THE STATE OF THE CALIFORNIA CURRENT, SPRING 2008–2009: COLD CONDITIONS DRIVE REGIONAL DIFFERENCES IN COASTAL PRODUCTION

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ABSTRACT

This report describes the state of the California Current system (CCS) between the springs of 2008 and 2009 based on observations taken along the west coast of North America. The dominant forcing on the CCS during this time period were La Niña-type conditions that prevailed from the summer of 2007 through early 2009, transitioning to neutral El Niño-Southern Oscillation conditions in the spring of 2009. The Pacific Decadal Oscillation index was negative during this time period and its values had not returned to normal by the spring of 2009. The general effects on the California Current system were stronger than normal southward winds and upwelling as well as generally colder than normal SST and shallow nitraclines; however, there were regional differences. Off Baja California sea surface temperatures did not respond to the La Niña conditions; however, concentrations of chlorophyll *a* (Chl *a*) were significantly above normal, probably due to the anomalously high upwelling off Baja during most of the year. Off southern California there was no clear evidence of increased primary or secondary production, despite observations that previous La Niña conditions affected mixed layer depth, temperatures, nutrients, and nitracline depths. In both central and northern California and Oregon, stronger than normal upwelling increased primary production and prevented potential spawning of sardine north of San Francisco. In central California the midwater fish community resembled that of recent cool years, and cover by kelp was much reduced along the coast. Off Oregon there was evidence of increased abundance of boreal copepods, although the neritic boreal species did not appear to extend as far south as central California. Current predictions are for cooler conditions to change to El Niño conditions by the end of 2009; these are expected to last through the Northern Hemisphere winter of 2009–10.

INTRODUCTION

This report describes the state of the California Current between the springs of 2008 and 2009 based on observations taken along the west coast of North America (fig. 1) by a variety of academic and government observing programs. The North Pacific Ocean has been in a cool phase since the 1998/99 El Niño-Southern Oscillation (ENSO) event, as reflected in values of the Pacific Decadal Oscillation (PDO, fig. 2B) that

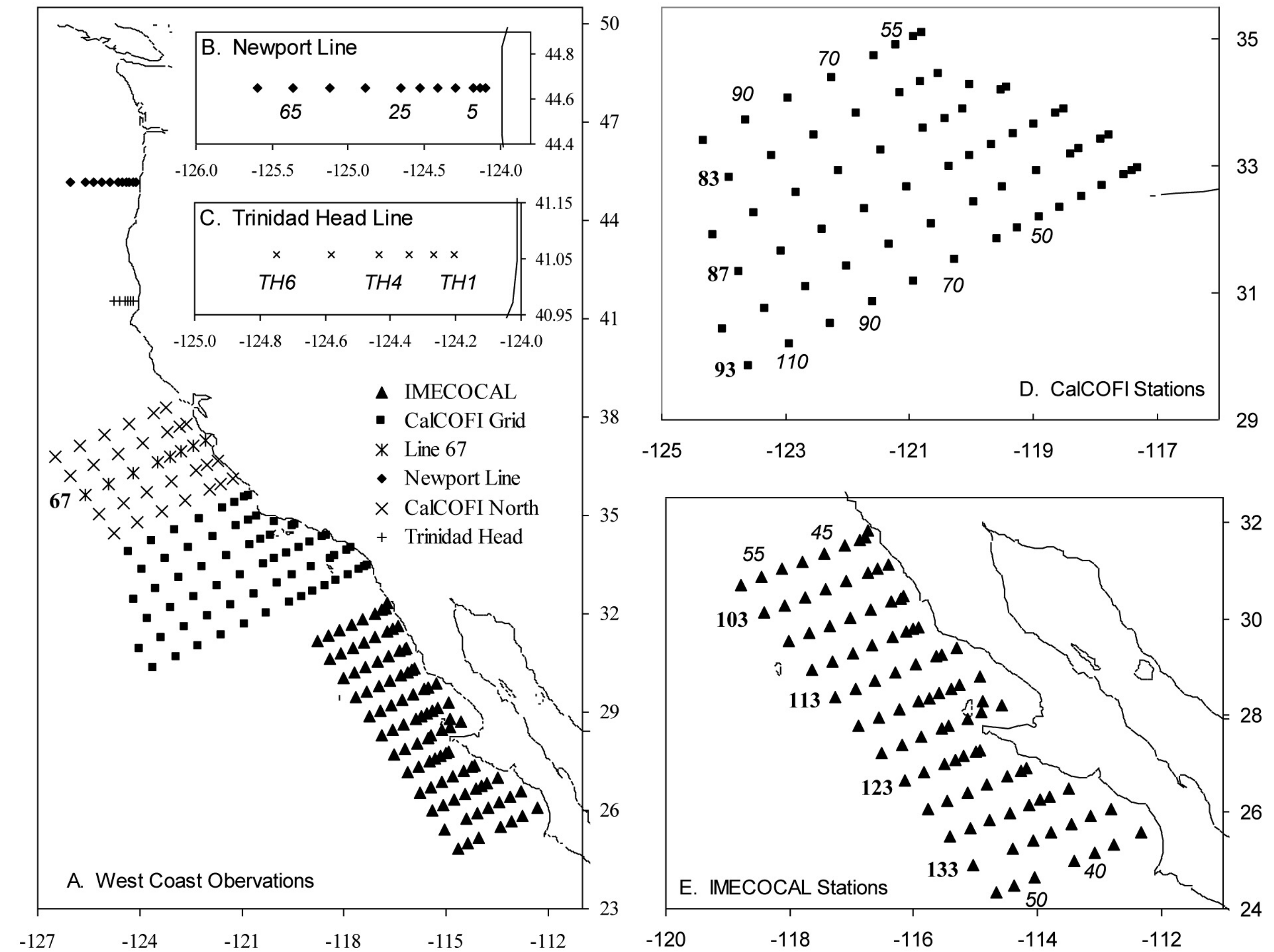

Figure 1. Location of stations where observations were made for this year's report. As appropriate, line numbers are indicated at the end of selected lines; station numbers are indicated above or below selected stations. Line and station numbers for the IMECOCAL and CalCOFI programs follow the CalCOFI line and station nomenclature.

have generally been negative, especially over the last 20 months. Indications of this cool phase are sea surface temperatures (SST) that, since 1999, have been significantly below long-term averages in many regions. At the same time dramatic changes in zooplankton biomass and community structure were observed in some areas (Bograd et al. 2008; Peterson and Schwing, 2003). El Niño events in 2003 and 2006 (fig. 2A) that were relatively weak along the equator, had small or negligible effects on the California Current system (CCS). Variability of biological indices over the last few years has primarily been driven by local- to regional-scale processes. For example the timing and strength of upwelling had very strong effects on local production at all trophic levels during 2005 and 2006 (Peterson et al. 2006; Goericke et al. 2007). In contrast, upwelling during 2007 started early and was anomalously strong, yet most biological indices were similar to their long-term averages (McClatchie et al. 2008).

During 2007, the CCS experienced very strong and persistent La Niña conditions, as reflected in low SST across the domain and upwelling volumes that were slightly above normal. Off southern California nitracline depths were unusually shallow and mixed layer concentrations of nitrate and chlorophyll *a* were unusually high (the latter signal was only evident from satellite data, not from cruise observations). Off Baja California concentrations of chlorophyll *a* were elevated as well, however, SST was normal, with the exception of January 2008. Zooplankton biomass was elevated off Baja and Oregon, but not off southern California, reinforcing the notion that phytoplankton and zooplankton biomass are not tightly coupled off southern California.

The long cool period appears to have had an adverse effect on the sardine population, especially sardine reproductive success, which is thought to respond more quickly to environmental conditions than total biomass or catch of sardine (Wada and Jacobson 1998). Anomalies of sar-

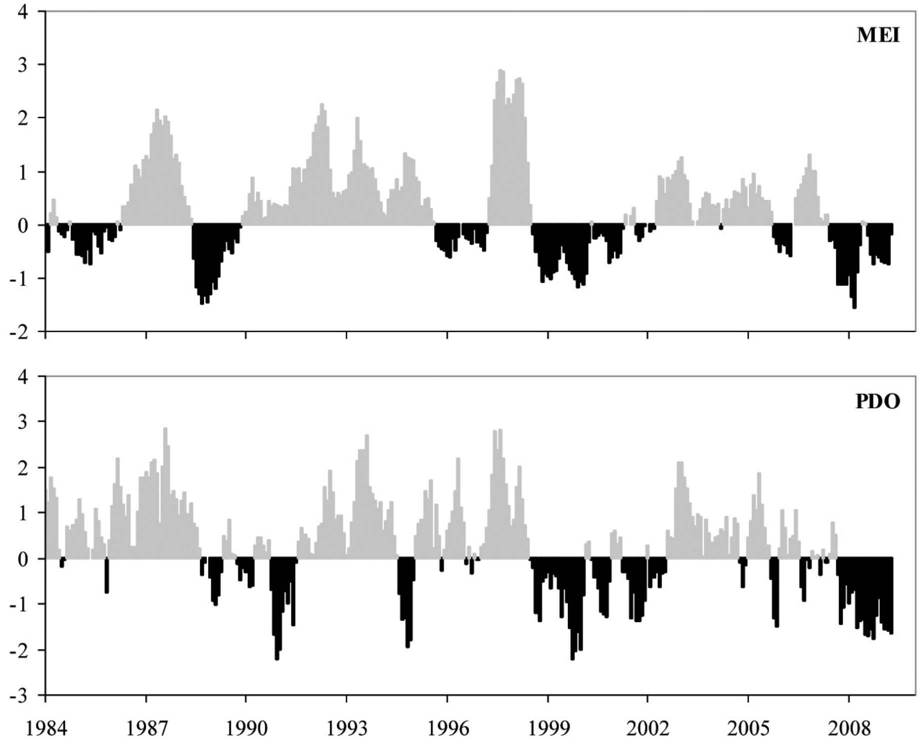

Figure 2. Time series of monthly anomalies of the Multivariate ENSO Index (MEI, http://www.cdc.noaa.gov/people/klaus.wolter/MEI/) and (B) the Pacific Decadal Oscillation (PDO, http://jisao.washington.edu/pdo/PDO.latest), for January 1984–March 2009.

dine reproductive success off California have been strongly negative in seven of the last 10 years (since 1999) (Hill et al. 2008). Based on the NOAA criteria for El Niño/La Niña classification using the Oceanic Niño Index, 1998–2000, 2000–01 and 2007–08 all contained seasonal periods classified as historical La Niñas, whereas 2002–03, 2004–05, and 2006–06/07 had periods classified as historical El Niños. Negative sardine reproductive success coincided with the cool La Niña conditions at the start and end of the decade, whereas the warmer El Niño conditions from 2002 to 2006 were associated with better (approximately average) sardine reproductive success.

Over the last year cold conditions have persisted, as reflected in the Multivariate ENSO (MEI) and PDO indices (fig. 2), resulting in one of the longest such cool periods in recent history. It is the objective of this report to summarize the response of the CCS to these continuing conditions, both from a physical and biological perspective. Basinwide SST anomalies associated with La Niña conditions typically have a horseshoe pattern delineating regions of positive anomalies in the central gyres, a horseshoe pattern of negative anomalies along the coast of the U.S. and Canada and a region of neutral or positive anomalies off Baja California (fig. 3). If local responses to the cool conditions were simply driven by local meteorological forcing, as reflected for example in SST or rates of upwelling, predicting the response of the ecosystem would be easy. However, since local systems are linked to remote systems through the CCS, local conditions are expected to be partially dependent on conditioning of the CCS upstream. Even though a rigorous analysis of these processes is beyond the scope of this report, this is an opportunity to compare the responses of different regions at different trophic levels and attempt to relate these responses qualitatively to either local forcing or remote forcing via the CCS.

DATA SETS AND METHODS

Climatology

Large-scale wind and temperature patterns were 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) were 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 were plotted against the harmonic mean of each buoy.

