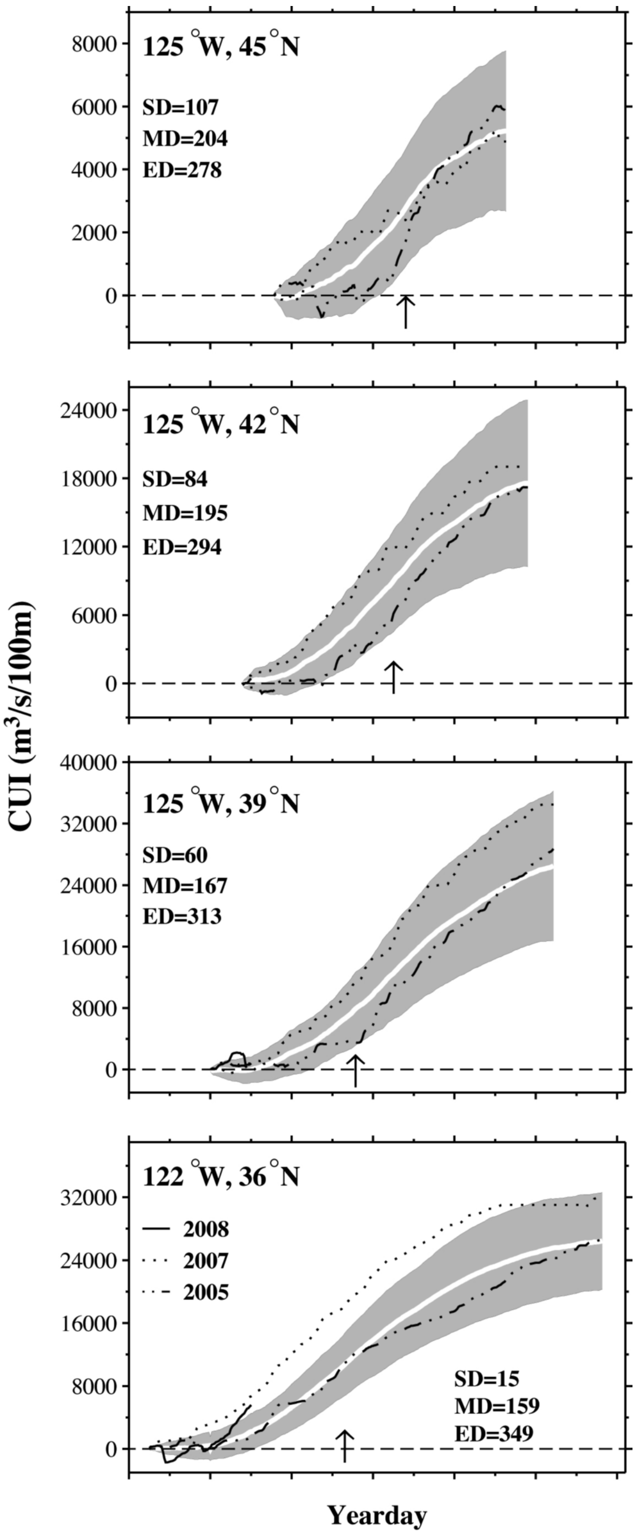

Figure 5. Cumulative upwelling index (CUI; m^3 s^{-1} 100 km^{-1}) for four locations in the California Current. Integration was performed over the climatological upwelling season at each latitude, and arrows mark the time of maximum climatological upwelling at each latitude. Julian days of start (SD) and end (ED) of upwelling season and maximum upwelling are shown for each location. Mean and standard deviation (black solid and shaded areas, respectively), and 2005, 2007, and 2008 are shown.

ductivity and recruitment failures in several populations. Extremely poor returns of Chinook salmon stocks in California, which has triggered the closure of much of the West Coast salmon fishery, are attributed to this. In contrast, the 2007 upwelling season began early, and upwelling remained unseasonably strong through May (fig. 5). Although upwelling reduced substantially in June and July, the cumulative upwelling for the 2007 season was greater than normal in the southern portion of the California Current system. Strong upwelling to date in 2008 indicates an early transition to upwelling this year as well. An important implication of this could be greater ecosystem productivity and reproductive success for many populations.

Conditions at coastal NDBC buoys have reflected these large-scale patterns. Buoy winds have been generally upwelling-favorable (southward), with a number of very strong upwelling episodes (fig. 6). The first half of 2007 was unusual in its relative lack of relaxation events, periods of northward (downwelling) wind when onshore recruitment can occur. Associated buoy SSTs were anomalously cool. The latter half of 2007 featured a strong regular cycle of upwelling/downwelling. The extension of this pattern in the California Current in late-2007 was linked to the active period of tropical MJO. Buoy SSTs have been unseasonably cool since fall 2007.

Remote Sensing

Data from ocean color satellites show that the magnitude of phytoplankton blooms in coastal areas of the California Current increased during the last 11 years (1997–2007, fig. 7). Ocean color data of 1997–2007 showed increased phytoplankton bloom magnitude along most of the West Coast of North America; the increase was weakest in the southern Baja California region (fig. 7). A very similar increase in bloom magnitude has been detected in other eastern boundary upwelling systems (Kahru and Mitchell, 2008). The distribution of the trend in the Gulf of California showed that increased bloom magnitude was characteristic of the eastern boundary region and not of the western boundary region.

Increased blooms in eastern boundary areas may be caused by increased upwelling due to stronger northwesterly winds, but we are unaware of any direct evidence supporting that. The increased blooms off Oregon are likely the cause of the increased "dead zones" of oxygen-depleted water (Service 2004, 2007). It is obvious that some of the observed trend in bloom magnitude is attributable to the strong El Niño of 1997–98 in the start of the time series as suppressed chlorophyll *a* levels in coastal areas of the California Current were associated with the 1997–98 El Niño (Kahru and Mitchell 2000, 2002). However, bloom magnitudes have increased in many areas even after 1997–98. The only larger area

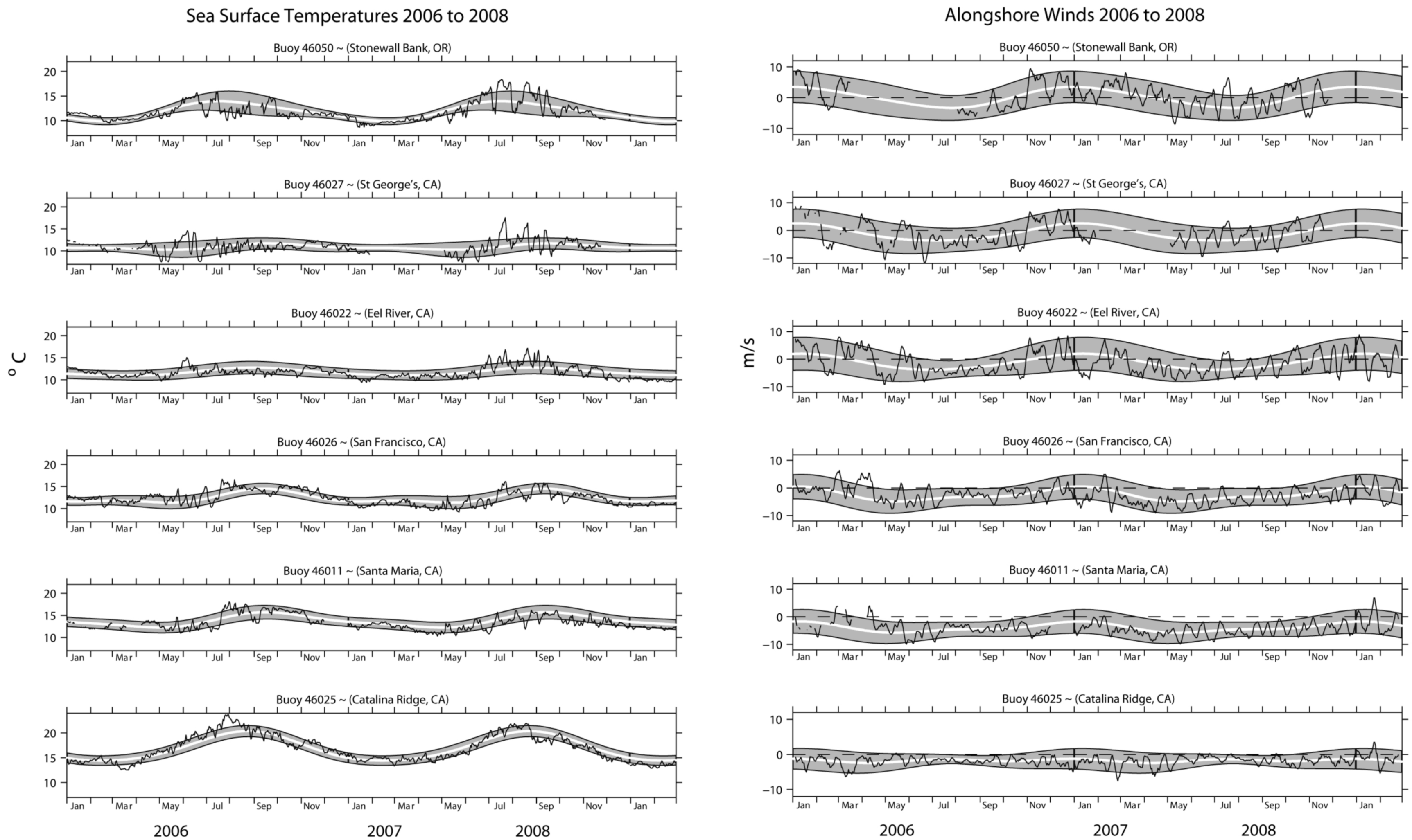

Figure 6. Time series of daily-averaged SST (left) and alongshore winds (right) for January 2006–February 2008 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a seven-day running mean. Data provided by NOAA NDBC.

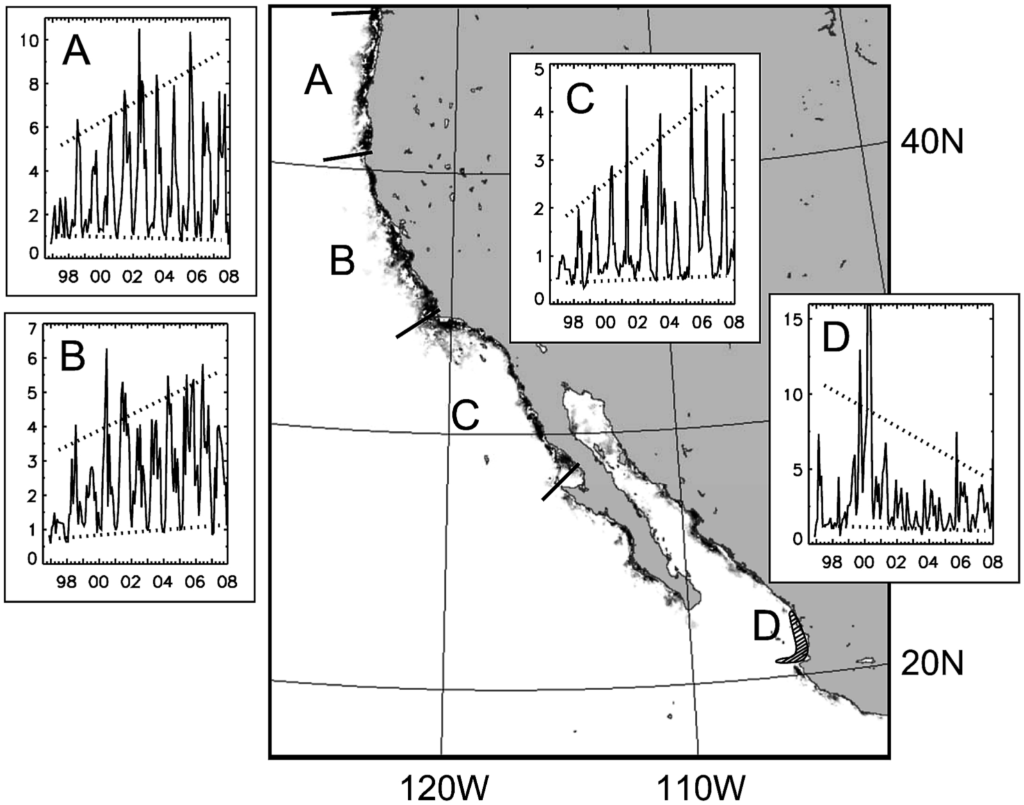

Figure 7. Trends in phytoplankton bloom magnitude detected by ocean color in 1997–2007. Areas of increased bloom magnitude (dark gray) are detected along coasts and no trend (white) is evident in offshore areas. An area of decreased bloom magnitude (striped) is off Mexican states of Nayarit and Jalisco (D). The trend and its significance are estimated using the Sen slope test at 95% confidence level. Individual time series of spatially averaged Chlorophyll *a* (mg/m^3) are shown as insets for 50 km near shore bands off the coast (A, B, C) or in the specified area (D). Linear trends in annual maxima (bloom magnitude) and minima are shown with dotted lines. The trends in maxima are significant at 95% level but the trends in minima are not.

of decreased bloom magnitude was found off the coast of the Mexican states Nayarit and Jalisco and was related to the exceptionally strong harmful algal blooms in that area in 2000.

REGIONAL STUDIES—HYDROGRAPHY

Oregon

SST at the NOAA Weather Buoy 46050 off Newport was slightly below average for most of 2007 with the notable exception of the months of July and August when SST anomalies of + 2.8° and 1.5°C were observed (fig. 6). SST values at our baseline station NH-05 (five miles off Newport, not shown) were also above long-term averages during the summer of 2007, reflecting weak upwelling conditions during July and August (fig. 4). Measurements of temperature and salinity measured every two weeks at a depth of 50 m at one of our baseline stations (NH 05, five miles off Newport) showed that the deep waters in spring and summer of 2007 were very cold and relatively salty (not shown). In fact, salinities were the highest that we have measured and temperatures were the fourth coldest since we began making CTD measurements off Newport in 1997.

A time series of temperature measured at a depth of 150 m at a shelf break station off Newport (NH 25, station depth of 300 m) shows a strong seasonal cycle as well as interannual variations (fig. 8). The water is warm and relatively fresh during the winter but cold and salty during summer. Temperatures at 150 m depth were cool during summers of 1999–2002 (ranging from 7.39°C in 1999 to 7.24°C in 2002), but warm in summer of 2003–06, (7.56°C in 2003, 7.71°C in 2004, 7.65°C in 2005, and 7.69°C in 2006). Cooler temperatures were again seen in summer 2007 at 7.34°C.

Salinity at 150 m continues to show a trend toward increased salinity in all months, beginning in spring 2005, similar to observations made during most months of the years 1999–2002. From this (albeit limited data set), it appears that relatively warm and fresh water occurs at depth during the positive phase of the PDO and colder and saltier water occurs during the negative phase, supporting a hypothesis that different water types occur off Oregon as a function of the phase of the PDO.

Northern California

Observations were made along the Trinidad Head line (41°3.50'N) from spring 2007 through winter 2008. Upwelling off northern California started early in the spring of 2007 and was unusually strong (fig. 4, fig. 5). Observations during spring 2007 captured a dominant signal of persistent upwelling, modified by a relaxation-downwelling that coincided with sampling (CS0704, fig. 9, top panels). The relaxation event likely contributed to the establishment of a phytoplankton bloom along the coast. By the summer, upwelling had weakened and the upper 50 m of the water column had stratified along the observational line. Offshore, a subsurface chlorophyll *a* maximum had formed with concentrations as high as 8 mg/m^3. Inshore, these high concentrations were observed in the mixed layer, likely due to the effects of nutrients brought into the mixed layer by the persistent, albeit weaker, upwelling in the area (fig. 4). Water-column structure in November 2007 reflected the effects of localized downwelling. In contrast, conditions during the 2007–08 winter and early spring were marked by shoaling of cooler, saltier water towards the coast (fig. 9, lower three rows), consistent with the trends in the monthly upwelling index between 39°N and 42°N (fig. 4).

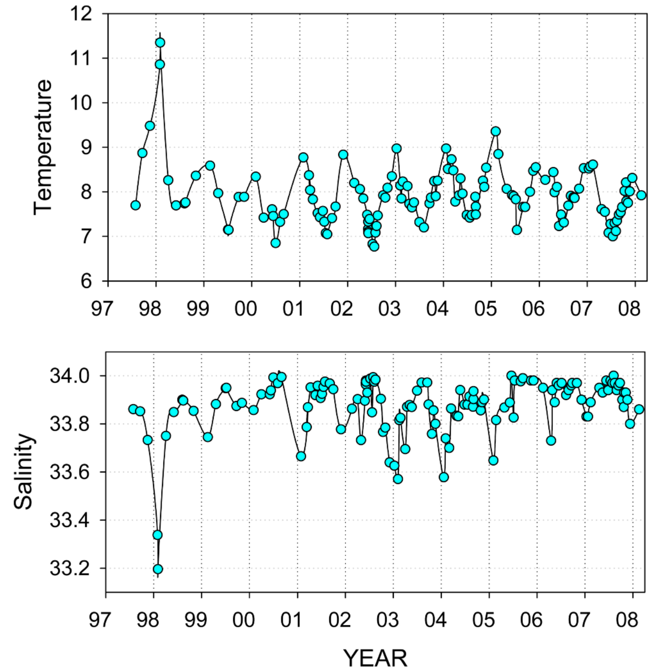

Figure 8. Time series of temperature and salinity measured at a depth of 150 m at station NH 25 (25 miles off Newport); station depth is 297 m.

Central California

Hydrographic data have been collected in the Monterey Bay region from mid-1988 through the end of 2007 and are presented here as anomalies (fig. 10). Temperature and salinity anomalies are inversely correlated and show that spring and summer temperature (salinity) anomalies were 1°C ($\Delta S = 0.04$ psu) cooler (saltier) than normal, most likely due to the strong and persistent upwelling-favorable winds that occurred. Summer chlorophyll *a* concentrations remained about 3 mg/m^3 higher than normal for the fourth year in a row. This marks the eighth year since 1999 that positive anomalies have occurred. Dinoflagellate concentrations returned to normal in Monterey Bay after three years of higher than normal abundance.

Hydrographic stations along CalCOFI lines 67 (off Monterey) and 60 (off San Francisco) to station 90 were occupied in June and November 2007 (Rago et al. 2007, 2008). Near-surface results of June measurements are shown in Figure 11. Off San Francisco, the core of southward geostrophic flow at the surface was centered at 124W. Along line 67, geostrophic flow was weaker and somewhat farther offshore to the southwest of Monterey, in part due to a cyclonic eddy at the entrance to Monterey Bay. Inshore, 10 m waters were strongly affected by coastal upwelling with temperatures less than 11°C in the Gulf of the Farallones and salinities greater than 33.8 psu in both the Gulf and Monterey Bay. Offshore, the core of subarctic waters ($S < 32.8$) was observed along the outer half of line 60 (off San Francisco) and followed the 0.96 dynamic meter isostere to the south, where it was narrower and deeper at line 67. At 10 m, warmest waters (15°C) were at the western corner of line 60. Chlorophyll-*a* concentrations at 10 m exceeded 4 mg/m^3 at inshore stations in Monterey Bay and the Gulf of the Farallones, decreasing offshore where they were less than 0.5 mg/m^3.

