

## THE STATE OF THE CALIFORNIA CURRENT, 2006–2007: REGIONAL AND LOCAL PROCESSES DOMINATE

RALF GOERICKE, ELIZABETH VENRICK,  
TONY KOSLOW

Integrative Oceanography Division  
Scripps Institution of Oceanography  
La Jolla, California 92093-0218  
rgoericke@ucsd.edu

WILLIAM J. SYDEMAN

Farallon Institute for  
Advanced Ecosystem Research  
P.O. Box 750756  
Petaluma, California 94975

FRANKLIN B. SCHWING,  
STEVEN J. BOGRAD

NOAA Fisheries, Southwest Fisheries Science  
Center Environmental Research Division  
1352 Lighthouse Avenue  
Pacific Grove, California 93950-2097

WILLIAM T. PETERSON,  
ROBERT EMMETT

National Marine Fisheries Service,  
Northwest Fisheries Science Center  
Hatfield Marine Science Center  
2030 SE Marine Science Drive  
Newport, Oregon 97365

J. RUBÉN LARA LARA,  
GILBERTO GAXIOLA CASTRO

Departamento de Oceanografía Biológica  
Centro de Investigación Científica y Educación  
Superior de Ensenada  
Apartado Postal 2732  
Ensenada, Baja California, México 22860

JOSÉ GÓMEZ VALDEZ

Departamento de Oceanografía Física  
Centro de Investigación Científica y  
Educación Superior de Ensenada  
Apartado Postal 2732  
Ensenada, Baja California, México 22860

K. DAVID HYRENBACH

Duke Center for Marine Conservation  
Duke University Marine Laboratory  
135 Duke Marine Lab Road  
Beaufort, North Carolina 28516

RUSSEL W. BRADLEY

Marine Ecology Division  
PRBO Conservation Science  
3820 Cypress Drive, No. 11  
Petaluma, California 94954

MICHAEL J. WEISE

Dept. of Ecology and Evolutionary Biology  
University of California, Santa Cruz  
Center for Ocean Health  
100 Shaffer Road  
Santa Cruz, California 95060

JAMES T. HARVEY

Moss Landing Marine Laboratories  
8272 Moss Landing Road  
Moss Landing, California 95039

CURTIS COLLINS

Department of Oceanography  
Naval Postgraduate School  
833 Dyer Road  
Monterey, California 93943

NANCY C. H. LO

NOAA Fisheries,  
Southwest Fisheries Science Center  
8604 La Jolla Shores Drive  
La Jolla, California 92038

### ABSTRACT

The state of the California Current System (CCS) between Oregon and Baja California is summarized in this report, covering spring 2006 to spring 2007. Observations reported here are based on contributions from various ocean observing programs along the West Coast of North America. Basin-scale indicators were variable or neutral over the last year. This indeterminate forcing was reflected in conditions in the CCS where no coherent patterns emerged, i.e., no single “state” could be ascribed to the system. Rather, regional or local processes dominated observed patterns. Similar to last year, delayed upwelling off Oregon and central California dramatically affected higher trophic levels: euphausiid recruitment was delayed and as a likely consequence seabird productivity off Central California was extremely depressed. For example, Cassin’s auklet had a complete reproductive failure, similar to 2006. Observations during the spring of 2007 demonstrate that these patterns were ephemeral since upwelling was normal and seabird productivity improved. Off southern and Baja California, upwelling-favorable winds were also weak or delayed during 2006, but biological consequences appear to have been relatively minor.

### INTRODUCTION

This report summarizes the climatology, oceanography, and biology of the California Current System (CCS) between the spring of 2006 and the summer of

2007. It is based on observations taken between Oregon and Baja California (fig. 1A). Participating programs or institutions include the Pacific Fisheries Environmental Laboratory (PFEL) providing basin- and coast-wide climatologies, the NOAA/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. 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.

Over the last decade the CCS has experienced dramatic changes. The system entered a cool phase after the El Niño of 1997–98 (Hayward et al. 1999). This cool state was reflected by strong negative values of the Pacific Decadal Oscillation (PDO, fig. 2) and by negative sea surface temperature (SST) anomalies throughout the CCS. Off Oregon and southern California, the transition into a cold regime was accompanied by dramatic changes in zooplankton biomass and community structure (Brinton and Townsend 2003; Lavaniegos and Ohman 2003; Peterson and Schwing 2003). However, concentrations of chlorophyll *a* (Chl *a*), a proxy for phytoplankton biomass, did not respond significantly to this change from a warm to a cool phase.

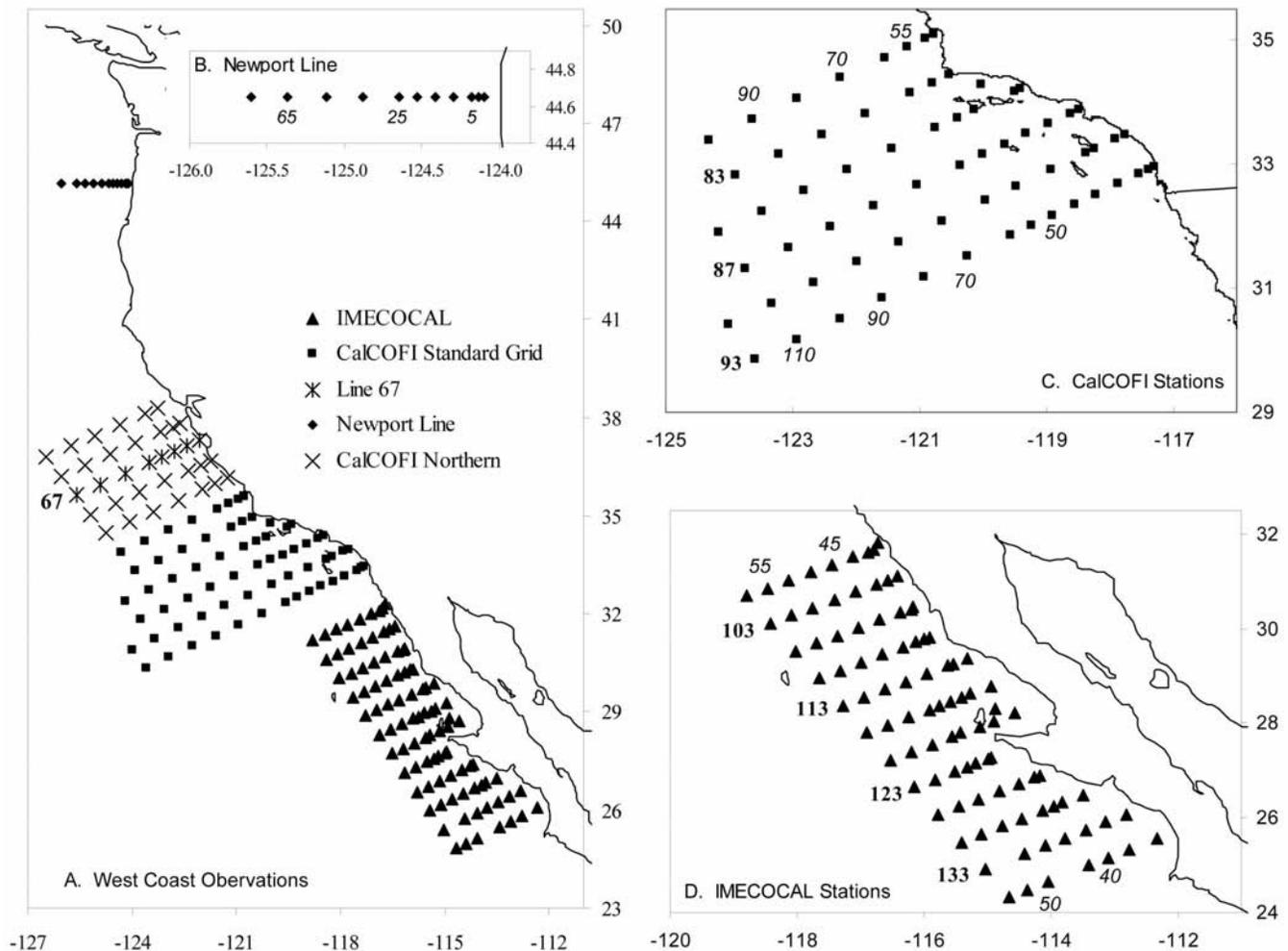


Figure 1. Location of stations where observations were made for this year's report. Observational lines are labeled using bold numbers positioned west of the line terminus; stations are labeled using numbers in italics immediately below or above the respective stations. Line and station numbers for the IMECOCAL and CalCOFI programs are following the CalCOFI line and station nomenclature. The IMECOCAL program covers all lines out to stations 60, i.e., the westernmost station on any IMECOCAL line is 60. The CalCOFI program covers lines 93 and 90 out to station 120, lines 87 and 83 to stations 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 along line 67 off Monterey Bay. The Newport line is covered biweekly out to station 25 and occasionally further offshore.

This cool phase lasted for about three years (Goericke et al. 2004). In 2002–03 a weak El Niño developed in the equatorial Pacific and the PDO became positive. Off Oregon SST anomalies also became positive, and off southern California SSTs increased. This switch of the PDO was not accompanied by any dramatic changes of zooplankton biomass or indicators of zooplankton community structure. Seabird communities, however, showed a shift from temperate-cold species to subtropical species. Central California male sea lion activity patterns responded to the warmer water, concurrent with geographic shifts in prey distribution (Brodeur et al. 2006). Chlorophyll *a* off southern California was not affected by this change. Off Oregon, summertime chlorophyll *a* has been variable but has

not changed systematically over the last decade. Thus, these time series showed no responses to the positive PDO in 2002.

Over the last four years, PDO signals have varied little (fig. 2). Significant events during the last four years were often driven by regional or local factors. The intrusion of subarctic surface waters into the CCS (Venrick et al. 2003) significantly affected concentrations of nutrients and chlorophyll *a* off Oregon. Off southern California the salinity anomalies were strong but confined only to the upper 200 m. These were accompanied by unusually low concentrations of silicic acid, which may have affected the growth of diatoms (Goericke et al. 2005). Off Baja California a pronounced negative salinity anomaly was observed but no other effects were

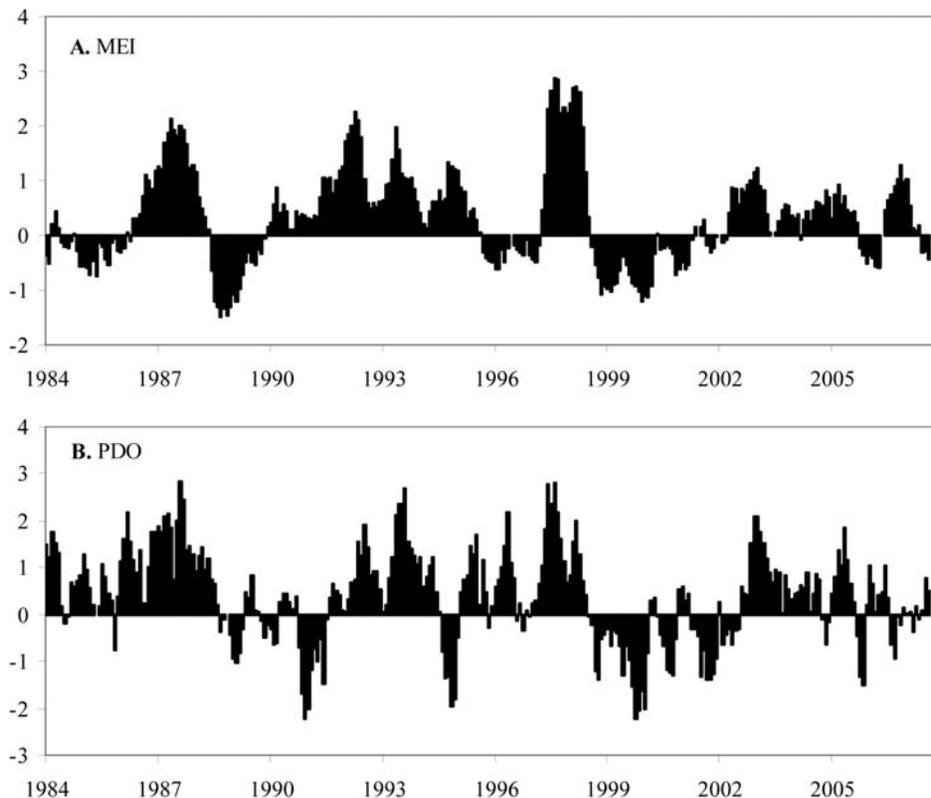


Figure 2. Time series of (A) the Multivariate ENSO Index (MEI, <http://www.cdc.noaa.gov/people/klaus.wolter/MEI/>) and (B) the Pacific Decadal Oscillation (PDO, <http://jisao.washington.edu/pdo/PDO.latest>) for the time period 1984 to August 2007.

reported. Upwelling off Oregon has been variable over the last four years, possibly affected by the position of the Jet Stream (Peterson et al. 2006). A delayed onset of upwelling in 2005 was accompanied by low abundances of euphausiids off Oregon and central California. The absence of these key prey species may have led to the unprecedented failure of Cassin's Auklet (*Ptychoramphus aleuticus*) recruitment at the Farallon Island colony in central California (Sydeman et al. 2006).

#### DATA SETS AND METHODS

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  $2^{\circ} \times 2^{\circ}$ ) 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 ( $21^{\circ}$ – $52^{\circ}$ 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  $44.65^{\circ}$ N (fig. 1A) continues on a biweekly basis along the inner portions of the line, at 7 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—Central California

CTD sections extending offshore off Monterey Bay to a distance of 315 km (CalCOFI Line 67, fig. 1B) have been carried out on a regular basis since 1997. CTD station spacing is 10 n. miles and the water column is sampled to a depth of 1000 m.

#### Regional Analyses—CalCOFI

The CalCOFI program continues to occupy 66 standard stations (fig. 1C) on a quarterly basis. Results from

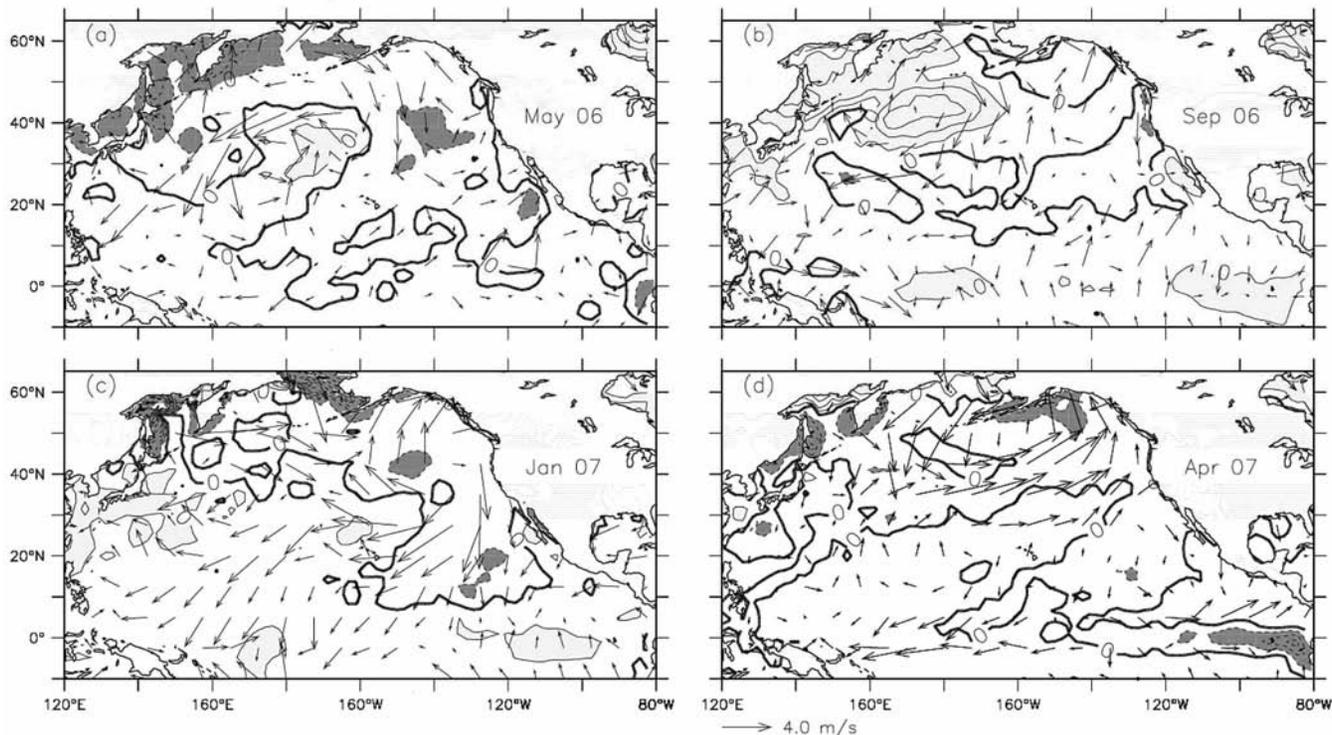


Figure 3. Anomalies of surface wind velocity and sea surface temperature (SST) in the north Pacific Ocean, for (A) May 2006, (B) September 2006, (C) January 2007, and (D) April 2007. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative (cool) SST anomalies are shaded. Wind climatology period is 1968–96. SST climatology period is 1950–79.

cruises in April, July, and November of 2006 and January 2007 are presented here. At each station, bottom depth permitting, water column properties (conductivity, temperature, pressure, oxygen, fluorescence, and light transmission) are continuously measured to a depth of ~ 525 m; salinity, dissolved oxygen, and nutrients are determined throughout the water column from 20 water samples; chlorophyll is determined from the top 14 bottles; and standard (505  $\mu\text{m}$  mesh) oblique bongo tows are conducted to 210 m depth. Detailed descriptions of sampling and analytical protocols and data reports from past cruises are archived on the CalCOFI website (<http://www.calcofi.org>).

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 1984–2006 time series. The mixed-layer (ML) depth is calculated using a density criterion and set either to 12 m or to the half-way point between those 2 sampling depths where the sigma-theta gradient first reaches values larger than 0.002 per m, whichever is larger. The 12 m cutoff avoids including the diurnal thermocline in the analysis. This procedure will introduce a positive bias in calculating 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  $\mu\text{M}$ , calculated from measure-

ments at discrete depths using linear interpolation. Anomalies are based on the period 1984–present. Two hundred meter anomalies are based on data from all offshore stations (numbers 60 and higher). Mesozooplankton displacement volumes were reprocessed for this year's analysis. Previously, untransformed values were averaged and plotted, at times on a log scale. For this year's analysis, displacement volumes for individual stations were log-transformed and then averaged over all stations. Individual data points are different, but major seasonal and interannual features are unchanged.

### Regional Analyses–IMECOCAL

The IMECOCAL monitoring program began in autumn 1997, consisting of quarterly cruises surveying 93 stations off Baja California, México (fig. 1D). The core oceanographic data set collected at each station includes a conductivity-temperature-depth (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, chlorophyll *a*, nutrients (NO<sub>3</sub>, NO<sub>2</sub>, PO<sub>4</sub>, SiO<sub>3</sub>), and primary production. IMECOCAL cruises schedules, data collection, methods, and analyses are fully described at <http://imecocal.cicese.mx>.