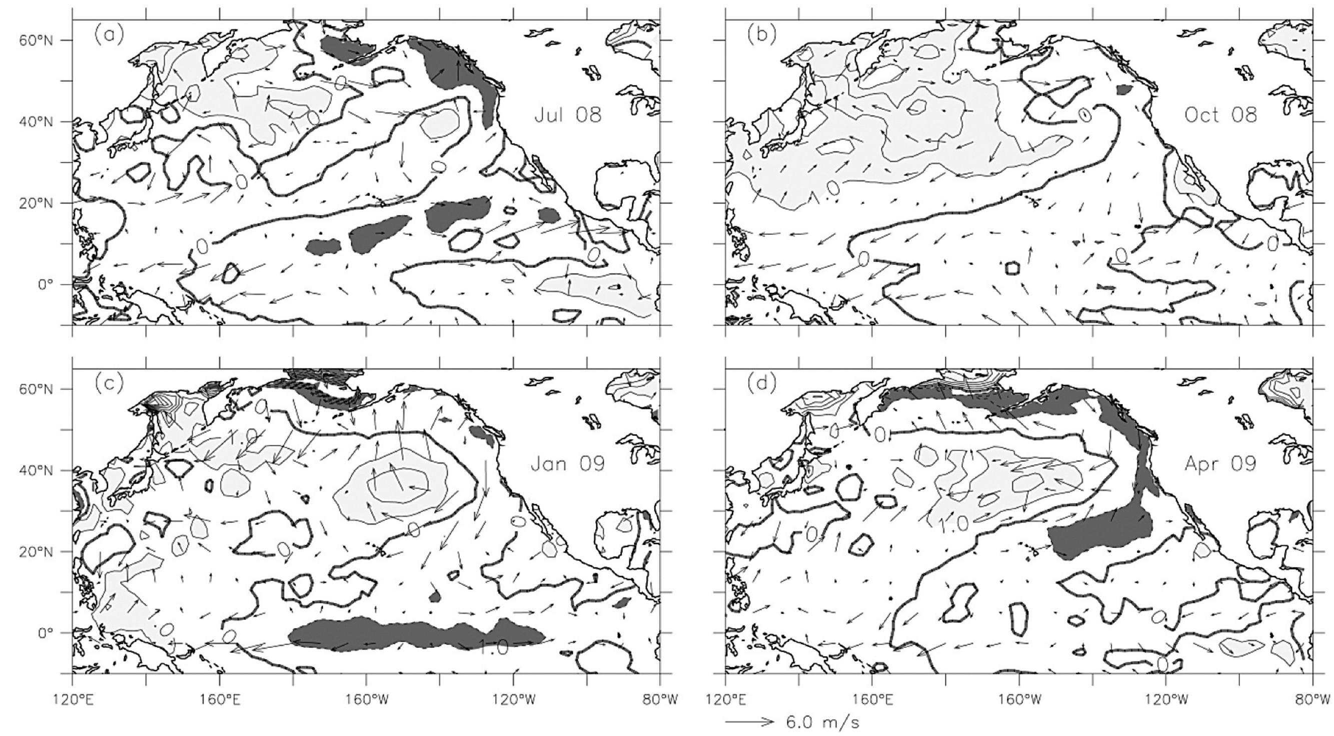

Figure 3. Anomalies of surface wind velocity and sea surface temperature (SST) in the North Pacific Ocean, for (A) July 2008, (B) October 2008, (C) January 2009, and (D) April 2009. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative (cool) SST anomalies less than -1° Celsius are shaded dark grey. Positive (warm) SST anomalies larger than 1° Celsius are shaded light grey. Wind climatology period is 1968–96. SST climatology period is 1950–79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

Remote Sensing

We used full resolution chlorophyll *a* (Chl *a*) and SST data (http://spg.ucsd.edu/Satellite_data/California_Current/) that were merged from multiple sensors in order to provide the best coverage at 1 km spatial resolution. OCTS (1996–97), SeaWiFS, MODIS-Aqua and MODIS-Terra Level-2 data sets were downloaded from the NASA Ocean Color Processing Group (http://oceancolor.gsfc.nasa.gov/) and AVHRR SST data from the Physical Oceanography DAAC (http://podaac.jpl.nasa.gov/). Corresponding sea surface temperature (SST) data were merged from AVHRR, MODIS-Aqua and MODIS-Terra sensors. A description of the satellite sensors is found in McClain 2009.

Monthly composites from November 1996 to April 2009, corresponding to the period of available high-quality ocean color data were used for both Chl *a* and SST. Monthly means were created at reduced spatial resolution (8 km) by averaging corresponding monthly composites over all years. Anomalies relative to the monthly means were calculated as either the ratio to the monthly mean (Chl *a*) or the difference from the monthly mean (SST). Principal components and respective empirical orthogonal functions (EOF) were calculated using the monthly anomaly data sets.

Time series of satellite-derived Chl *a* or SST were plotted as mean values on a 3 x 4 grid of characteristic areas parallel to the coast with bands of 0–100 km, 100–300 km and 300–1000 km from the coast (Kahru and Mitchell 2001; 2002).

REGIONAL STUDIES

Oregon (Newport Line)

Regular sampling of the Newport Hydrographic (NH) line along 44.65°N (fig. 1) began in 1996 and continues on a biweekly basis along the inner portions of the line, at seven stations, ranging from 1 to 25 nm from shore. The Newport Line station names designate distance (nm) from shore. Occasional cruises sampled further offshore. Methods and measurements are reported in Peterson et al. 2006. Standard hydrographic measurements are made and zooplankton are collected with a 0.5 m diameter, 200 µm mesh net, hauled vertically from a maximum of 100 m to the sea surface. Since 1998, pelagic forage and predatory fish have been sampled from shelf waters biweekly, at night, 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 pelagic rope trawl was towed for 30 minutes between the surface and 20 m. Additional details may be found in previous reports.

Northern California (Trinidad Head Line)

Regular sampling at roughly monthly intervals was carried out along the Trinidad Head Line (six stations along 41°3.50'N, 124°12'N to 124°45'N; fig. 1), subject to constraints imposed by weather and vessel availability. All cruises were conducted aboard Humboldt State University's RV *Coral Sea* except for the March 2008 cruise which was conducted aboard the NOAA RV *Miller Freeman*. All sampling since November 2007, with the exception of cruises in March 2008 and early April 2009, has been conducted at night. Since the fall of 2008 the Newport Line zooplankton protocol has been used on the Trinidad Head transect. Only three stations (TH02, TH03, and TH04) were sampled on 12 April 2009.

Northern and Central California Kelp Surveys

Kelp canopy surface areas are compiled by the California Department of Fish and Game. Data are collected using kelp-fly-over methodology between Pigeon Point and the Oregon border (http://www.dfg.ca.gov/biogeodata/gis/mr_nat_res.asp).

Central California Hydrographic Surveys (Line 67)

A CTD section extending offshore from Monterey Bay to a distance of 315 km (CalCOFI Line 67, fig. 1A) has been sampled on a regular basis since 1997. CTD station spacing is 10 nm and the water column is sampled to a depth of 1000 m. Between spring 2008 and spring 2009, surveys were conducted in June and October 2008 and January 2009.

Central California Coastal Time Series

Data are collected from eight stations in Monterey Bay. Daily means are interpolated to two-week intervals and smoothed with a nine-point running average. The long-term mean is based upon values collected between 1989 and 2008.

Central California Midwater Trawl Survey

The Fisheries Ecology Division (NOAA Fisheries, SWFSC) has conducted a midwater trawl survey annually since 1983 during May–June. Detailed methods are given by Baltz 2008. For this paper, statistics have been summarized from the core area of the survey off central California, extending from 36°30'–38°30'N (Point Piños to Bodega Head). Within this area hydrographic data collected by CTD casts were coarsely stratified by latitude (37° and 38°) and bottom depth (<200m vs. >200m). A variety of epipelagic fish and invertebrate micronekton/nekton are sampled by the midwater trawl, which is fitted with a 1cm mesh cod-end liner. Young-of-the-year (YOY) groundfishes have been counted since 1986, including rockfishes (*Sebastes* spp.), sanddabs (*Citharichthys* spp.), Pacific whiting (*Merluccius productus*), and lingcod (*Ophiodon elongatus*). Likewise, catches of several important coastal pelagic species (northern anchovy [*Engraulis mordax*], Pacific sardine [*Sardinops sagax*], and market squid [*Loligo opalescens*]), as well as deep-scattering layer mesopelagic species (e.g., lanternfishes [Myctophidae], California smoothtongue [*Leuroglossus stilbius*], and sergestid shrimp) have been routinely recorded.

Southern California (CalCOFI)

The CalCOFI program samples 66 stations on a quarterly basis along six lines between Point Conception and the Mexican Border (fig. 1D), 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. The water column is routinely profiled to a depth of 500 m, or 10 m off the bottom, using conductivity, temperature, pressure, oxygen, fluorescence, and light transmission sensors. Water samples are retrieved from 12 to 20 depths and salinity, dissolved oxygen, nutrients, and chlorophyll are determined. Standard (0.505 mm mesh) oblique bongo tows are conducted to 210 m depth at each station. The following sampling and analytical protocols are presented in data reports and on the CalCOFI website; both at http://www.calcofi.org.

Results from four cruises off southern California (CC0807, CC0811, CC0901 and CC0903) are presented and compared to the long-term conditions in the study area. Detailed descriptions of the cruises and methods used to collect data and analyze samples are given at http://www.CalCOFI.net. Results from these cruises are presented as time series of cruise averages over all 66 stations (fig. 1C) or as anomalies with respect to the 1984–2008 time series. The mixed layer depth is calculated using a density criterion and set either to 12 m or to the half-way point between the two sampling depths where the σ_θ gradient first reaches values larger than 0.002 per m, whichever is larger. The 12 m cutoff avoids including the daytime thermocline in the analysis. This procedure will introduce a positive bias in calculation of the mixed layer 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.

Cetaceans

Two trained marine mammal observers were posted on the flying bridge (0803JD) or bridge wings (0808NH, 0810NH, 0901NH) to scan for cetaceans using binoculars (7-power and 18- or 25-power magnification) and the naked eye. Visual observations were conducted during daylight hours while the ship was underway steaming at approximately 10 kn between stations. Search effort was curtailed in Beaufort sea states of 6 or more and/or in visibility of less than 0.5 nm. Opportunistic sighting data were also recorded while the ship was on station or during inclement weather/sea state.

During daylight transits, we towed a six-element hydrophone array with recording bandwidth of 3 kHz to 96 or 250 kHz, effective for recording primarily odontocete clicks and whistles. At about 1–2 nm distance from each daylight station, we deployed an omnidirectional Navy sonobuoy with effective recording bandwidth of ~5 Hz to 22 kHz for recording baleen whale calls and low-frequency odontocete sounds such as whistles.

NOAA Coast-Wide Surveys

In 2008, two coast-wide surveys (NMFS California Current Ecosystem Survey) were conducted by Fisheries Resources Division (NOAA Fisheries, SWFSC). Both surveys were planned to cover the area from San Diego to the U.S.-Canadian border. Surveys ran from March 24 to May 1 (survey 0804) and from June 30 to August 20 (survey 0807). During the survey, ichthyoplankton samples were taken aboard the NOAA RV *Miller Freeman* (1–30 April, 0804MF) from Cape Flattery, Washington, to San Francisco (48.47°–36.6°N), and aboard the NOAA RV *David Starr Jordan* (24 March–1 May, 0804JD) from San Diego to San Francisco (CalCOFI Line 93.3–62.3). The *Jordan* cruise included the routine CalCOFI cruise (CalCOFI Line 93.3–76.6, 24 March–8 April, fig. 1D). Adaptive sampling of sardine eggs was applied during the coast wide survey but not during the CalCOFI cruise. Survey 0807JD was conducted entirely aboard the *David Starr Jordan* with ichthyoplankton and trawl samples. Hydrographic, acoustic and seabird data were also collected, but are not presented here (see McClatchie 2009)

Baja California (IMECOCAL)

The IMECOCAL monitoring program began in autumn 1997, consisting of quarterly cruises surveying 93 stations off Baja California, México (fig. 1E). Station designation follows the traditional CalCOFI nomenclature; thus sampling followed lines 100 to 137. The IMECOCAL program covers all lines out to stations 60, i.e., the westernmost station on any IMECOCAL line is 60. 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 l Niskin bottles at 0, 10, 20, 50, 100, 150, and 200 m depths to determine dissolved oxygen, Chl *a* , nutrients (NO3, NO2, PO4, SiO3), and primary production.

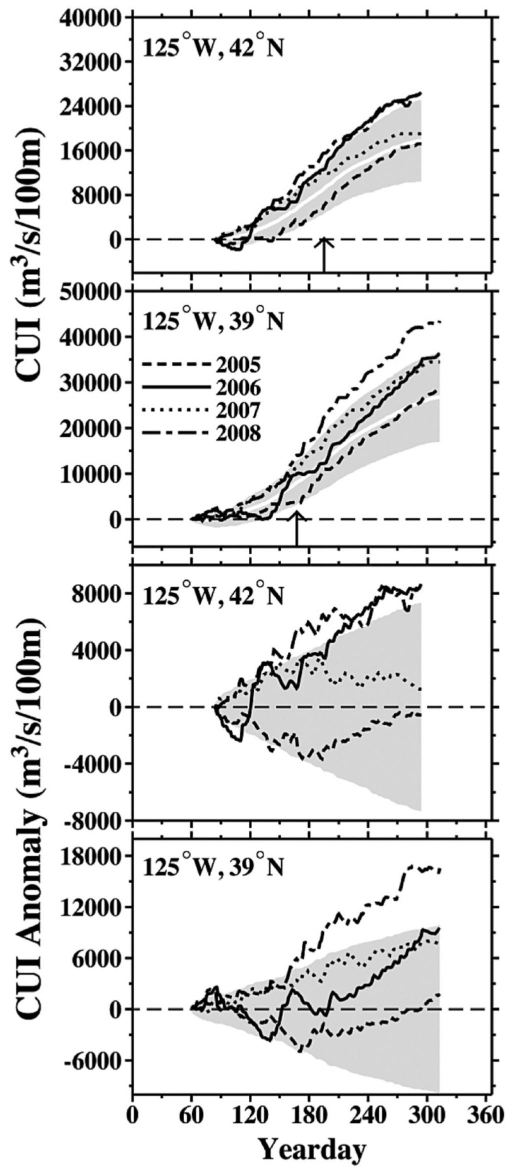

Figure 4. Cumulative upwelling index (CUI; m^3/s/100 km; upper two panels) and CUI anomalies (m^3/s/100 km; lower two panels) for two locations in the California Current. Integration was performed over the climatological upwelling season at each latitude, and arrows mark the time of maximum climatological upwelling at each latitude. Mean and standard deviation (white solid and shaded areas, respectively), and 2005, 2006, 2007, and 2008 are shown.