In November (fig. 12), the California Current flowed to the east through the western portion of the sampling grid, turning to the southeast and exiting at about the middle of line 67. This flow was oriented along the 0.88–0.92 dynamic meter isosteres and was also marked at 10 m by $S = 32.8$ psu and 14.5°–15°C. Waters in Monterey Bay and the Gulf of the Farallones were colder (<13°C) with higher salinity (~33.3) than those found farther offshore. Chorophyll *a* at 10 m was between 0.09 and 0.27 mg/m^3, except at the head of Monterey Bay (Drakes Bay), where 1.6 (0.9) mg/m^3 was observed.

Compared with the 1988–2001 climatology (Collins et al. 2003), conditions to the southwest of Monterey (Line 67) indicated that subarctic influences (vs. equatorial) were stronger. For example, Figures 11 and 12 show the inshore edge of the California Current (marked by $S = 32.9–33.0$) intersecting the section at about its halfway point, 150 km from Monterey Bay. During 1988–2003, the inshore edge of the California Current was found near the offshore limit of the section except during the period of the 1997–98 El Niño. Central

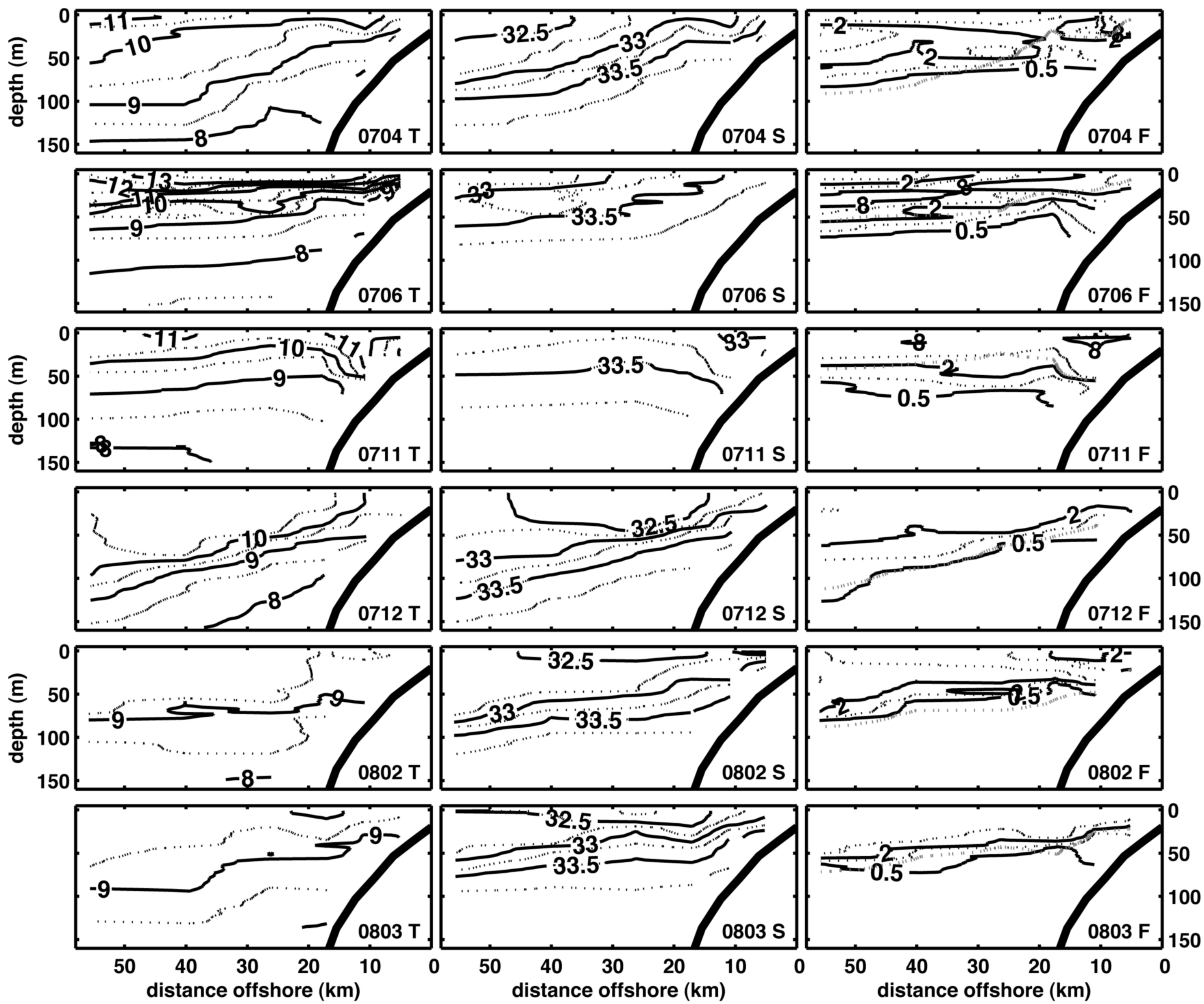

Figure 9. Temperature (left panels), salinity (middle panels), and estimated chlorophyll (converted from fluorescence, right panels) for surveys of the Trinidad Head line from April 2007 to March 2008. Label in lower right of each panel indicates the cruise (YYMM). Temperature and salinity are contoured on a linear scale. Chlorophyll is contoured on a geometric scale; contour line values differ by a factor of two. Grey dotted line on fluorescence plots indicates the $\sigma_t = 25.8$ isopycnal. Approximate bottom depth is denoted by the solid dark line in lower right of each panel.

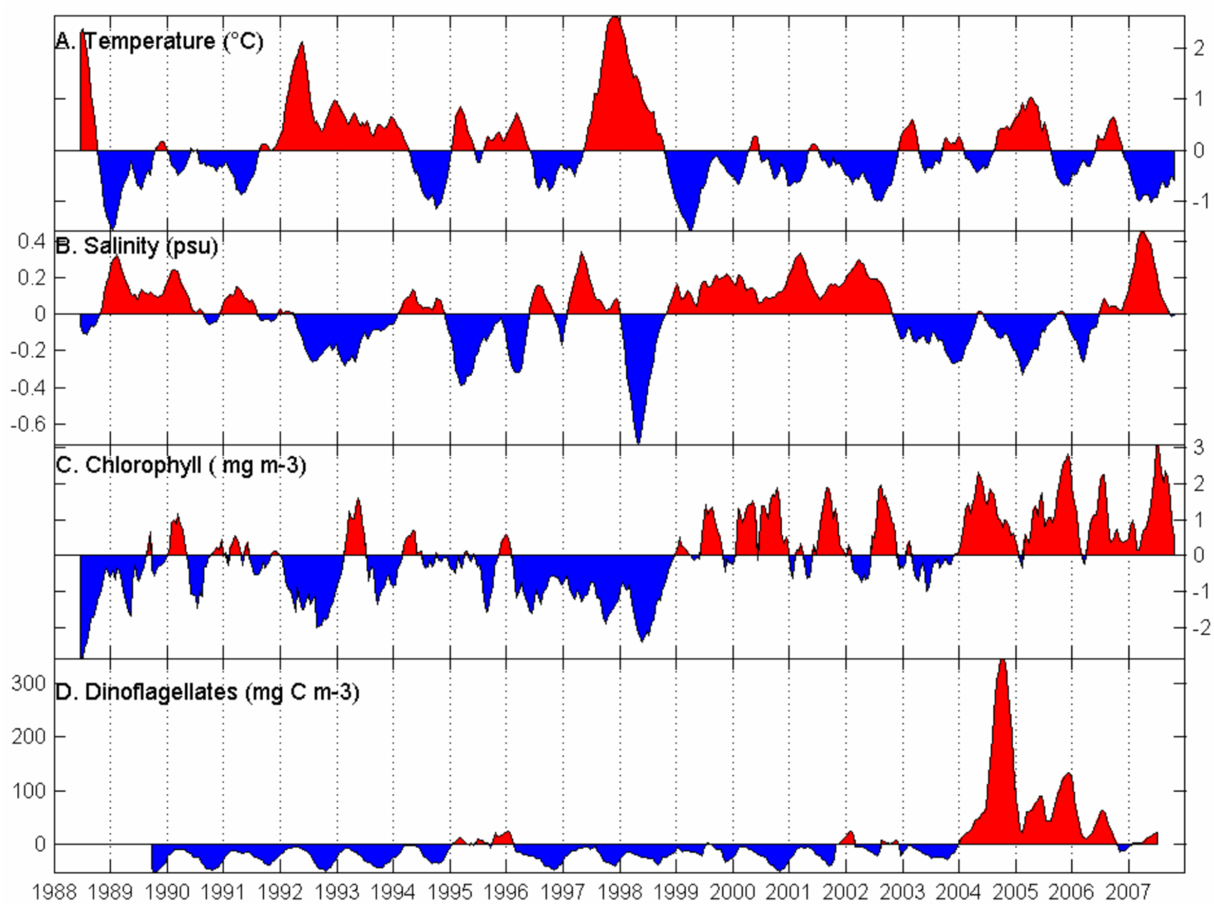

Figure 10. Ocean anomalies for the Monterey Bay region. Data are from Monterey Bay oceanographic stations which have been sampled triweekly since mid-1988.

California conditions reported by Goericke et al. (2007) continued. The mean halocline temperatures remained low, 8.8°C, and the thermocline salinity (34.33) and deep salinity (34.1) continued to freshen. For upper waters (T > 10°C), strong summer upwelling conditions (fig. 5) resulted in a mean salinity of 33.3 in June, which by November had decreased to 33.0.

Southern California: *CalCOFI Cruises*

This year's report on conditions off southern California is based on four cruises in April, July, and November of 2007 and January of 2008 covering 66 stations off southern California (fig. 1). Off southern California, upwelling in the spring of 2007 began slightly early and was slightly stronger than usual (fig. 5). Mixed-layer temperatures, averaged over the 66-station CalCOFI grid, were significantly below long-term averages for the entire time period (fig. 13A), consistent with the basin-wide La Niña conditions described above. With the exception of the summer of 2007, mixed-layer depths were deeper than long-term averages throughout the year (fig. 13B). At the beginning of 2007, mixed-layer salinity was anomalously high, but decreased over the course of the year to values close to the long-term average (fig. 13C). At the beginning of the year temperature at a depth of 200 m was slightly above long-term values (fig. 14A), similar to values observed over the last eight years. By the end of the year and the beginning of 2008 temperatures had dropped below long-term averages. Salinities at 200 m have been decoupled from mixed-layer salinities over the last 8 years; these continued to be significantly higher than long-term averages (fig. 14B). TS (temperature-salinity) plots for different regions of the CalCOFI study area illustrate that sub regions of the study area responded differently to the basin-scale forcing. Salinities in 2007 in the upper thermocline and the mixed layer were significantly higher than long-term averages in the coastal areas and the CC South; in the CC North and at the edge of the central gyres these were close to long-term averages (e.g., fig. 15). In contrast, temperatures in 2007 in the upper thermocline and the mixed layer were lower than long-term averages in the offshore areas (edge of the gyre, CC North and South) but not in the coastal areas (e.g., fig. 15C).

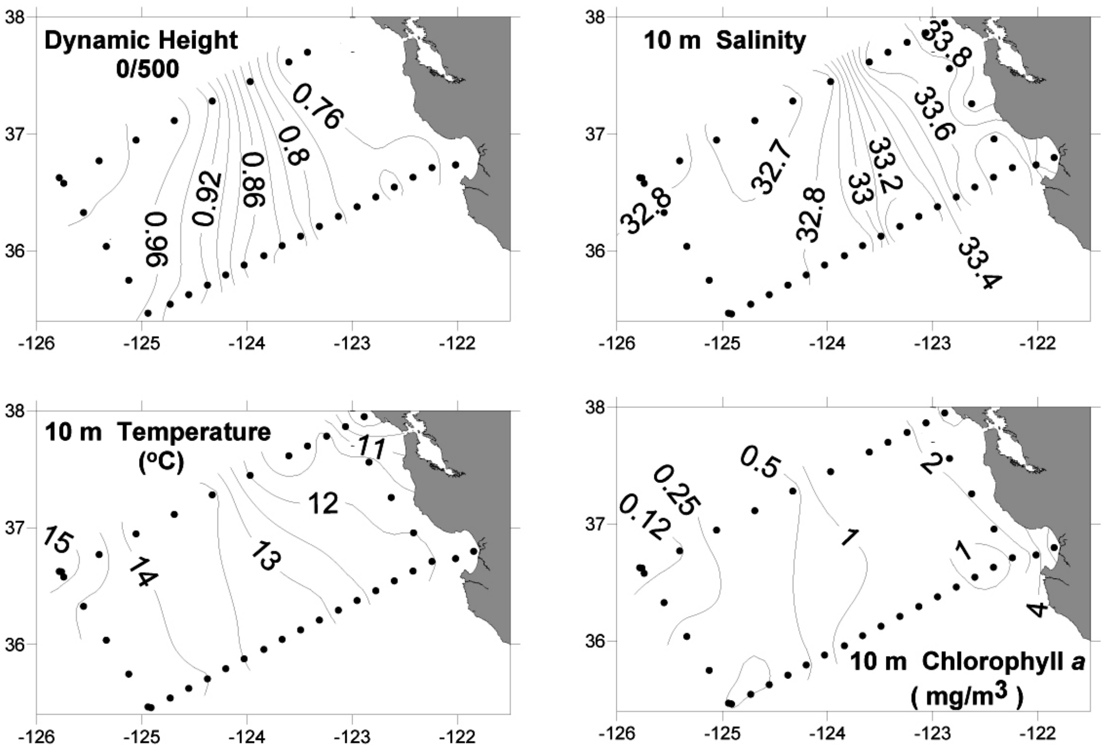

Figure 11. Spatial patterns of hydrographic properties off central California during June 4–9, 2007 (NOAA Ship *McArthur II*). Dynamic height for the surface relative to 500 dbars in dynamic meters (upper left). Salinity at 10 m (upper right). Temperature, °C, at 10 m (lower left). Chlorophyll *a*, mg/m^3, at 10 m (lower right).

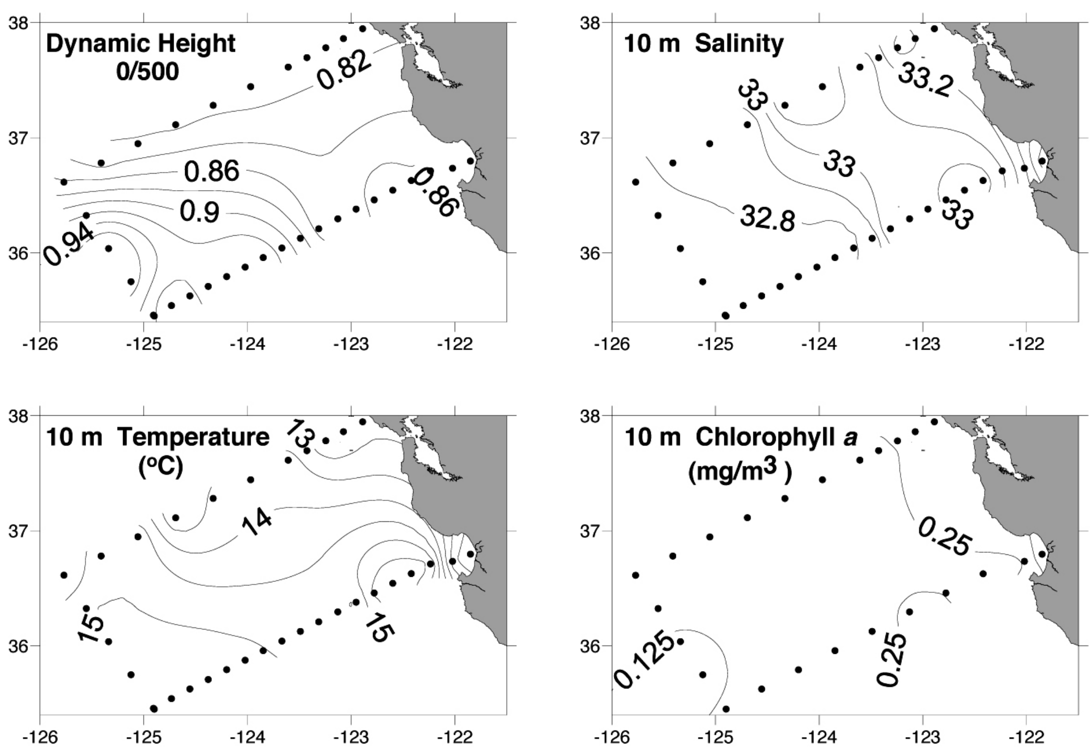

Figure 12. As Figure 11, except during 6–10 November 2007 (NOAA RV *David Starr Jordan*).