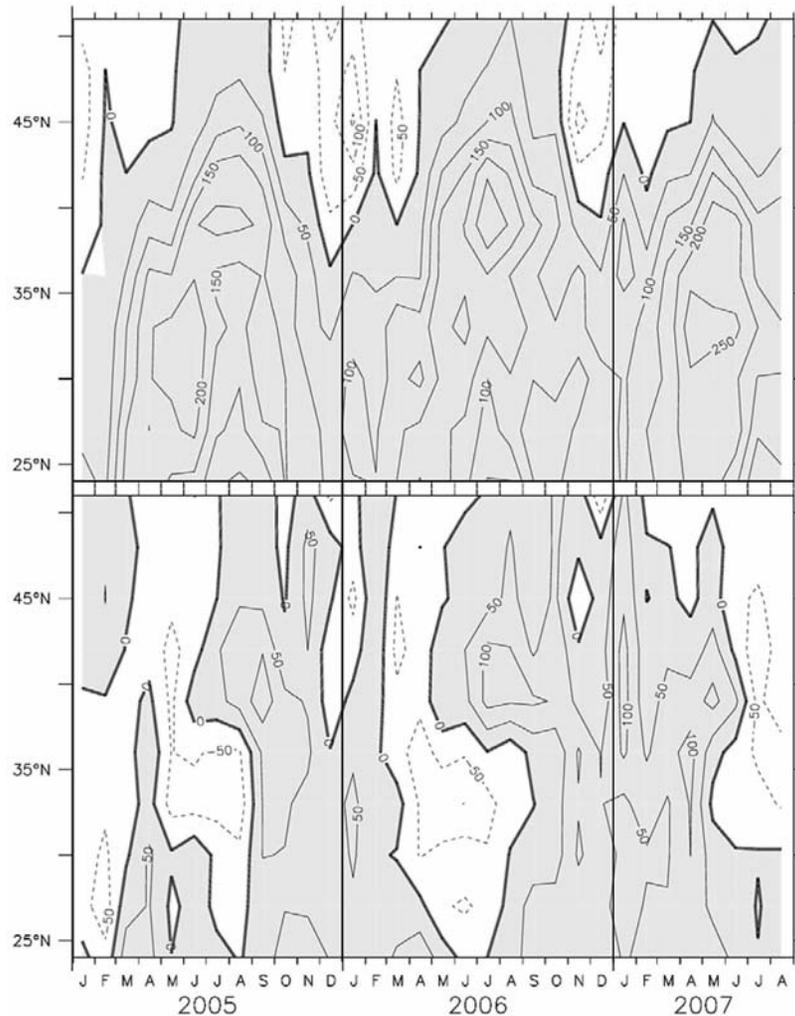


Figure 4. Monthly upwelling index and upwelling index anomaly for January 2005–August 2007. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in  $m^3/s$  per 100 km of coastline.

### Fish Egg Surveys off California

In 2006, a coast-wide survey for sardine was conducted in April–May to cover the area from San Diego, U.S., to British Columbia, Canada, with ichthyoplankton samples taken aboard the NOAA RV *Oscar Dyson* (11 April–8 May) and the NOAA RV *David Starr Jordan* (5–28 April), plus the routine CalCOFI cruise aboard SIO RV *New Horizon* (1–18 April). The *Dyson* occupied 17 transects from latitude 51°N to 30.7°N. The *Jordan* occupied 10 CalCOFI lines (95.0–51.7°N). CUFES samples were taken aboard the *Dyson* and *Jordan* but not on the *New Horizon*.

### California Sea Lion

Diet studies of California sea lion (*Zalophus californianus*) have been conducted in central California from 1997 to the present. Included are sites in Monterey Bay from 1997 to 1999 and Año Nuevo Island (37°6'N,

122°20'W) from 2001 to 2006, which is one of the largest haul-out sites for sea lions in central and northern California (Weise 2000; Lowry and Forney 2005). Annual variation in sea lion diet was determined by identifying fish otoliths and cephalopod beaks found in fecal samples collected at Año Nuevo Island. Prey hard parts were measured and species-specific correction factors were used to estimate standard length and mass of prey consumed (Orr and Harvey 2001). To detect changes in sea lion diet in relation to climatic forcing, each prey species in the diet for each year was expressed as an anomaly of the mean percentage of the total ingested mass (%M) of that prey species.

### 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).

## LARGE-SCALE PATTERNS

The North Pacific was dominated in recent months by an unusually strong North Pacific high pressure system, which created anomalously strong clockwise winds over the northeast Pacific (fig. 3). This was particularly strong during the fall and winter of 2006–07. Associated with this wind pattern were unusually cool sea surface temperatures (SST) through much of the northeast Pacific (fig. 3).

The large-scale climate indices commonly used to assess the interannual state of the Pacific were generally unremarkable in 2006 and 2007. The Multivariate ENSO Index (MEI; fig. 2A; Wolter and Timlin 1998) indicated weak equatorial Pacific El Niño conditions through the end of 2006, and an ENSO-neutral state since. A positive Northern Oscillation Index (NOI), indicative of La Niña-like conditions and upwelling-favorable winds in the CCS, has been seen throughout 2006–07. Much of the tropics have been dominated by the 60–90 day signal of the Madden-Julian Oscillation (MJO), and Pacific SSTs have been described as “extremely volatile.” The PDO signal (fig. 2B) remained positive (warm phase) for the first half of 2006, but switched signs briefly in July 2006 and has been neutral since the fall of 2006.

The regional expressions of this large-scale pattern are anomalously strong southward coastal winds and stronger than normal upwelling along the West Coast over the last year (fig. 4). After a period of anomalously weak upwelling in spring and early summer of 2006, particularly in the Southern California Bight, the CCS experienced stronger-than-normal upwelling in late summer and fall. Unlike 2005 and 2006, when the onset of seasonal upwelling in spring was up to two months later than usual (Schwing et al. 2006), the 2007 upwelling season began early, and upwelling remained unseasonably strong through May.

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. 5). 2007 has been unusual in its relative lack of relaxation events, which are periods of northward (downwelling) wind when on-shore recruitment of pelagic larval stages can occur. Buoy SSTs have been anomalously cool during 2007 (fig. 6). Note especially the cool SSTs in May 2007 compared to those in May of the past two years.

**Projection:** SST and other measures of the equatorial Pacific suggest developing La Niña conditions as of fall 2007 (NOAA CPC Climate Diagnostics Bulletin, <http://www.cpc.ncep.noaa.gov>). Most models project a weak La Niña pattern for the next several months. Although upwelling reduced substantially in June and July, the cumulative upwelling for the 2007 season was greater than normal. An important implication of this could be greater ecosystem productivity and reproductive success for many populations.

## REGIONAL STUDIES

### Oregon

From November 2002 through April 2006, SST anomalies off Oregon (fig. 6, NOAA buoy 46050 which is 22 miles off Newport in 140 m water depth) were 1° to 2°C above normal, at times exceeding those seen during the 1998 El Niño event. In 2006, coastal upwelling began in early May, somewhat earlier than usual, but after two weeks, atmospheric conditions changed and several strong southwesterly storm events moved up the coast, erasing any signature of upwelling. Sustained upwelling was not initiated until the end of May, and remained weak through late June. Winds were strong and persistent from July through September, favoring upwelling, albeit late. By July 2006, SST anomalies once again turned negative, and they remained either negative or neutral through May 2007, consistent with the pattern throughout the northeast Pacific (fig. 3).

A time series of temperature measured at a depth of 150 m at a shelf break station off Newport (NH 25; 300 m water depth) shows a strong seasonal cycle as well as interannual variations (fig. 7). 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). Following this, the deep waters in summer warmed to 7.56°C (2003), 7.71°C (2004), 7.65°C (2005) and 7.69°C (2006). Cooler temperatures (7.3°C) have been seen through June 2007. Winter temperatures were cooler in 2005–06 and 2006–07 by 0.5°C. Salinity at 150 m at the same station showed the opposite pattern, with relatively high values during summers 1999–2002 (averages ranged from 33.92 to 33.96 psu), decreasing to 33.90 psu in 2003, and 33.89 psu in 2004. A slight increase was seen in 2005 (33.93 psu), 2006 (33.95 psu), and 2007 (33.95 psu through June). For the winter months, there was a trend towards increased salinity from 2003–04 until present. Thus, the trend seems to be towards colder and saltier water in 2006 and 2007, similar to that observed from 1999–2002. From this (albeit limited) data set, it appears that relatively warmer and fresher water occurs at depth during the positive phase of the PDO and colder and saltier water during the negative phase, supporting

## Alongshore Winds 2005 to 2007

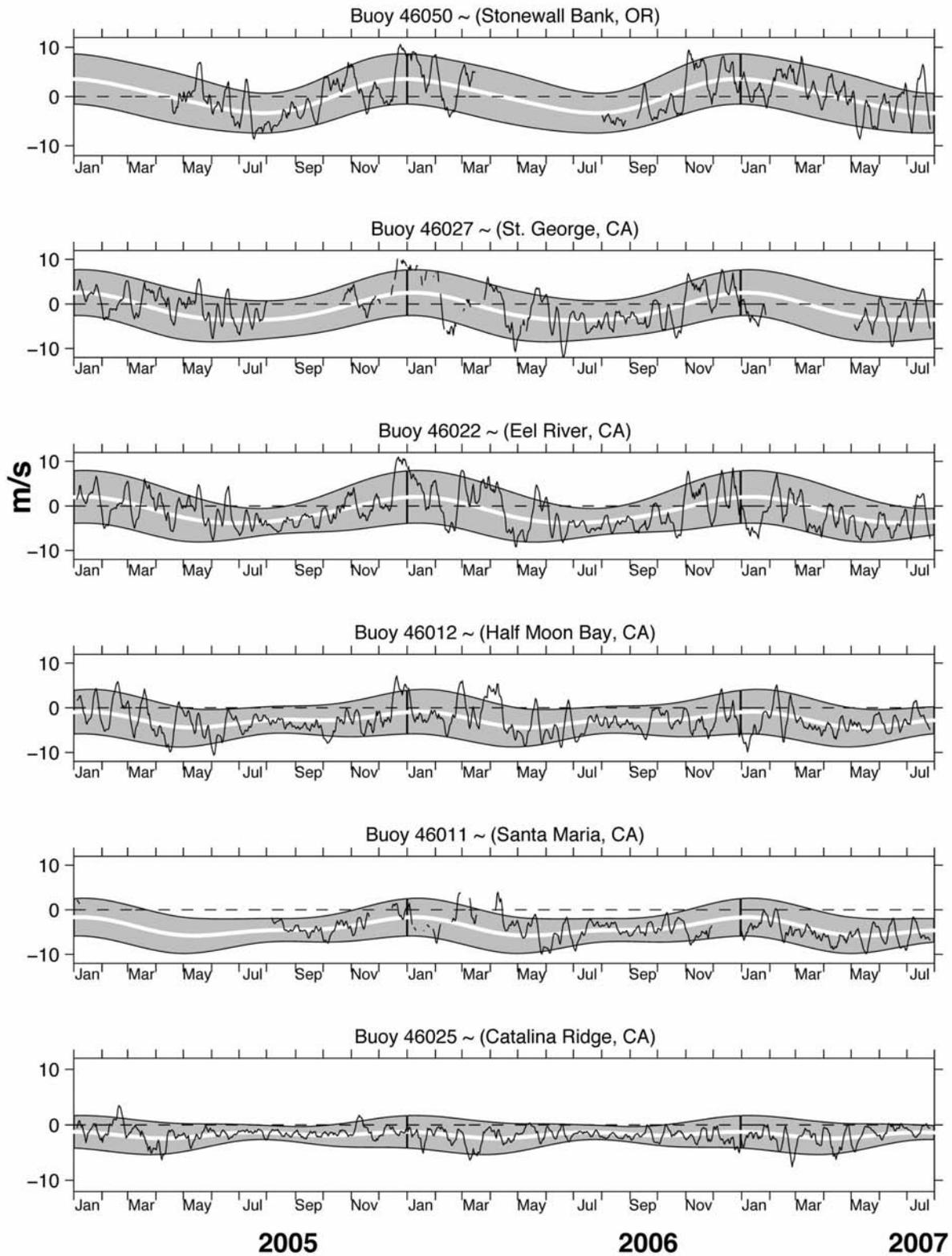


Figure 5. Time series of daily-averaged alongshore winds for January 2005–July 2007 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a seven-day running mean. Data provided by NOAA NDBC.

## Sea Surface Temperatures 2005 to 2007

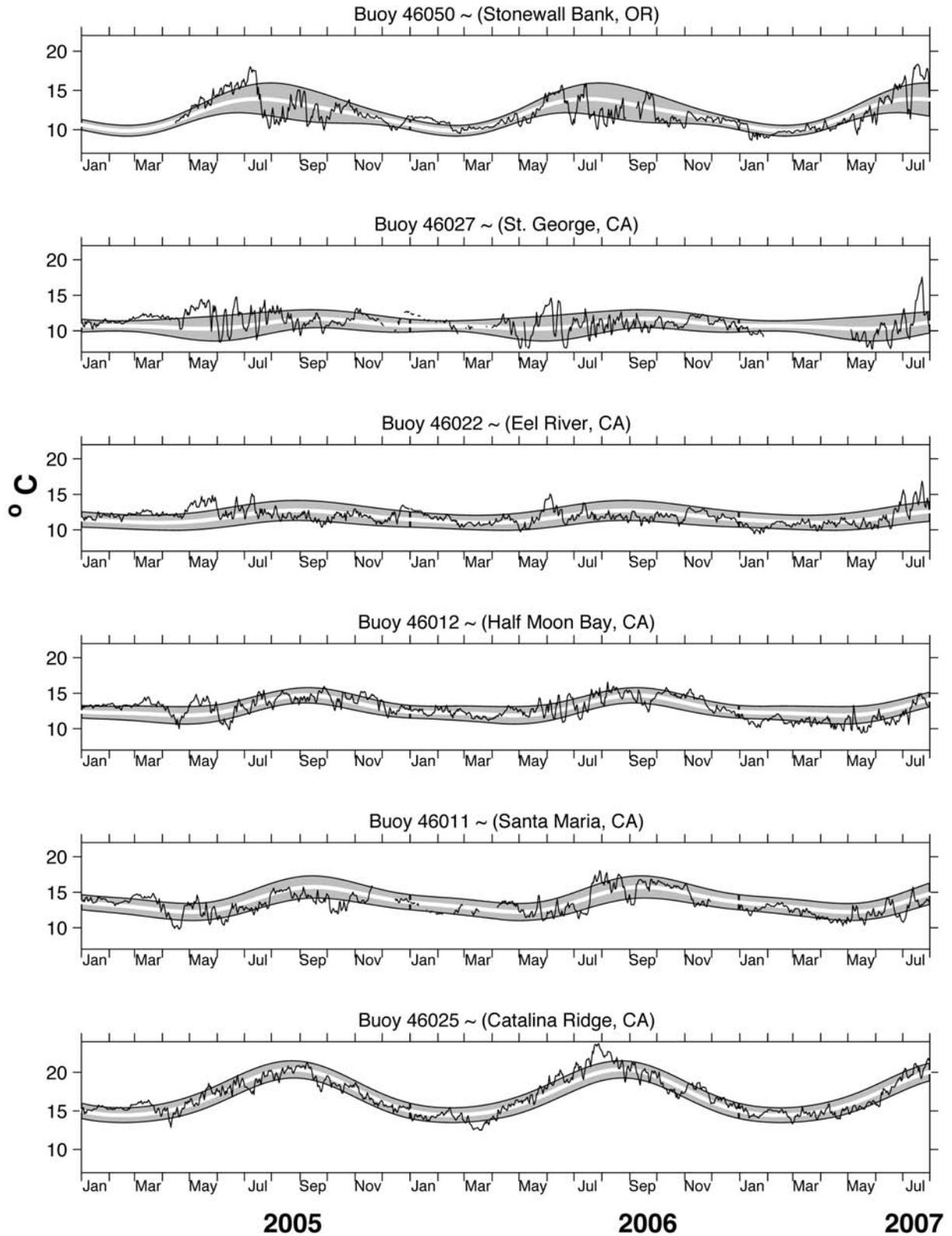


Figure 6. Time series of daily-averaged SST for January 2005–July 2007 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Data provided by NOAA NDBC.

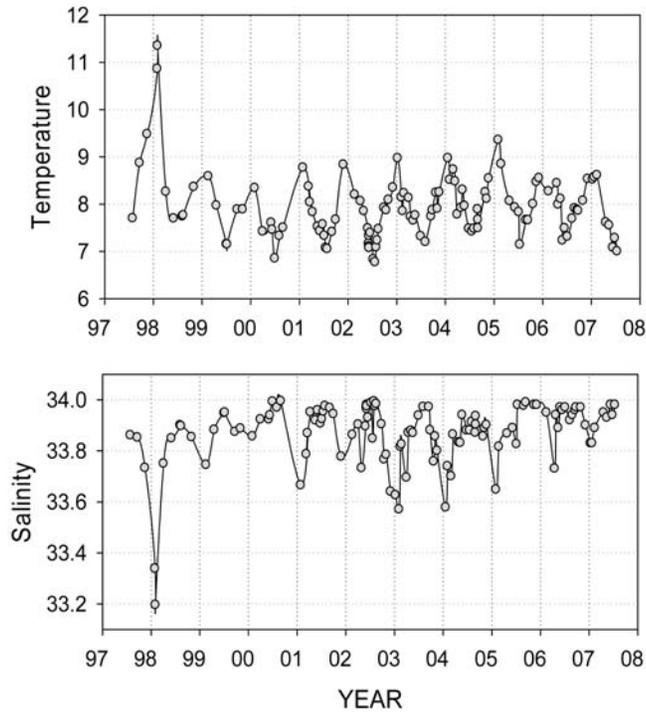


Figure 7. Time series of temperature (upper panel) and salinity (lower panel) measured at a depth of 150 m at station NH 25 (25 miles off Newport); station depth is 297 m.

a hypothesis that different water types occur off Oregon as a function of the phase of the PDO.

### Central California

CTD sections extending offshore of Monterey Bay have been carried out on a regular basis since 1997. Mean temperature-salinity curves for each cruise are shown in Figure 8A. The regular features of the temperature-salinity curves include: (1) an upper layer ( $T > 10^{\circ}\text{C}$ ) with strong seasonal and year to year variability, (2) a strong halocline between  $S = 33.6$  to  $33.4$ , (3) a region of rapid temperature change between  $6^{\circ}\text{C}$  to  $8^{\circ}\text{C}$ , and (4) a lower layer where  $T < 6^{\circ}\text{C}$ . The temporal variabilities of the mean properties of these four layers are shown in Figure 8B-D. The salinity of the upper layer (fig. 8B) appears to have been near normal levels in 2006-07,  $\sim 33.3$  psu, while the salinity of the thermocline and deeper layer (fig. 8D) appears to have leveled off after a decade of steadily increasing salinity. The mean temperature of the halocline (fig. 8C) was highly variable although the cruises in June and July 2007 indicated a temperature of  $8.8^{\circ}\text{C}$ , near the minimum observed. Based on these data, it appears that transport of equatorial intermediate waters into the region has leveled off while the upper waters remain near normal conditions.

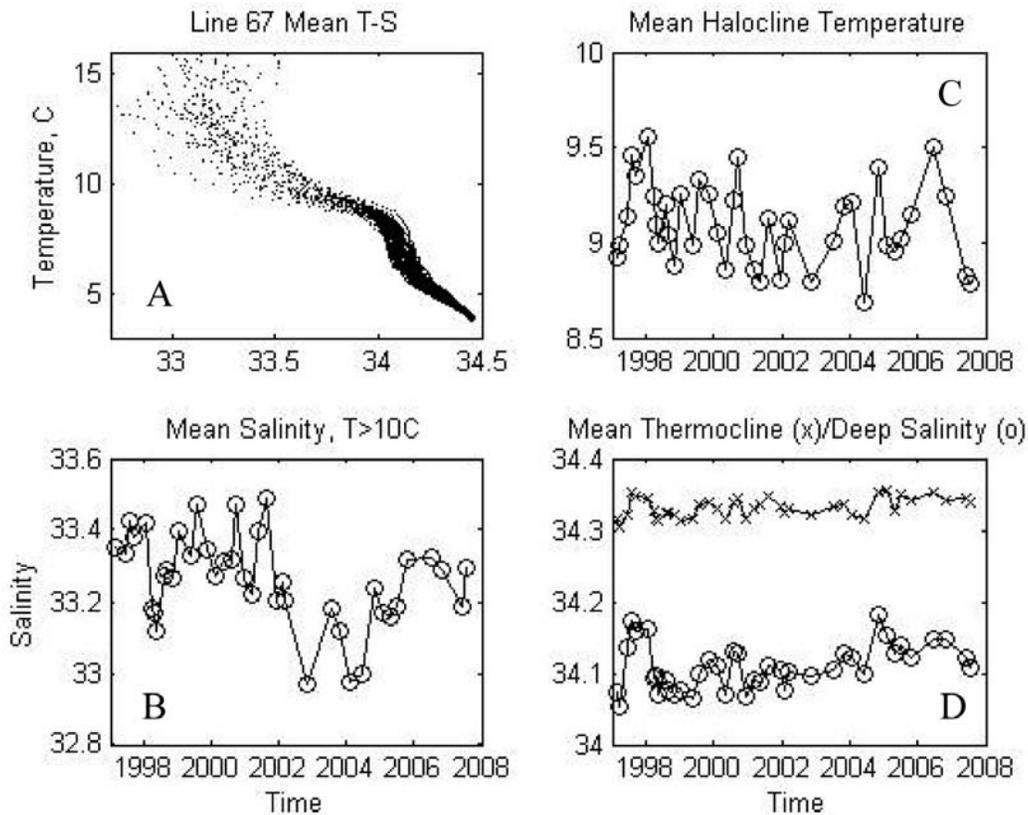


Figure 8. Conditions along Line 67 off Monterey Bay. (A) Mean temperature-salinity curves for all cruises since 1997. (B) Salinity of the upper layer ( $T > 10^{\circ}\text{C}$ ). (C) Mean halocline temperature. (D) Salinity of the thermocline region and the deeper layers.