Macrozooplankton is sampled with bongo net tows from 200 m to the surface. IMECOCAL cruise schedules, data collection, methods, and analysis are fully described at http://imecocal.cicese.mx.

Anomalies used in this report were calculated by removing the seasonal means of the period 1997–2008.

RESULTS

Large-Scale Patterns

Climatology: La Niña conditions prevailed in the tropical Pacific from summer 2007 through early 2009,

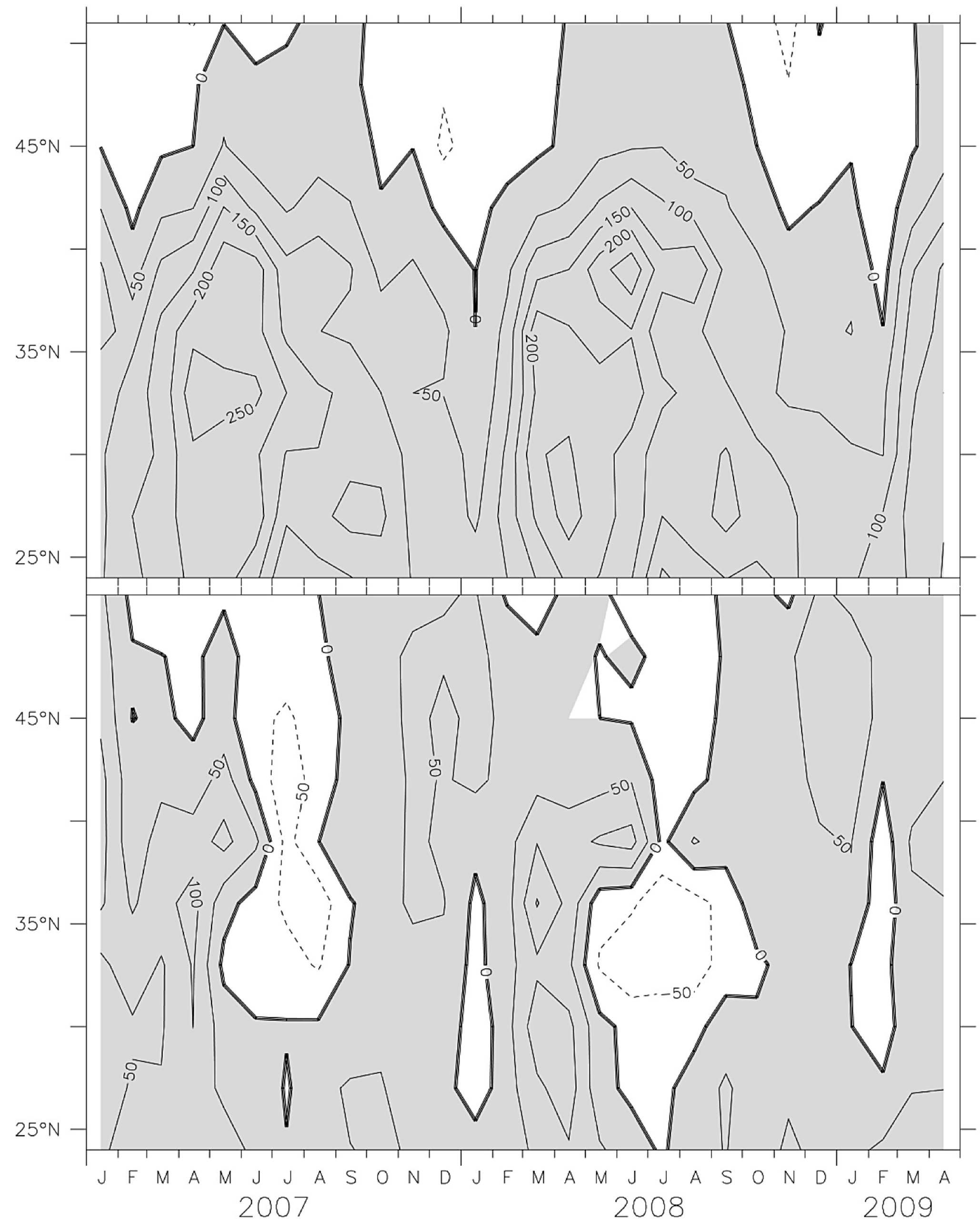

Figure 5. Monthly upwelling index (top) and upwelling index anomaly (bottom) for January 2007–April 2009. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m^3/s per 100 km of coastline.

with SST anomalies in the Niño3.4 region (5°N to 5°S, from 170°W to 120°W) exceeding −1°C from October 2007 through February 2008 (fig. 3). The 2007–08 La Niña event was the strongest since 2000 (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/). Near-neutral conditions returned in summer 2008, followed by cooling and the re-development of a weak La Niña. By April 2009, negative SST anomalies had weakened and positive SST anomalies had strengthened in the equatorial Pacific, thus ending the 2008–09 La Niña, transitioning briefly to ENSO-neutral conditions and by June to El Niño conditions (NOAA CPC Climate Diagnostics Bulletin) (www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/index.shtml).

In the extra-tropical North Pacific Ocean, SST anomalies displayed the typical horseshoe pattern of La Niña through the latter half of 2008 and continuing into early 2009 (fig. 3). This pattern also reflects the negative phase of the PDO, which has persisted since autumn 2007 (fig. 2). Negative SST anomalies on the order of −1°C

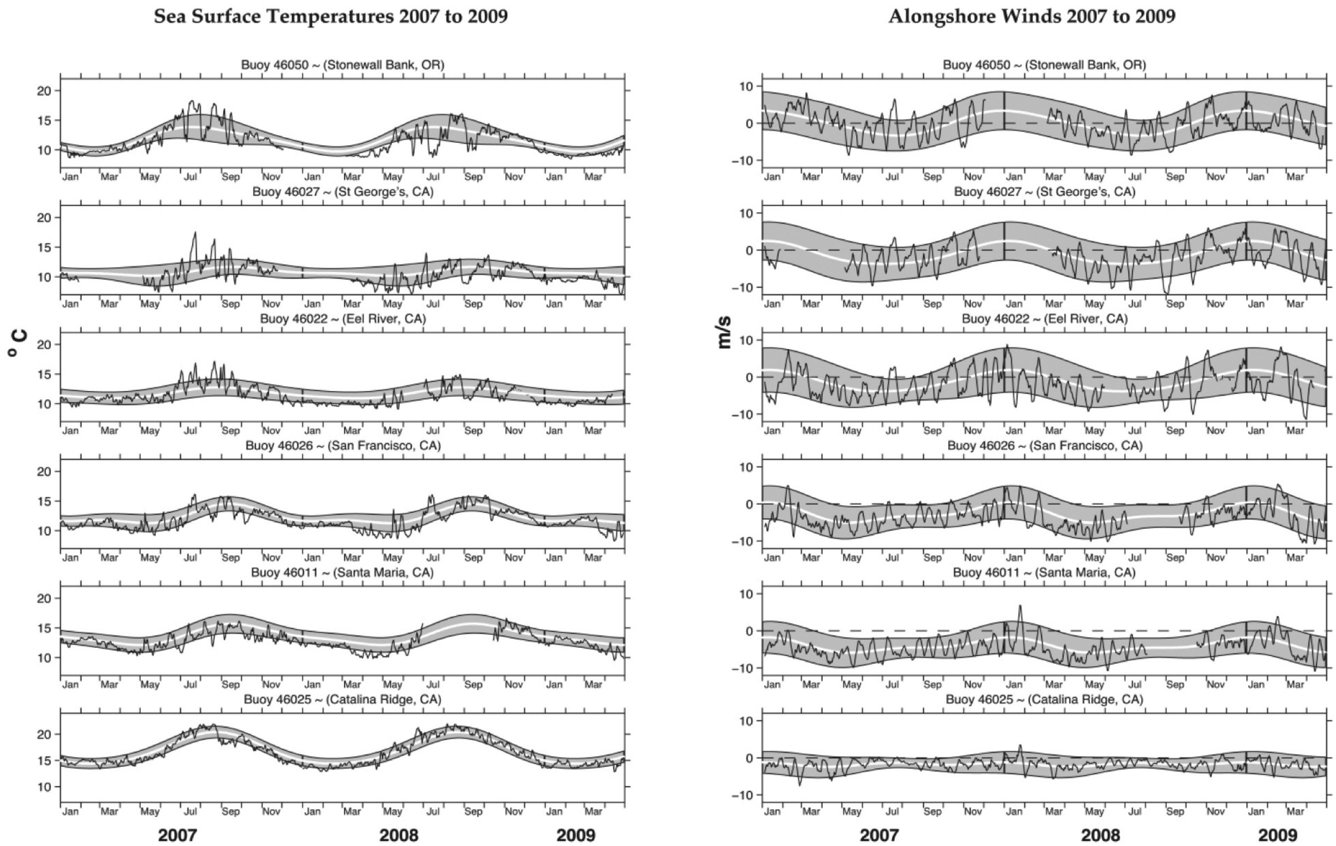

Figure 6. Time series of daily-averaged SST (left) and alongshore winds (right) for January 2007–February 2009 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a seven-day running mean. Data provided by NOAA NDBC. Coordinates for buoy locations are at http://www.ndbc.noaa.gov/to_station.shtml.

extended throughout the California Current and Gulf of Alaska through winter 2008–09 and into spring 2009, and wrapped in a horseshoe shape around a broad region of positive SST anomalies (up to +2°C) in the central North Pacific Ocean (fig. 3). Month-to-month SST anomaly changes in the North Pacific Ocean have been controlled locally by a combination of air-sea heat fluxes and Ekman transport and pumping (open ocean upwelling).

The effect of this large-scale pattern on the California Current has been anomalously strong southward coastal winds, stronger than normal upwelling along the West Coast (figs. 4 and 5) and reduced SST. With the exception of a brief period of weaker than normal upwelling in the summers of 2007 and 2008, West Coast upwelling index anomalies have been positive since late summer 2006. Wind anomaly patterns in early 2009 reflect anomalously strong high pressure over the northeast Pacific (fig. 3C, D) and very high upwelling (figs. 4 and 5).

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 (e.g., March 2009 at Eel River; fig. 6). This has included several strong upwelling episodes in autumn 2008 and winter 2009, which could lead to a pre-conditioning of the California Current toward a more productive state (Schroeder et al. 2009). A strong cycle of upwelling/downwelling events has been evident since 2007, and may be linked to an active period of the intraseasonal Madden-Julian Oscillation, which is characterized by 30–60 day variability in the tropics. Buoy SSTs were near-normal in 2008 but have become anomalously cool in 2009.

Satellite remote sensing: Trends and patterns in the time series of satellite-derived chlorophyll *a* concentrations and SST in the California Current were analyzed for the period of 1996–2009. Near-shore areas (within 100 km from the coast) in central and southern California showed a trend of increasing Chl *a*. SST was colder than normal over most of the area in the first half of 2008 but turned warmer than normal along the coast of Baja California in the second half of 2008.

We used the first EOFs of Chl *a* and SST as an indicator of the dominant variability pattern. For Chl *a*, the main features of variability were associated with the intensity of upwelling off Point Conception, off the coasts

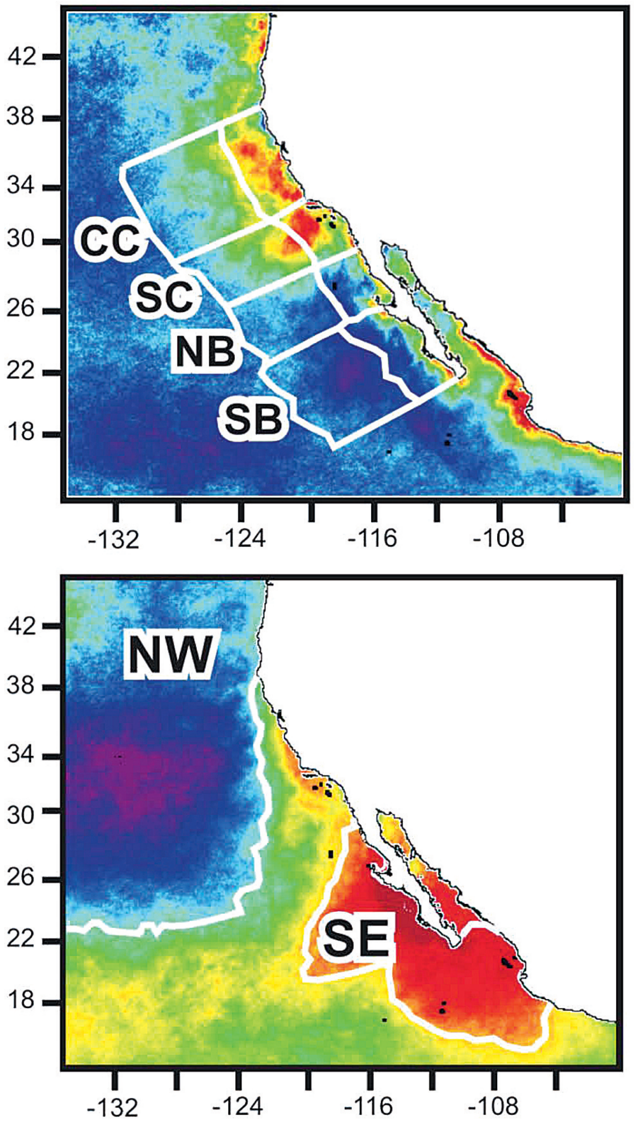

Figure 7. (top) First EOF of the distribution of Chl *a* using monthly anomalies from November 1997 to April 2009. The white lines parallel to the coast are 1000 and 300 km from the coast. (bottom) First EOF of the distribution of SST using the monthly anomalies. The white contours show the main domains of the variability pattern for SST (NW and SE).

of central California and Oregon and off the Mexican mainland (fig. 7A). For SST the main pattern was a dipole-like structure between the north-west and south-east (fig. 7B). Chl *a* distribution had a much more complex variability structure than the SST distribution as the first EOF explained only 5.8% of the total variance in Chl *a* compared to 15.4% of the total variance in SST.