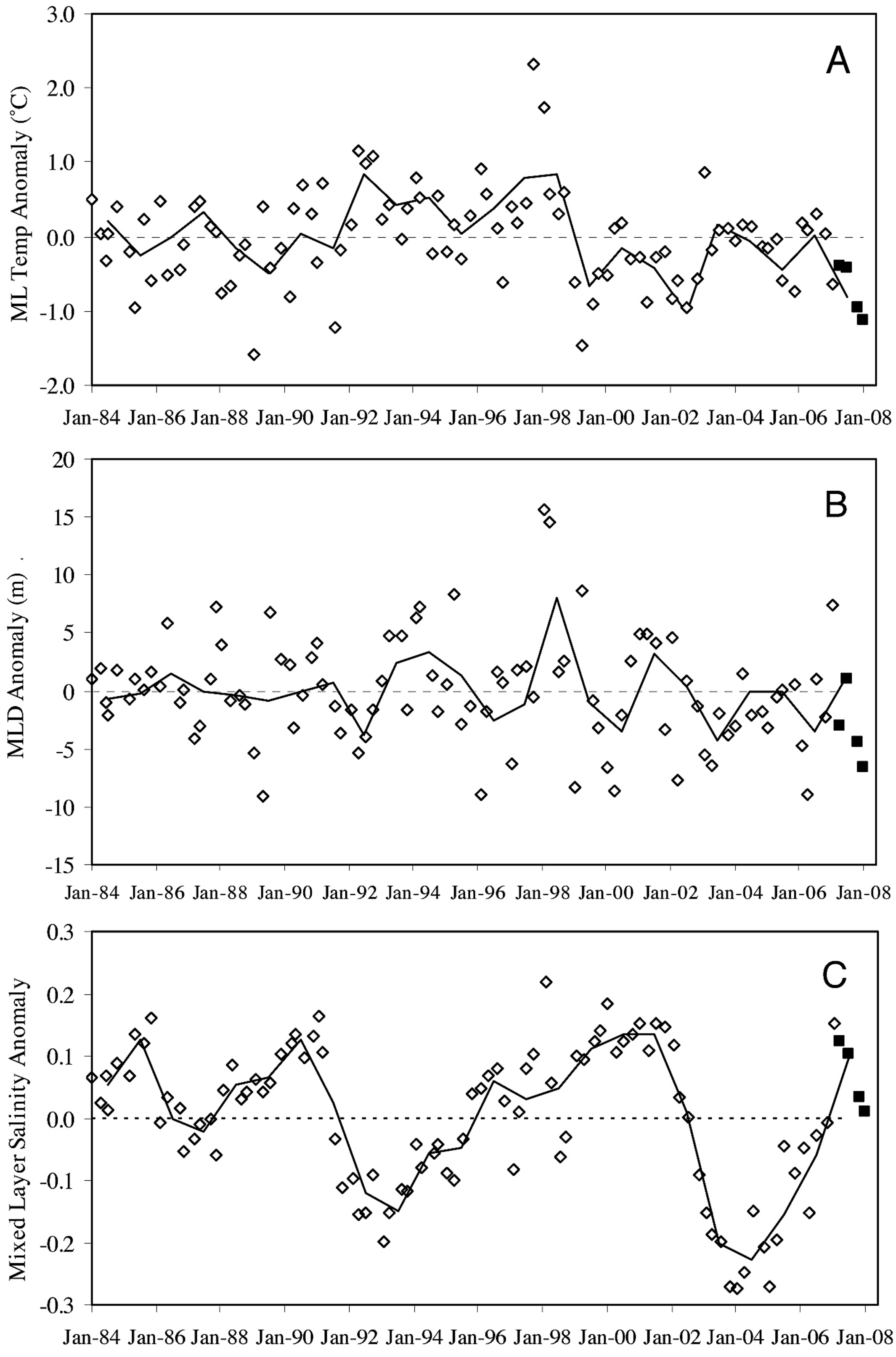

Figure 13. Anomalies of mixed-layer (ML) temperature (A), ML depth (B), and ML salinity (C) off southern California (CalCOFI standard grid, Figure 1). Data from the last four CalCOFI cruises are plotted as solid symbols, data from previous cruises are plotted as open diamonds. The solid lines represent the annual averages and the dotted lines the climatological mean, which in the case of anomalies is zero.

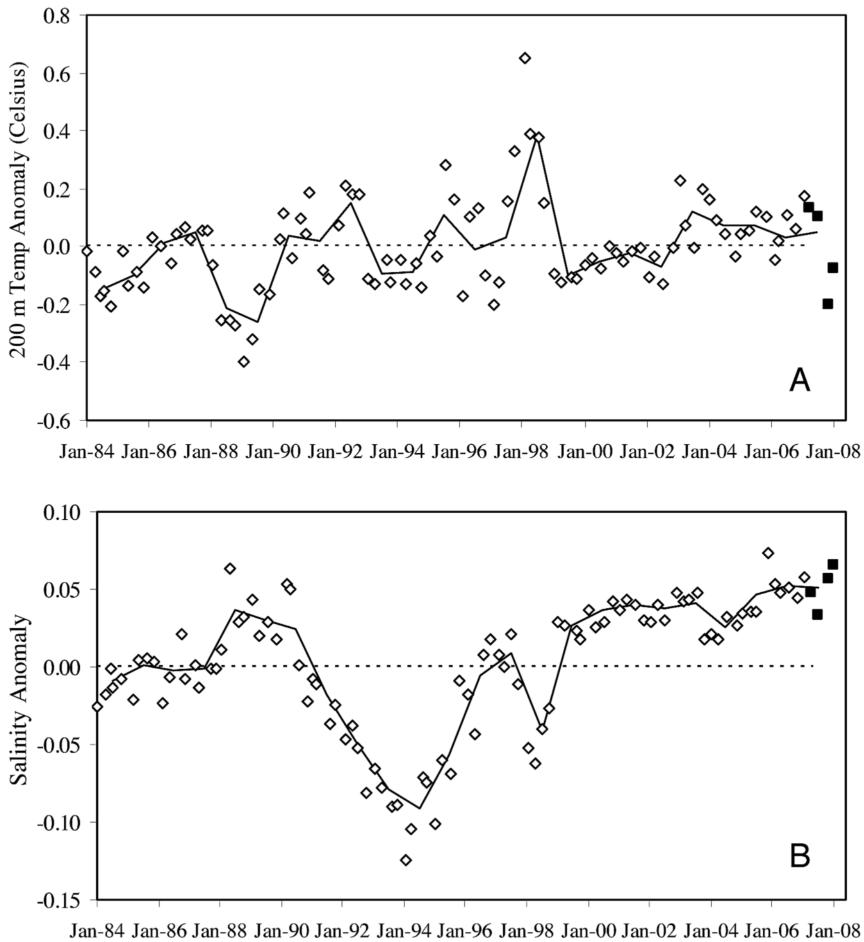

Figure 14. Anomalies of temperature (A) and salinity (B) at a depth of 200 m, calculated and presented as described above for Figure 12.

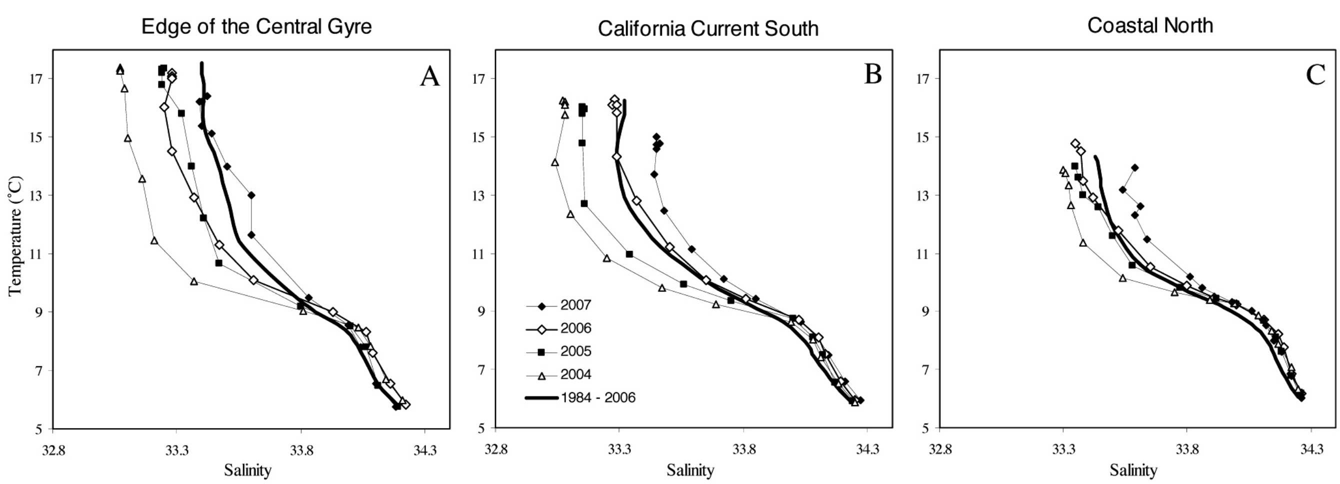

Figure 15. TS plots for three representative areas of the CalCOFI region. A. the edge of the central gyre (Lines 90–93, Stations 100–120), B. the southern California Current region (Lines 87–93, Stations 60–90), and C. the coastal areas in the north (Lines 77–80, Stations 60 and inshore). Each data point represents the average TS characteristic of one standard depth level for the specified time periods, i.e., 1984–2006, 2004, 2005, 2006, and 2007.

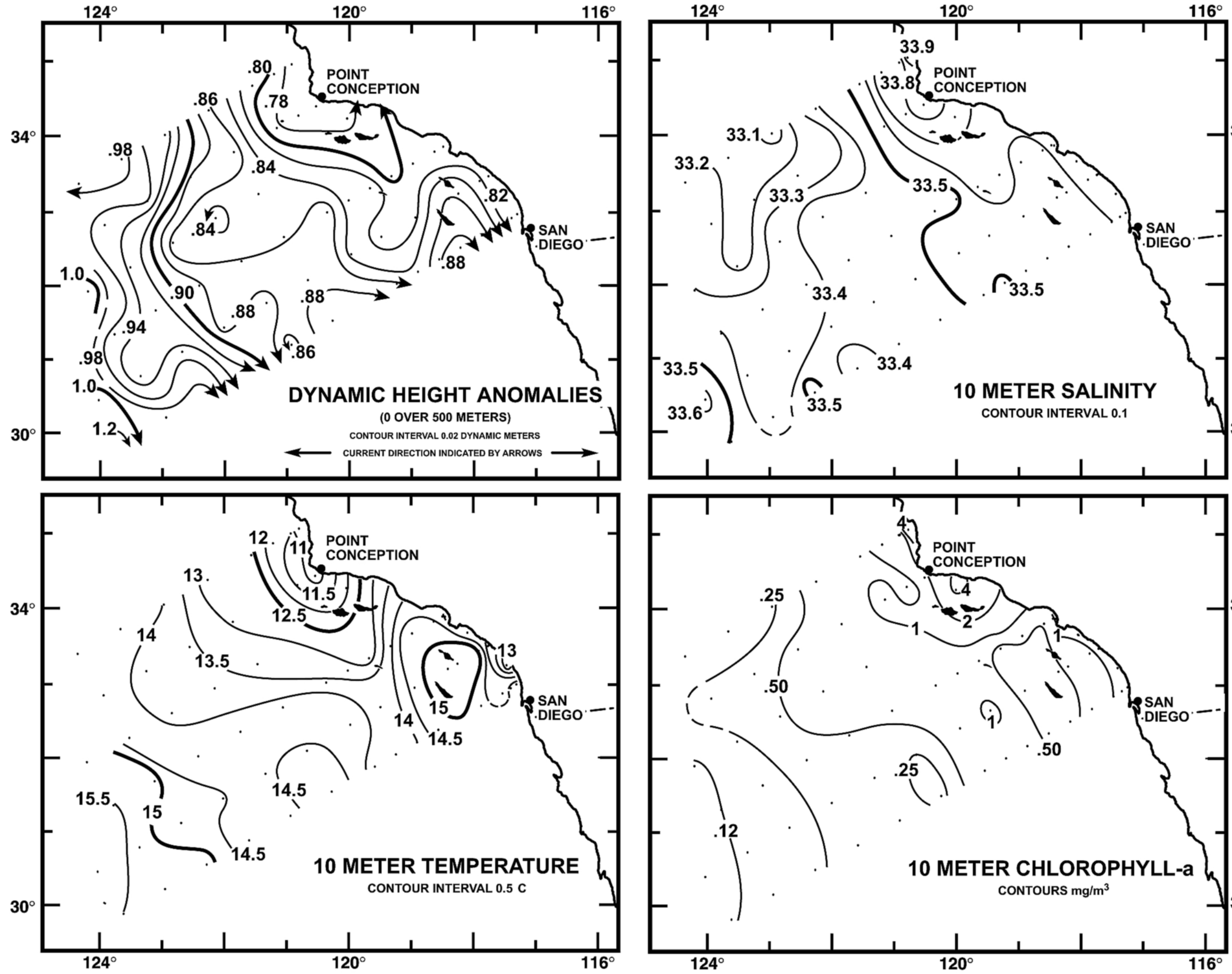

Figure 16. Spatial patterns for CalCOFI cruise 0704 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

CalCOFI Cruise 0704
(3 March–25 April 2007; fig. 16)

In the spring of 2007 the California Current (CC) entered the CalCOFI study region at the center of line 77, flowed southwest and turned on line 83 southeast to exit the area between stations 93.080 and 93.100. The Southern California Eddy (SCE) had not yet formed. A current loop with anticyclonic flow (downwelling in its center) was found at station 93.40. The northern coastal areas were strongly affected by coastal upwelling, which left its characteristic mark of low temperatures (<12.5 °C) and high salinities (>33.6) in these areas. The center of the study area was characterized by small dynamic height gradients. A small cyclonic eddy was present at station 83.080. Unusually high concentrations of nitrate were observed along lines 77 and 80, out to stations 60 and 70. Unusually high concentrations of nitrate were also observed along line 87, stations 45 to 55. Observations on the inshore portion of line 83 were not carried out due to bad weather. Biologically the system had not yet responded to the enrichment of the euphotic zone with plant nutrients; concentrations of chlorophyll *a* in the northern coastal area, with the exception of the Santa Barbara basin, were low and below long-term averages for the respective stations.

CalCOFI Cruise 0707
(28 June–13 July 2007; fig. 17)

In the summer of 2007 the CC entered the study area still through the center of line 77 but had begun to meander in and out of the study area along its western edge. The cyclonic eddy centered on station 83.080 was still present. A strong poleward flow was observed throughout the study area. The SCE had formed by now, centered on station 87.050. The salinity field followed the flow fields with low salinities associated with the CC

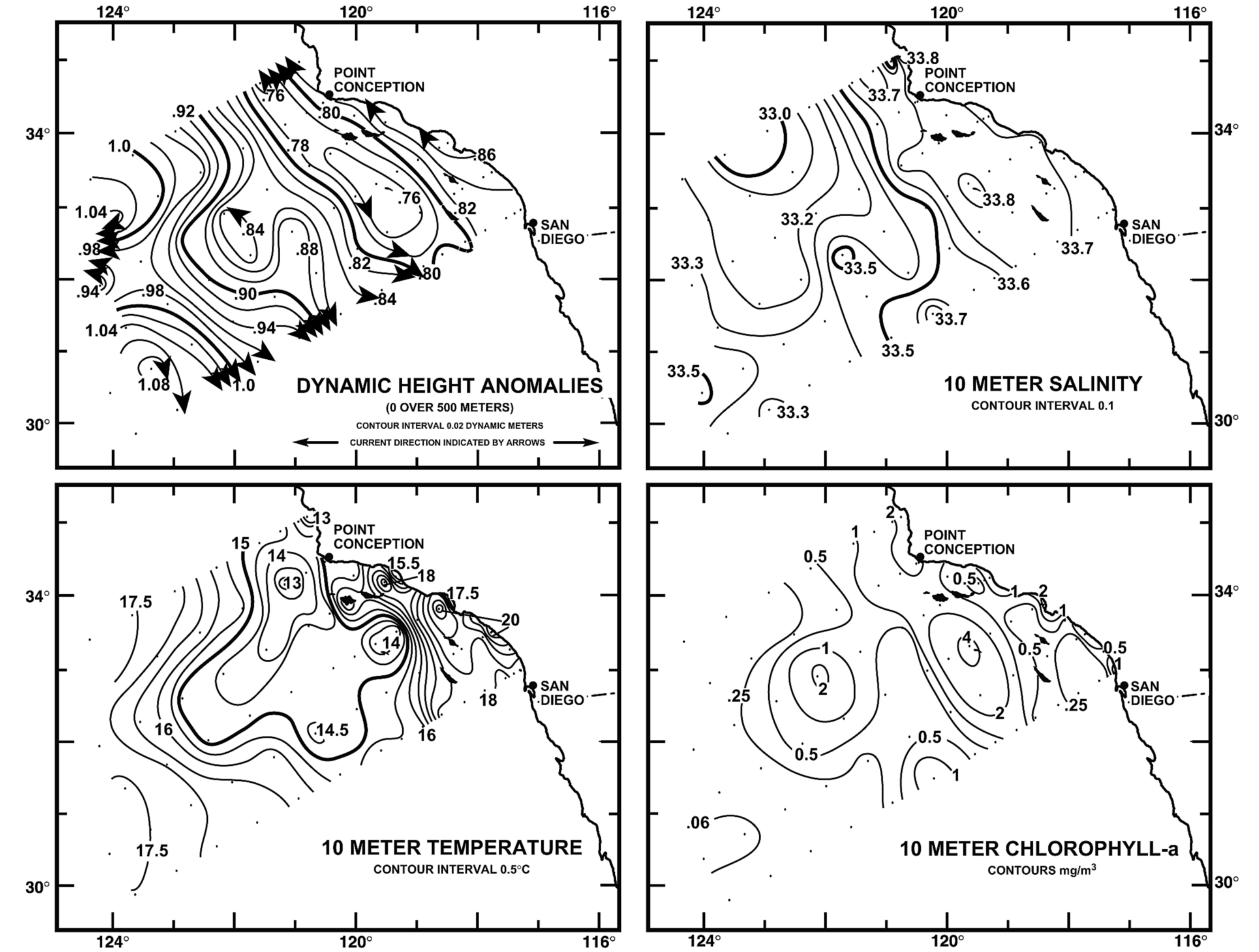

Figure 17. Spatial patterns for CalCOFI cruise 0707 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

and higher salinities along the coast and the center of the SCE. Unusually high concentrations of nitrate were observed in the region roughly demarcated by the 15°C isotherm, with concentrations in this area up to 10 μM. High concentrations of chlorophyll *a* observed during the summer—along the coast and associated with cyclonic eddies, i.e., the SCE and the eddy at station 83.080—did not coincide with areas of high nitrate concentrations. This suggests that phytoplankton growth may have been limited by nutrients other than nitrate, e.g., iron (King and Barbeau 2007).

CalCOFI Cruise 0711 (2–8 November; fig. 18)

In the fall of 2007 the CC entered the study domain from the northwest and formed a strong loop centered on lines 80 and 83, first flowing northeast and then southwest to the offshore portions of lines 90 and 93. The CC exited the study domain along the offshore portions of line 93. The SCE was still centered on station 87.050. Poleward flow along the coast had weakened. Temperature at 10 m ranged from 15° to 17°C with the exception of a tongue of colder water extending southeast from Point Conception. Concentrations of chlorophyll *a* were low throughout the domain with high concentrations only observed along the coast.