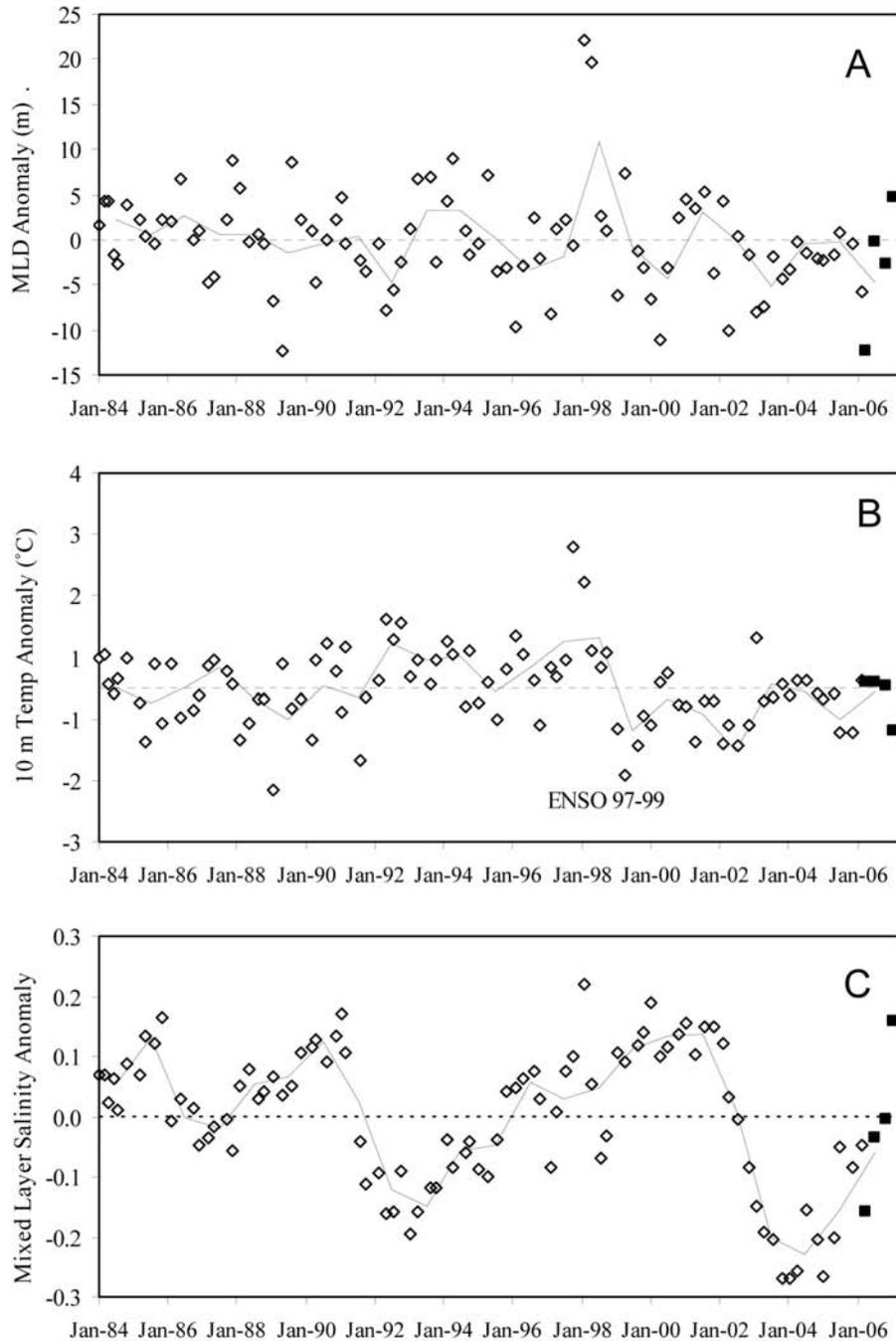


Figure 9. Anomalies of mixed-layer (ML) depth (A), 10 m temperature (B), and ML salinity (C). Data from the last four cruises are plotted as solid symbols, data from previous cruises are plotted as open diamonds. The solid lines represent the annual averages and the dotted lines the climatological mean which in the case of anomalies is zero.

**Southern California**

**CalCOFI Overview:** Anomalies of mixed-layer depth (MLD) over the last year were variable. After a low value in January, anomalies returned to near normal (fig. 9A). Temperature anomalies at a depth of 10 m (fig. 9B) were also close to zero. The trend of increasing temperatures is significant for the time period

January 1984 to August 1998 ( $p < 0.05$ ), continuing the trend since 1949, the beginning of CalCOFI data (Roemmich and Mc Gowan 1995). When the period of the strong 1998–99 ENSO event is excluded from the analysis, the trend is not (yet?) significant for the time period of August 1999 to the present. Temperature anomalies at a depth of 200 m were slightly but not sig-

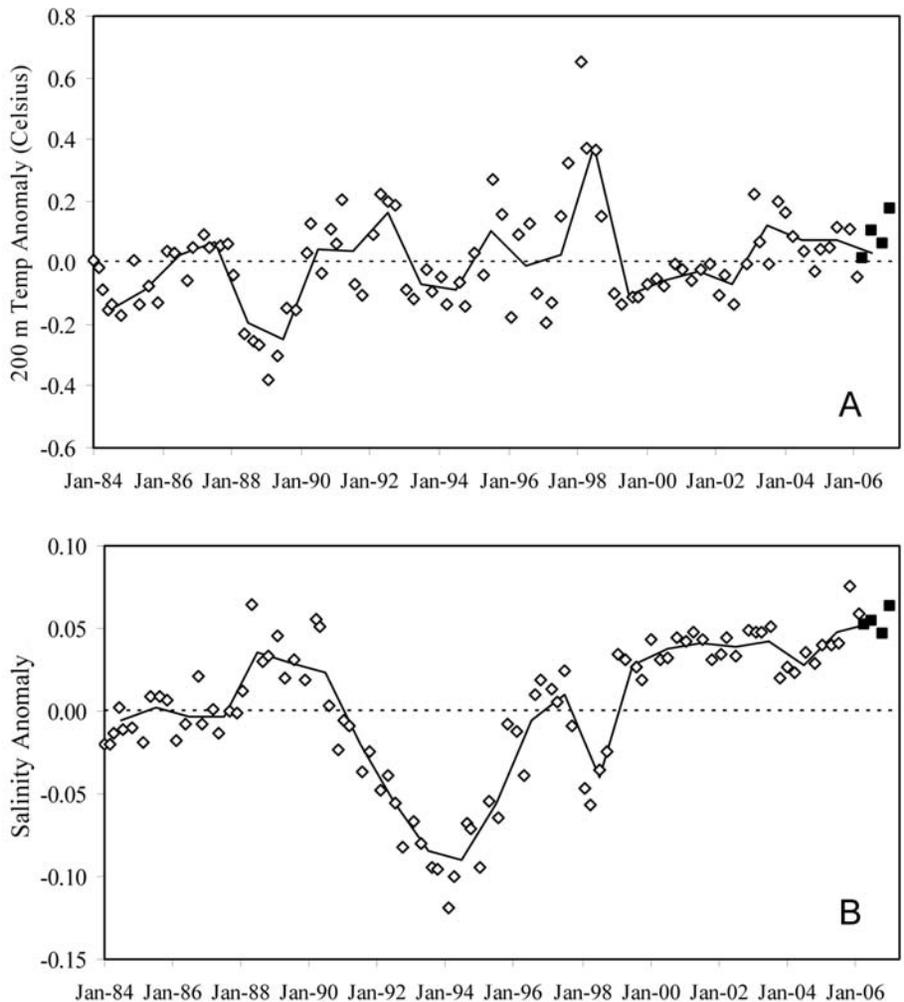


Figure 10. Anomalies of temperature (A) and salinity (B) at a depth of 200 m, calculated and presented as described above for Figure 9.

nificantly positive during the last year, with values similar to those observed since 2003 (fig. 10A). Anomalies of mixed-layer salinities had returned to zero (fig. 9C) after a period of strong negative values between 2003 and 2005. This return of salinities to values close to their long-term averages was seen throughout the CalCOFI region (fig. 11), with the exception of the edge of the Central Gyre of the North Pacific (fig. 11). Salinity anomalies at 200 m were slightly higher than those observed since 1999 (fig. 10B). Note that the 2003–06 negative sea surface salinity anomaly (fig. 9C) is virtually absent from salinities at 200 m (fig. 10B), illustrating the shallow nature of this anomaly.

**CalCOFI Cruise 0604 (1–18 April 2006; fig. 12).**

The California Current was strongly expressed throughout the study domain in April 2006. Across line 77 it was located close to the coast, making a large meander out to station 100 across line 87 and jetting further inshore, crossing line 93 in the vicinity of stations 70 to

90. Close to the coast the poleward countercurrent was present. In contrast with recent years, the relatively cool temperatures and elevated concentrations of nitrate that indicate upwelling were not evident at the inshore stations of lines 77 to 83. Only the inshore stations of lines 87 and 90 showed signs of recent upwelling (SST < 13°C, nitrate 5 to 8 μM). High concentrations of chlorophyll *a* were only observed in the vicinity of the Santa Barbara Basin and along the inshore sections of lines 83 to 90. The spatial restriction of elevated concentrations of chlorophyll *a* and rates of primary production were a likely consequence of the restricted upwelling.

**CalCOFI Cruise 0607 (7–25 July 2006; fig. 13).**

During the summer flow, patterns of the California Current were similar to those observed during the spring, with the exception of the large meander which was no longer observed. Poleward flow close to the coast was stronger than in the spring, similar to previous years. Spatial patterns and values of SST and chlorophyll *a* were

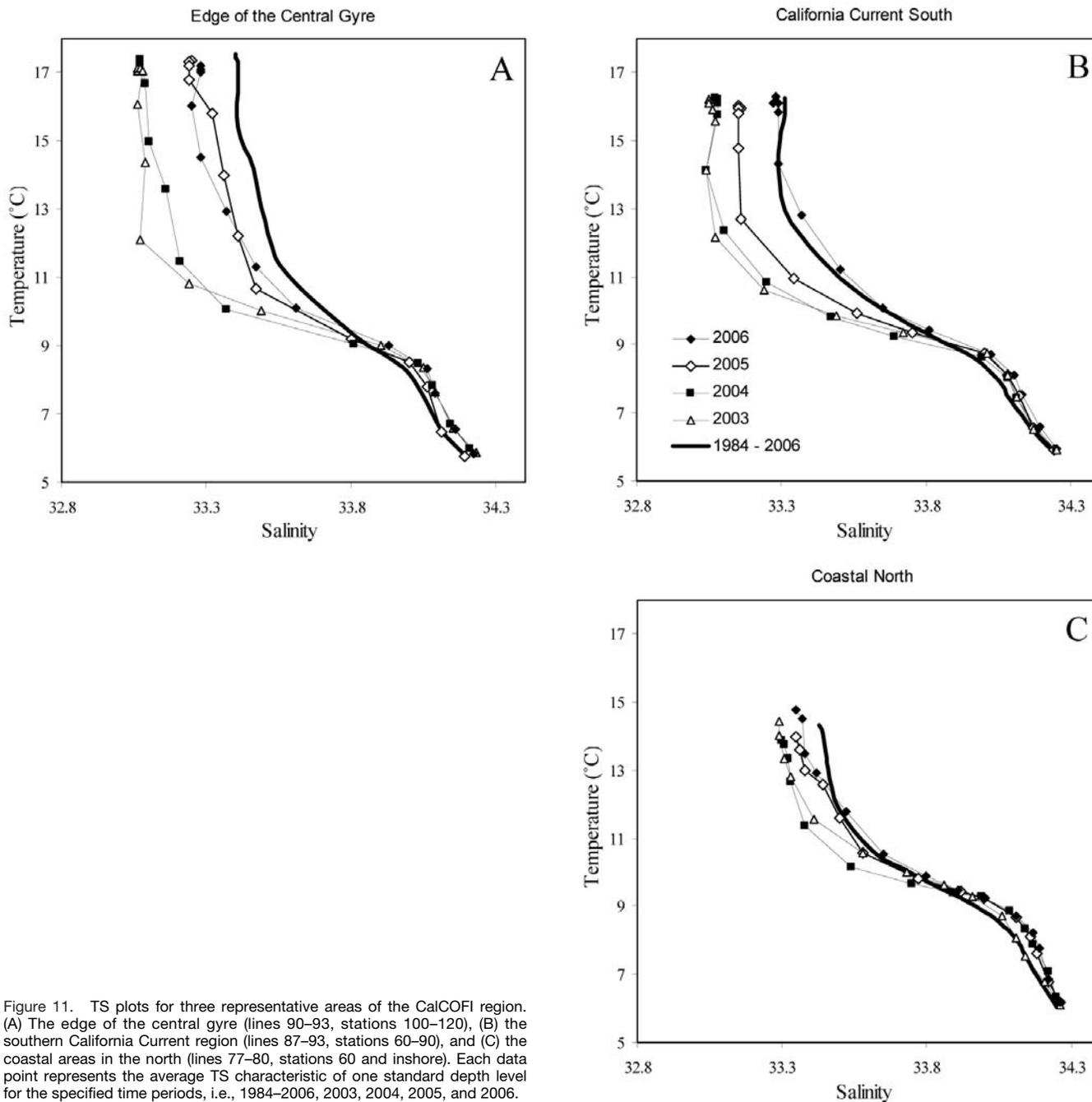


Figure 11. TS plots for three representative areas of the CalCOFI region. (A) The edge of the central gyre (lines 90–93, stations 100–120), (B) the southern California Current region (lines 87–93, stations 60–90), and (C) the coastal areas in the north (lines 77–80, stations 60 and inshore). Each data point represents the average TS characteristic of one standard depth level for the specified time periods, i.e., 1984–2006, 2003, 2004, 2005, and 2006.

typical for this season—with the exception of higher-than-normal SST along the inshore section of line 90.

**CalCOFI Cruise 0610 (21 October–6 November 2006; fig. 14).** Data for this cruise are preliminary. By fall, the California Current had split with one weak branch entering the study domain along line 77 close to the coast and another entering at the northwest corner. The stronger offshore branch meandered in and out of the domain at its western edge, merging with the inshore branch along line 93. The Southern California

Eddy was centered on stations 90.35 and 87.40. The coastal countercurrent was typical for this time of the year. Concentrations of chlorophyll *a* were low in the offshore areas; high values were only found close to the coast.

**CalCOFI Cruise 0701 (12 January–3 February 2007; fig. 15).** Data for this cruise are preliminary. In January, the California Current was located in the offshore portion of the study domain, entering between stations 77.09 and 77.100 and exiting the domain through the

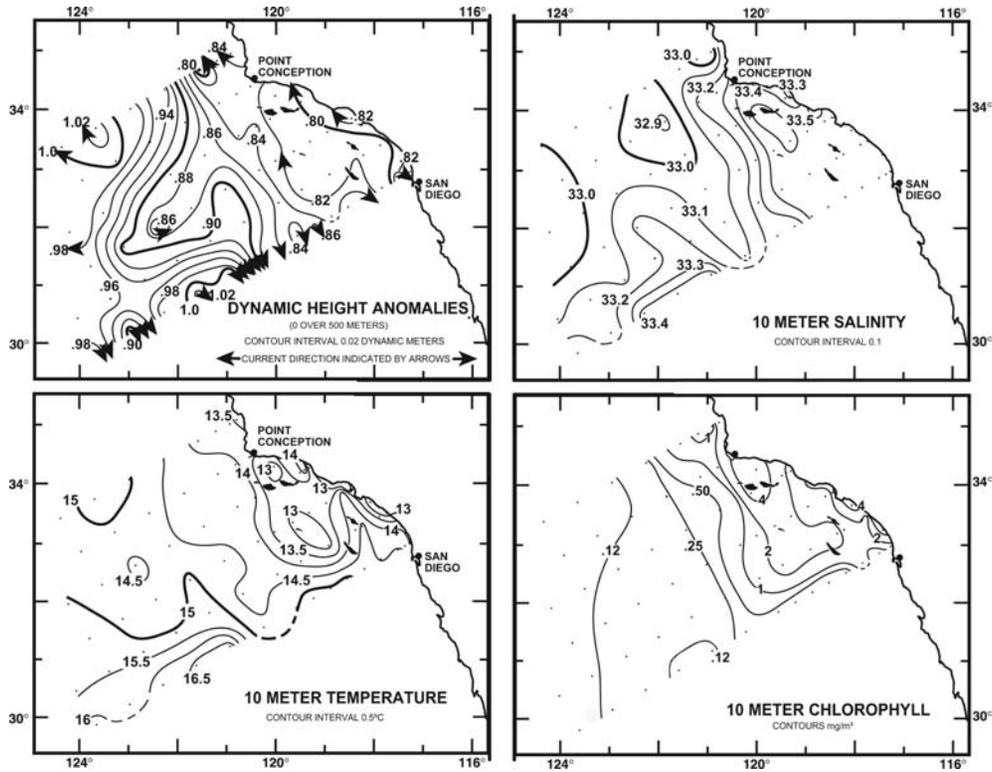


Figure 12. Spatial patterns for CalCOFI cruise 0604 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll a.

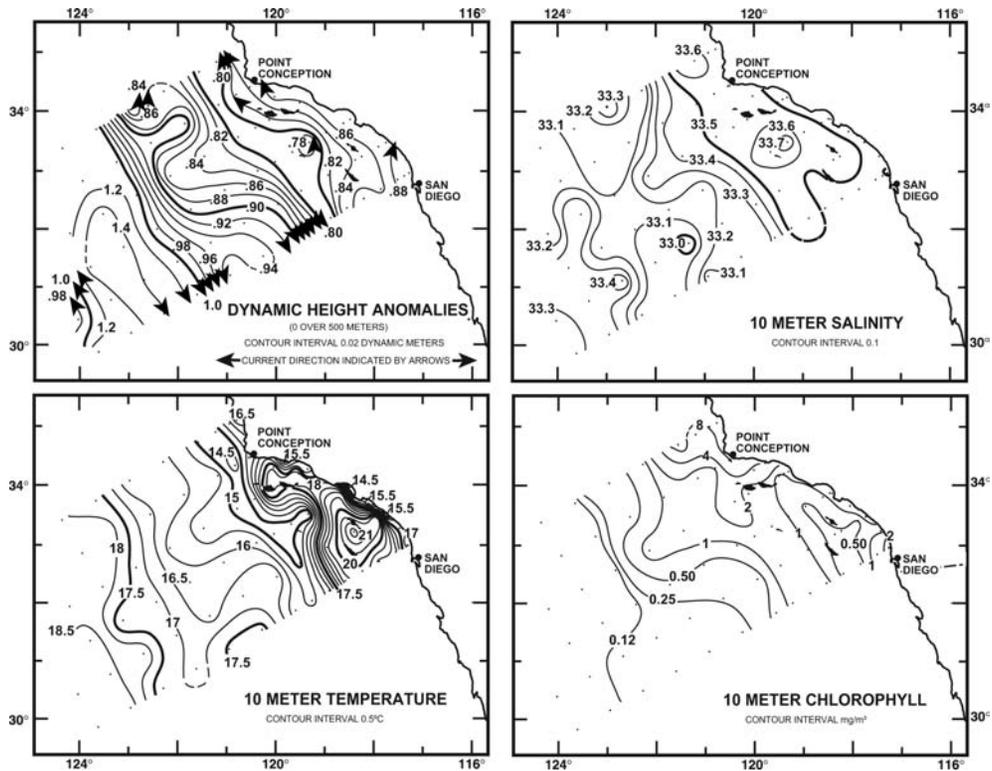


Figure 13. Spatial patterns for CalCOFI cruise 0607 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll a.