Time series of Chl *a* concentrations within the 100 km wide coastal zone showed some contrasting patterns. A significant trend of increasing Chl *a* was detected off central California (fig. 8, CC). The increasing phytoplankton bloom magnitude was reported earlier (Kahru and Mitchell 2008; Kahru et al. 2009). The more variable but still significant increasing trend off southern California (fig. 8, SC) was interrupted by periods of strong positive anomalies (+200% anomaly in the summer of 2003, +90% anomaly in the winter of 2007/08) and negative anomalies (winter of 2004/05). Strong interannual variability without a significant trend was evident off the northern and southern Baja domains (fig. 8, NB

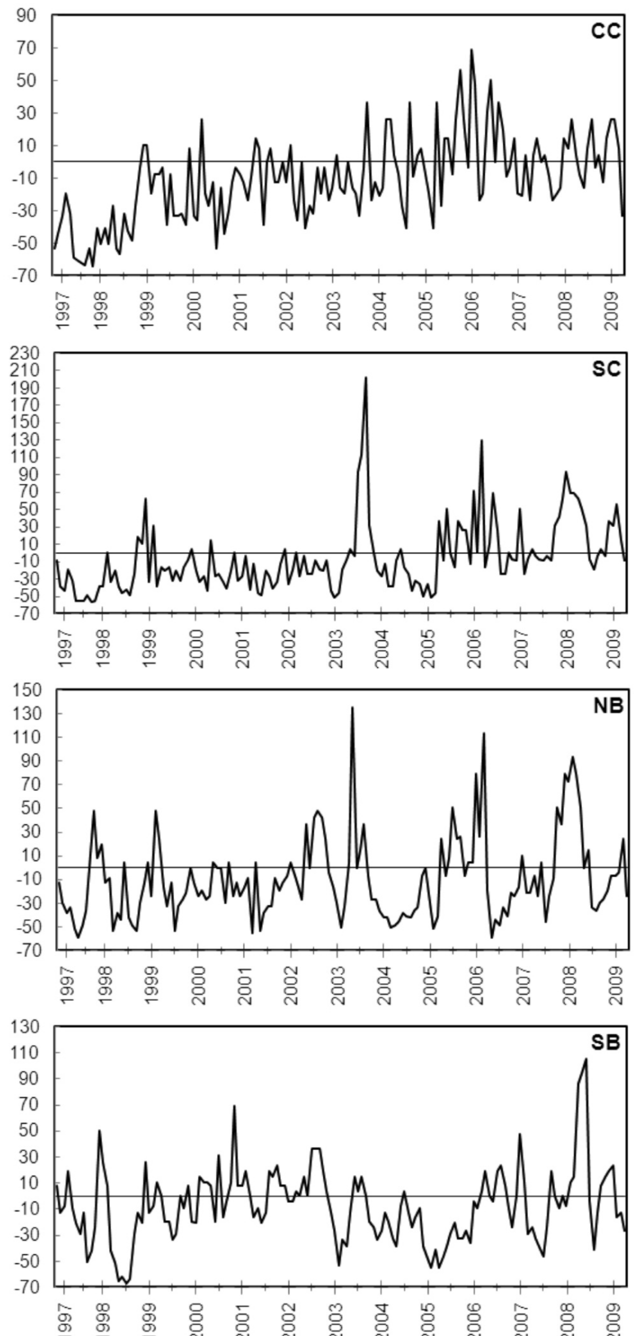

Figure 8. Monthly anomalies of Chl *a* concentration (%) in the 100 km wide band along the coast in central California (CC), southern California (SC), northern Baja California (NB) and southern Baja California (SB). Long-term means are the horizontal lines.

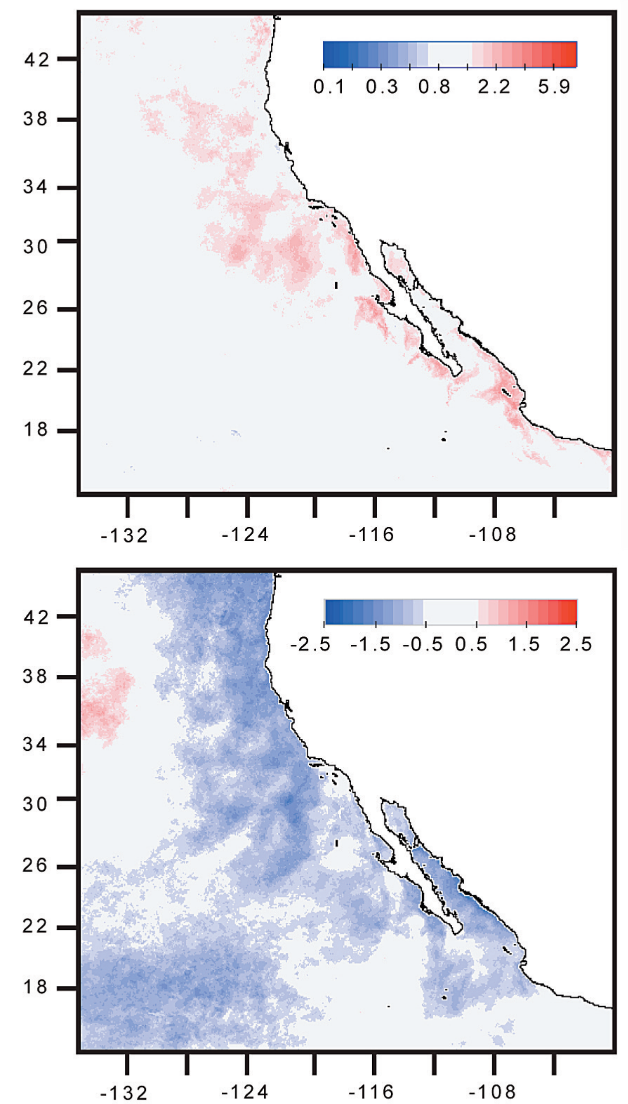

Figure 9. Means of the January 2008 to June 2008 monthly anomalies for Chl *a* (top) and SST (bottom) showing the dominance of areas with higher than normal Chl a and colder than normal SST. The anomaly for Chl a is expressed as a ratio of the actual values to the long-term mean value. The anomaly for SST is expressed as the deviation from the long-term monthly value.

and SB). From the spring of 2008 to the spring of 2009, Chl *a* was generally slightly above the long-term mean in the central and southern California domains but fluctuated strongly in the two Baja domains. The first half of 2008 showed higher than normal Chl *a* and colder than normal SST over large areas (fig. 9).

Regional Studies

Oregon: Sea surface temperatures at the Stonewall Bank NOAA Buoy located 22 miles off Newport were highly variable during the summer of 2008 (fig. 6). The sea surface temperature anomaly for May–September 2008 at the Newport mid-shelf station, NH 05, was −0.81°C. Off Newport, upwelling timing and volume were close to long-term averages during the summer of 2008 (fig. 5, 44.7°N). Averaged over the year, upwelling volumes were slightly above average. In contrast to previous years when most summer cruises showed some degree of hypoxia, oxygen concentrations at 50 m at our mid-shelf station (NH 05) only fell below the hypoxic level of 1.4 mL/L on two cruises out of 15 cruises carried out in May through September. Early summer (April–June) surface nitrate concentrations (8.0 μM) were above the long-term average (5.1 ± 2.7 μM); July–August concentrations were similar to long-term average, 13.1 vs. 10.0 ± 2.8 μM. Concentrations of Chl *a* were similar to long-term averages during the early summer and slightly below long-term averages during July and August.

The years 2007–09 were characterized by conspicuously high abundances of the boreal oceanic copepods *Neocalanus plumchrus* and *N. cristatus* off the coasts of Oregon and northern California. Although the reasons for this are not yet clear, this observation does suggest a greater influence of sub-arctic waters on the northern California Current, beginning in February/March 2007. The time series of copepod biomass and species composition collected at the baseline station NH 05 off Newport showed a resurgence of "northern copepods" beginning in 2006, and continuing through 2007–09 (fig. 10A). The May–September average values of northern copepod biomass and the PDO generally covary (fig. 10B).

Comparison of Newport, Oregon line with Trinidad Head, California line: The samples collected at Trinidad Head station TH02 have been analyzed to compare zooplankton community structure along the Trinidad and Newport lines. TH02 was selected for the initial analysis because it was in the same water depth (~ 70 m) as the most frequently sampled station on the Newport line, NH 05, in 62 m of water. Along the Trinidad Head transect 2008-shelf waters were colder than in 2007. Initial results show that despite the two stations being in inner-to-midshelf waters, TH02 is quite different from station NH 05 in two ways: first, TH02 had a more oceanic zooplankton assemblage including the boreal oceanic species *Neocalanus plumchrus, N. cristatus, Microcalanus pusillus*, and the warm-water oceanic copepod *Calanus pacificus*, second, TH02 had much lower abundances of the boreal neritic copepod species that are common off central Oregon: *Calanus marshallae, Tortanus discaudatus* and *Centropages abdominanlis*.

Planktivorous and Predatory Pelagic Fish Surveys

Results of the bi-weekly pelagic fish surveys in 2008 have not yet shown that small planktivorous pelagic fish have had the expected positive response to the change to cold ocean conditions that began in September 2007 (fig. 11). We hypothesize that the populations of adult anchovy, herring, and white bait smelt were reduced to

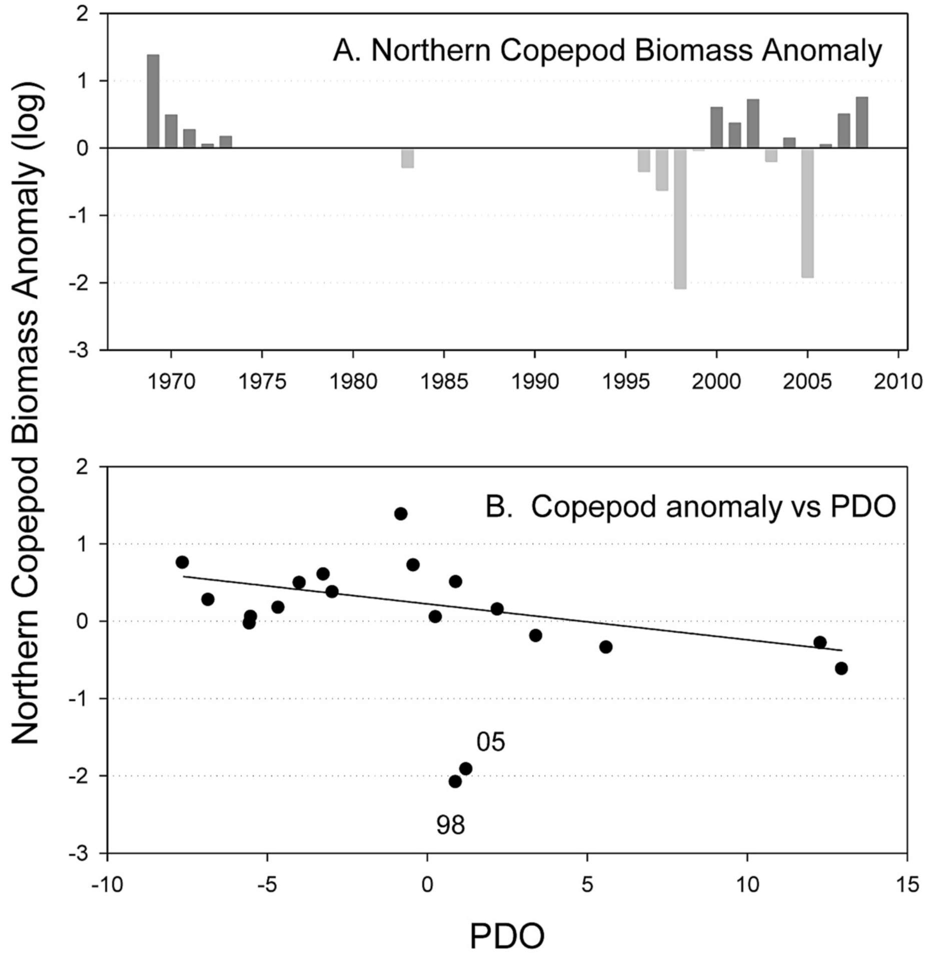

Figure 10. (A) Biomass anomalies of northern copepods (*Calanus marshallae*, *Pseudocalanus mimus* and *Acartia longiremis*) at a mid-shelf station (NH 05) off Newport, Oregon-averaged over the months May–September, showing both historical data (1969–73, 1983) and data from the more recent time series (1996–present). (B) correlation of the northern copepod biomass with the PDO, both averaged over May–September [y = 0.224x – 0.046; R^2 = 0.34, p = 0.015]. Note the similarity between biomass anomalies in 1998 and 2005.