CalCOFI Cruise 0801 (7–25 January 2008; fig. 19)

In January 2008 the CC entered the study area through the center of line 77 and split up into three branches. One branch formed a current loop in the offshore areas of lines 83 to 77 and left the area through the offshore portions of lines 80 and 77. The main branch, marked by the 0.90 dyn. m isostere, flowed southeast, exiting the area along the offshore portion of line 93. It is possible that the CC formed an eddy southwest of the study area, which would explain the strong flow

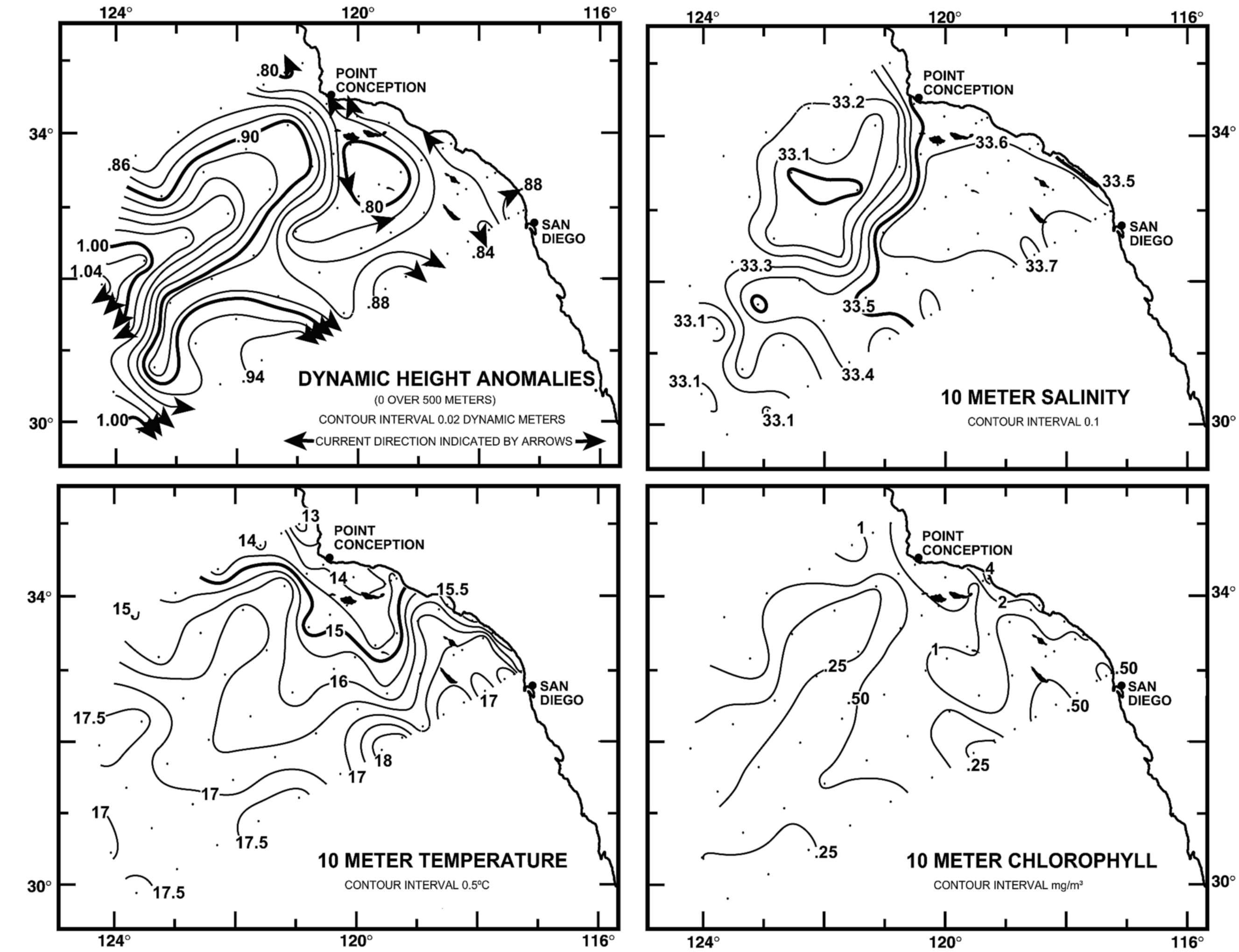

Figure 18. Spatial patterns for CalCOFI cruise 0711 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*. Data used for these plots are still preliminary.

coming from the termini of lines 90 and 93, to merge with the CC in the vicinity of stations 93.100 to 93.090. Low salinities of 32.9 along line 77 mark the core of the CC. Relatively low salinities off and south of Point Conception show that upwelling has not yet set in. Temperatures at 10 m were low over large areas of the region. Temperatures of less than 13°C in the northern area of the study area and less than 14°C in the southern area coincided with elevated concentrations of nitrate in the mixed layer. Concentrations of chlorophyll *a* were uniformly low over most of the area with the exception of some coastal regions.

Baja California: *IMECOCAL Cruises*

IMECOCAL surveys off Baja California were conducted in the spring and summer of 2007 and the winter of 2008. In contrast to other areas described above, lower temperatures were not observed off Baja California during the study period, in spite of basin-wide La Niña conditions. Temperatures above the pycnocline in the northern section of the study area were close to long-term averages in 2007; in the southern section these temperatures were actually above long-term averages (fig. 20). Similar to observations to the north, salinity above the pycnocline was significantly higher in both areas during 2007, particularly the southern area (fig. 20). By January 2008, 10 m salinity anomalies were slightly negative (data not shown), similar to observation in the CalCOFI study area to the north. During the January to February 2008 survey (fig. 23) out-of-season upwelling was observed off Ensenada and farther south.

IMECOCAL 0704 (26 April–7 May 2007; fig. 21)

Due to bad weather, it was only possible to cover stations north of line 120. The California Current was found approximately 100 km offshore, splitting in two

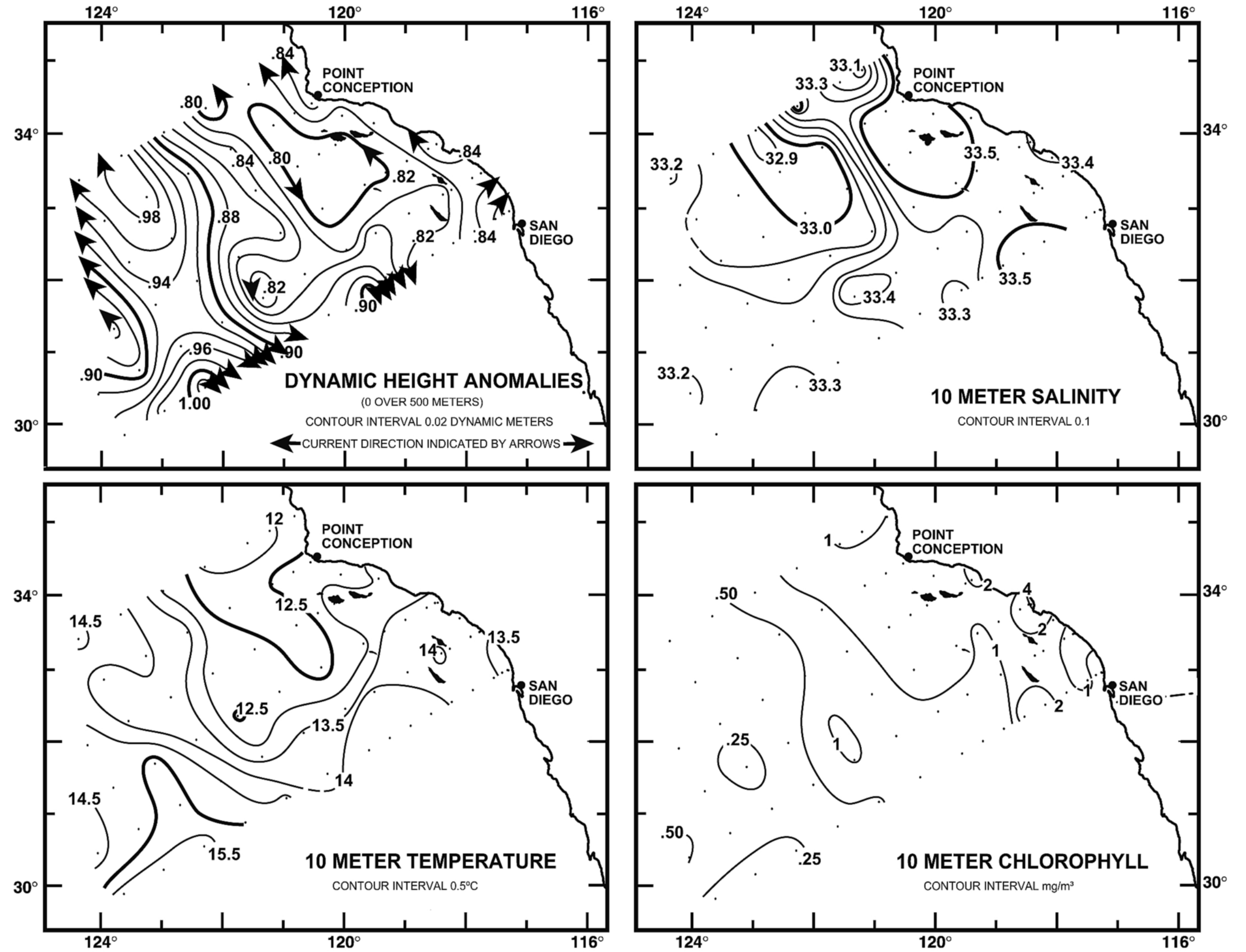

Figure 19. Spatial patterns for CalCOFI cruise 0801 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*. Data used for these plots are still preliminary.

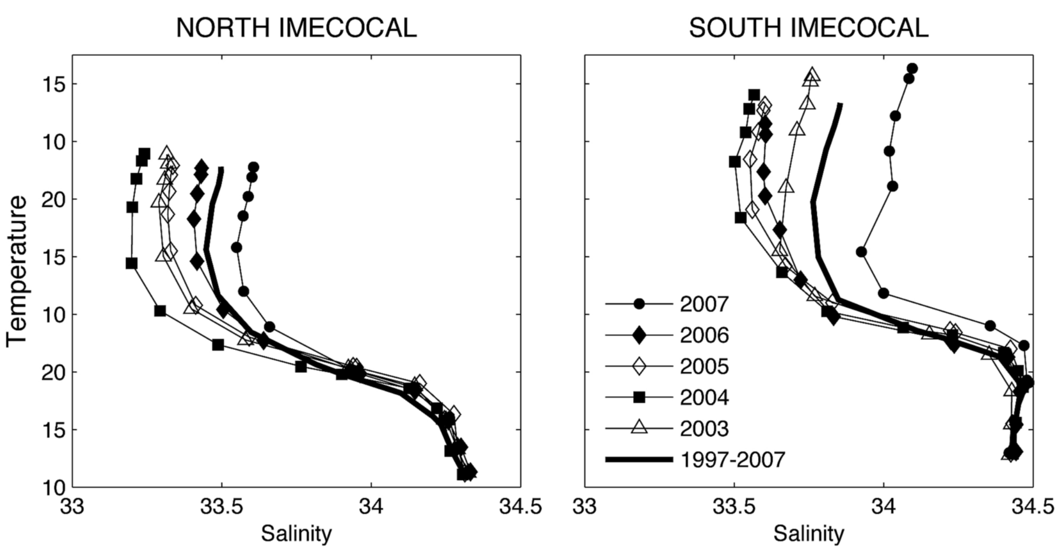

Figure 20. TS plots for the northern (A, Lines 100 to 110) and southern (B, Lines 123 to 130) sections of the IMECOCAL study area. Each data point represents the average TS characteristic of one standard depth level for the specified time periods, i.e., 1997–2007, 2003, 2004, 2005, 2006, and 2007.

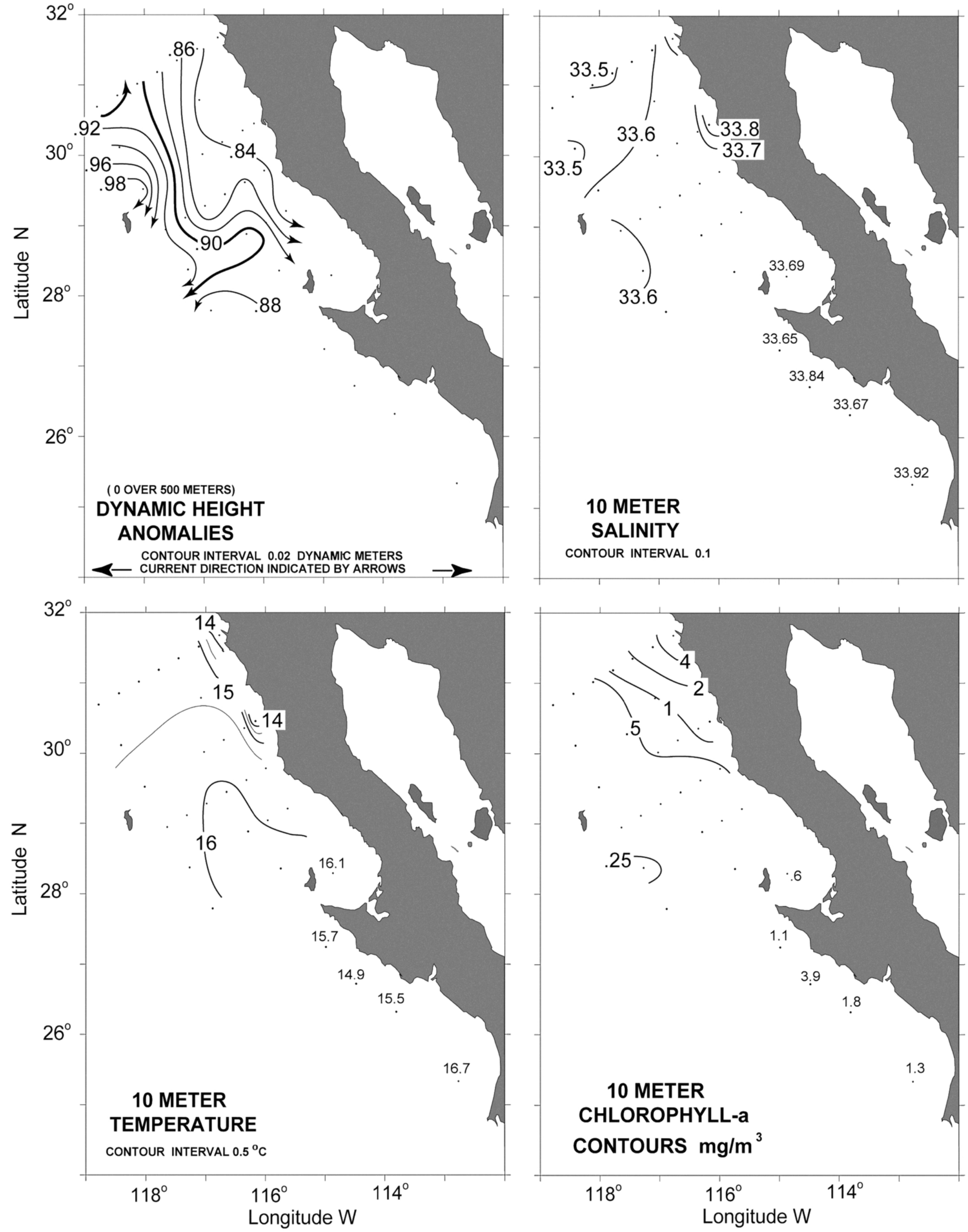

Figure 21. Spatial patterns for IMECOCAL cruise in spring 2007, showing upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height anomalies, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

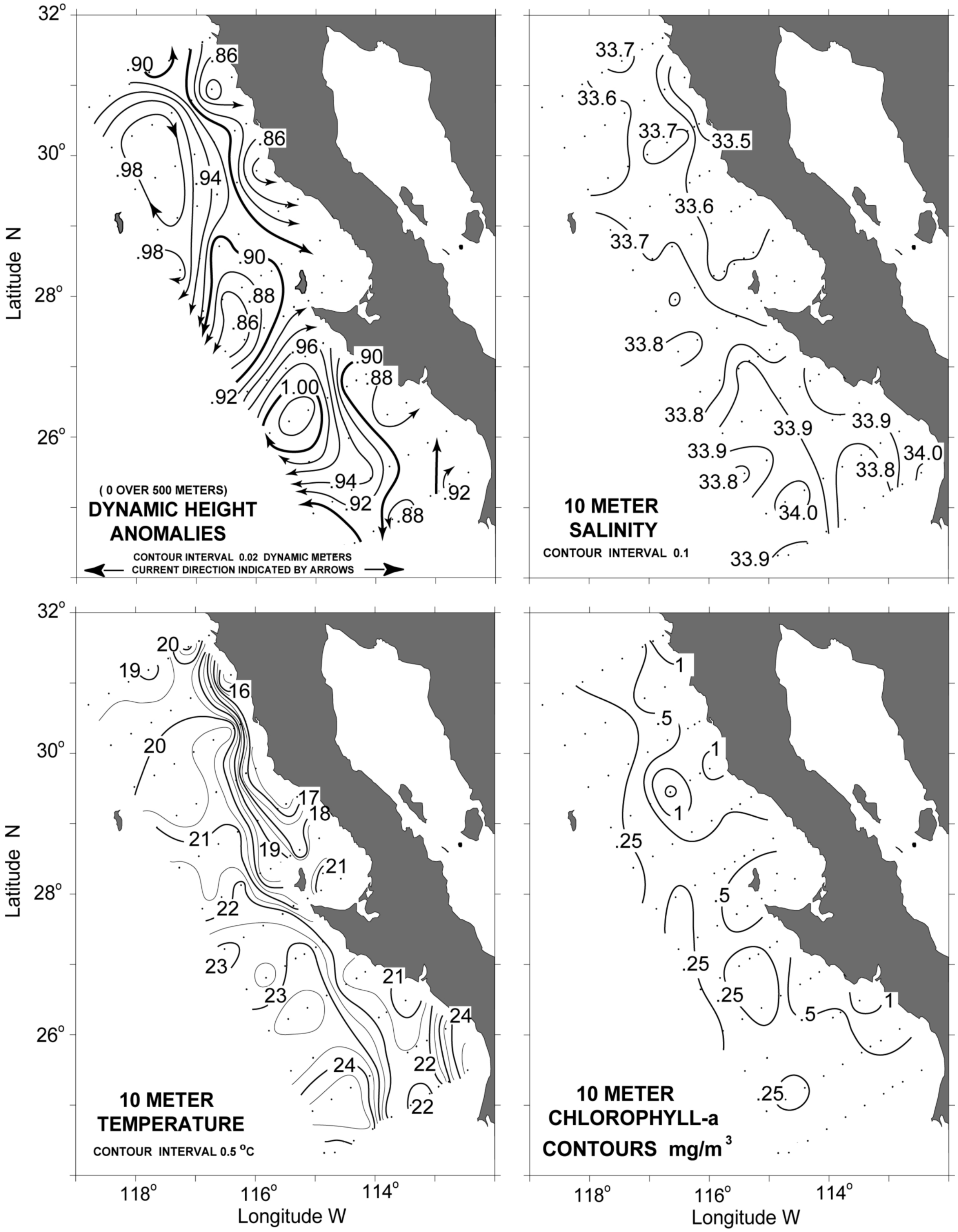

Figure 22. Spatial patterns for IMECOCAL cruise in summer 2007, showing upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height anomalies, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