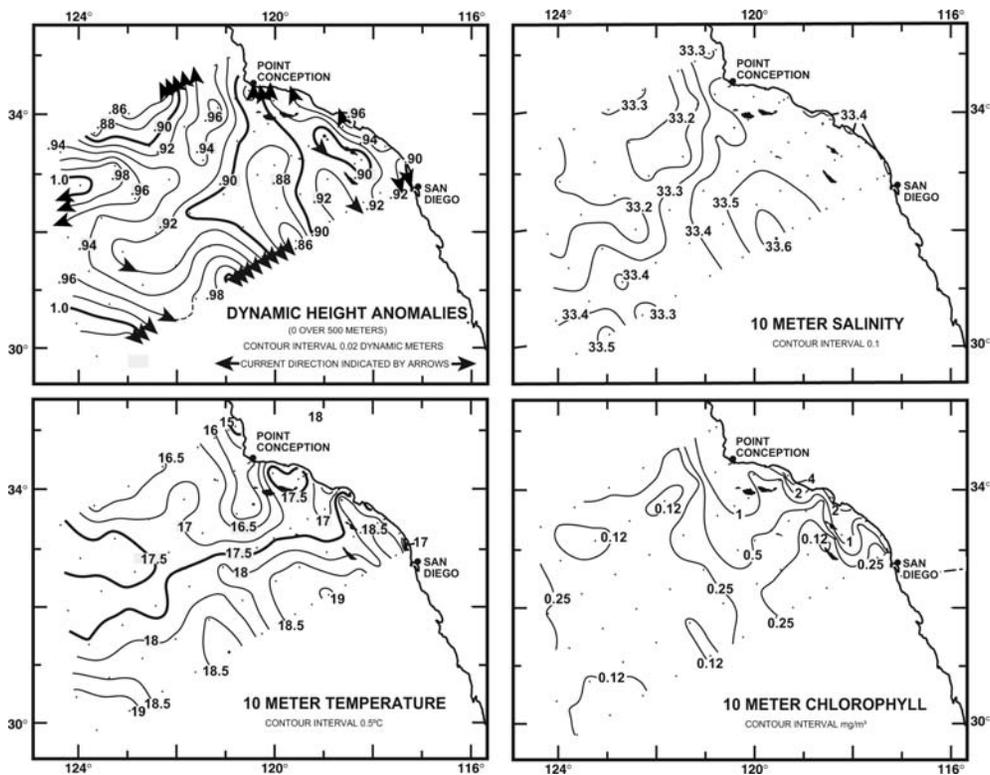


Figure 14. Spatial patterns for CalCOFI cruise 0610 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*. Data used for these plots are still preliminary.

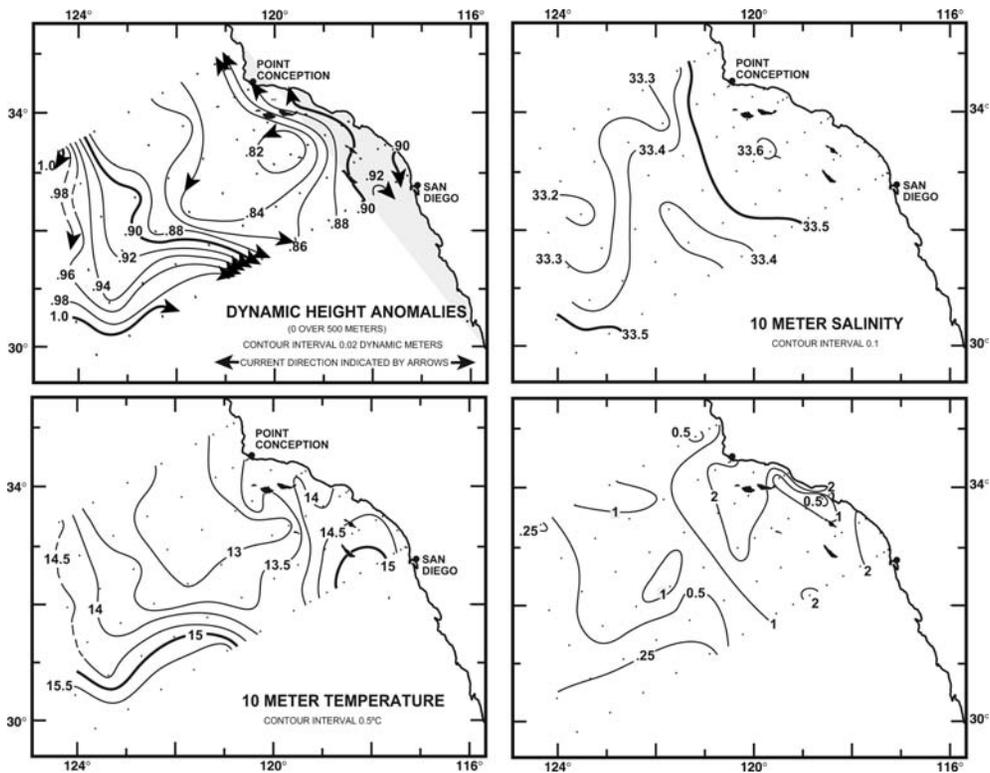


Figure 15. Spatial patterns for CalCOFI cruise 0701 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*. Data used for these plots are still preliminary.

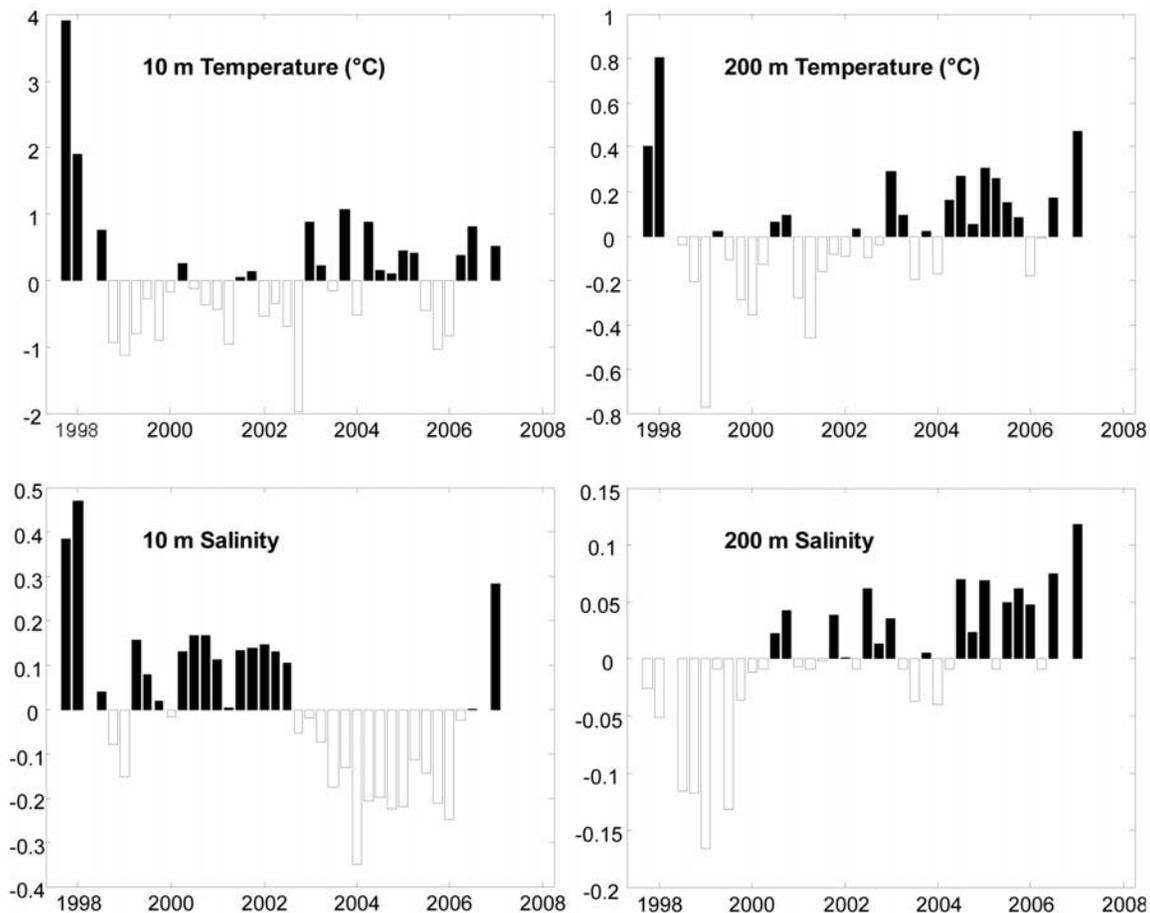


Figure 16. Temperature and salinity anomalies at 10 m and 200 m for the entire IMECOCAL survey area off Baja California. Anomalies are based on the time period 1997–2007.

center of line 93. Flows in the center of the domain were weak. The Southern California Eddy was centered on stations 87.50 to 55. A strong poleward current extended from the inshore section of line 87 to north of Point Conception. Temperatures at a depth of 10 m along the coast ranged from 13.0° to 14.5°C and concentrations of nitrate and chlorophyll *a* were low, suggesting that upwelling was insignificant.

### Baja California

**IMECOCAL Overview:** IMECOCAL surveys were completed in April and July 2006 and January 2007 off Baja California (fig. 1D). Data shown here are relative to the climatology of 1997–2005. The most relevant feature during this period is a clear transition to warmer conditions as of April 2006, reflected in positive temperature anomalies at depths of 10 and 200 m (fig. 16). Salinity anomalies at 10 m were neutral for most of the year after a 4-year period of strong negative anomalies (fig. 16). There was a strong positive anomaly in January 2007. Temperature anomalies at continental shelf stations show tendencies similar to those observed in the offshore re-

gion (not shown). Also evident was the anomalous advection of warm and saltier water at depth from the south in January 2007 (fig. 16). As usual, April showed the highest chlorophyll *a* values due to upwelling, decreasing values in July, and minimum values in January 2007.

#### **IMECOCAL 0604 (19 April–3 May 2006; fig. 17).**

The circulation in April was dominated by the California Current, which was stronger offshore. The water mass associated with its core had low temperature (16.5°C–17.0°C) and low salinity (33.4 psu). Inshore 10 m water temperatures below 16°C and salinities of 33.45 psu were probably related to upwelling in the northern region. Temperatures in the study domain at 10 m ranged from 16° to 17.5°C; corresponding salinities ranged from 33.4 to 33.5 psu. High chlorophyll *a* concentrations (~2 mg m<sup>-3</sup>) were associated with the coastal upwelling in the northern part off Ensenada, and in the central Peninsula inside Vizcaino Bay with values up to 6 mg m<sup>-3</sup>. In the offshore areas chlorophyll *a* reached values as low as 0.12 mg m<sup>-3</sup>.

**IMECOCAL 0607 (7–27 July 2006; fig. 18).** A cyclonic eddy off Punta Eugenia perturbed the main south-

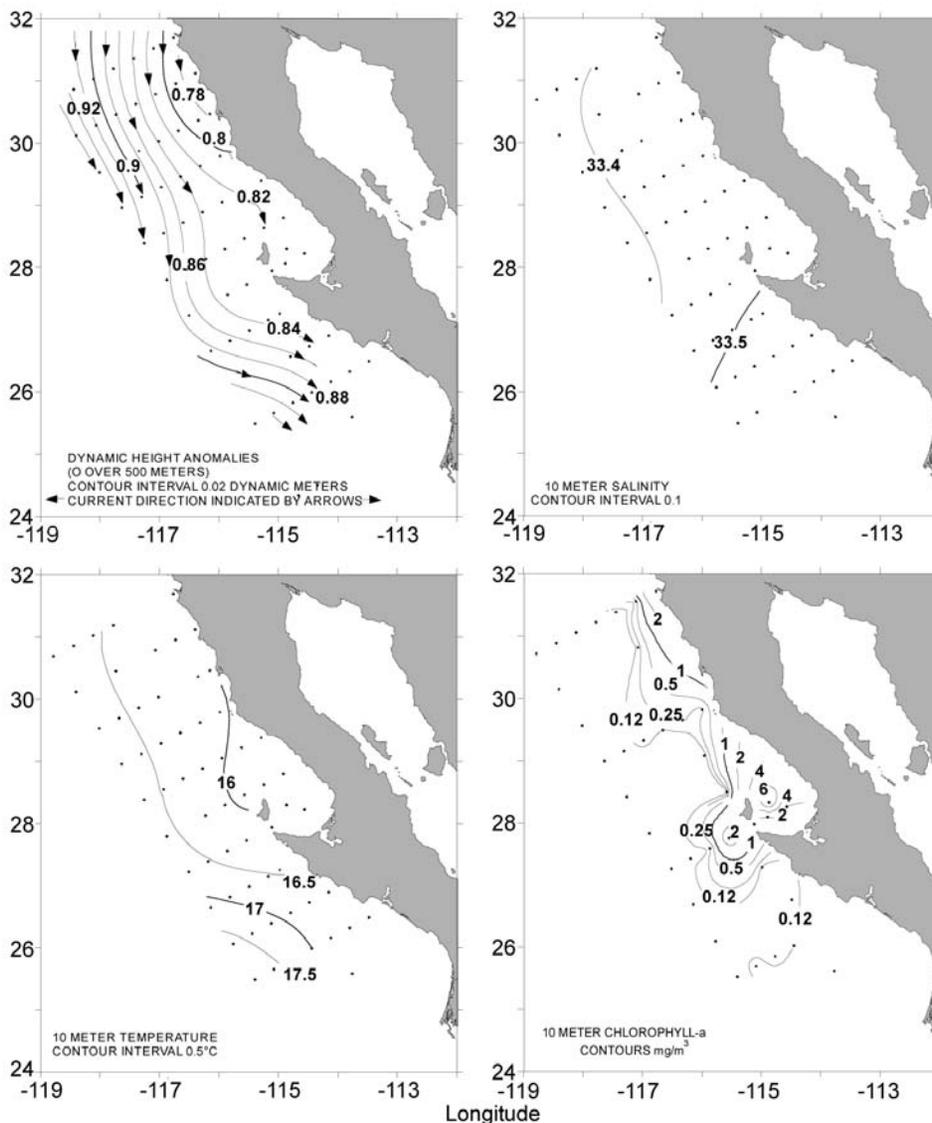


Figure 17. Spatial pattern for IMECOCAL cruise in spring 2005, showing upper ocean geostrophic flow estimated from the 0/500 dynamic height field, 10 m temperature, 10 m salinity, and 10 m chlorophyll *a*.

ward flow. The center of the eddy was characterized by high surface temperature (21°C) and low salinity (33.5 psu). North of the eddy, the core of the California Current was deflected shoreward at 29°N. South of the eddy, the California Current veered inshore at 26°N. Temperatures in the study domain ranged from 18° to 23°C, while salinities varied from 33.5 to 33.9 psu. High chlorophyll *a* concentrations (~2 mg m<sup>-3</sup>) were observed along most of the coast, probably as a response of upwelling during this period. Chlorophyll *a* in the domain ranged from 0.12 to 4 mg m<sup>-3</sup>.

**IMECOCAL 0701 (23 January–12 February 2007; fig. 19).** The surface-circulation pattern showed a weak southward flow inshore. The 10 m salinity field shows strong gradients west and northwest of Punta Eugenia,

suggesting that warm salty water had been advected into this region prior to the cruise. Temperatures ranged from 15° to 20.5°C, while salinities varied from 33.5 to 34.4 psu. Chlorophyll *a* concentrations, ranging from 0.25 to 2 mg m<sup>-3</sup>, were low, typical of the winter, with highest values in the Vizcaino Bay region and south of Punta Eugenia.

## BIOLOGICAL PATTERNS AND PROCESSES

### Macronutrients, Chlorophyll *a* and Primary Production

**Oregon:** Sea surface nitrate concentrations at station NH 05 in spring 2006 (April–June) were the highest measured during the spring, averaging 10.1 μM (tab. 1).

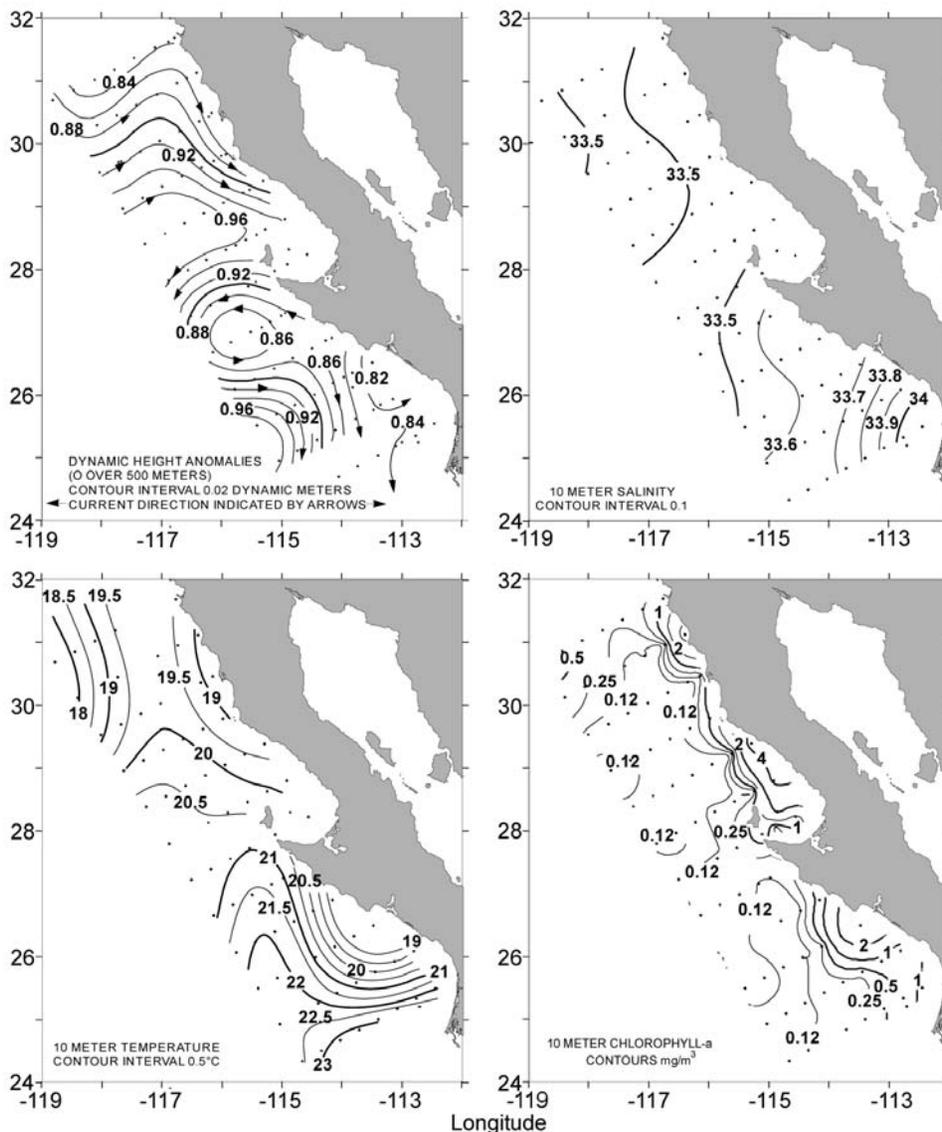


Figure 18. Spatial pattern for IMECOAL cruise in summer 2006, showing upper ocean geostrophic flow estimated from the 0/500 dynamic height field, 10 m temperature, 10 m salinity, and 10 m chlorophyll *a*.