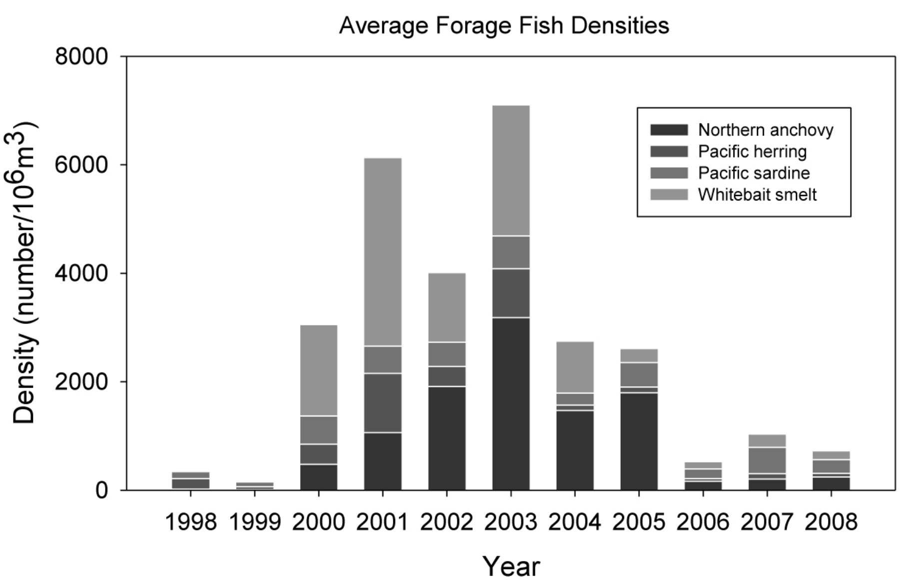

Figure 11. Catches of small pelagic fishes sampled off the Columbia River and Willapa Bay, Washington, with a pelagic rope trawl, at night. Data are averaged over the biweekly May–August cruises.

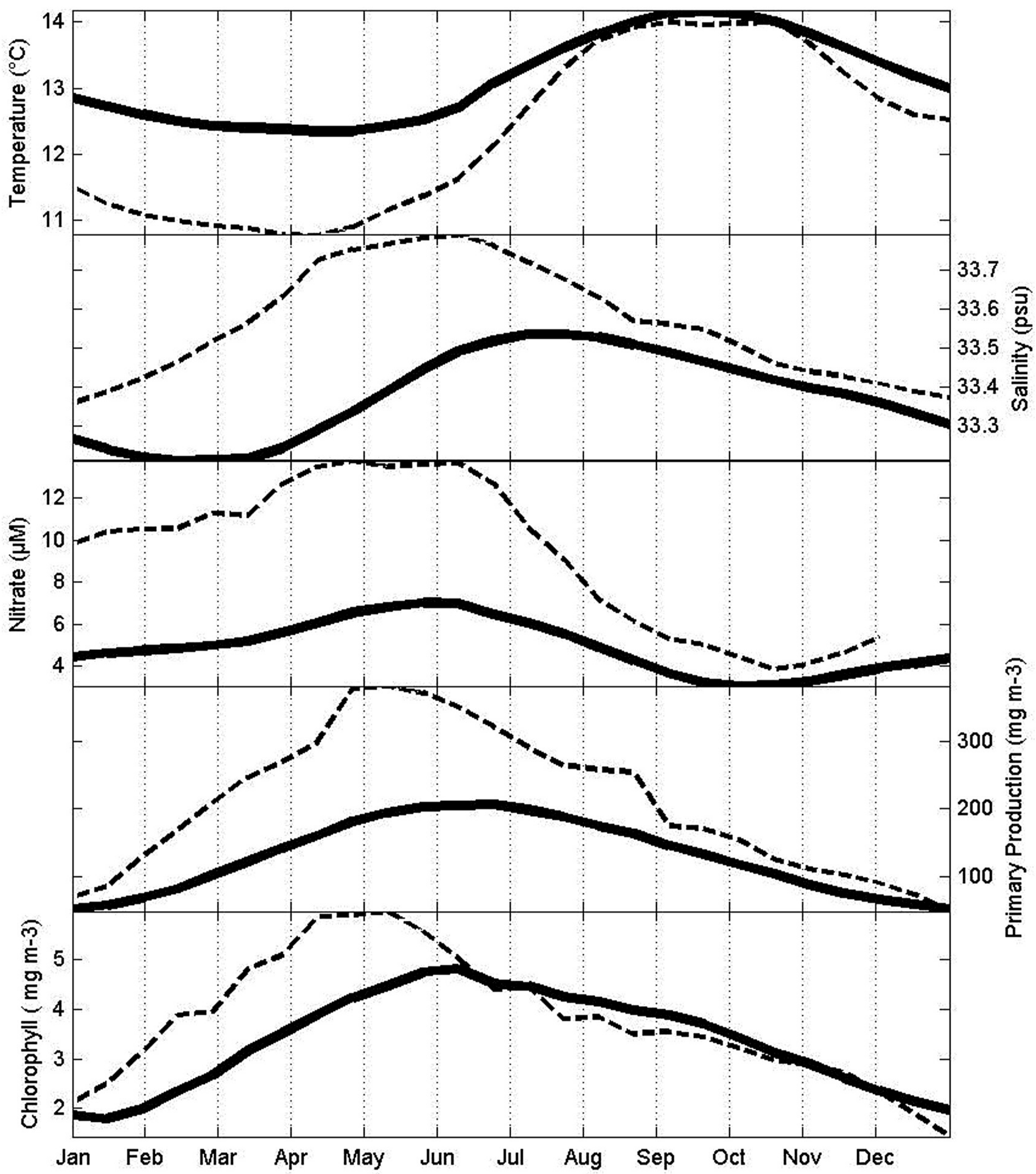

Figure 12. Annual variability in Monterey Bay from hydrographic data. The solid line is the long term mean for 1989–2008 and the dashed line represents measurements from 2008.

such low numbers during the previous warm phase of the PDO that there is an insufficient number of adult spawners to produce dramatic increases in recruits.

Central California Hydrographic Surveys

Along Line 67, the distance of the California Current from the coast varied from 200 km in June 2008 to 300 km in October 2008 and January 2009. This was indicated by the strong gradient of westward-increasing dynamic height observed at the three offshore stations on Line 67. The subarctic character of these waters was also indicated by a salinity <33 at 10 m, temperature <5°C at 10 m at the station farthest from shore and vessel-mounted ADCP measurements which indicated 0.5 m/s south-southwest flow.

Although upwelling-favorable gale force winds occurred in June, the ocean's response seemed to be confined to shallower coastal waters. Despite the strong winds, waters in the upper 50 m remained stratified. High concentrations of Chl *a* in coastal waters confirm the limited extent of the upwelling response to the strong winds. Below 300 m, isopycnals sloped downward toward the

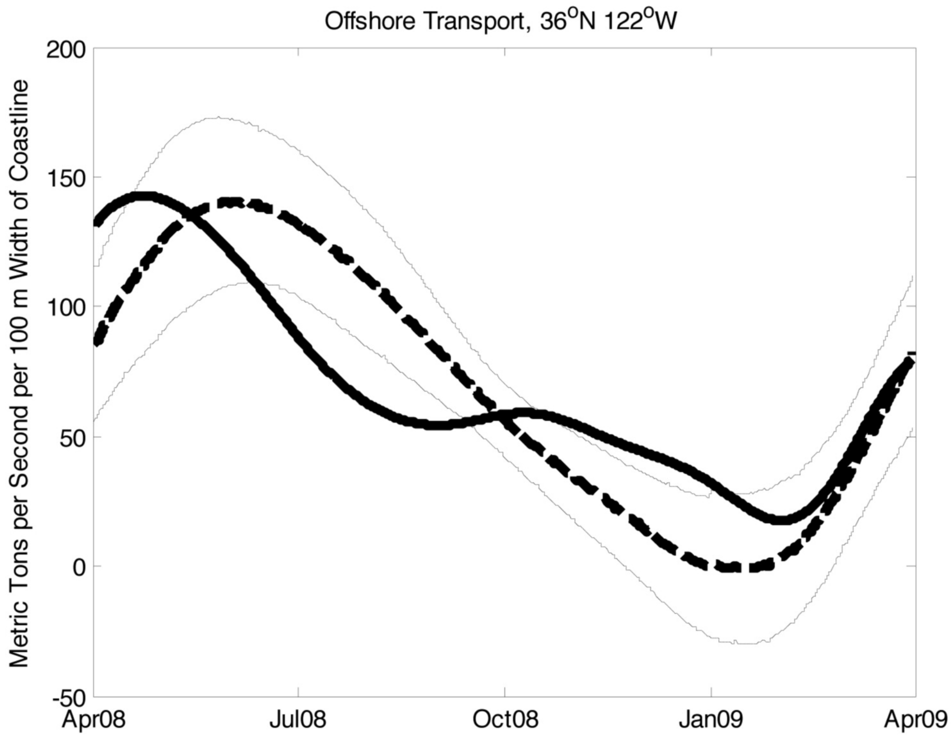

Figure 13. PFEG Offshore Transport at 36°N, 122°W estimated from geostrophic-derived wind stress. Transport for April 2008 to April 2009 is shown by the solid line. The annual mean transport is shown by the thicker dashed line and the variability (± one standard deviation) of the mean is shown by thin dashed lines.

coast within 100 km of the coast indicating poleward flow of the California Undercurrent over the continental slope.

Coastal time series measurements indicated that in late winter and spring 2008, maximum upwelling-favorable wind stress occurred about 1.5 months earlier than usual, resulting in a corresponding seasonal acceleration of the usual cycles of coastal sea surface temperatures, salinities, nitrate, Chl *a*, and primary productivity (fig. 12). This seasonal response is superimposed upon the continuing cool phase of the Pacific Decadal Oscillation, resulting in continued large positive anomalies of nitrate, Chl *a*, and primary productivity. Coastal conditions returned to normal in late summer and fall 2008.

A principle forcing agent of central California waters is offshore Ekman transport of ocean waters caused by alongshore wind stress (fig. 13). The magnitude of the 2008 springtime wind forcing was the same as that of the long-term mean; but the maximum occurred in mid April, about a month and a half earlier than usual. This month and a half lead in the offshore transport cycle continued through August, resulting in less offshore transport in the summer than normal. Offshore Ekman transport during fall was about 50 tonnes/s, larger than normal, and the minimum in February 2009 occurred about a month later than normal. In March and April 2009, offshore transport was almost the same as the long-term mean.

Chavez (2009) described conditions observed in Monterey Bay in 2008 in the context of both global warming trends as well as the continuing cool phase of the PDO. He noted that within the Bay the coolest temperatures in the past 20 years were observed in June 2008 and that primary production continued at high levels in 2008, as documented by a positive seasonal Chl *a* anomaly of about 1 mg/m^3. Sightings of the jumbo squid (*Dosidicus gigas*) by remotely-operated vehicles continued during this cool phase in 2008 at the rate of about 500 per year vs. zero prior to 1998. Values of pCO2 (pH) were ~450 ppm (8), with accelerating upward- (downward-) trends observed in the previous 15 years.