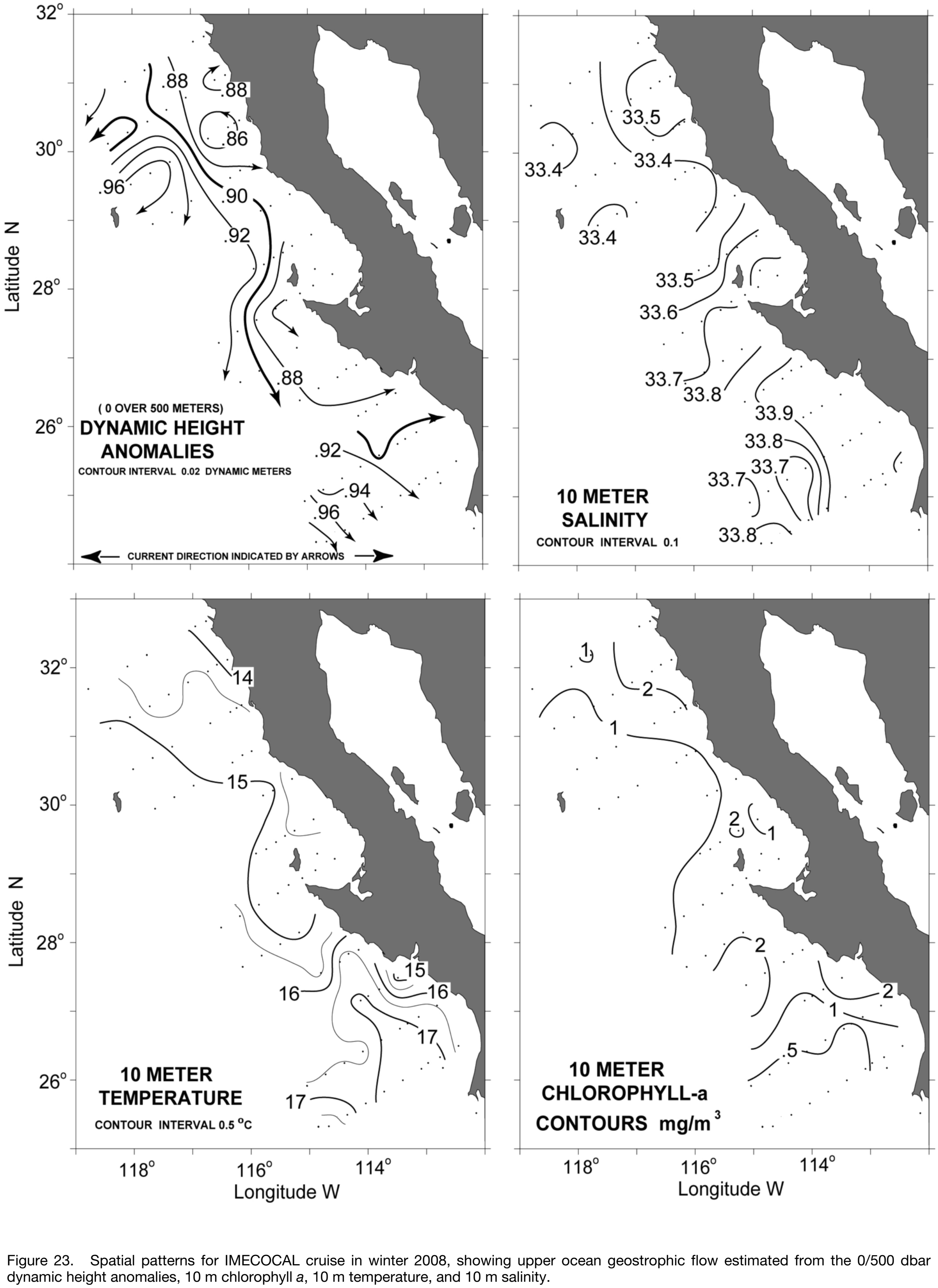

Figure 23. Spatial patterns for IMECOCAL cruise in winter 2008, showing upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height anomalies, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

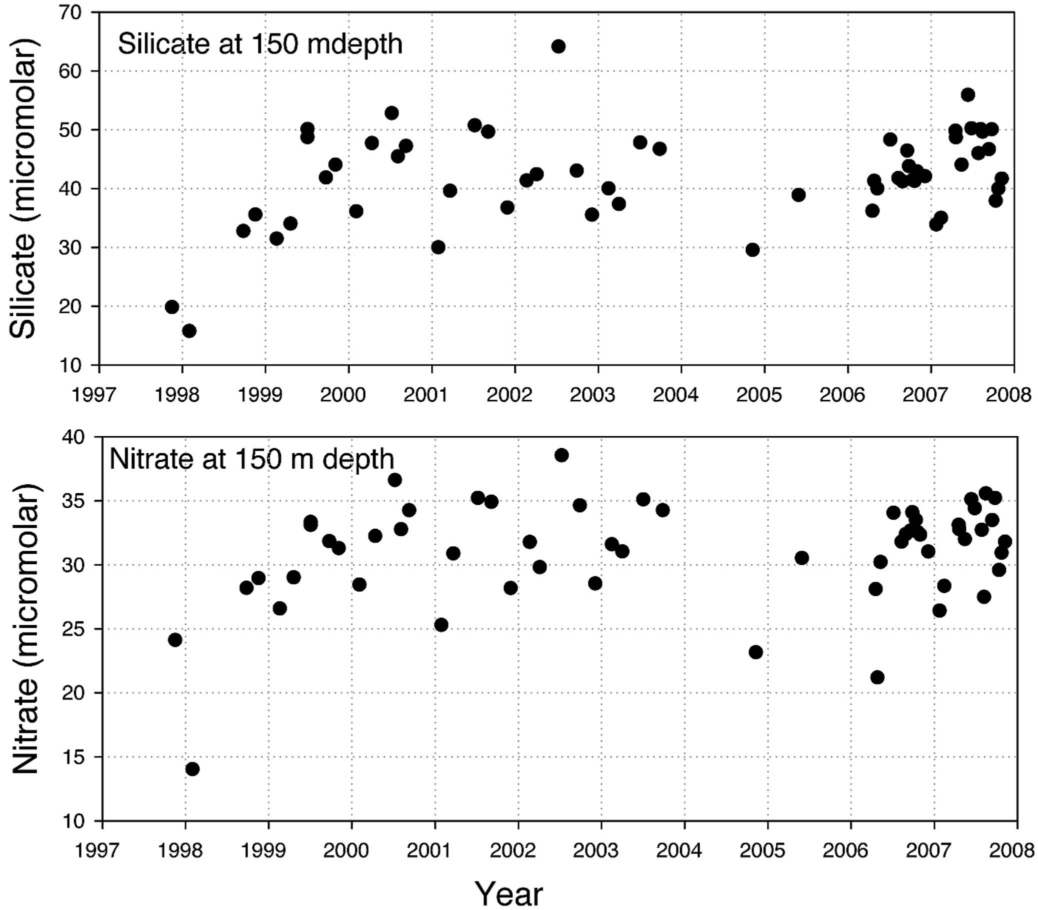

Figure 24. Time series of silicate and nitrate concentrations from station NH 25 (25 miles off Newport). Station depth is 300 m; sampling depth is 150 m.

branches at station 117.40. Between Ensenada (line 100) and San Quintin (line 107), relatively low temperatures and high salinities were encountered in the coastal areas, and show the effects of coastal upwelling. Phytoplankton chlorophyll *a* was high in these areas with values up to 4 µg/L, as is typical for these upwelling events.

IMECOCAL 0708
(25 August–14 September 2007; fig. 22)

Dynamic height anomalies depict a meandering California Current, with two large anticyclonic eddies at northern and southern locations, and a cyclonic eddy in between at ~28°N. As indicated by the relatively low salinities, the core of the current appears to be restricted to the northern region, both as part of the northern clockwise eddy and as nearshore flow. Coastal upwelling between Ensenada and Punta Baja is indicated by the relatively low temperatures (15°–17°C) and high chlorophyll *a* concentrations (>1 mg/m^3) near the coast in the northern region, while warmer (>21°C) and salty (>33.8 psu) conditions were observed in the southern region.

IMECOCAL 0801
(22 January–11 February 2008; fig. 23)

Similar to April 2007, bad weather during this survey did not permit sampling at some offshore stations. The flow pattern of the California Current in the northern section was similar to that observed during April 2007. The southern section was characterized by southeastward flows. Coastal upwelling likely occurred off Ensenada and in the south at ~29.5°N, where 10 m water temperatures less than 15°C and chlorophyll-*a* concentrations higher than 2 mg/m^3 were observed. Upwelling at this time of the year is atypical for these regions.

BIOLOGICAL PATTERNS AND PROCESSES

Macronutrients, Chlorophyll *a* and Primary Production

Oregon: Sea surface nitrate concentrations at NH 05 in spring 2007 (April–June) were 4.6 µM, about average for our 11-year time series (tab. 1). During July–August, despite the weak upwelling, nitrate con-

TABLE 1
Average nitrate (μM) and chlorophyll (μg chlorophyll *a* L^{-1}) concentrations measured at the sea surface at station NH 05, five miles off Newport, in spring (April–June) and summer (July–August) for the years 1997–2007.

	Nitrate (μM)		Chlorophyll *a* (μg chl *a* L^{-1})	
YEAR	April–June	July–August	April–June	July–August
1997	5.21	7.95	1.1	6.1
1998	1.91	2.25	2.2	10.5
1999	4.95	10.20	1.8	5.5
2000	8.65	12.00	1.9	8.4
2001	4.16	9.43	6.6	9.0
2002	4.28	11.49	6.1	10.9
2003	4.37	10.30	3.0	9.7
2004	3.62	8.41	4.9	8.1
2005	0.67	11.70	2.6	8.7
2006	10.1	11.74	2.2	10.1
2007	4.6	11.0	3.5	9.2

centrations were also about average, 11.0 μM. This suggests that despite the warm SST, there were a sufficient number of active upwelling events that surface nutrient levels were not anomalously low.

The chlorophyll-*a* values averaged for spring (April–June) and summer (July–August) 2007 were 3.5 μg/L and 10.1 μg/L respectively, similar to other years (tab. 1). This result would be expected with "average" nitrate concentrations and again suggests that although upwelling was weak, it was not so weak as to result in a lack of production.

Nitrate and silicate measured at a depth of 150 m at NH 25 are shown in Figure 24. One clear pattern is the increase in nitrate and silicate concentration from the 1997–98 El Niño period until 2000, after which there was a tendency towards relatively constant values for each nutrient: most recent values fall into the range of the long-term average of 30–35 μM for nitrate and 40–50 μM for silicate.

CalCOFI: Since the 1997–98 El Niño, nitracline depths have been approximately 5 m deeper than long-term averages, with values ranging from 31 to 49 m. Early in 2007 nitracline depth anomalies for the whole CalCOFI region were similar to those observed since 2000 (fig. 25); i.e., slightly deeper than long-term averages. In the fall of 2007 and winter of 2008 nitracline depths shoaled to extremely low values, 33 and 27 m, similar to the shallowest observed values during the strong La Niña of 1989. Consistent with shallow nitracline depths and stronger than usual southward winds in the area (fig. 6), mixed-layer concentrations of nitrate were elevated during 2007 and early 2008 (fig. 26A). In contrast, mixed-layer concentrations of silicate and phosphate were, when averaged over the seasons, close to long-term averages, albeit variable. Whereas concentrations of silicate covaried with mixed-layer salinity during the last eight years, no such covariation was apparent during the last year (fig. 26C).

Standing stocks of chlorophyll *a*, integrated from the surface to the bottom of the euphotic zone (fig. 27A), were similar to long-term averages, with the exception of the spring 2007 value, which was one of the lowest spring values on the record. Mixed-layer concentrations of chlorophyll *a* (data not shown) had the same pattern. The response of phytoplankton biomass to the cooling of the system was similar to what was observed during the spring of the La Niña Year 1989; in contrast, spring chlorophyll *a* during the La Niña Year 1999 was one of

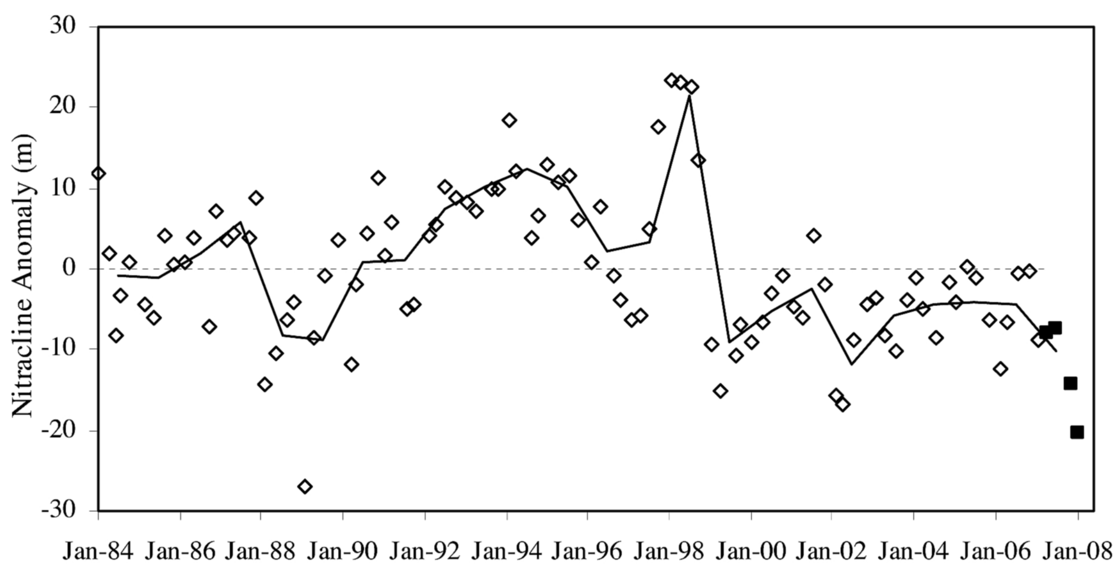

Figure 25. Cruise averages for nitracline depth anomaly. The nitracline depth was assumed to be the depth where nitrate reached values of 1 μM. Data are plotted as described in Figure 13.

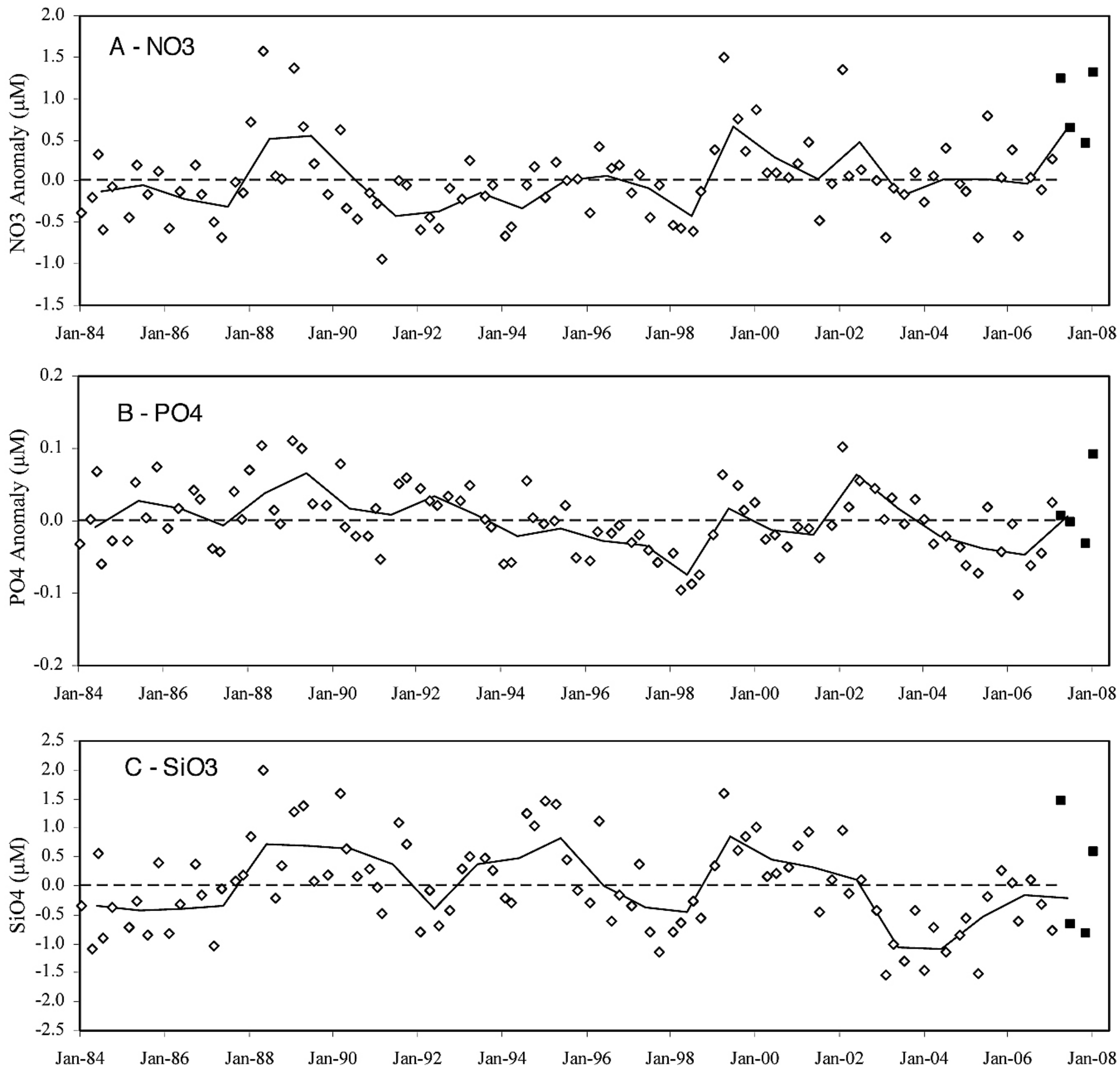

Figure 26. CalCOFI region anomalies for concentrations of (A) nitrate, (B) phosphate, and (C) silicate in the mixed layer. Data are plotted as described in Figure 13.

the highest on record. Rates of primary production were similar to long-term averages with the exception of those observed during the spring of 2007, which were below expected values (fig. 27B). Chlorophyll-*a* concentrations in all other areas were either above long-term averages (CC North and South and Edge of the Gyre; fig. 28A, B) or similar to these (Coastal South).

Zooplankton, Fish, and Seabirds

Oregon Zooplankton: The time series of copepod biomass (fig. 29) shows both a pronounced seasonal cycle with peaks in July/August, and pronounced interannual variations. Lowest averages for summer (May–September) were seen from 1996–99, and highest during the summers of 2000–04. The summer of 2005 had the lowest biomass of any summer, due to the delayed upwelling (Peterson et al. 2006). Biomass rebounded in 2006 and remained high through the summer of 2007.