This is in strong contrast to spring 2005 when the lowest concentrations of our time series were found. During July–August, the two months when upwelling is usually the strongest, nitrate concentrations averaged 11.7  $\mu\text{M}$ , one of the highest values observed in those months.

Average chlorophyll *a* values were 2.2  $\mu\text{g L}^{-1}$  during the spring (April–June) and 10.1  $\mu\text{g L}^{-1}$  during the summer (July–August) of 2006. These values are typical of most years (tab. 1). Nitrate and silicate concentration at 150 m at station NH 25 increased from the 1997–98 El Niño period until 2002 (fig. 20). These trends match those observed at 200 m both in the Monterey region and CalCOFI/Southern California Bight (see below and Peterson et al. 2006). Since late 2003, the concentra-

TABLE 1  
Average nitrate ( $\mu\text{M}$ ) and chlorophyll ( $\mu\text{g chl-a L}^{-1}$ ) 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 1997–2006.

YEAR	Nitrate ( $\mu\text{M}$ )		Chlorophyll <i>a</i> ( $\mu\text{g chl-a L}^{-1}$ )	
	April–June	July–August	April–June	July–August
1997	5.21	7.95	1.14	6.1
1998	1.91	2.25	2.23	10.5
1999	4.95	10.20	1.79	5.5
2000	8.65	12.00	1.93	8.4
2001	4.16	9.43	6.59	9.0
2002	4.28	11.49	6.09	10.9
2003	4.37	10.30	2.99	9.7
2004	3.62	8.41	4.92	8.1
2005	0.67	11.70	2.63	8.7
2006	10.10	11.74	2.22	10.1

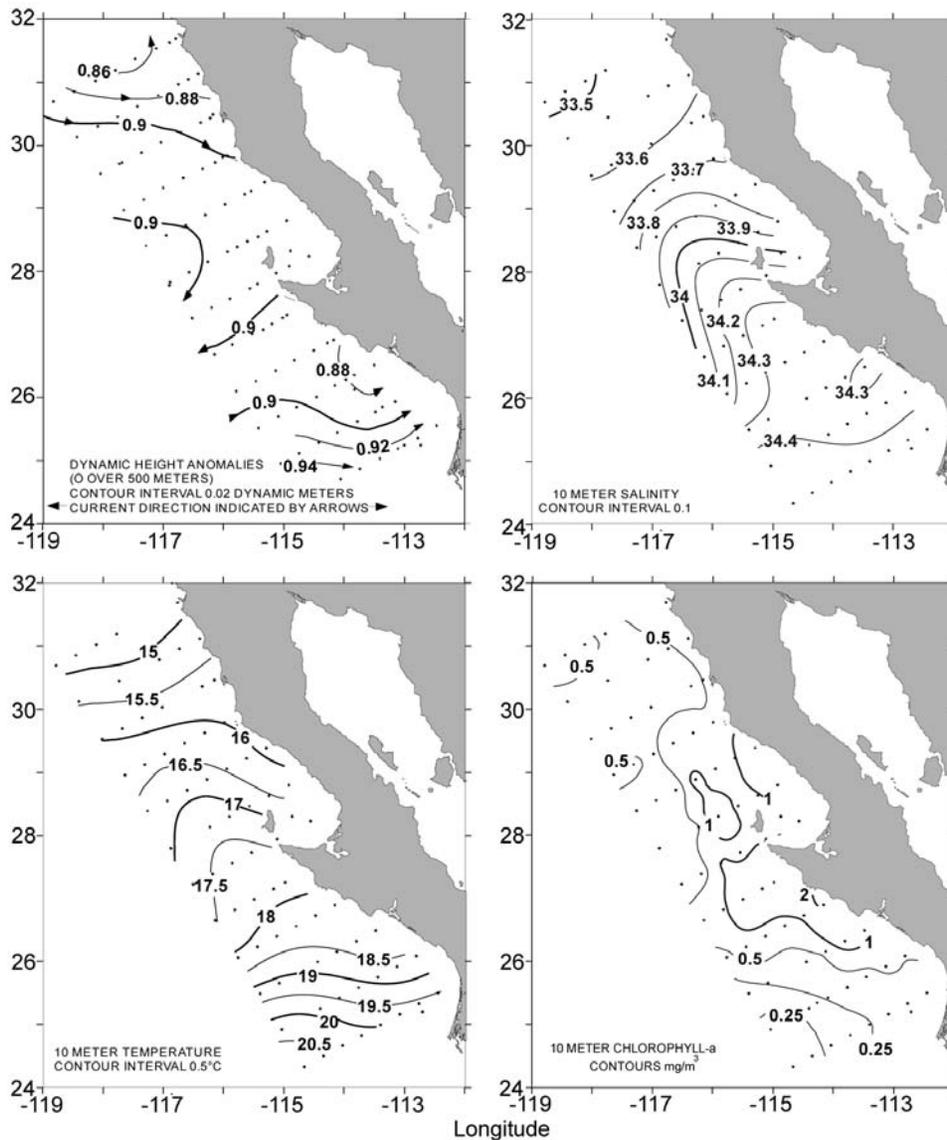


Figure 19. Spatial pattern for IMECOCAL cruise in winter 2007, showing upper ocean geostrophic flow estimated from 0/500 dynamic height field, 10 m temperature, 10 m salinity, and 10 m chlorophyll *a*.

tions have stabilized: recent values (including 2006) fall into the range of the long term average of 30–35  $\mu\text{M}$  for nitrate and 40–50  $\mu\text{M}$  for silicate.

**CalCOFI:** Nitracline depth anomalies for the whole CalCOFI region were slightly negative over the last year (fig. 21) with values similar to those observed since 2000. Anomalies of nitrate in the mixed layer were close to zero (fig. 22A), and anomalies of phosphate were slightly negative (fig. 22B). The trend of decreasing phosphate since 2003 continued. Anomalies of silicic acid have increased to zero after unusually negative anomalies during 2003 to 2005 (fig. 22C). Recent trends in silicic acid concentrations mirror those observed for salinity.

Anomalies of chlorophyll *a* were variable, about zero during the past year (fig. 23A). Anomalies of depth-in-

tegrated rates of primary production were slightly negative (fig. 23B), similar to those observed over the last three years. The apparent decoupling between concentrations of chlorophyll *a* and rates of primary production is puzzling, suggesting either a change in insolation or a change in phytoplankton community structure over the last 20 years. The subsurface chlorophyll *a* maximum at the edge of the central gyre (fig. 24A) was 20 m above the long-term average, similar to 2003. In other areas (e.g., fig. 24B), concentrations were above long-term averages, consistent with the long-term trend in chlorophyll *a* standing stocks. Noteworthy are relatively low concentrations of chlorophyll *a* in the Northern Coastal region below the mixed layer (fig. 24C). It is possible that these low concentrations of chlorophyll *a* are related

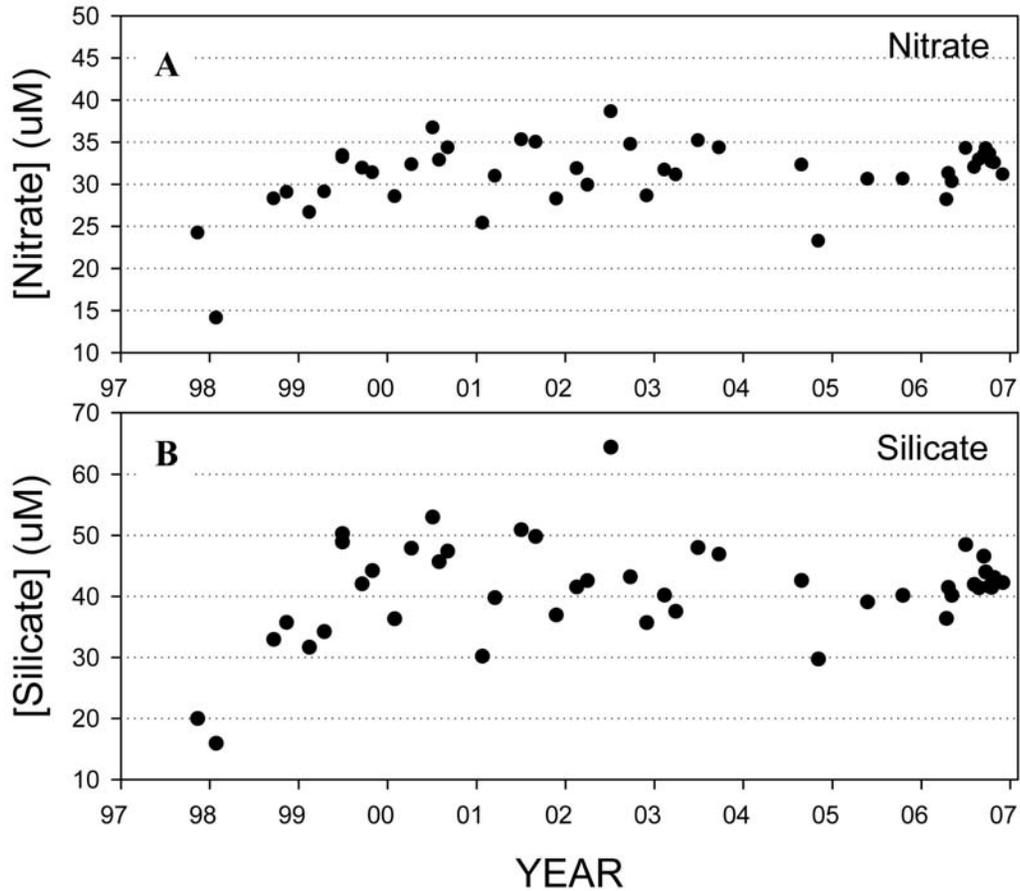


Figure 20. Time series of nitrate and silicate concentrations from station NH 25 (25 miles off Newport). Data from 1998–2003 are from P. Wheeler (Oregon State University, GLOBEC, LTOP Program, the years 1997–2003); the remainder are from the Newport Time Series.

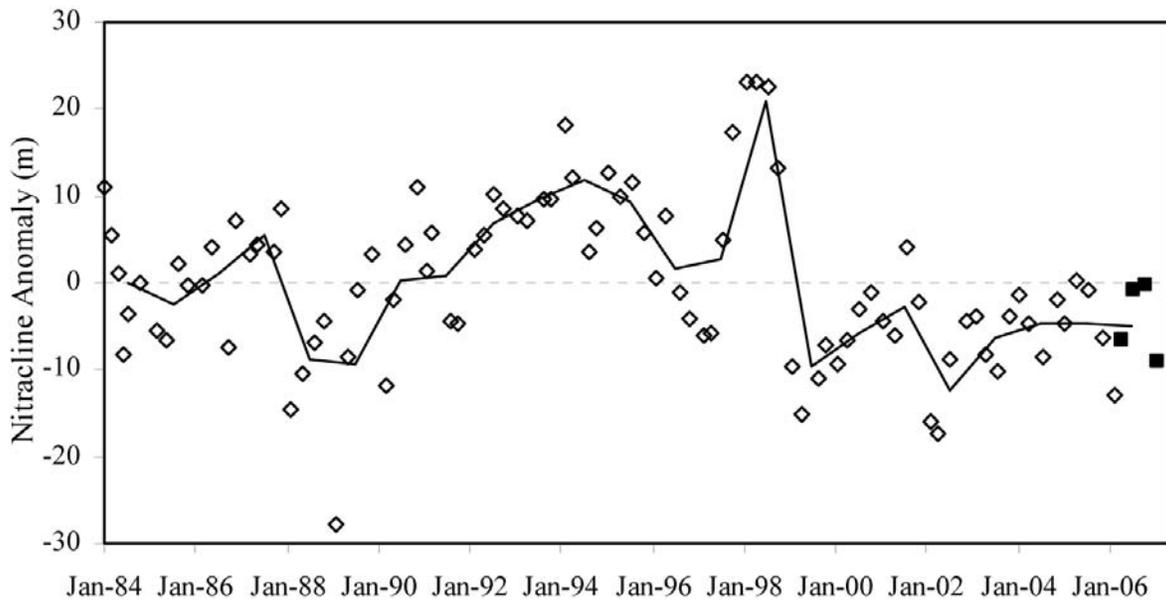


Figure 21. Cruise averages for nitracline depth anomaly. The nitracline depth was assumed to be the depth where nitrate reached values of 1 µM. Data are plotted as described in Figure 9.

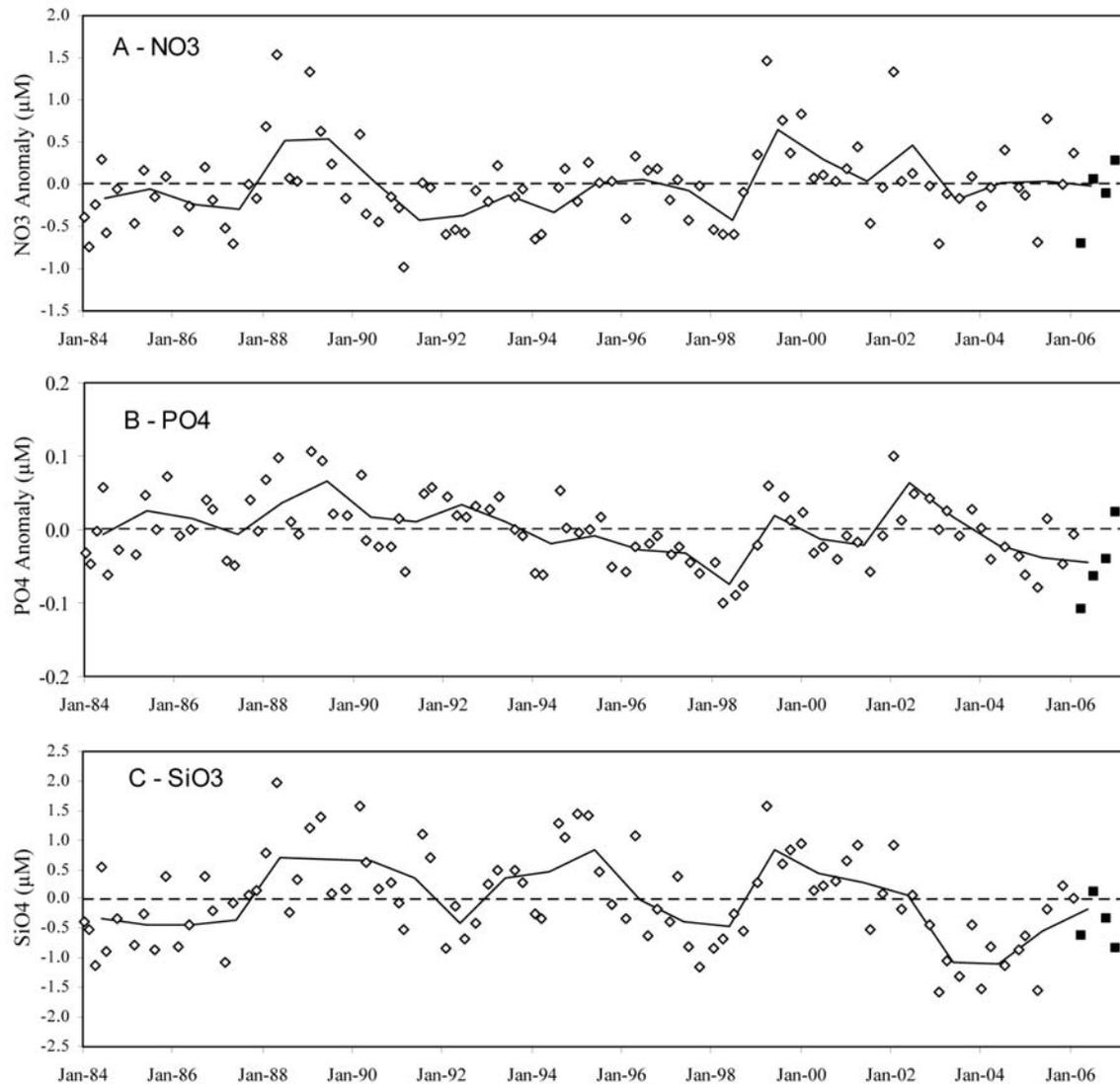


Figure 22. CalCOFI region anomalies for concentrations of (A) nitrate, (B) phosphate, and (C) silicate in the mixed layer. Data are plotted as described in Figure 9.

to weak and upwelling-unfavorable winds off southern California in 2006 (fig. 4).

**Macrozooplankton**

**Oregon:** Copepod biomass varied seasonally, with peaks in July–August, and interannually (fig. 25A). Lowest averages for summers (May–September) were seen from 1996–99, and were highest during the summers of 2000–04 (fig. 25B). The summer of 2005 had the lowest biomass of any summer on record due to the delayed upwelling. With stronger, albeit interrupted, upwelling in 2006, biomass rebounded to values twice those observed in 2005, and close to values observed from 2000–04 (fig. 25). Although copepod biomass was higher than average in 2006 (usually related to cool conditions with good reproduction), copepod biodiversity remained

high (usually related to warm conditions, see fig. 26B). Thus, although the “physical spring transition,” as measured by a drop in sea level, was somewhat early, the “biological” transition, as measured by changes in the species composition of the zooplankton, from a warm-water winter community to a cold-water summer community, was delayed.

Copepod species richness off Oregon covaries with the SST off Newport (Peterson 2006). Copepod species richness was low from 1999 until 2002, high from 2003 until the fall of 2006, turning negative in autumn 2006 and remaining negative (fig. 26B). These patterns may be related to transport processes in the northern California Current: anomalously low numbers of copepod species are associated with the transport of coastal subarctic water into the coastal waters of the northern California Current

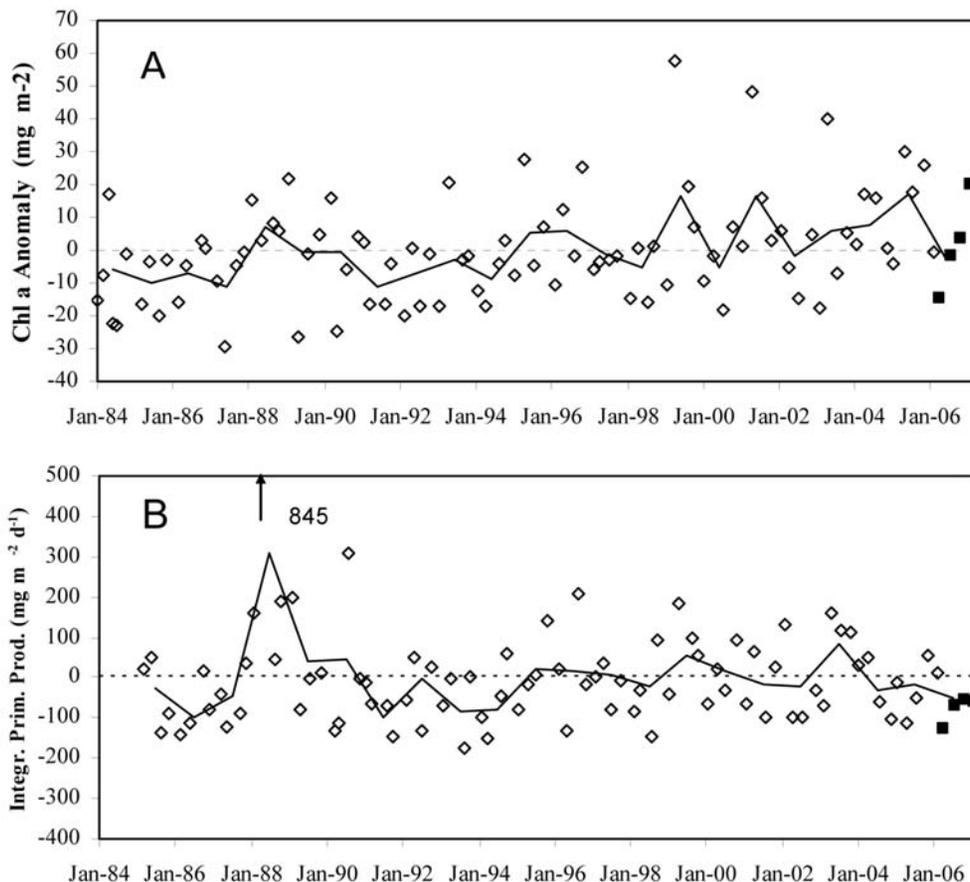


Figure 23. CalCOFI region averages for standing stocks of chlorophyll a (A) and rates of primary production integrated to the bottom of the euphotic zone (B) plotted against time. Data and symbol codes are the same as those in Figure 9.