Central California Midwater Trawl Survey

A principal components analysis of fish catches from the annual midwater trawl survey (fig. 14) indicated that the composition of this forage community in 2005 and 2006 was most similar to that observed during the 1998 El Niño, with very low abundances of young-of-the-year groundfish and market squid, but with relatively high catch rates of anchovy and sardine. However, since 2006 the midwater trawl assemblage has trended back towards a species composition more characteristic of the cool, productive conditions experienced in 2002,

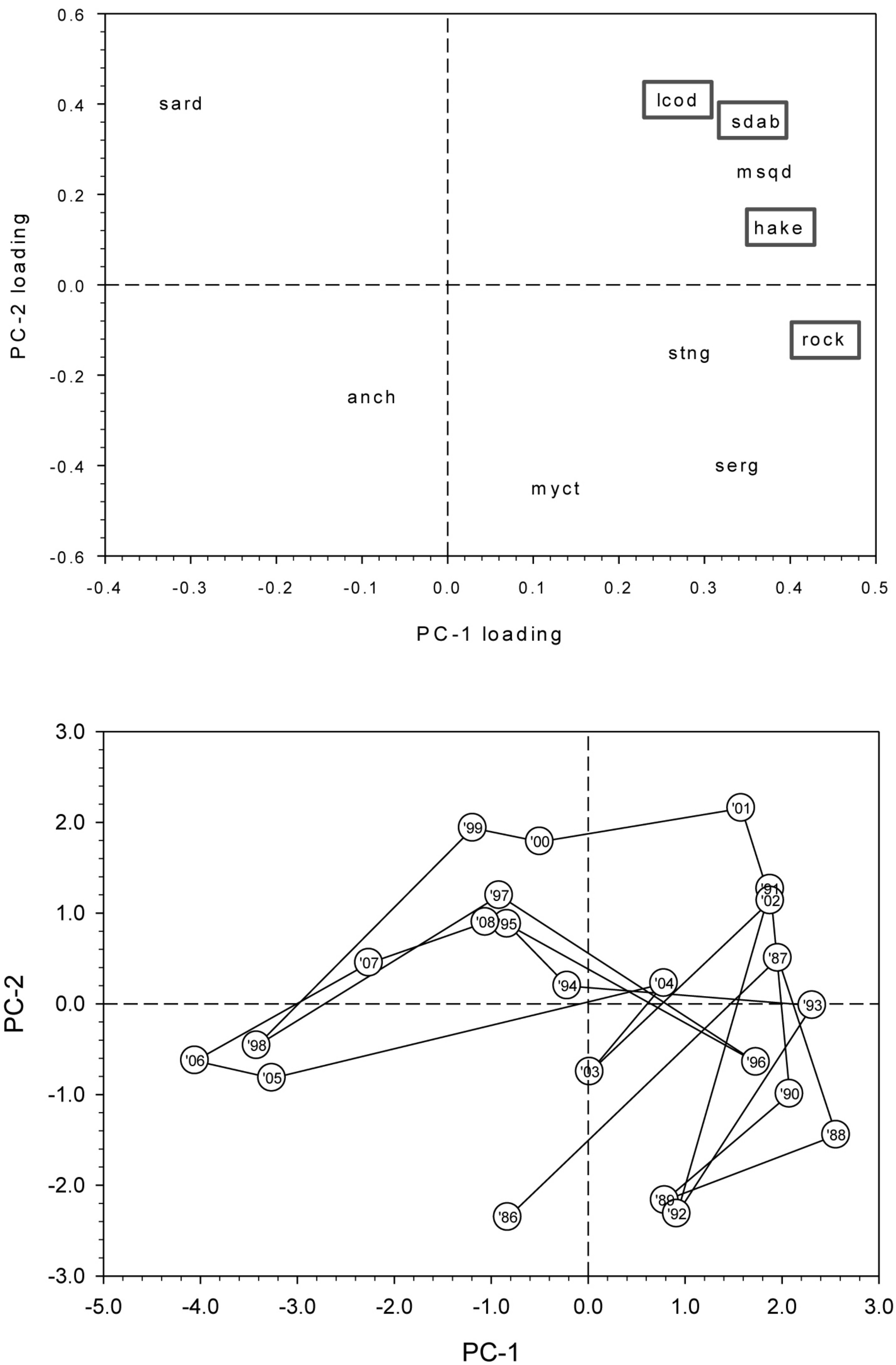

Figure 14. Principal components ordination of the SWFSC Fisheries Ecology Division midwater trawl survey data (1986–2008). The upper panel plots taxon-specific loadings from the first and second eigenvectors (rectangles identify young-of-the-year groundfishes); the lower panel shows the first and second annual principal component scores for the entire assemblage.

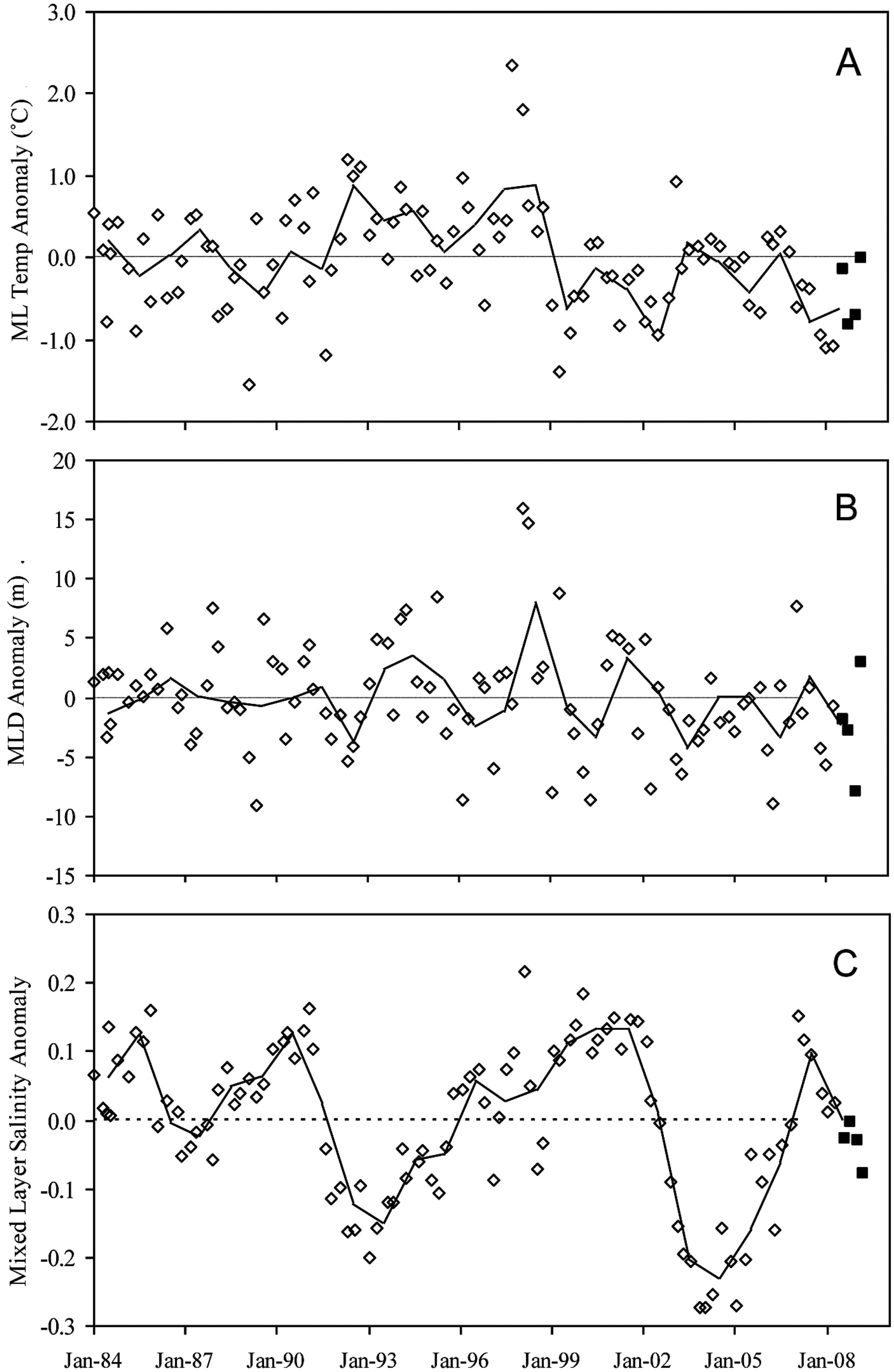

Figure 15. Anomalies of mixed layer (ML) temperature (A), ML depth (B), and ML salinity (C) off southern California (CalCOFI standard grid, Figure 1). Data from the last four CalCOFI cruises are plotted as solid symbols, data from previous cruises are plotted as open diamonds. The solid lines represent the annual averages and the dotted lines the climatological mean, which in the case of anomalies is zero.

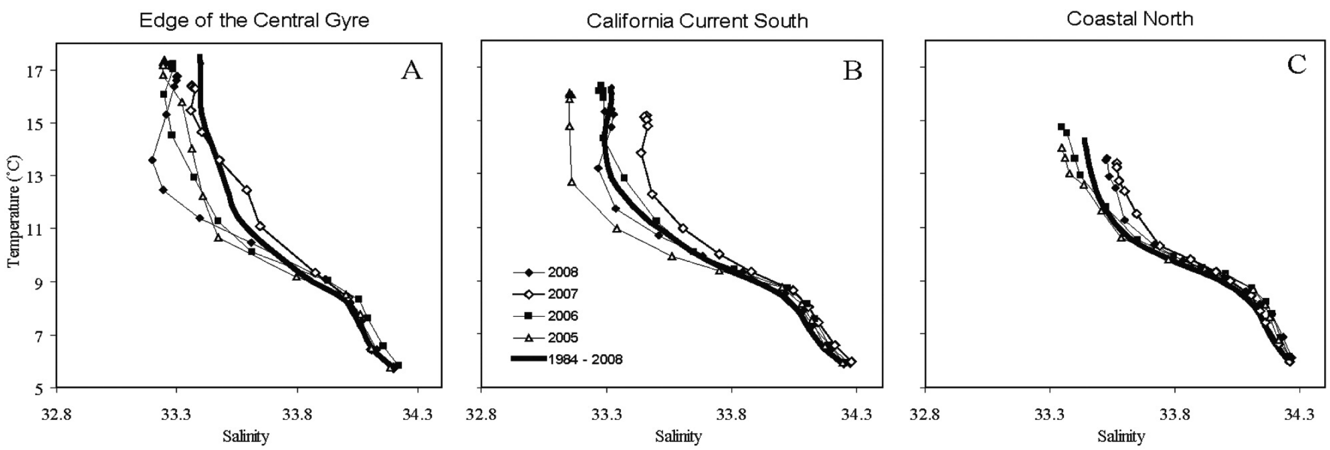

Figure 16. TS plots for three representative areas of the CalCOFI region. A. The edge of the central gyre (Lines 90–93, Stations 100–120), B. the southern California Current region (Lines 87–93, Stations 60-90) and C. the coastal areas in the north (Lines 77–80, Stations 60 and inshore). Each data point represents the average TS characteristic of one standard depth level for the specified time periods, i.e., 1984–2006, 2004, 2005, 2006, and 2007.

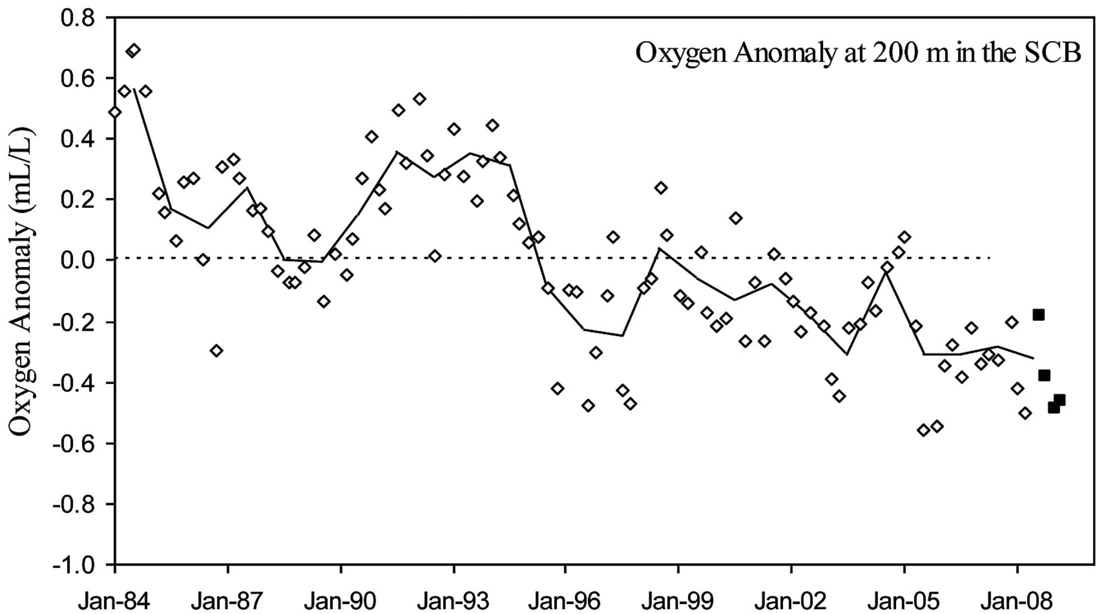

Figure 17. Oxygen concentration anomalies (mL/L) in the Southern California Bight (SCB) at a depth of 200 m. Data are presented as described for Figure 16. It was assumed that all CalCOFI stations along lines 83 to 90 with numbers less than 50 are representative of the SCB.

although the first component score for 2008 remained negative. In a general sense, the species-specific catch rates of the midwater fish assemblage appears to reflect the shift from warmer to cooler conditions that has been observed since 2005.