Monthly-averaged copepod species richness was anomalously high throughout most of 1996–98, low from winter 1999–autumn 2002, then high from autumn 2002–spring 2006 (fig. 30). Richness anomalies turned negative in autumn 2006 and remained either negative or neutral through 2007. This pattern is similar to the pattern of PDO and MEI, suggesting that coherent patterns of PDO, SST, and copepod species richness may be related to transport processes in the northern California Current (NCC): anomalously low numbers of copepod species are associated with the transport of coastal subarctic water into the coastal waters of the NCC (as in

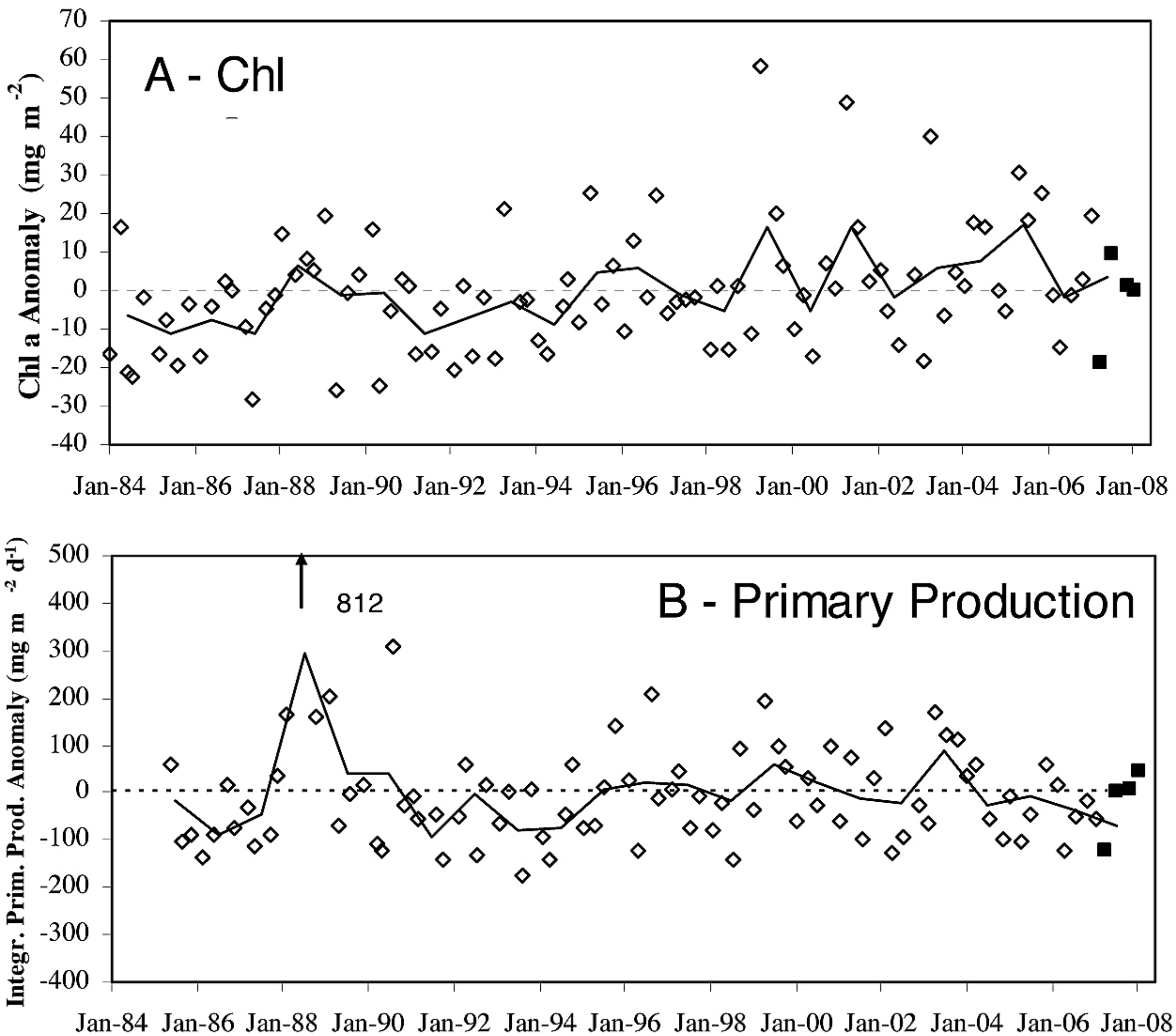

Figure 27. CalCOFI region averages for (A) standing stocks of chlorophyll *a* and (B) rates of primary production both integrated to the bottom of the euphotic zone, plotted against time. Data and symbol codes are the same as those in Figure 13.

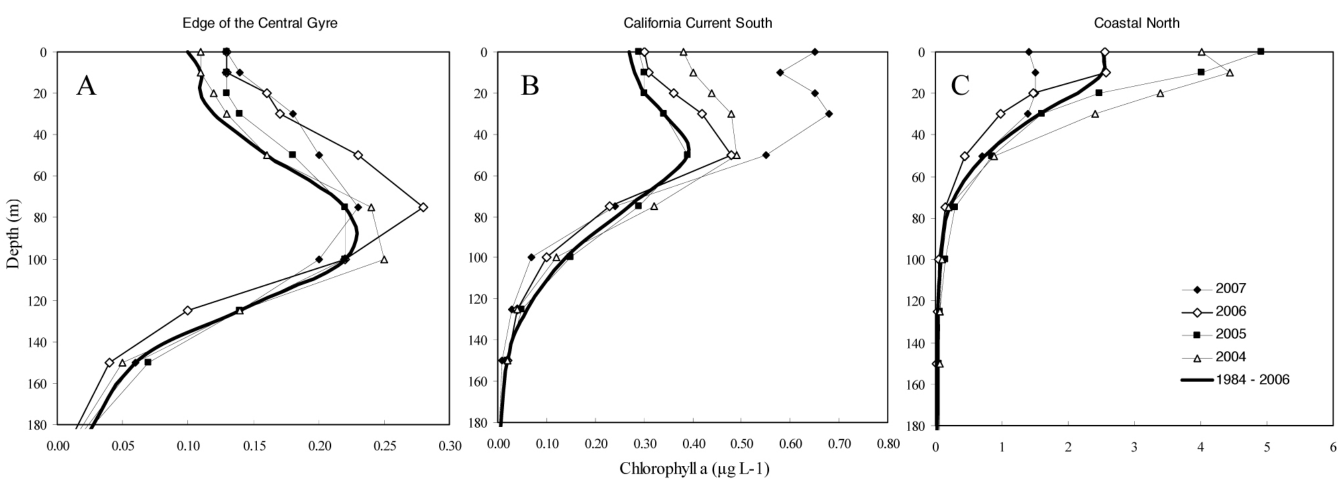

Figure 28. Depth profiles of chlorophyll *a* for the three areas of the CalCOFI region that were described in Figure 15, (A) the edge of the central gyre, (B) the southern California Current region and (C) the northern coastal areas (C). Data were calculated and are presented as described in Figure 15.

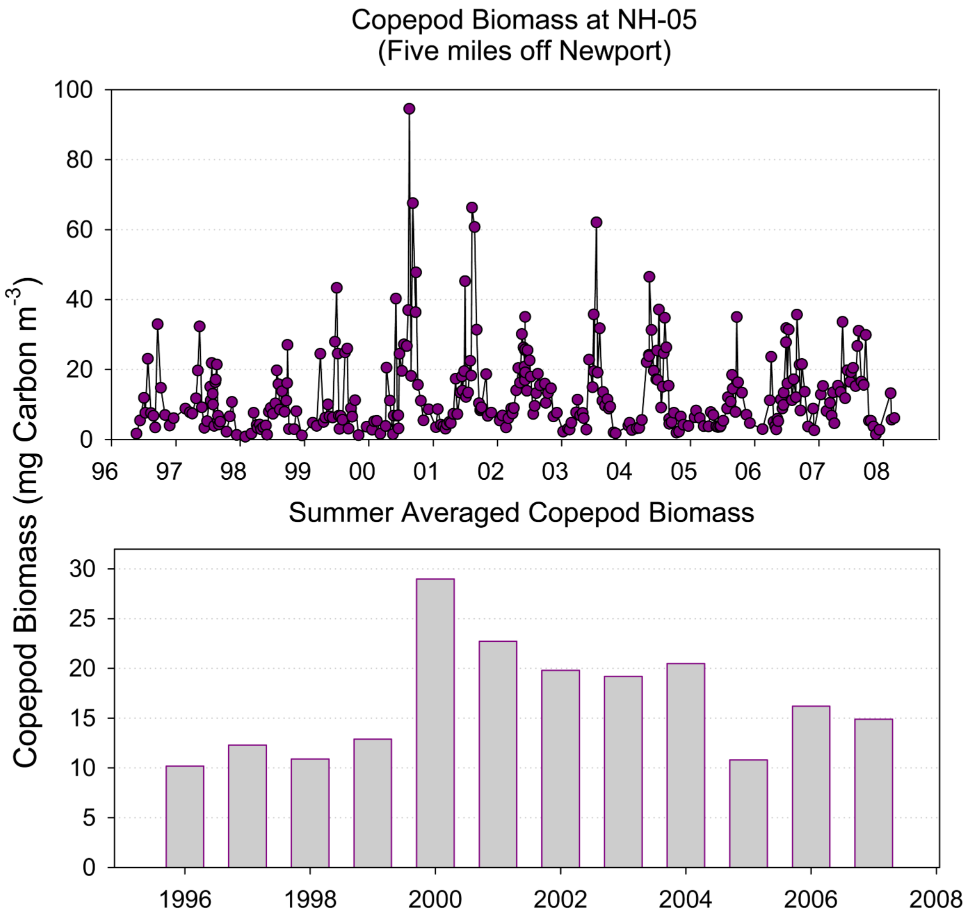

Figure 29. Newport Time series of monthly-averaged values of copepod biomass measured at a mid-shelf station, NH 05, from 1996–present, along with summer-averaged values of copepod biomass measured at NH 05.

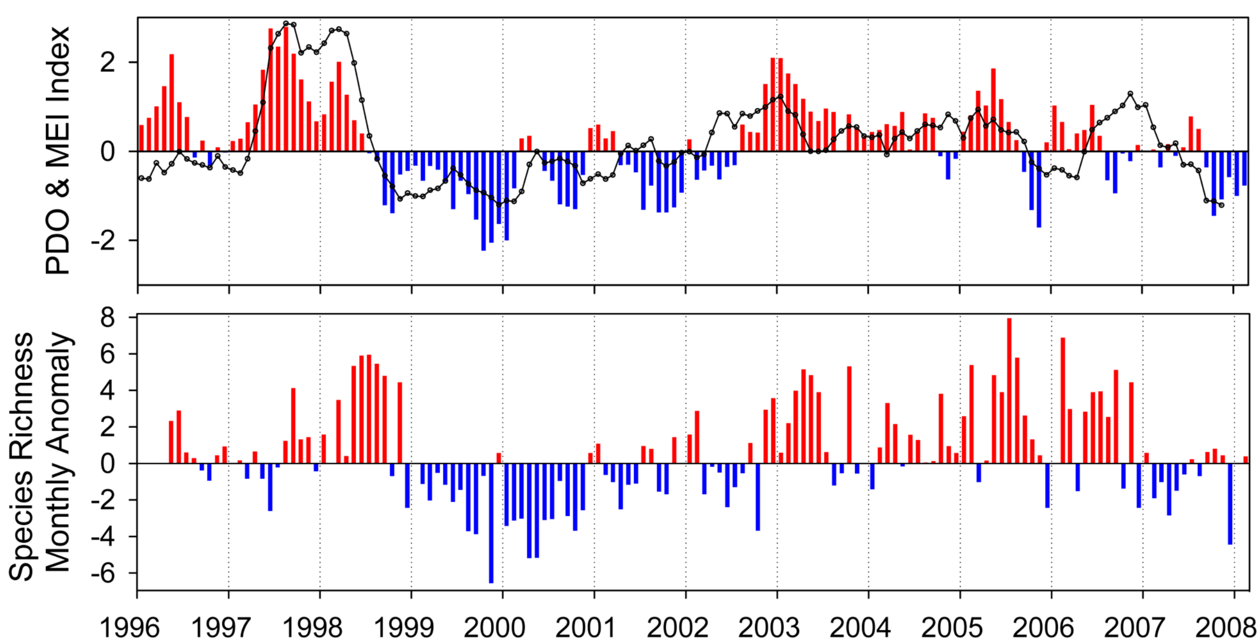

Figure 30. Time series of the Pacific Decadal Oscillation (upper panel, bars), Multivariate ENSO index (upper panel, line), and monthly anomalies of copepod species richness at station NH-05, from May 1996 through February 2008.

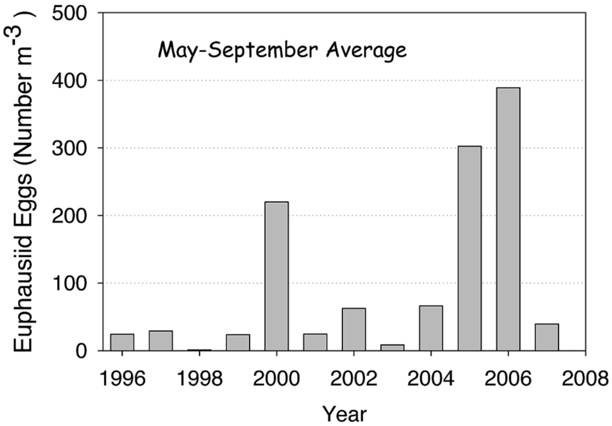

Figure 31. Time series of euphausiid eggs at NH 05, from 1996 through 2007. Note the extraordinary peaks in summer 2000, 2005, and 2006. Egg abundances were low in 2007.

1999–2002), whereas anomalously high numbers of species are associated with either a greater amount of onshore transport of warm, offshore, subtropical water, or northward transport of subtropical coastal neritic water along a coastal corridor (as in late 2002 to early 2006). See Hooff and Peterson (2006) for details.

The interannual variability in euphausiid egg abundances at station NH 05 (fig. 31) is very high; seasonal averages of egg abundances range over an order of magnitude among years. Highest abundances were seen in summers of 2000, 2005, and 2006. We attribute the enhanced egg concentrations in these years to higher numbers of adults in coastal waters during summer months. Low numbers suggest the absence of adult females in coastal waters.

CalCOFI Zooplankton: Macrozooplankton displacement volumes were slightly below long-term averages for the respective seasons in the spring and summer of 2007 and the winter of 2008. These were slightly above long-term averages during the fall of 2007 (fig. 32). Average macrozooplankton displacement volumes for 2007 continued the significant trend of declining zooplankton displacement volumes observed for the time period 1984 to 1998 and 1999 to 2007 (Goericke et al. 2007), with slopes for the two time periods which are virtually identical, -0.00020 and -0.00021 (± 0.00004 and 0.00005, respectively, fig. 32B).

Washington Forage Fish: Forage fish densities continued to follow the same trend as in 2006 of very low

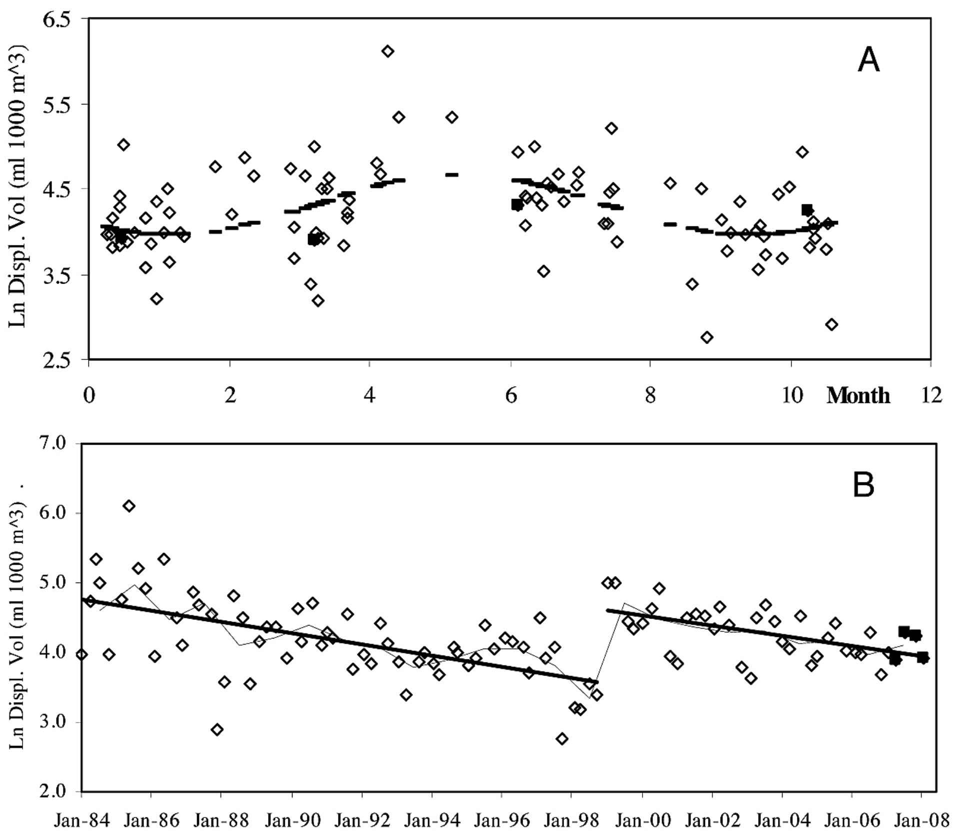

Figure 32. The natural logarithm of CalCOFI cruise-mean macrozooplankton displacement volumes (Ln Displ. Vol.) plotted against the month of the year (A), and the year (B). Annual averages are connected by thin solid lines. Results of regressions of Ln displacement volumes against time for the periods 1984 to 1997 and 1998 to 2006 are shown using the two straight lines.

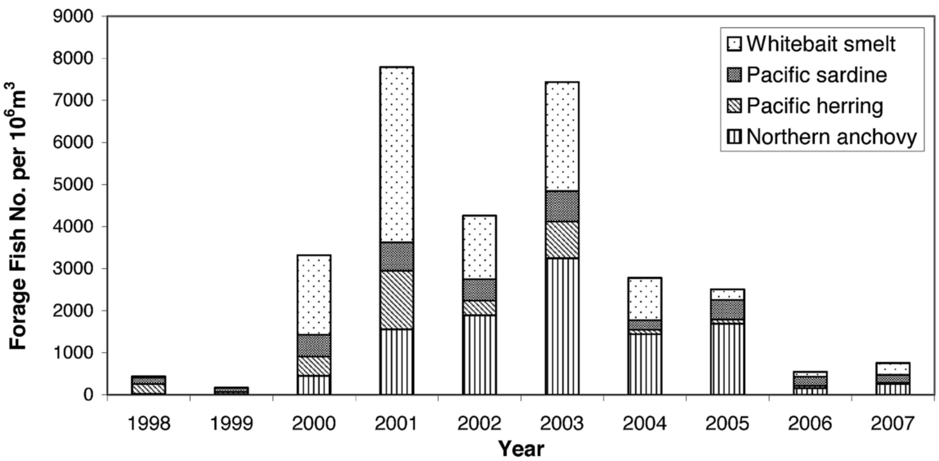

Figure 33. Forage fish densities averaged from rope trawls taken biweekly from May–August 1998 to present.