(as in 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 happened in late 2002–early 2006). Copepod species richness may also be related to the PDO (fig. 26A), lagging that index by about six months.

Interannual variability of euphausiid egg abundances is very high off Oregon (station NH 05, fig. 27). Seasonal averages of egg abundances vary by orders of magnitude among years (tab. 2). The year 2005 was extraordinary in that large numbers of eggs were found early in the year (900 per cubic meter in February), but few eggs in March through June. Once upwelling was initiated (in mid-July) euphausiids began to spawn, and by September average egg abundances were among the highest of any summer. 2006 saw the continuation of a trend to very high concentrations of euphausiids at this inner-to-mid shelf station. We attribute the enhanced egg concentrations to higher numbers of adults in coastal waters during late summer 2005 and into the summer of 2006.

**CalCOFI:** Macrozooplankton displacement vol-

TABLE 2  
Abundance of euphausiid eggs (number  $m^{-3}$ ) at station NH 05 on the Newport line, averaged for spring (March–June), summer (July–August), and for the May–September upwelling season.

Year	Mar–Jun	Jul–Aug	May–Sep
1996	0.4	45.2	24.2
1997	0.6	50.0	30.6
1998	0.2	0.5	1.2
1999	99.3	27.3	23.8
2000	22.9	437.7	220.0
2001	11.4	52.1	24.5
2002	3.8	112.5	62.5
2003	0.2	18.2	8.4
2004	6.9	154.1	66.2
2005	0.2	38.8	302.4
2006	0.8	867.0	416.7

umes were reprocessed for this year’s report as described in methods. Macrozooplankton displacement volumes were below expected values for the respective seasons in July 2006 and January 2007 and close to expected values for the summer and fall of 2006 (fig. 28A). Lower-than-expected values during the summer may have been due to upwelling-unfavorable conditions off southern

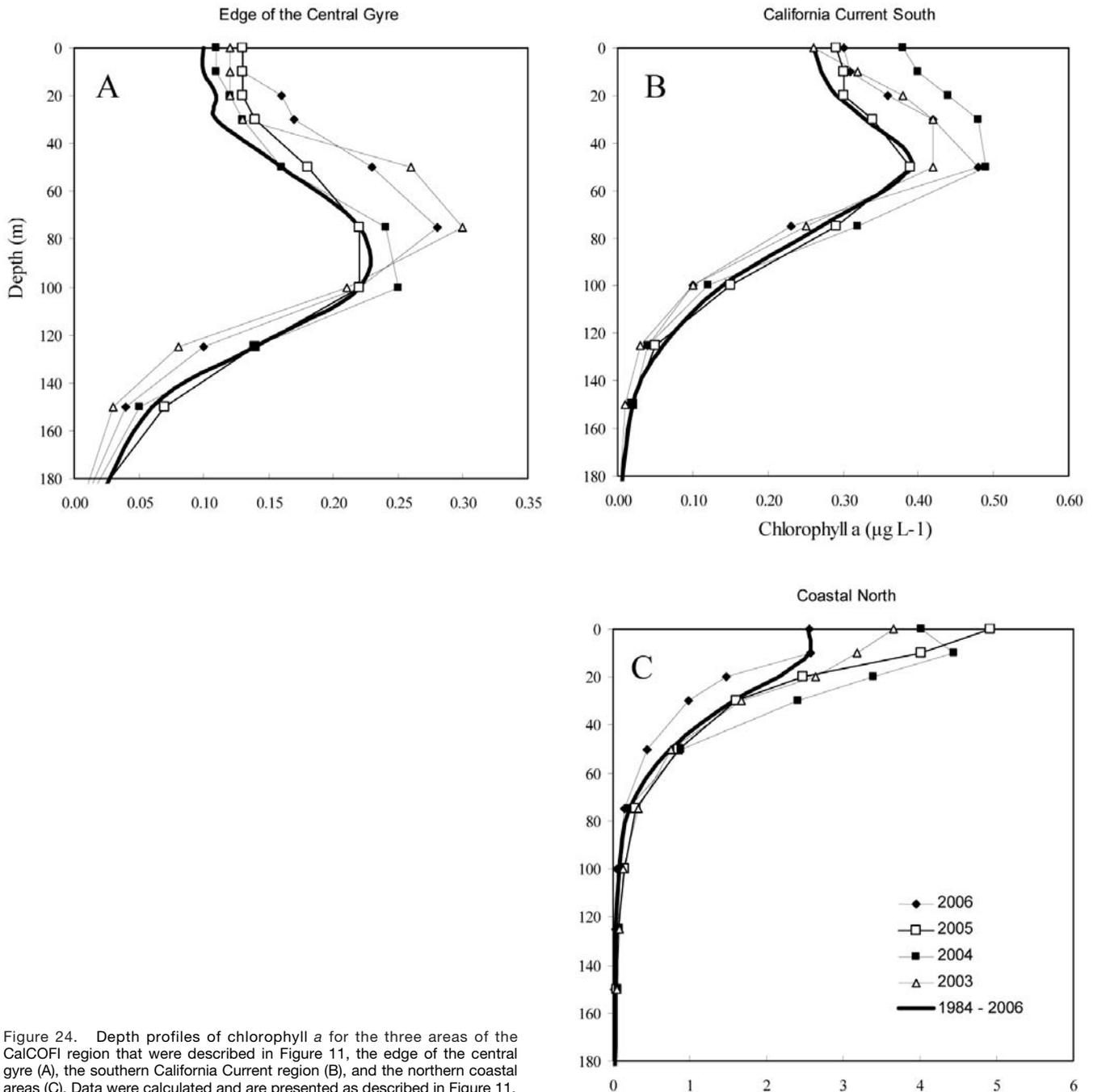


Figure 24. Depth profiles of chlorophyll a for the three areas of the CalCOFI region that were described in Figure 11, the edge of the central gyre (A), the southern California Current region (B), and the northern coastal areas (C). Data were calculated and are presented as described in Figure 11.

California during this time (fig. 4). Average macrozooplankton displacement volumes for 2006 continued the trend of declining zooplankton volumes observed since the beginning of 2000 (Peterson et al. 2006). Trends of declining zooplankton volume observed in the time periods (A) 1984 to 1998 and (B) 1999 to 2007 (fig. 28B) are clear ([A]  $r^2 = 0.32$ ; [B]  $r^2 = 0.33$ ). Excluding data corresponding to the 1997–98 El Niño does not change regressions (data not shown).

## Fish

**Washington–Oregon: Forage Fish species (whitebait smelt, herring, anchovies, sardines):** Very low numbers of all species of small pelagic fishes were seen during the 1998 El Niño event and during 1999 (fig. 29A). As temperatures cooled, stocks increased by factors ranging from 5.6 (sardines) to 240 (whitebait smelt) in 2000, and they remained high through 2003. Following the change to warm ocean conditions in 2003, they declined

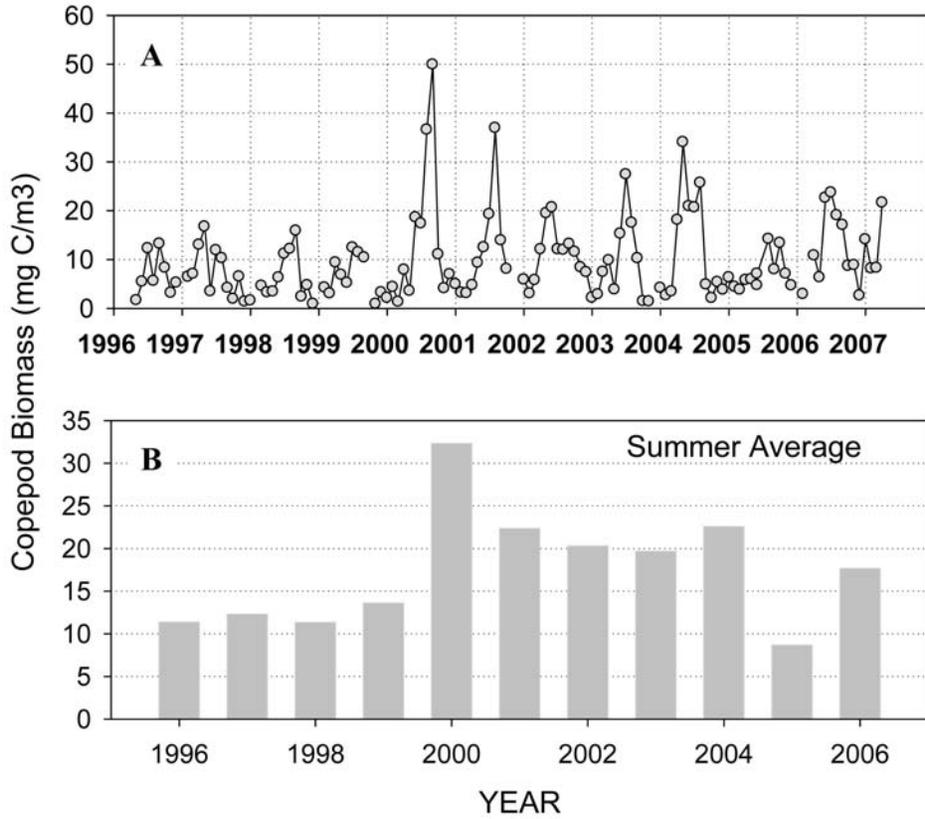


Figure 25. Newport Time series of monthly-averaged values of copepod biomass measured at a mid-shelf station, NH-05, from 1996–present, along with summer-averaged values of copepod biomass measured at NH-05.

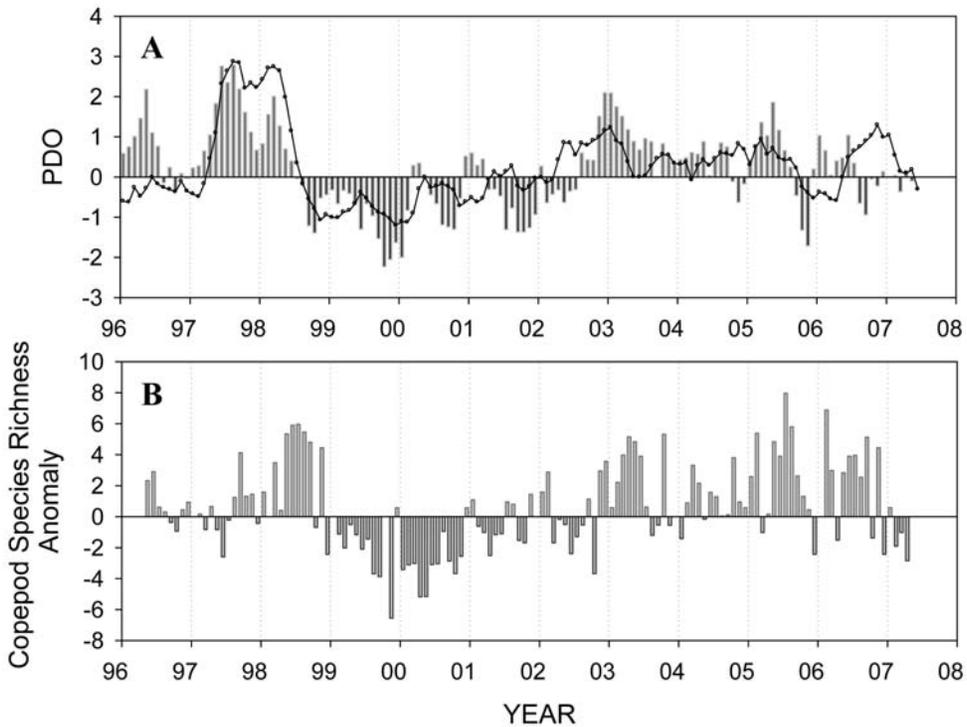


Figure 26. Newport. Time series of the Pacific Decadal Oscillation (upper panel, bars), Multivariate ENSO Index (upper panel, line), and monthly anomalies of copepod species richness at station NH-05, from May 1996 through March.

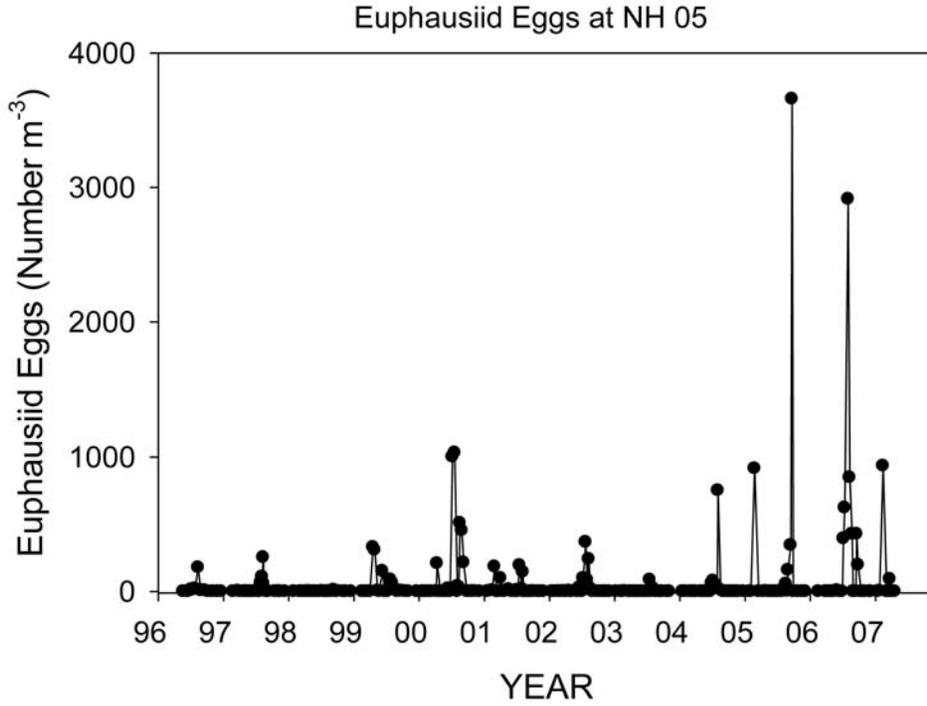


Figure 27. Time series of euphausiid eggs at station NH 05, from 1996 to spring 2007. Note the extraordinary peaks in summer 2005 and 2006.

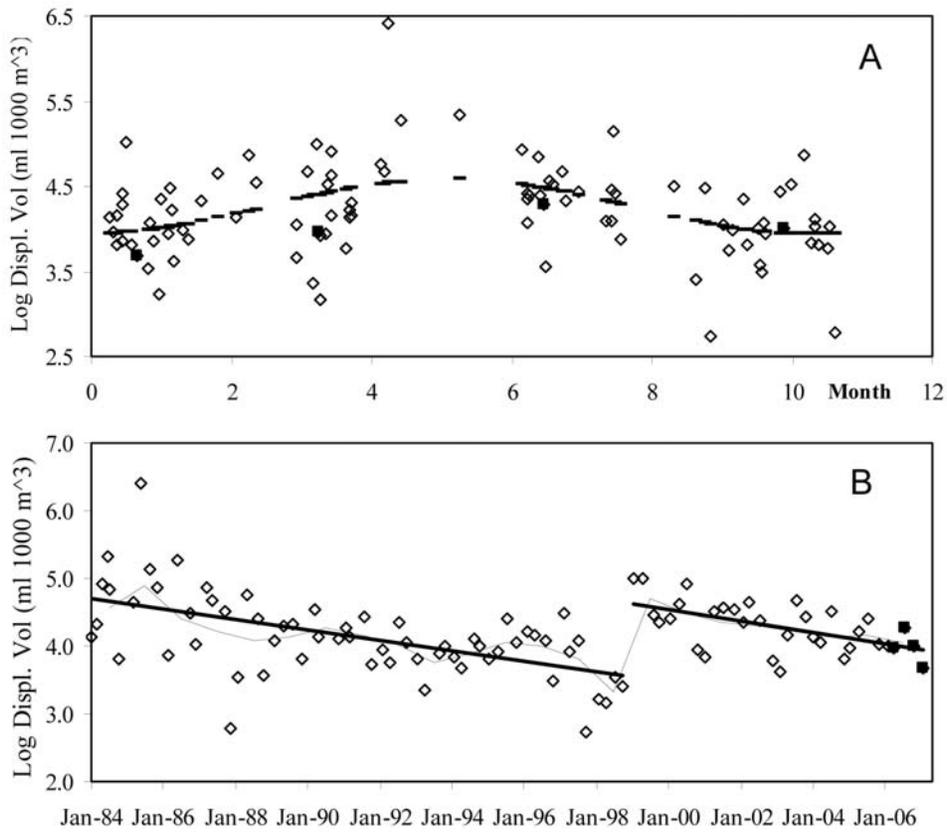


Figure 28. The Log of CalCOFI cruise mean macrozooplankton displacement volumes plotted against the time (A) and the month of the year (B). Annual averages are connected by solid lines; long term trends for the time periods 1984 to 1997 and 1998 to 2006 are indicated using the two straight lines.