Northern and Central California Kelp Canopy

In northern California, from Point Arena to the Oregon border, the surface area of the *Nereocystis* kelp canopy in 2008 was the largest in the seven-year record with 7.1 km^2. This region had as little as 0.2 km^2 of kelp canopy in the warm year 2005 and an annual average of 2.9 km^2 in the past. In the central California region, from Point Arena south to Pigeon Point, the surface area of both *Nereocystis* and *Macrocystis* kelp canopy at 7.9 km^2 was also high with 2008 being the second highest in the seven-year record compared with the low in 2005 of 2.3 km^2, and an average of 5.0 km^2.

Southern California

The region covered by the quarterly CalCOFI surveys (fig. 1D) continued to exhibit cooler-than-average temperatures in the upper mixed layer during 2008 and 2009, a pattern observed since 1999 (fig. 15A). Mixed layer temperatures during the second half of 2007 and the first half of 2008 were among the lowest observed since 1984, reflecting the basin-wide La Niña conditions. Mixed layer temperatures during late 2008 and

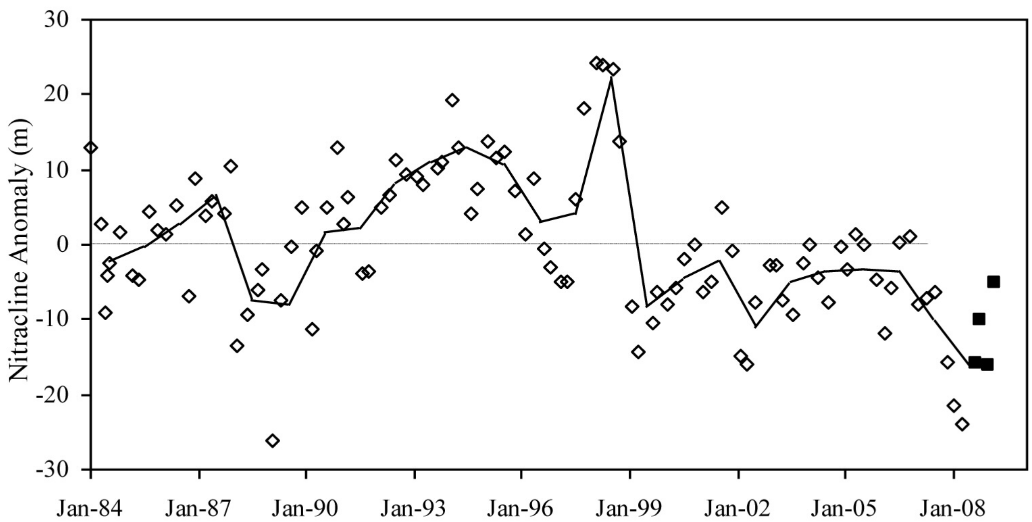

Figure 18. Cruise averages for nitracline depth anomaly. The nitracline depth was assumed to be the depth where nitrate reached values of 1 μM. Data are plotted as described in Figure 15.

early 2009 were similar to those observed over the last decade. Mixed layer salinities were slightly below long-term averages (fig. 15C). Depictions of hydrographic conditions observed during the individual CalCOFI cruises can be found at http://www.calcofi.net.

Temperature and salinity patterns varied across the CalCOFI survey region (fig. 16). In the coastal region north of Point Conception, the mixed layer was anomalously cool and salty in 2008, similar to 2007 but in contrast to 2005 and 2006, when the mixed layer was relatively fresh in this region (fig. 16C). On the other hand, the southern portion of the California Current was relatively cool but salinity did not vary from the long-term mean, unlike 2007, when salinity within the CC was anomalously high (fig. 16B). However, the base of the mixed layer at the edge of the central gyre (the western end of the CalCOFI grid) was fresher than average and also fresher than conditions over the past five years (fig. 16A).

Concentrations of oxygen continued to decline at depth in the Southern California Bight (fig. 17), a trend consistent with the recent report by Bograd et al. 2008. If this trend continues, negative impacts on important fisheries are expected (McClatchie et al. submitted[1]).

Over the last year nitracline depths continued to be relatively shallow, about 10 m shallower than the long-term mean, following a pattern observed since 1999 (fig. 18). In contrast, mixed layer concentrations of the main nutrients (nitrate, phosphate, and silicate) were not significantly higher than average (fig. 19).

Except for the most recent spring cruise (CC0903), standing stocks of Chl *a* averaged over the CalCOFI survey area were near the long-term mean (fig. 20A), following the pattern observed in nutrient concentrations (fig. 19). In April 2009, Chl *a* was anomalously low, likely due to a delay in the initiation of the spring bloom west and southwest of Point Conception. Average annual depth profiles of Chl *a* (fig. 21) show higher than normal concentrations of Chl *a* throughout the euphotic zone in all regions with the exception of the northern coastal region, again reflecting that the spring cruise did not sample a spring bloom. Rates of primary production were variable in 2008, with mean levels relatively high in two cruises and average or anomalously low in the other two (fig. 20B).

Zooplankton displacement volume, which has dramatically declined since observations began 60 years ago (Roemmich and McGowan 1995), followed over the last year the pattern of relatively low mean concentrations observed since about 1993: concentrations even in spring and fall have not increased notably from the low values observed through the winter (fig. 22).

Overall the conditions off southern California in 2008 appeared to follow the cool PDO pattern observed since 1999, with relatively cool, salty conditions in the mixed layer and a shallow nitracline. However, these conditions did not lead to higher nutrient or phytoplankton concentrations in the upper mixed layer, nor have they led to higher zooplankton volumes. This contrasts with observations further north in regions more affected by upwelling.

Southern California Cetaceans

Cetacean visual survey data from spring 2008 through spring 2009 suggest a decrease in overall species diver-

[1]McClatchie, S., R. Goericke, G. Auad, R. Cosgrove, and R. Vetter. Submitted. Oxygen in the Southern California Bight: multidecadal trends, and implications for demersal fisheries. Submitted to Limnology and Oceanograpy.

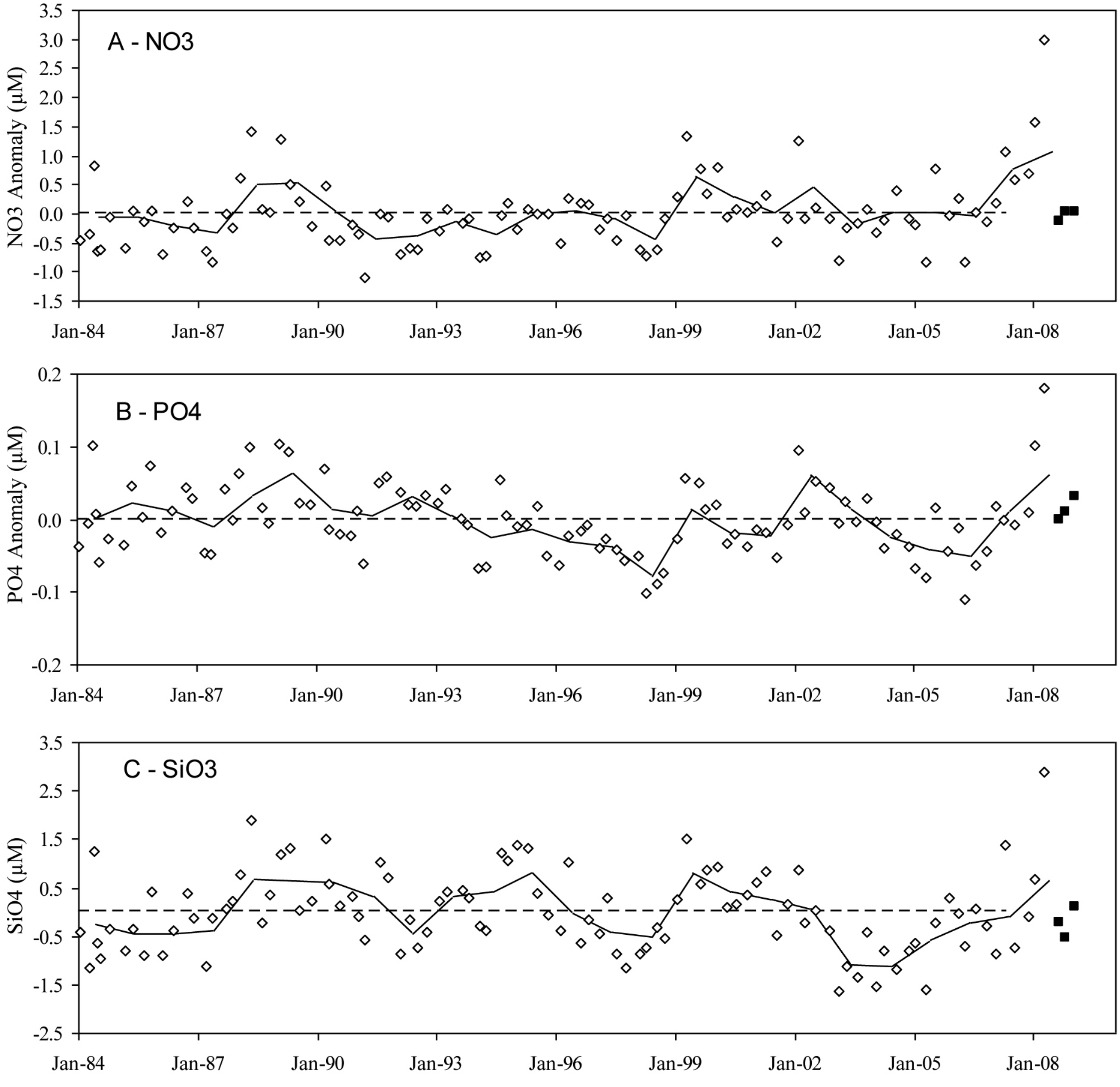

Figure 19. CalCOFI region anomalies for concentrations of (A) nitrate, (B) phosphate, and (C) silicate in the mixed layer. Data are plotted as described in Figure 15. Data for cruise 200904 are not yet available.

sity and changes in abundance for some species within the CalCOFI study area. Species diversity in summer 2008 was lower than usual for the summer season, with observers recording only four dolphin species (including both forms of common dolphins) and five large whale species (including one opportunistic sperm whale sighting). Common dolphin (*Delphinus* spp.) counts were low throughout the year compared to previous years, and blue whale counts in 2008 were the lowest they have been since the initiation of a systematic marine mammal survey effort in 2004. These apparent decreases in animal density may reflect geographic shifts in populations in response to colder than normal temperatures (common dolphins prefer warmer temperatures, Forney et al. 1995), poor feeding conditions (it has been suggested that blue whales are reoccupying former feeding grounds to the north or elsewhere (Dohl et al. 1986; Barlow 1995), and/or other habitat variables. Counts of Dall's porpoise (*Phocoenoides dalli*), a cold-temperate species, were greater than usual for a winter cruise in 2009. Due to low sample sizes it is difficult to detect statistically significant trends at this time.

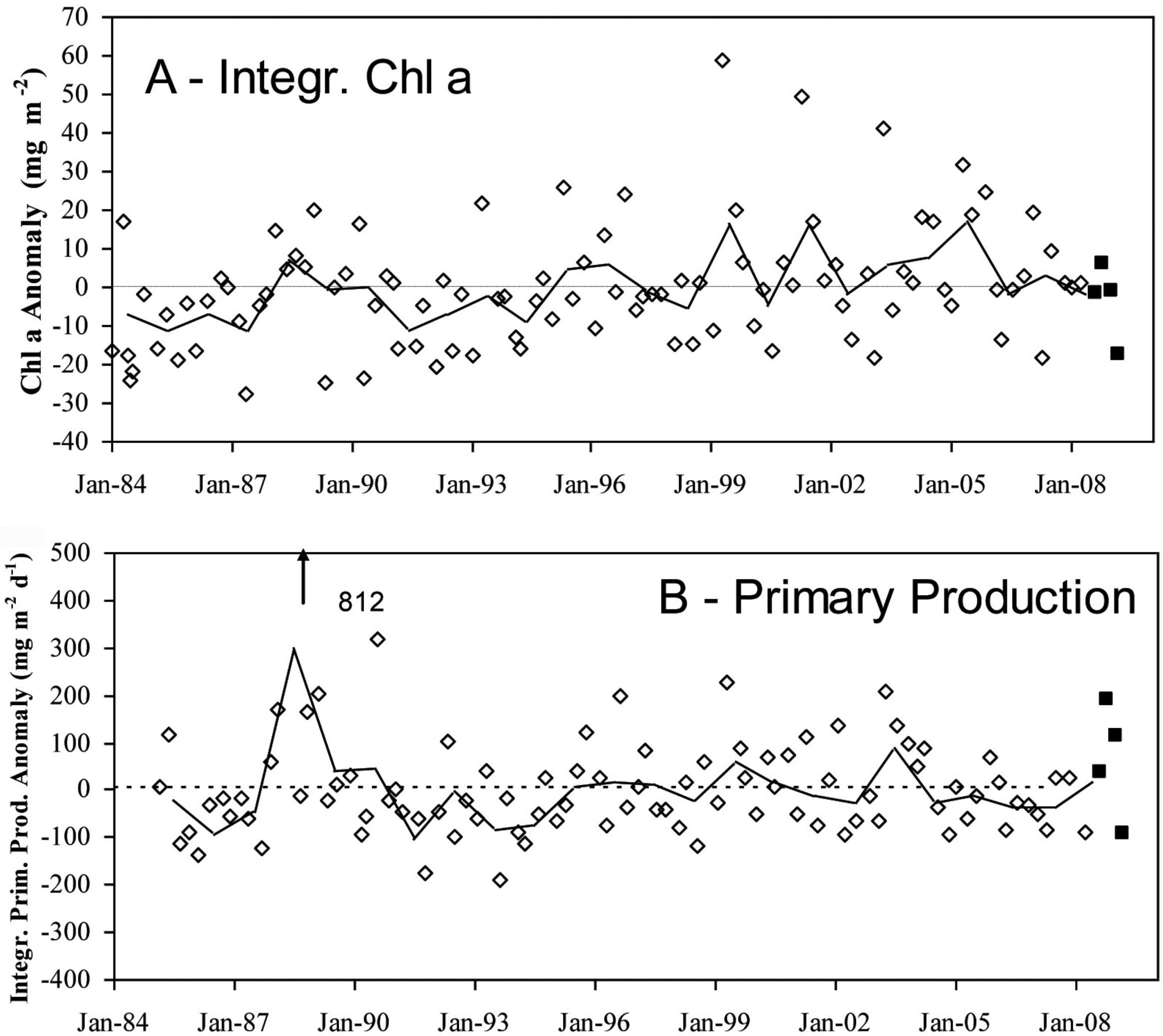

Figure 20. CalCOFI region averages for standing stocks of Chl *a* (A) and rates of primary production (B) both integrated to the bottom of the euphotic zone, plotted against time. Data and symbol codes are the same as those in Figure 15.