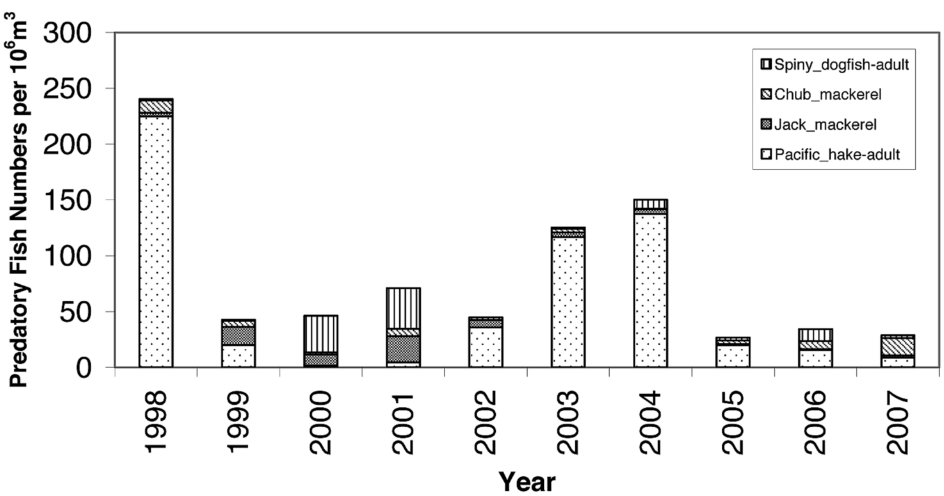

Figure 34. Predatory fish densities averaged from pelagic rope trawls taken biweekly from May–August 1998 to present.

abundances (fig. 33). This may have been due in part to low abundances of northern copepod species, which appears to be unfavorable for smelts, Pacific sardines, herring (*Clupea pallasi*), and northern anchovy. Highest abundances of forage fish were seen in 2000–03, and followed closely the four-year period of negative PDO in 1999–2002, but with a one-year lag.

Washington/Oregon Predatory Fish: Until recently, catches of predatory fish appeared to be related to warm ocean conditions—that is, highest numbers were found in shelf waters during the 1998 El Niño, and during the warm period 2003 and 2004. However, although warm conditions prevailed through 2005 and 2006, numbers of predatory fish declined in our pelagic rope trawl surveys (fig. 34). We have no explanation for this. Not shown in this graph are the high numbers of one-year-old Pacific hake (*Merluccius productus*) observed in 2007. These were 0-age in 2006 and were reported on by Phillips et al. (2007) at the 2006 CalCOFI meeting. Based on the recent occurrence of larval hake off Oregon and Washington and increased abundance of Age 0 and 1 fish, it seems likely that Pacific hake are now spawning in the northern California Current (Phillips et al. 2007).

CalCOFI Fish Spawning: In spring 2007, as in spring 2005, the eggs of Pacific sardine and jack mackerel were not as abundant as in other recent years. This was in contrast to the more abundant northern anchovy eggs (fig. 35). Sardine eggs were widely distributed, and most abundant between San Diego and Avila Beach (fig. 35). Sardine eggs were less abundant in the north, which was also the case in spring 2004. Anchovy eggs were confined to the Southern California Bight, and jack mackerel eggs were found offshore of the sardine eggs, with relatively little overlap, as found in many other years. The area between Avila Beach and Monterey was not sampled as planned due to weather conditions.

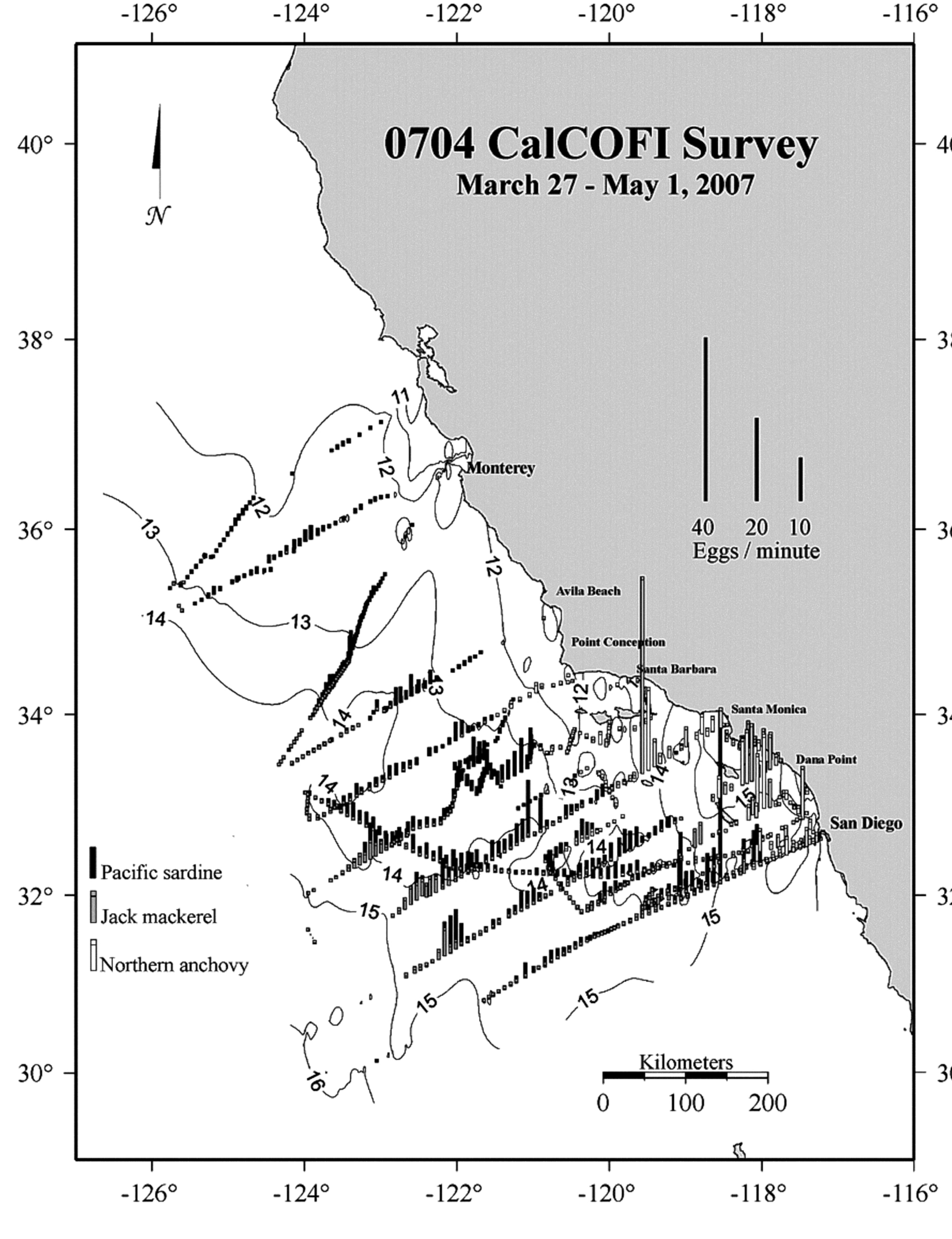

Figure 35. Rate of occurrence of eggs of Pacific sardine (*Sardinops sagax*), northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*) sampled with the continuous underway fish egg sampler (CUFES) and sea surface temperatures in 27 March–1 May 2007. One egg per minute corresponds to approximately 6.6 eggs per cubic meter (Note the ratio may vary from year to year).

Overall, the eggs of sardine and anchovy were more abundant than jack mackerel eggs.

In 2007 Pacific sardine eggs were found in temperatures between 10.1°C and 15.6°C. The weighted mean sea surface temperature was 13.8°C for the area occupied by the standard DEPM survey as compared to 14.95°C in 2006, 14.21°C in 2005, 13.4°C in 2004, and 13.7°C in 2003.

The spawning biomass of Pacific sardine is a fishery independent population index, and it is useful to see how the spawning related to the sea surface temperature in the past years based on CalCOFI surveys (Lo et al. 2007).

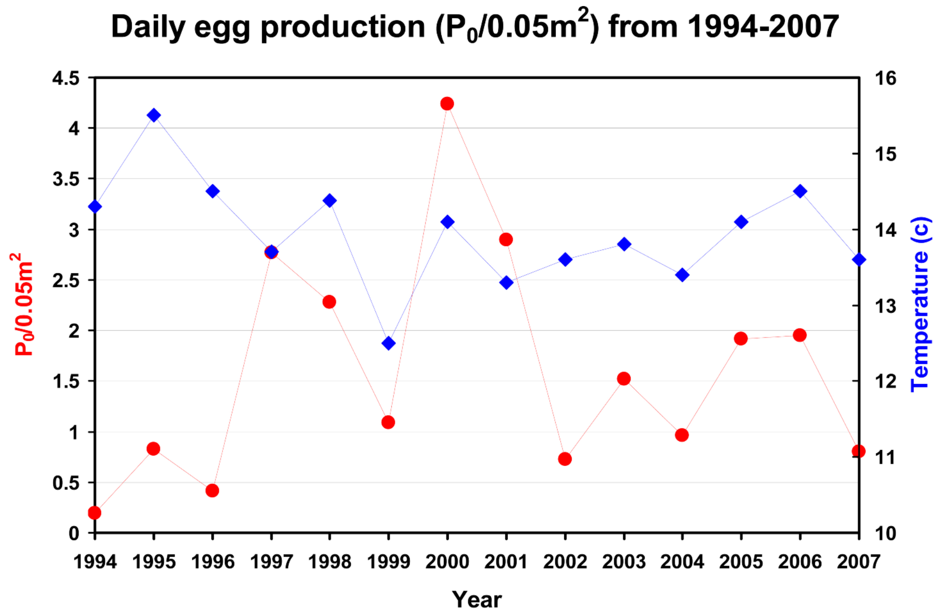

Figure 36. Daily egg production/0.05m² of Pacific sardine (circle) and average sea surface temperature (°C) (diamond) during March–April CalCOFI cruises from 1994–2007.

The spawning biomass of Pacific sardine is related to the daily egg production to some degree, in particular if the number of oocytes per biomass weight remains constant (Lo et al. 2005). The relationship between the daily egg production /0.05 m² and the average sea surface temperature (°C) during 1994–2005 indicated that in most years, except in 1997 and 2002, the increase of daily egg production coincides with the increase of sea surface temperature (fig. 36). This relationship is consistent with the assertion that high temperature is favorable for the Pacific sardine (Jacobs and MacCall 1995), in particular in recent years (after 2000, fig. 36).

CalCOFI Larval Fish and Squid in Relation to Oceanographic Features: In April 2007 the surface oceanography of the Southern California Bight showed strong physical features created by processes that were likely to affect the spatial distribution of larval fish. The important physical features (c.f. fig. 16) were two semi-coastal features in the northern (33.2°–34.5°N, 120°–122°W) and southern (32°–33.5°N, 117°–118°W) parts of the CalCOFI study area and the core of the California Current running roughly parallel to the coast (121°–123°W) with a meander at approximately (31°–33°N, 122°–124°W). Between these three features was a region of lower flows in the upper 200 m as well as a weak cyclonic eddy centered on station 83.80. Distributions of the Pacific sardine (*Sardinops sagax*) and market squid (*Loligo opalescens*) are discussed here in relation to this physical structure.

Pacific sardine larvae were anomalously high in abundance in spring 2007, but this anomaly was largely restricted to an approximately 50 km (east-west) by 150 km (north-south) area (fig. 37). The southern area of high sardine larval abundance was associated with the inshore edge of the California Current south of 31°N, and the northern area of high sardine larval abundance was associated with the region of low dynamic height gradients, east of the small cyclonic eddy at station 83.80. The sardine larvae were in a region of quite homogeneous temperature (approximately 14°–14.5°C) and salinity (33.4–33.45). The concentration of sardine larvae was associated with a minor positive anomaly in small zooplankton displacement volume.

A market squid paralarval concentration was found much closer to shore (200–300 km offshore along line 90) compared to the sardine larvae (400–500 km offshore), but were certainly not in the nearshore zone. The paralarvae were small, no more than a few days old, and the high concentration at station 90.53 was in the vicinity of the Tanner-Cortez Bank, not far from shallow water and potential squid spawning habitat (and a place where it is not unusual to find shorefish larvae). A second lower concentration at station 80.55 is just outside the mouth of the Santa Barbara Channel, where paralarvae might have been transported from the San Miguel-Santa Rosa spawning grounds. Squid were in slightly cooler water (13.5°–14°C) and slightly saltier water (33.45–33.5) than the sardine larvae (see fig. 16).

In summary, for 2007 the anomalies of Pacific sardine larvae were both related to well-defined oceanographic features. Sardine anomalies were positive in relation to the offshore edge of an eddy feature and to the inshore

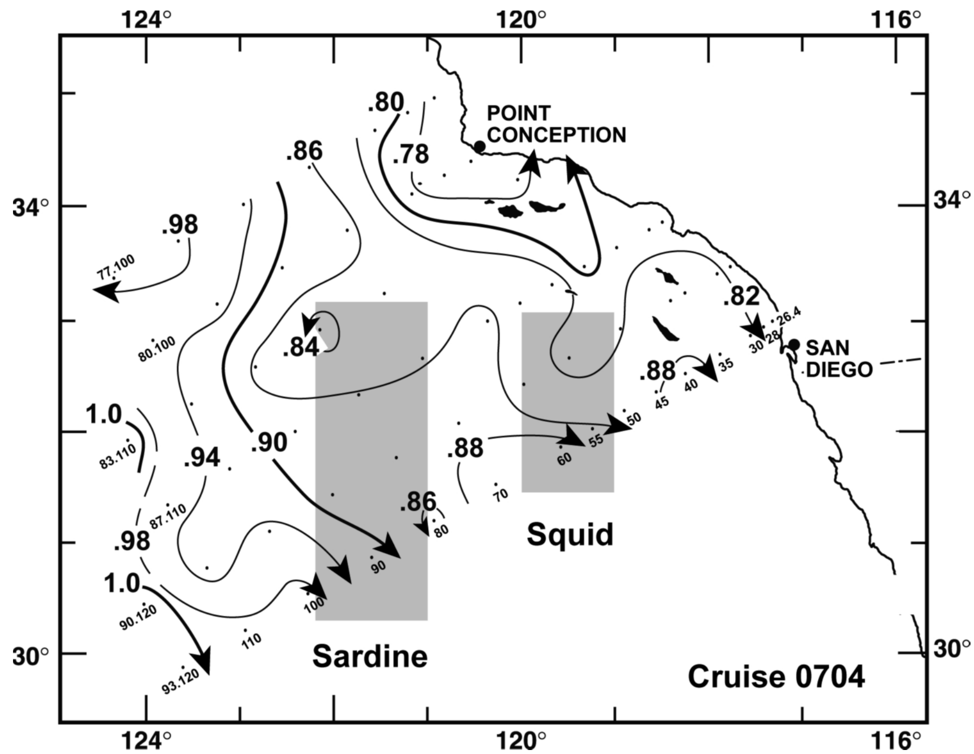

Figure 37. Dynamic height anomaly contours at 25 m referenced to 200 m indicating near-surface geostrophic flows. Shaded boxes show the location of positive anomalies in Pacific sardine (*S. sagax*) abundance (offshore) and market squid (*L. opalescens*) abundance (inshore).

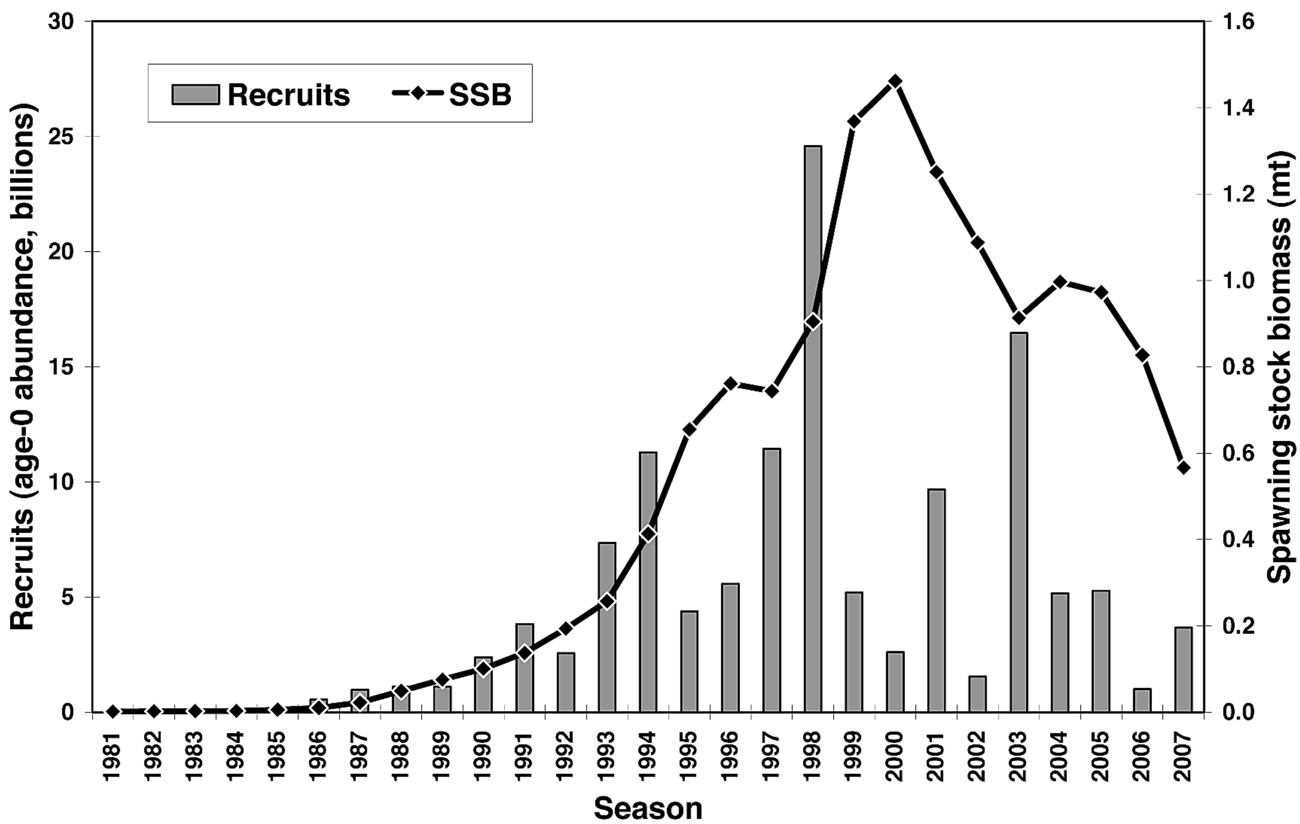

Figure 38. Pacific sardine spawning biomass and recruitment estimates from the Stock Synthesis 2 integrated assessment model.

edge of the California Current. Market squid paralarvae showed less relation to oceanographic structure and may have reflected proximity to spawning habitat.

Trends in Pacific Sardine Spawning Biomass and Recruitment: The SWFSC assesses the Pacific sardine population annually in support of the Pacific Fishery Management Council's process for establishing harvest limits for the U.S. fishery. The latest population assessment (Hill et al. 2007), based on the fully-integrated model Stock Synthesis 2 (SS2; Methot 2005), incorporated a time series of spawning stock biomass from the egg production surveys conducted each spring between San Diego and San Francisco (Lo et al. 2007), as well as 27 years of catch, size, and age composition data from fisheries occurring between Ensenada and British Columbia.