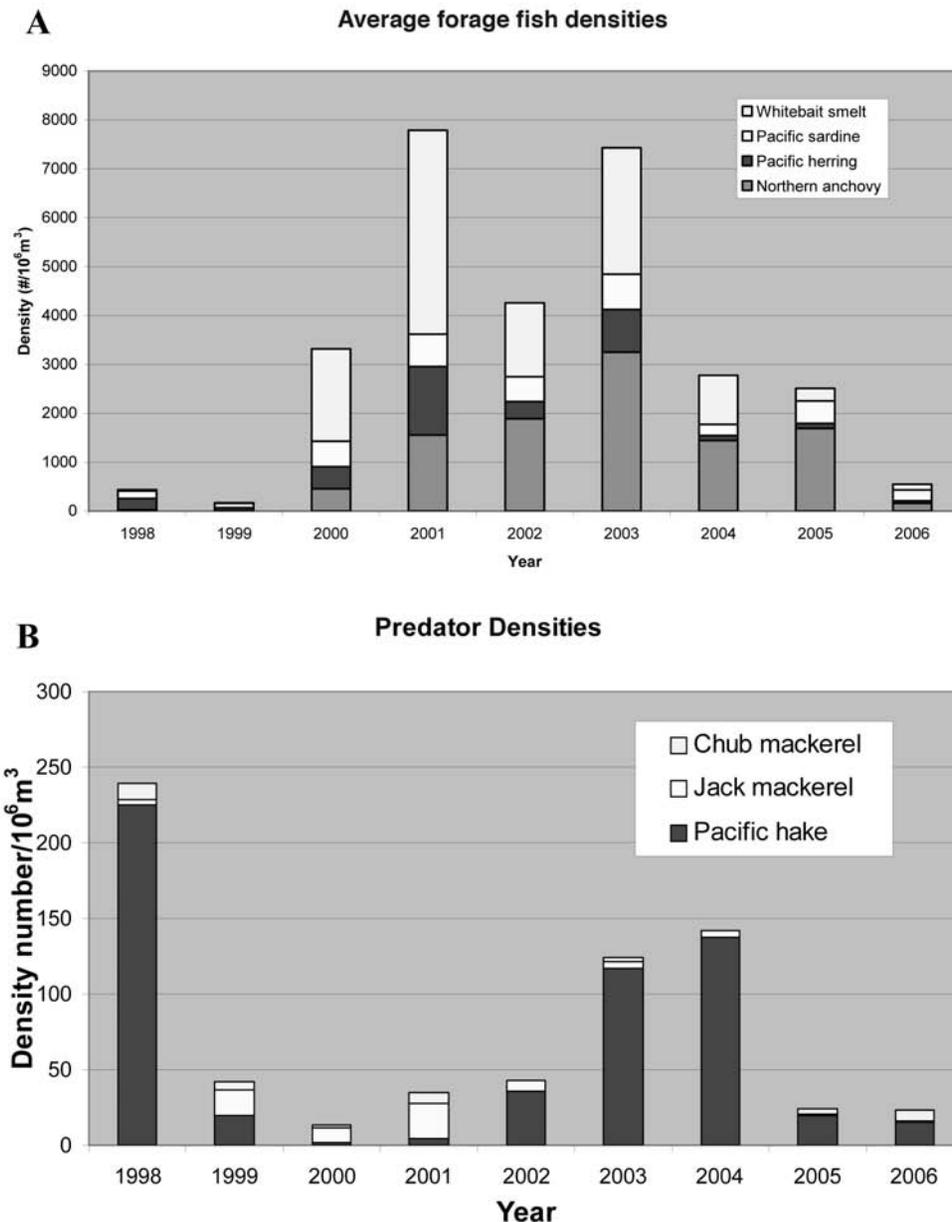


Figure 29. Densities of forage fish (A) and predatory fish (B) from rope trawl surveys conducted in coastal waters off southern Washington.

in 2004–05. Numbers of anchovies and sardines remained relatively high through 2005, whereas herring and whitebait smelt declined to 10% of the maximum numbers observed in 2001. Forage fish numbers in 2006 were among the lowest of the nine-year time series.

Because most forage fish recruitment (i.e., the larval-to-juvenile transformation in summer and fall) happens after our survey period (spring and summer), we do not catch most forage fishes in our trawls until they are at least one year old. Thus, forage fish densities appear to reflect oceanographic conditions from the previous year. Very low values observed in 2006 (fig. 29A)

are almost certainly due to very poor forage fish recruitment from adults that spawned in 2005, due to the very warm and poor ocean conditions in spring and early summer of 2005.

**Washington-Oregon: Predatory Fish:** The pelagic rope trawl also captures Pacific hake, jack and chub mackerel, and spiny dogfish. Catches of adult Pacific hake were somewhat related to ocean conditions. High catches occurred during the warm 1998 El Niño event, low catches during the subsequent cool years (1999–2002). Although increasing abundances were seen during the warm years of 2003–04 (fig. 29B), numbers were re-

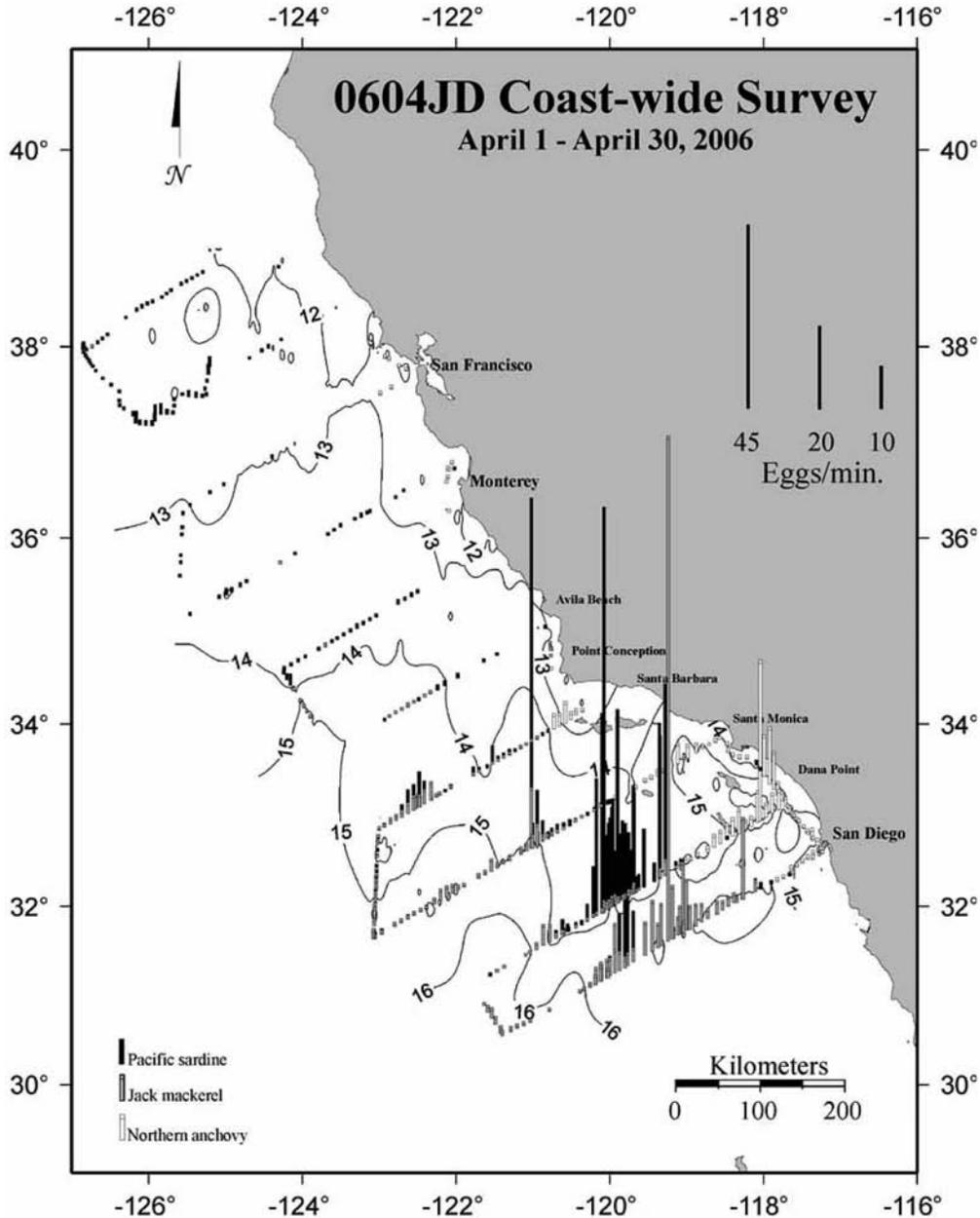


Figure 30. Rate of occurrence of eggs of Pacific sardine (*Sardinops sagax*), northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*) sampled with the continuous underway fish egg sampler (CUFES) and sea surface temperatures in 1–30 April 2006. One egg per minute corresponds to approximately three eggs per cubic meter.

duced in both 2005 and 2006, also warm years. We had expected to see increased numbers of adult Pacific hake in 2005 and 2006, because hydrographic conditions and zooplankton species composition resembled the 1998 El Niño event. However, this expectation was not met and we do not have an explanation.

**California: Spawning of small pelagics:** In the spring of 2006, eggs of sardine and jack mackerel were more abundant than anchovy during early April (fig. 30). In late April to early May few sardine eggs were observed

south of Cape Mendocino, yet relatively abundant anchovy and jack mackerel were observed south of Point Conception, with anchovy near the shore in the California Bight and jack mackerel offshore (fig. 31). Sardine eggs were concentrated in two areas: between CalCOFI lines 95–86.7, and a narrow strip between 40°N and 42°N latitude (fig. 30 and 31). The area with low density of eggs north of CalCOFI line 86.7 had high egg density in 2005 (Lo and Macewicz 2006), and the distribution of sardine eggs in 2006 differed from

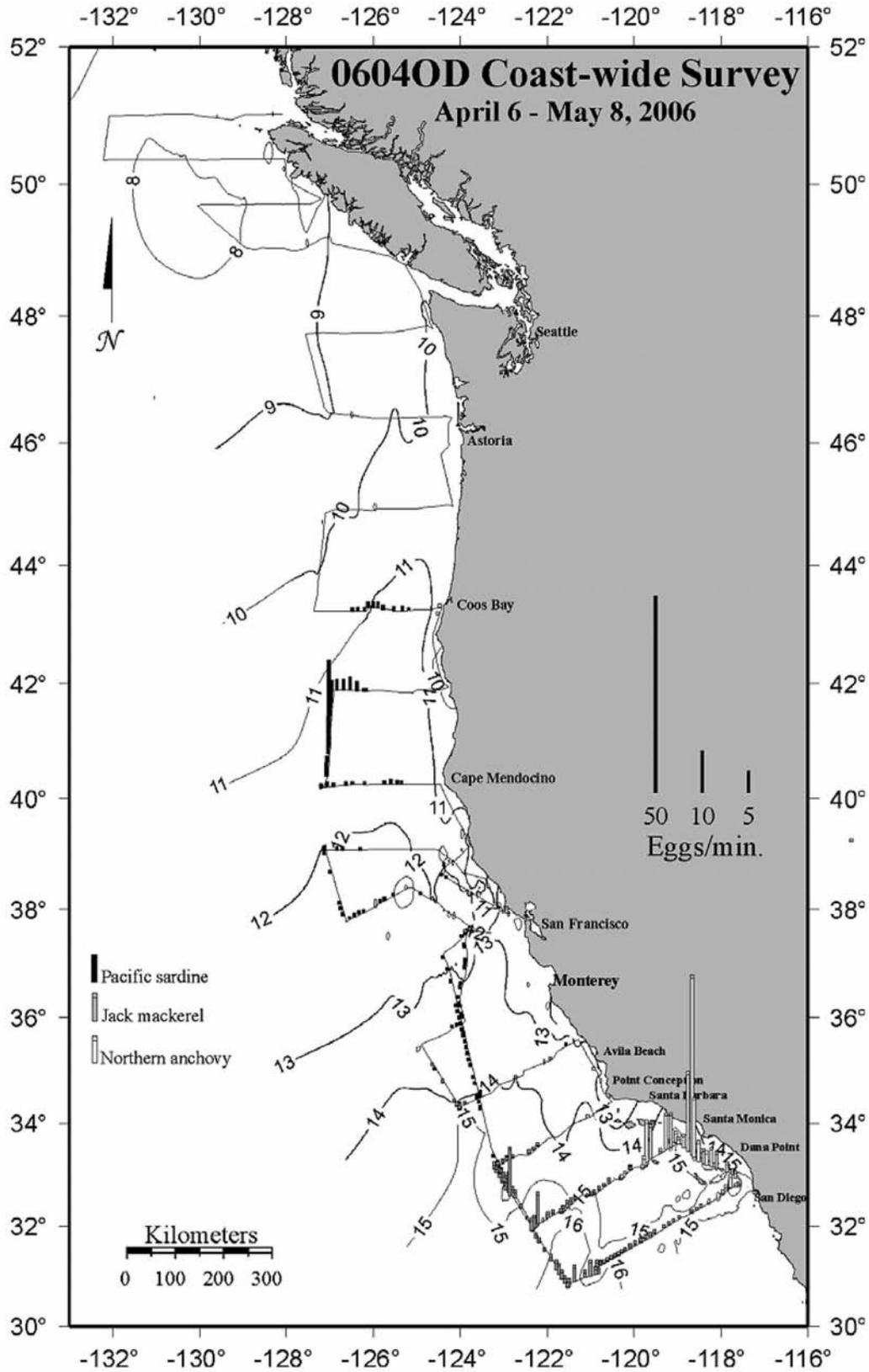


Figure 31. Rate of occurrence of eggs of Pacific sardine (*Sardinops sagax*), northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*) sampled with the continuous underway fish egg sampler (CUFES) and sea surface temperatures in April 6–May 8, 2006.

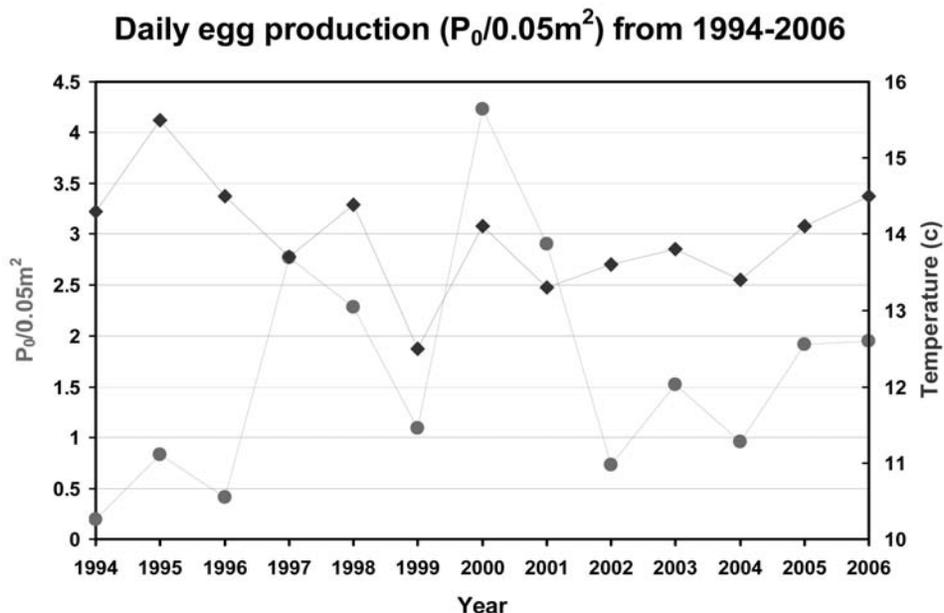


Figure 32. Daily egg production/0.05m<sup>2</sup> of Pacific sardine (*Sardinops sagax*) (circle) and average sea surface temperature (°C) (diamond) during March–May CalCOFI cruises and DEPM surveys from 1994–2006.

the past two years because very few were collected between CalCOFI lines 73.3 and 60 (fig. 30). This could be due to the shift of the spawning grounds, or to the delay of coverage of the central California area by the NOAA RV *David Starr Jordan*. The area north of 40°N latitude has been sampled relatively little using ichthyoplankton net tows. The high concentration of sardine eggs in this area was an indication of a spawning ground for sardine (fig. 2). In addition, unlike recent years, spawning activity in 2006 was strong in the southern part of the survey area off San Diego. The extent of spawning south of San Diego will not be known without information from Mexican surveys, i.e., IMECOCAL.

The spawning biomass of Pacific sardine, a fishery-independent population index, is positively related to the daily egg production, in particular if the number of oocytes per biomass weight remains constant (Lo et al. 2007). Daily egg production and the average SST during 1994–2006 are not directly related. However, in most years, except 1997 and 2002, year to year changes in daily egg production are inversely related to changes of sea surface temperature (fig. 32). This relationship is consistent with the assertion that high temperature is favorable for the Pacific sardine (Jacobs and MacCall 1995).

### California Sea Lions

California sea lions are one of the most abundant apex predators in the California Current System, with an estimated 237,000 to 244,000 sea lions in U.S. waters (Carretta et al. 2006). Sea lions respond to climatic forcing with changes in diet, movement, and foraging behavior, highlighting the utility of this predator as a sentinel

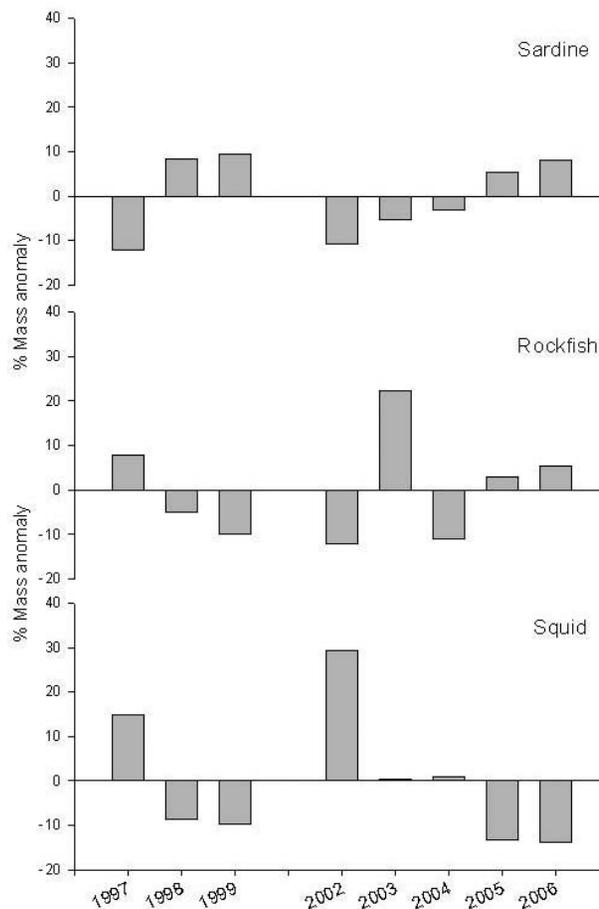


Figure 33. Time series of percentage mass anomaly of sardine, rockfish (*Sebastes* spp.), and market squid in the diet of California sea lions, Monterey Bay, 1997 to 1999 (Weise 2000; Weise and Harvey, In Review) and Año Nuevo Island 2002, to 2006 (Weise 2006; Weise and Harvey unpublished data).

TABLE 3  
 Mean, standard deviation, and sample size of prey species identified in California sea lion (*Zalophus californianus*) fecal samples collected in Monterey Bay from 1997 to 1999 (Weise 2000; Weise and Harvey, In Review) and Año Nuevo Island from 2002 to 2006 (Weise 2006; Weise and Harvey unpublished data).