SS2 model estimates of recruitment (year-class abundance) and spawning stock biomass are presented in Figure 38 (Hill et al. 2007). Recruitments increased rapidly from the early 1980s through the 1990s, peaking at 24.6 billion age-0 fish in 1998. Recruitments have been relatively lower since 1999, with the exception of the 2003 year class, which was the second highest in recent history (16.5 billion fish). As a result of declining year-class production, sardine spawning stock biomass, which peaked at 1.46 million mt in 2000, has since trended steadily downward.

Reasons for declining sardine production since the late 1990s are currently unknown. Exploitation by the combined fisheries is relatively low (about 15%), so overfishing is an unlikely explanation for the decline. The Scripps Pier based temperature criterion for the sardine harvest guideline remains high (see Hill et al. 2007).

Avifauna: CalCOFI research cruises have provided the opportunity to relate fluctuations in marine bird community structure to changes in physical and biological attributes of the California Current large marine ecosystem over inter-annual and longer temporal scales (Hyrenbach and Veit 2003; Yen et al. 2006). Colony-based studies of seabird reproductive performance and diet have also documented coupled climate-ecosystem fluctuations at multiple temporal scales (Sydeman et al. 2001; Mills et al. 2007). Herein we place these recent observations (2007) of seabird reproductive performance and community structure at-sea in the context of the conditions experienced since the transition from a warm to a cold regime of the Pacific Decadal Oscillation (PDO) in the late 1990s (Bograd et al. 2000).

Most recently, summer-time CalCOFI surveys and colony-based studies have documented unprecedented breeding failures and nest abandonment by planktivorous auklets on the Farallon Islands (central California), in response to unusual atmospheric and oceanographic conditions in 2005 and 2006 (Sydeman et al. 2006; Goericke et al. 2007). To interpret the oceanographic mechanisms responsible for these auklet responses, we investigate the response of planktivorous auklets to basin-scale (north Pacific Ocean) and regional-scale (CCS) environmental conditions using a nine-year time series (1999–2007).

Farallon Island Seabird Productivity: We have observed seabird productivity for six species breeding at southeast Farallon Island (SEFI) for 36 years (1971–2006). To illustrate life-history variation, we have grouped species according to basic reproductive patterns: those producing a single egg clutch (Cassin's auklet *Ptychoramphus aleuticus*, common murre *Uria aalge*, rhinoceros auklet *Cerorhinca monocerata*) and those producing multiple-egg clutches (Brandt's cormorant *Phalacrocorax penicillatus*, pigeon guillemot *Cepphus columba*, pelagic cormorant *Phalacrocorax pelagicus*).

All six marine bird species experienced an increase in reproductive success from the previous year (2006), even though four species experienced negative anomalies well below the long-term (1999–2007) mean (fig. 39). Only the Brandt's cormorant and the common murre performed at a level exceeding the baseline of the last nine years. Most notably, the Cassin's auklet experienced a recovery in reproductive success (0.31 chicks per breeding pair) after two years of complete failures (0.00 chicks per breeding pair) in 2005 and 2006. Yet, this value falls well below the long-term (36-year) average of ~0.7 chicks per pair (Sydeman et al. 2001, 2006) and the reproductive success experienced in recent "normal" periods (0.83 chicks per breeding pair in 1999–2000), and in very productive years when some birds raised more than one chick (1.11 chicks per breeding pair in 2001–02; fig. 39).

Clustering of seabird productivity data over the nine-year period revealed three distinct clusters. The current year (2007), clustered with the last two years of breeding failures (2005, 2006; fig. 40), and contrasted sharply with the first two years (1999, 2000) of high seabird productivity for all species. Three years of intermediate productivity (2001, 2002, 2004) clustered together, despite inter-annual fluctuations. The only year that stood out alone was 2003, a warm-water year characterized by depressed reproductive success for all six seabird species monitored.

Seabirds at Sea in the CalCOFI Region: To illustrate fluctuations in marine bird communities, we focus on three sub-arctic species, indicative of cold-water conditions in the CCS: the locally-breeding Cassin's auklet and common murre and the sooty shearwater (*Puffinus griseus*), a spring–fall visitor from the southern hemisphere (fig. 41). The at-sea abundances of the shearwater, murre, and auklet have declined in the southern CCS over the long-term (1987–98), despite incursions during cold-water years (Hyrenbach and Veit 2003; Bograd et al. 2000).

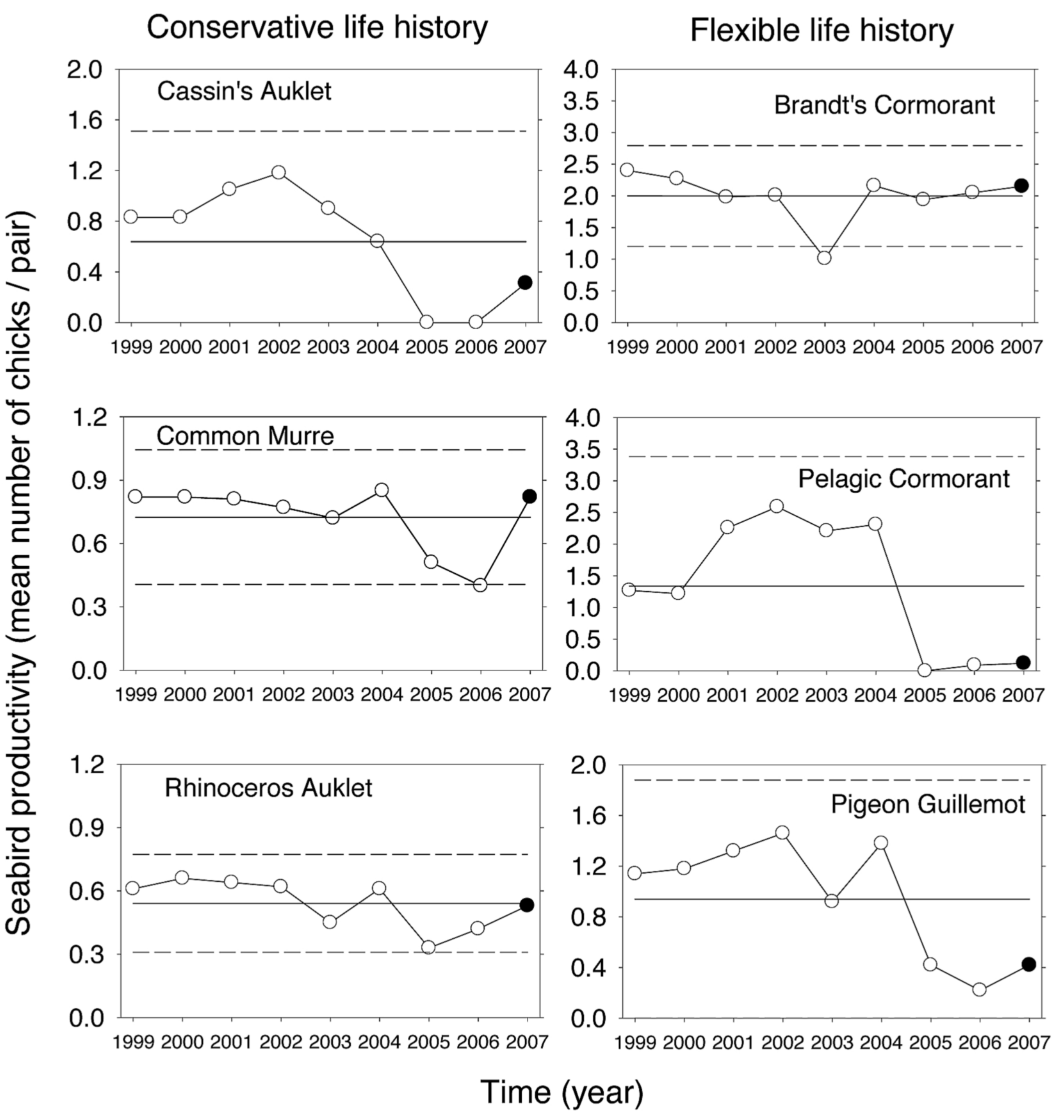

Figure 39. Productivity of six seabird species breeding at the Farallon Islands (37° 42'N; 123° 00'W). The long-term average (1999–2007) productivities are depicted by the solid horizontal lines, and the hatched lines illustrate the year-to-year variability (mean + 2 S.D.). Filled circles highlight productivity values in 2007.

More specifically, to investigate the extent of the Cassin's auklet post-breeding redistribution southwards into the Southern California Bight, we focus on summer-time (July) CalCOFI–CCE LTER cruises. The summer densities of the sooty shearwater and the common murre were anomalously low in 2007 (fig. 41). Only the auklet abundance was anomalously high, reaching the highest value observed since 1999.

Responses of Planktivorous Auklets: Together, the two dominant principal component (PC) factors explained 65% of the observed variance. The first factor was characterized by positive loading of auklet density at sea, positive loading of upwelling indices (winter, early spring, late spring), and negative loadings of MEI and PDO (in early and late spring). This PC underscores the links between regional upwelling dynamics, basin-wide atmospheric and oceanographic processes, and seabird distributions at sea. The second PC, which was characterized by contrasting loadings of auklet at sea abundance (positive) and productivity (negative), had positive MEI and PDO loadings (late winter, early spring, late spring). Most notably, late spring (May–June) upwelling at 36°N had a large negative loading, highlighting the importance of local productivity to auklets breeding off central California (SEFI).

Avifauna Conclusions: In 2007, the reproductive performance of Farallon seabirds was better than in 2005 and 2006 (fig. 39). Surprisingly, 2007 clustered with the two preceding years of breeding failures (2005 and 2006) (fig. 40), even though we found anomalously high at-sea

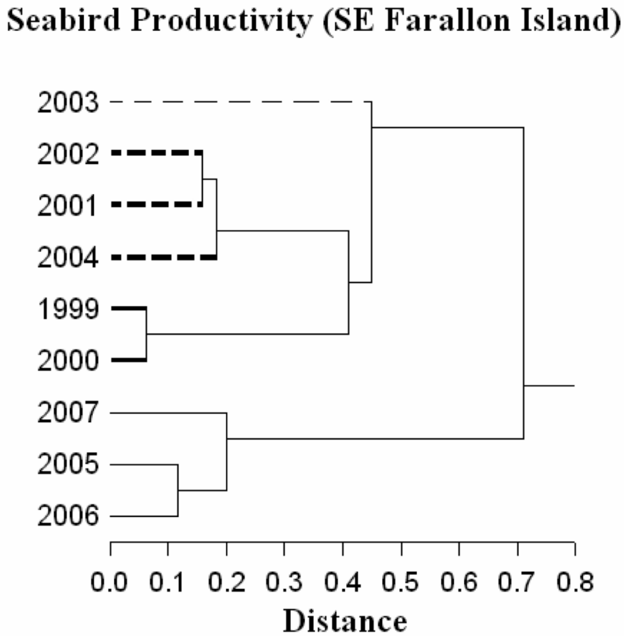

Figure 40. Cluster tree of marine bird productivity for the seabirds breeding on the Farallon Islands. The Euclidean distances are based on the hierarchical clustering technique, with the median linkage algorithm. The thickness and hatching of the lines identify those years in the same cluster.

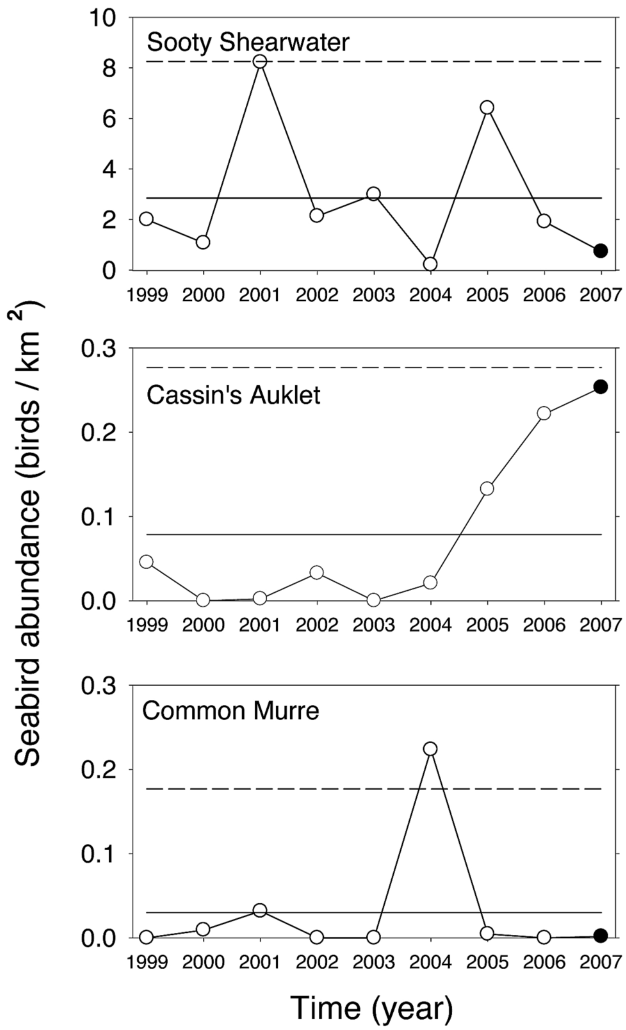

Figure 41. At-sea abundance of three seabird species with an affinity for cold-water conditions during summertime CalCOFI–CCE LTER cruises. The long-term average (1999–2007) densities are depicted by the solid horizontal lines and the hatched lines illustrate the year-to-year variability (mean + 2 S.D.). Filled circles highlight abundances in 2007.

densities of planktivorous auklets for the third summer in a row (fig. 41). Despite the concurrent increase in auklet reproductive success and at-sea abundance in 2007, these two metrics remain negatively correlated across the time series (Spearman rank, rs = –0.65, n = 9). This result underscores the notion that large numbers of auklets disperse southwards into the CalCOFI region in years of poor reproductive success and high nest abandonment (Sydeman et al. 2006). Furthermore, the PCA highlights the responses of planktivorous auklets to basin-wide and regional-scale oceanographic variability. We contend that the observed changes in colony productivity and at-sea distributions are mediated by shifts in the regional availability of prey resources, in this case the abundance of the euphausiids *Thysnoessa spinifera*, *Euphausia pacifica*, and *Nyctihanes simplex*.

DISCUSSION

The California Current system (CCS) has overall been in a cool phase since the 1998–2000 ENSO event. A variety of system parameters responded strongly to this forcing. Examples of the parameters that responded strongly to this "regime shift" are SST in many areas of the CCS (e.g., Monterey, fig. 10A, CalCOFI area, fig. 13 A), nutricline depth in the CalCOFI area (fig. 25), concentrations of chlorophyll *a* in Monterey Bay (fig. 10C), and zooplankton displacement volume in the CalCOFI area (fig. 32). Current values of these parameters suggest that this basic state of the system has not changed.

The El Niño of 2006 was of moderate strength in the equatorial Pacific but had little effect on the CCS (Goericke et al. 2007). El Niño conditions ended in early 2007 and since the late spring of 2007 various indicators displayed La Niña conditions (e.g., the NINO 3.4 indicator, fig. 2A). By early 2008 these indicators had attained values only previously observed during the strongest La Niña's of the last few decades. Mixed-layer temperatures off central and southern California responded strongly to these conditions, attaining values similar to those observed during the 1999–2000 La Niña (figs. 10A and 13A). Interestingly, neither SST off Oregon (fig. 6A) nor SST off Baja California responded to these conditions; indeed, unusually high mixed-layer temperatures were observed off Oregon during the summer and off southern Baja during 2007 (fig. 20). Biological properties of the system showed barely discernable responses; examples are copepod biomass off Oregon (fig. 29), chlorophyll *a* concentrations off Monterey (fig. 10C), and chlorophyll *a* concentrations and zooplankton displacement volumes off southern California (figs. 27A and 32B). This result is surprising since these parameters, with the exception of chlorophyll *a* off southern California, showed a very strong response to the 1999–2000 La Niña conditions. It must be noted that copepod species richness off Oregon changed significantly in 2007 compared to the previous years (fig. 30). However, the change was observed even before La Niña conditions set in, so these changes cannot be unambiguously attributed to La Niña.

Higher trophic levels did not respond systematically to the La Niña conditions in the CCS. The biomass of forage and predatory fish off Oregon and small pelagic fish off California is too variable to attribute any specific change to a single cause. Furthermore, if fish were directly affected by SST, as opposed to system state, these would be expected to respond to the unusually warm conditions off Oregon during the summer. Seabird productivity on the Farallon Islands might have been expected to be affected by the La Niña conditions. However, the timing of the upwelling season is another important factor. The response of seabird productivity during 2007 was mixed. Even though upwelling started early off central California and was strong, seabird productivity for seabirds with conservative life histories showed only modest increases, with the exception of the common murre, which showed a dramatic change. Productivity of seabirds with flexible life histories hardly changed at all compared to the previous two years when productivity was very low.

ACKNOWLEDGMENTS

This report would have been impossible without the dedicated work of the ship crews and the technician groups that collected the data, often under adverse conditions, and processed these ashore. NH-line CTD data from both LTOP and PaCOOS programs was processed by Jane Fleischbein. The GLOBEC LTOP program in the northern California Current is supported by the National Science Foundation (OCE-0000733 and OCE-0434810). The May, June, and November 2004 sampling of the NH-line sampling was supported by the National Oceanic and Atmospheric Administration. CalCOFI cruises off southern (central) California were supported by NOAA (NOAA/JIMO NA17RJ1231). We thank the NOAA and Scripps CalCOFI technicians—Dave, Amy, Dimo, Dave, Kathryn, Jennifer, Jim, and Robert—and volunteers who collected data at sea and who processed the data ashore. The IMECOCAL project thanks officials and crew of CICESE RV *Francisco de Ulloa*, as well as students and technicians participating in the surveys of 2007 and 2008. Special thanks to J. García, J. L. Cadena, and M. de la Cruz. IMECOCAL surveys were supported by SEP-CONACYT 23947 and SEMARNAT-47044 projects. M. de la Cruz was responsible for chlorophyll *a* analysis. The work off northern California was supported by Captain and crew of the Humboldt State University's RV *Coral Sea* and numerous student volunteers who assisted with the data collection. The PRBO studies on CC seabirds have been supported by the U.S. Fish and Wildlife Service, Packard Foundation, Resources Legacy Fund Foundation, Friends of the Farallones, and PRBO. This is PRBO contribution no. 1631. PRBO staff and volunteers collected the data on seabird reproductive success at SEFI and seabird distribution and abundance at sea on CalCOFI–CCE LTER cruises. Christine Abraham and Chris Rintoul managed the seabird databases used in this report. We thank Andy Leasing and Alec MacCall for their reviews of the manuscript.

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