	Rockfish			Sardine			Squid			Anchovy		
	Mean (cm)	SD (cm)	n	Mean (cm)	SD (cm)	n	Mean (mm)	SD (mm)	n	Mean (cm)	SD (cm)	n
1997	29.2	9.9	79	22.8	3.8	99.0	117.2	11.4	623	10.8	2.4	107
1998	16.7	8.2	268	19.0	3.4	949.0	70.7	15.1	707	11.3	2.1	305
1999	22.2	9.3	35	18.5	2.2	394.0	100.8	19.8	55	11.9	2.0	221
2002	25.5	10.2	195	22.3	4.8	47.0	108.1	23.8	1422	12.8	1.7	72
2003	18.4	28.4	260	19.0	5.4	110.0	90.8	38.6	596	10.9	2.2	141
2004	14.2	4.3	6	23.9	5.4	8.0	108.6	15.9	174	10.2	1.7	122
2005	24.8	12.1	17	16.9	8.6	62.0	86.5	25.4	33	11.5	1.7	298
2006	25.8	4.4	36	18.3	4.0	185.0	82.2	15.8	22	11.2	2.1	642

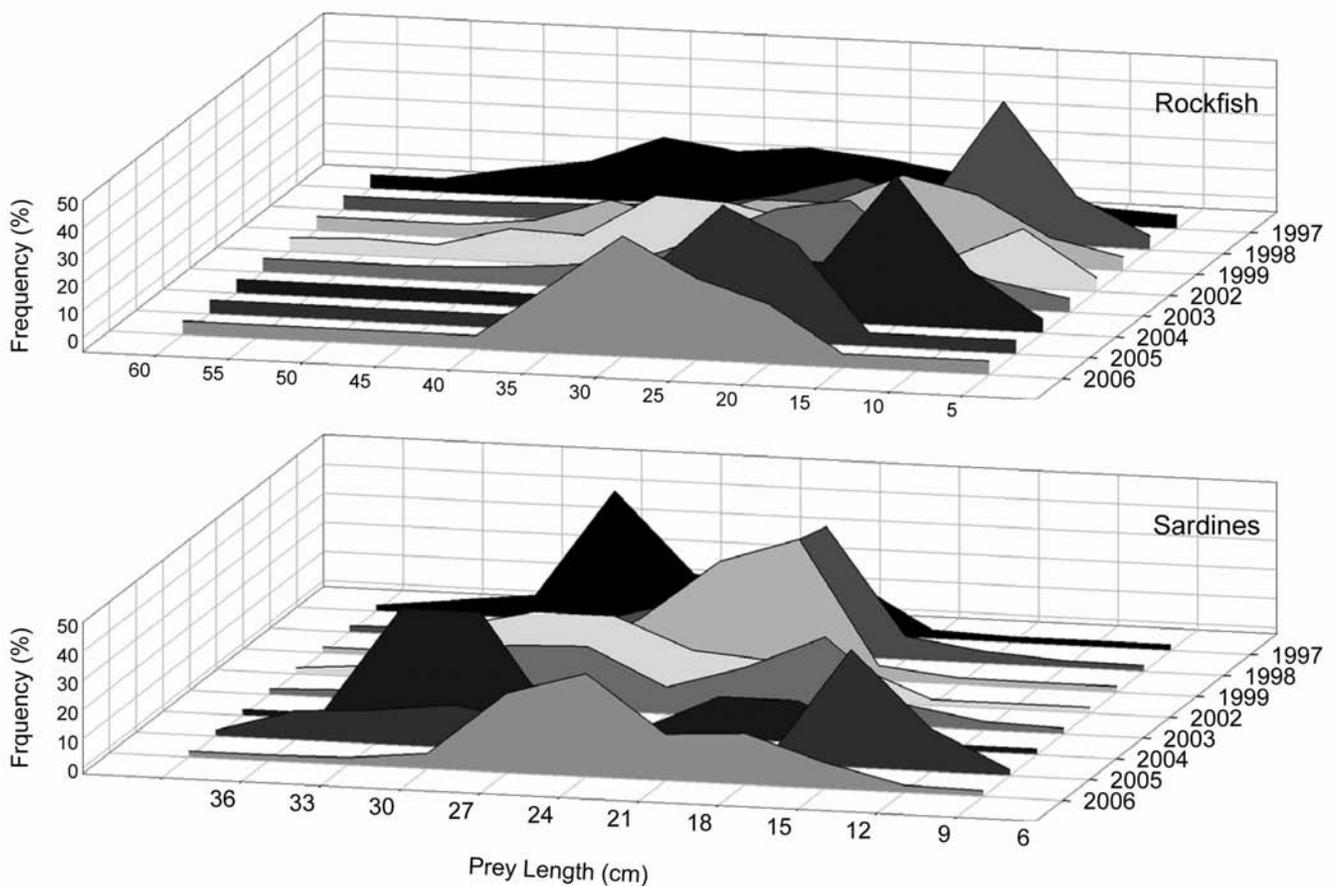


Figure 34. Time series of the size distribution of sardines and rockfishes (*Sebastes* spp.) utilized as prey by California sea lion reconstructed from sea lion fecal samples collected in Monterey Bay, 1997 to 1999 (Weise 2000; Weise and Harvey, In Review), and Año Nuevo Island, 2002 to 2005 (Weise 2006; Weise and Harvey unpublished data).

of climatic and biological variability and change (Weise et al. 2006).

The diet of California sea lions during 2006 off central California was similar to 2005. Anomalous oceanographic conditions early during the season resulted in positive anomalies in the consumption of rockfish (*Sebastes* spp.) and sardines (*Sardinops sagax*), and negative anomalies in market squid (*Loligo opalescens*; fig. 33). These

species dominated the overall diet with rockfish constituting 27.5% of the total mass consumed and sardines 25.6%. Although northern anchovies (*Engraulis mordax*) were the most important prey item in 2005 (31.2%), in 2006 they had only a slightly positive percentage mass anomaly and they had decreased to the third most important prey species (20.6%); however, length of anchovy consumed remained unchanged between years (tab. 3).

Decreased anomaly of market squid and increased anomaly of sardine in the diet during 2005 and 2006 were similar to trends observed in sea lion diet during the 1997–98 El Niño (fig. 33). Size of sardine consumed in 2006 were adults (27–36 cm) and similar in size to those eaten during 1997–98 El Niño (ANOVA, Tukey MSD Multiple comparisons,  $F = 25.83$ ,  $p = 0.228$ ,  $n = 1846$ ), but smaller than sardines consumed during 2005 ( $p = 0.178$ ; tab. 3, fig. 34). Squid were comparatively smaller in size during 2005 and 2006 and were similar to sizes consumed during the 1997–98 El Niño (tab. 3). Sizes of rockfish consumed in 2006 were similar to those eaten during 2005 (ANOVA, Tukey MSD Multiple comparisons,  $F = 31.83$ ,  $p = 1.000$ ,  $n = 1003$ ), but larger than rockfish consumed during the 1997–98 El Niño ( $p < 0.001$ ). Similar diet anomalies during 2005 and 2006 in central California may reflect the late onset of upwelling during both years. This work highlights the plasticity of the sea lion diet, and how it varies with climatic and biological conditions.

### Avifauna

The 2005 breeding failure of planktivorous auklets on the Farallon Islands was unprecedented (Sydeman et al. 2006). To further explore the relationships between breeding and foraging, we focus on a comparison between reproductive success of seabirds on the Farallones and summer-time distribution and abundance of birds at sea in the CalCOFI region, using the data from 2006. To provide a longer-term perspective we also compare recent observations to reproductive and community dynamics in the cold-water period (August 1998–July 2002) and subsequent warm-water period (August 2002–September 2005).

**Farallon Island Seabird Productivity, 2006.** The productivity of 6 species of seabirds at southeast Farallon Island has been monitored for the last 37 years by the PRBO. For comparative purposes we grouped species according to a basic life history pattern: those producing a single egg clutch, i.e., a conservative life history, such as Cassin's auklet (*Ptychoramphus aleuticus*), common murre (*Uria aalge*), and rhinoceros auklet (*Cerorhinca monocerata*); and those producing multiple-egg clutches, i.e., flexible life histories, such as Brandt's cormorant (*Phalacrocorax penicillatus*), pigeon guillemot (*Cepphus columba*), and pelagic cormorant (*Phalacrocorax pelagicus*). Five of these six species experienced pervasive breeding failures or significant reductions in breeding success in 2006, with only the Brandt's cormorant performing at a level comparable to the previous eight years. Most notably, the Cassin's auklet experienced nearly complete breeding failure in 2006 for the second year in a row. Productivity for this species has increased slightly in 2007 (~0.3 chicks/pair; PRBO unpublished data), but is still

well below the 36-year average of ~0.7 chicks per pair (Sydeman et al. 2001, 2006). The pelagic cormorant also essentially failed to reproduce (0.09 chicks/breeding pair), and common murre, pigeon guillemot, and rhinoceros auklet showed substantial negative productivity anomalies (fig. 35).

Clustering of seabird productivity data over the eight-year period revealed three distinct clusters. The last two years (2005 and 2006), characterized by pervasive reductions in productivity, clustered together (fig. 36) and contrasted sharply with the first two years (1999 and 2000) of high seabird productivity for all species. Three years of intermediate productivity (2001, 2002, and 2004) clustered together, despite some year-to-year fluctuations. The only year that stood alone was 2003, a warm-water year characterized by a decline in seabird productivity from the previous year (2002) for all the six seabird species monitored. The cluster analysis demonstrates the tremendous variability in seabird productivity observed over the past eight years, corresponding to a number of oceanographic and atmospheric anomalies.

**Pelagic Seabirds in the CalCOFI Region.** To illustrate fluctuations in marine bird communities, we focus on four "indicator" species with different water mass and biogeographic affinities (fig. 37), as observed during the summer CalCOFI cruises. The subtropical pink-footed shearwater (*Puffinus creatopus*) occurs off southern California waters between spring and fall, and in the past has become more abundant three to six months before warm water arrives in the regions (Hyrenbach and Veit 2003). The Cook's petrel (*Pterodroma cookii*) also occurs off southern California during spring–fall and moves shoreward during periods of warm water (Hayward et al. 1999). We also consider two species that breed on the Farallones: the Cassin's auklet and the common murre (Sydeman et al. 2001). Off southern California these latter species are more abundant during cold-water periods (Hyrenbach and Veit 2003). To assess the responses of these species to oceanographic variation, we correlated their summertime densities with the mean 10 m water temperature along CalCOFI line 90 using Spearman rank correlations.

The summer densities of the two warm-water indicators (Cook's petrel and pink-footed shearwater) varied substantially from year to year (fig. 37). The petrel occurred at densities above average during 2002–2004, and was slightly below average in 2006. Conversely, this warm-water species occurred at very low densities (<0.1 bird km<sup>-2</sup>) during the cold-water years of 1999–2001. Overall, Cook's petrel densities were significantly correlated with line 90 near surface temperatures for the period ( $r_s = 0.65$ ,  $n = 8$ ). The abundance of the pink-footed shearwater peaked in 2001 (>1 bird km<sup>-2</sup>) with low densities (0.1–0.5 bird km<sup>-2</sup>) during the rest of the

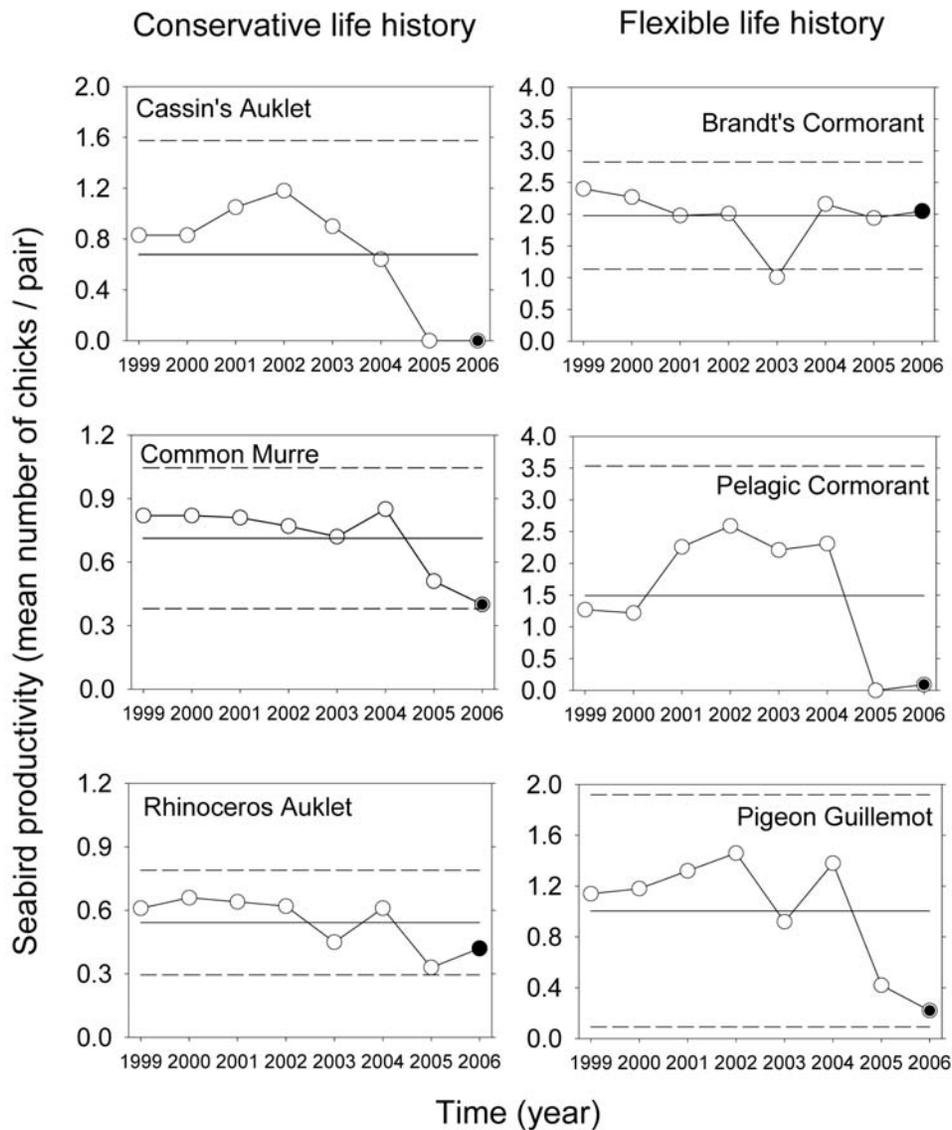


Figure 35. Productivity of six seabird species breeding at southeast Farallon Island (central California). The average (1999–2006) productivity is depicted by the solid horizontal lines and the hatched lines illustrate the year-to-year variability (mean  $\pm$  2 S.D.). Filled circles highlight productivities in 2006.

time series. Shearwater densities and concurrent water temperature were not significantly correlated ( $r_s = +0.02$ ,  $n = 8$ ). The Cassin's auklet was anomalously abundant in 2005 and especially 2006, with densities well above the long-term mean. While the auklet abundance was not correlated with concurrent water temperature ( $r_s = +0.37$ ,  $n = 8$ ), we found a significant negative correlation between auklet reproductive success at the Farallones and density at sea during summertime CalCOFI cruises ( $r_s = -0.63$ ,  $n = 8$ ). This result reinforces the idea put forth by Sydeman et al. (2006) that during the recent years (2005 and 2006) of catastrophic reproductive failure at the Farallones, auklets dispersed south and occurred in exceptionally high densities off southern California. Other auklet colonies breeding on

Seabird Productivity (SE Farallon Island)

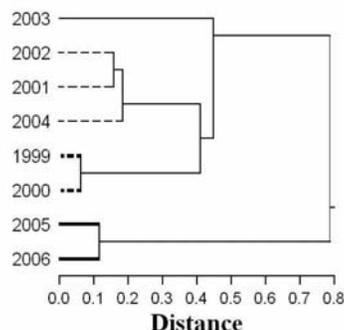


Figure 36. Cluster tree of marine bird productivity for the sea birds breeding in the Gulf of the Farallones. The Euclidean distances are based on the hierarchical clustering technique, with the median linkage algorithm. The thickness and hatching of the lines identify years that clustered together.

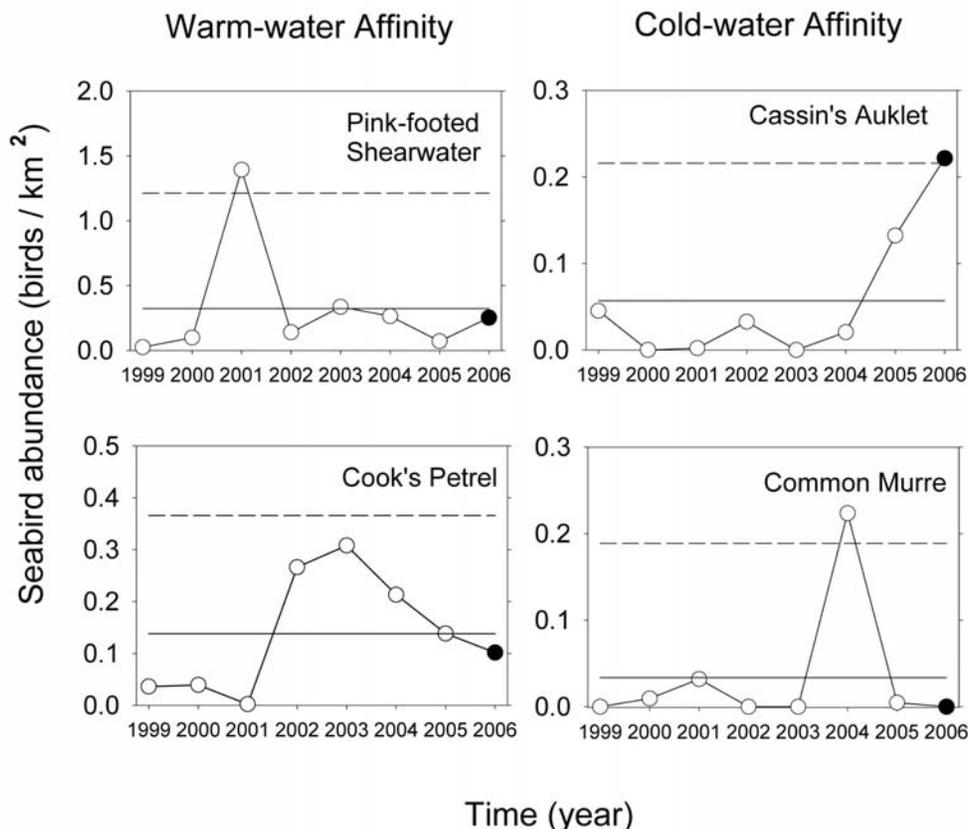


Figure 37. CalCOFI area at-sea abundance of four seabird species with different water temperature affinities during the summer. The average (1999–2006) densities are depicted by the solid horizontal lines and the hatched lines illustrate the year-to-year variability (mean  $\pm$  2 S.D.). Filled circles highlight abundances in 2006.

the Channel Islands and south of the Southern California Bight (San Benitos Islands, Mexico) also showed reproductive failures in 2006 (J. Adams and S. Wolf, pers. comm.). The Farallones population is the largest population, and is thus the most likely source of birds observed in the Southern California Bight, but some birds may have originated from the south. The common murre was anomalously abundant during the summer of 2004, but was essentially absent in other years, including 2005 and 2006. Murre abundance was weakly negatively correlated with concurrent water temperatures ( $r_s = -0.46$ ,  $n = 8$ ).

## DISCUSSION

External forcing acting on the CCS includes local forcing with time scales on the order of months to years, forcing by ENSO events with time scales on the order of a year, and basin-scale changes on the order of years to decades, which may or may not be cyclical. In addition, global temperatures are increasing. The last years have been unusual in the California Current System. Basin scale climate indicators were neutral. Coherent patterns did not emerge for the whole CCS; no single “state” could be ascribed to the whole system. The last event

that affected the CCS as a whole was the intrusion of fresh and cold water from the subarctic (Venrick et al. 2003). Corresponding salinity anomalies were evident in all time series collected along the coast from about 2002 until 2005 or 2006, depending on location. These salinity anomalies have returned to normal in all regions.

Observations over the last few years have shown that regional and local processes can dominate events in the different parts of the CCS, although biological interactions may spread local effects more broadly. For example, off Oregon and central California the dominant event over the last three years has been the onset of upwelling (Schwing et al. 2006; Peterson et al. 2006; this report). A late onset of upwelling in 2005 and 2006 caused delays or failures in the development of euphausiid populations. The absence of these prey items during time periods critical for breeding seabirds led to significant reductions and even total failures of seabird reproduction (Sydeman et al. 2006; this report). The productivity of Cassin’s auklets and pelagic cormorants on the Farallon Islands was virtually zero during these two years. The significant increase of auklet populations off southern California during the summers of 2005 and 2006 suggests that populations based on the Farallon

Islands may have migrated south in search of feeding grounds (Sydeman et al. 2006; this report). The early and strong onset of upwelling off Oregon and central California in 2007 and the partial recovery of auklet productivity suggest that the 2005 and 2006 upwelling anomalies and their effects were ephemeral.

Upwelling-favorable winds were also weak or delayed off southern and Baja California during 2005 and 2006, but the biological consequences appear to have been relatively minor (this report).

In coming years, the dominant aspect of change in the CCS may be that which is driven by global climate change. As global temperatures have been increasing, so have local temperatures, at least in the areas of the CCS with sufficiently long temperature records (Roemmich and McGowan 1995; this report). It is likely, though difficult to prove, that these local changes are linked to global forcing. Other system properties are co-varying with these changing temperatures (e.g., nitracline depth, chlorophyll *a*, zooplankton displacement volume), suggesting that changing temperatures have significant impacts, directly or indirectly, on ecosystem structure. Currently our understanding of the linkages between temperature and ecosystem function are rudimentary, yet they are essential for accurate prediction of ecosystem response to global change. We conclude this annual report with a plea to all working in the CCS to search for relationships between changing temperatures and various indices of ecosystem function so that we may arrive at a deeper understanding of these when we synthesize these data for future reports.

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