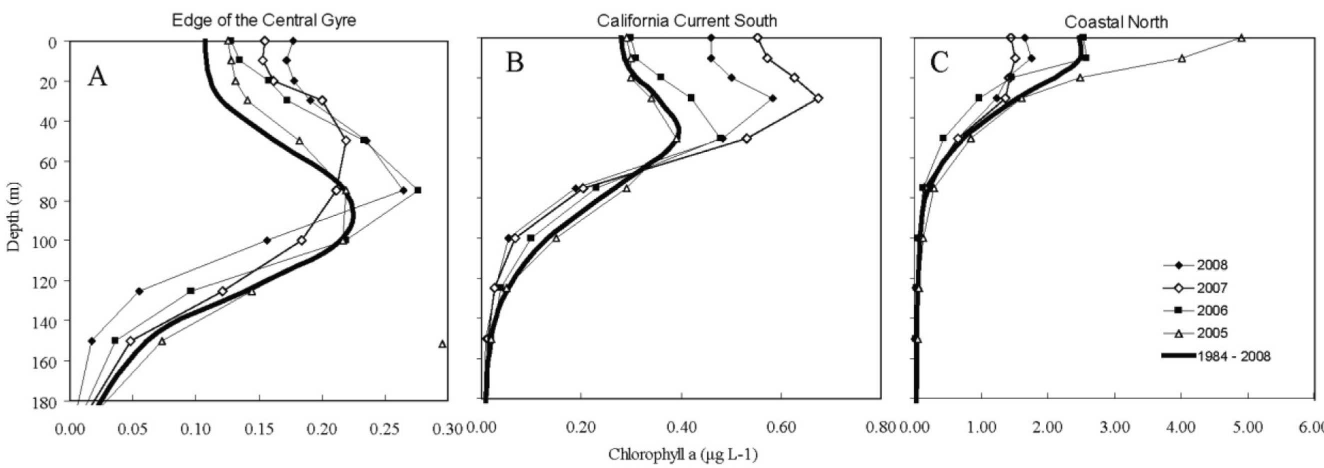

Figure 21. Depth profiles of Chl *a* for the three areas of the CalCOFI region that were described in Figure 1, the edge of the central gyre (A), the southern California Current region (B), and the northern coastal areas (C). Data were calculated and are presented as described in Figure 16.

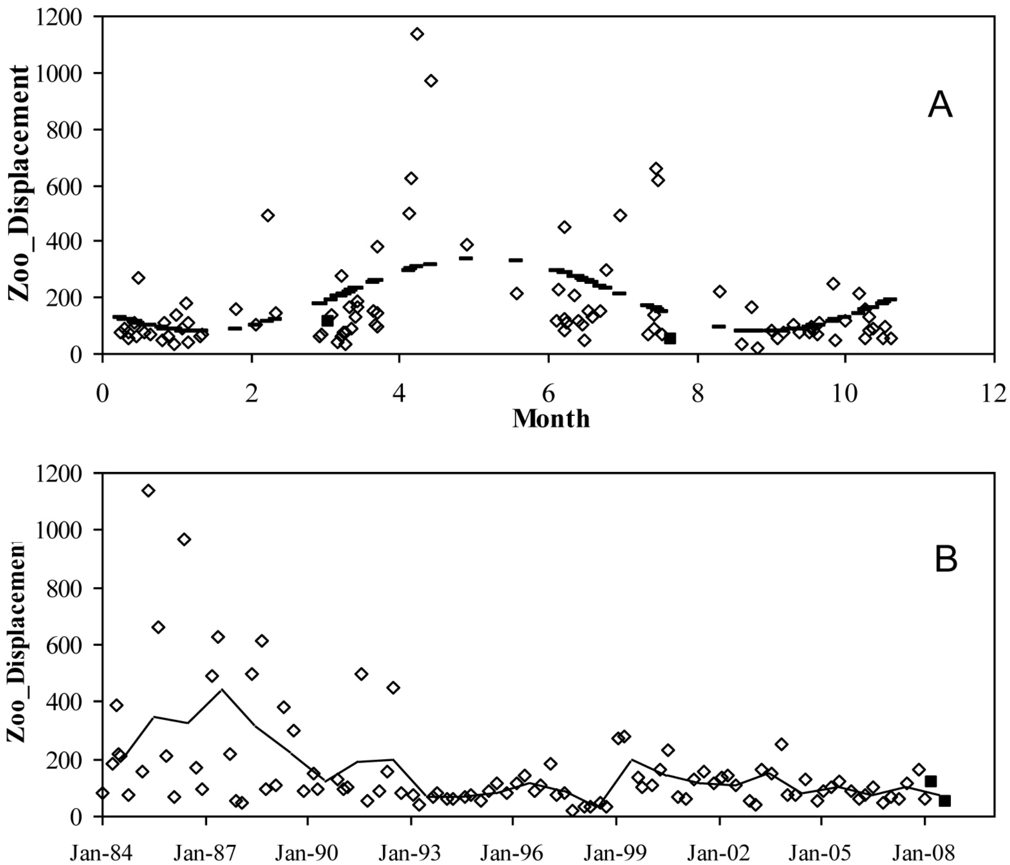

Figure 22. CalCOFI cruise-mean macrozooplankton displacement volumes plotted against the month of the year (A) and time (B). Annual averages are connected by thin solid lines.

NOAA Coastwide Surveys

In April 2008, Pacific sardine eggs were found at sea surface temperatures (SST) greater than 10°C and less than 15°C in April (fig. 23). Very few sardine eggs were found north of San Francisco (37.9°N), and no eggs at all were detected north of Point Arena (or north of 39°N) due to cool surface temperatures. Sardine eggs were found in offshore waters to the south of San Simeon (36°N) where surface waters were warmer (fig. 23). Highest concentrations were found between 30°–35°N, but few eggs were found in Mexican samples off northern Baja California, Mexico (unpublished data). A full time series of sardine, anchovy and mackerel egg maps are available at <http://swfsc.noaa.gov/textblock.aspx?Division=FRD&id=1121>.

Sardine spawning is now concentrated in the spring and consequently very few sardine eggs were found anywhere along the entire U.S. west coast during the July/August survey (fig. 24). However a few sardine eggs were encountered at the most southern location sampled in waters as warm as 19°–20°C SST (fig. 24) and a few sardine eggs were also found offshore of the Columbia River where SST was 15°–16°C (fig. 24).

The area north of 40°N latitude has rarely been sampled for ichthyoplankton. The high concentration of sardine eggs off southern California indicates that the spawning ground in 2008 was similar to 2006 and 2007 (Lo et al. 2007; McClatchie et al. 2008), in contrast to 2002–05 when eggs were concentrated farther north off central California.

The cooler conditions did not appear to prevent adult sardine from migrating north after spawning. In April, adult sardine were caught in trawls south of 34°N and west of 120°W, mainly in the same areas where eggs were collected (fig. 23). By July/August no sardine at all were caught south of 37°N. Virtually all catches of sardine were north of 40°N (fig. 24), and were inshore, consistent with the concept that sardine leave their spawning ground and migrate to feed in the more productive inshore coastal regions further north.

The spawning biomass of Pacific sardine is positively related to the daily egg production, in particular if the number of weight-specific oocytes in spawning female fish remains constant (Lo et al. 2008). The relationship between the daily egg production ($0.05/m^2$) and the average sea surface temperature (°C) during 1994–2008

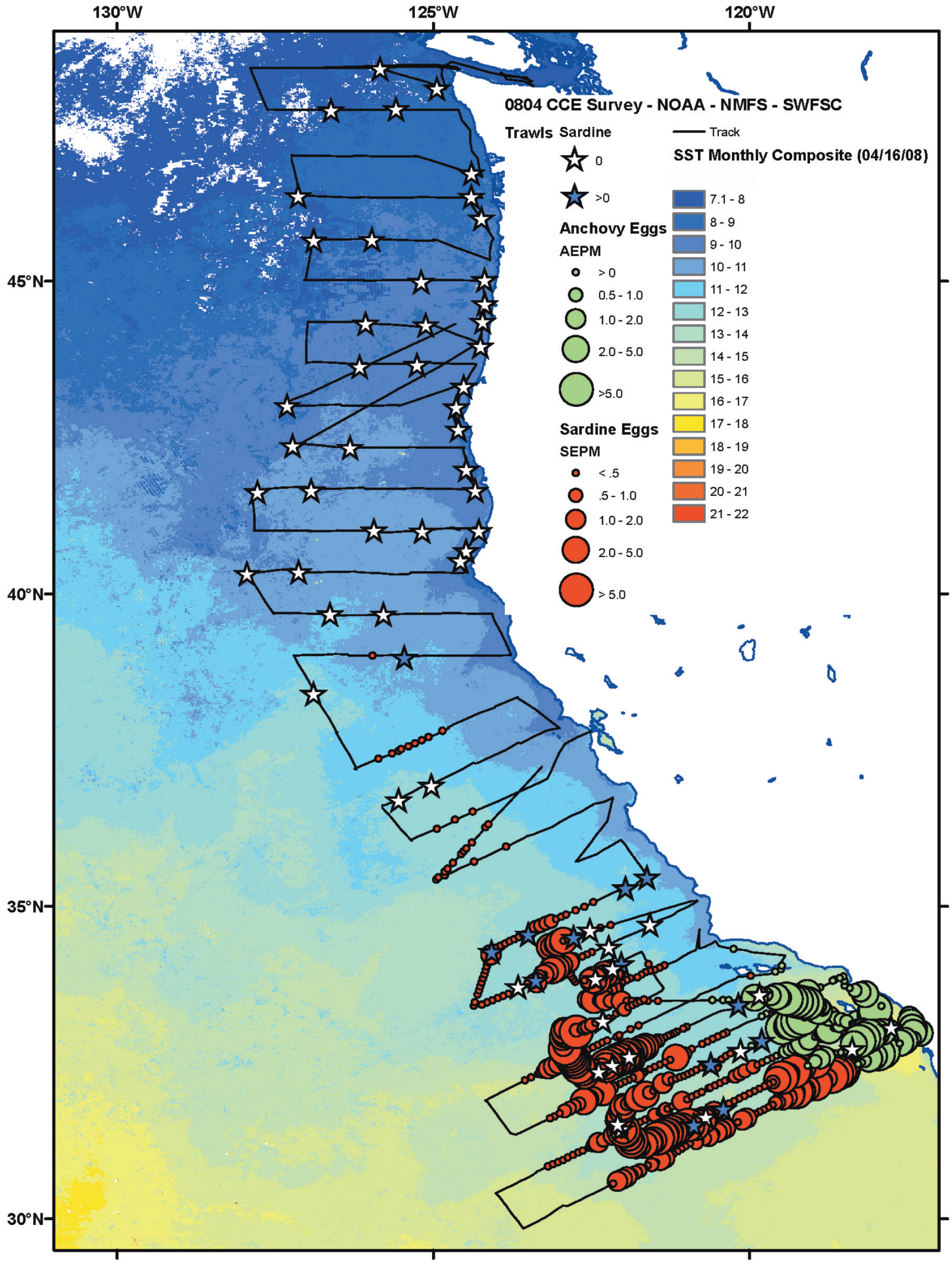

Figure 23. Egg distributions from CUFES and the locations and catches from surface trawls overlaid on a month-long composite of sea surface temperature (satellite SST) for the April 2008 survey. Blue stars indicate positive catches of Pacific sardine (*Sardinops sagax*), white stars indicate no catch of sardine.

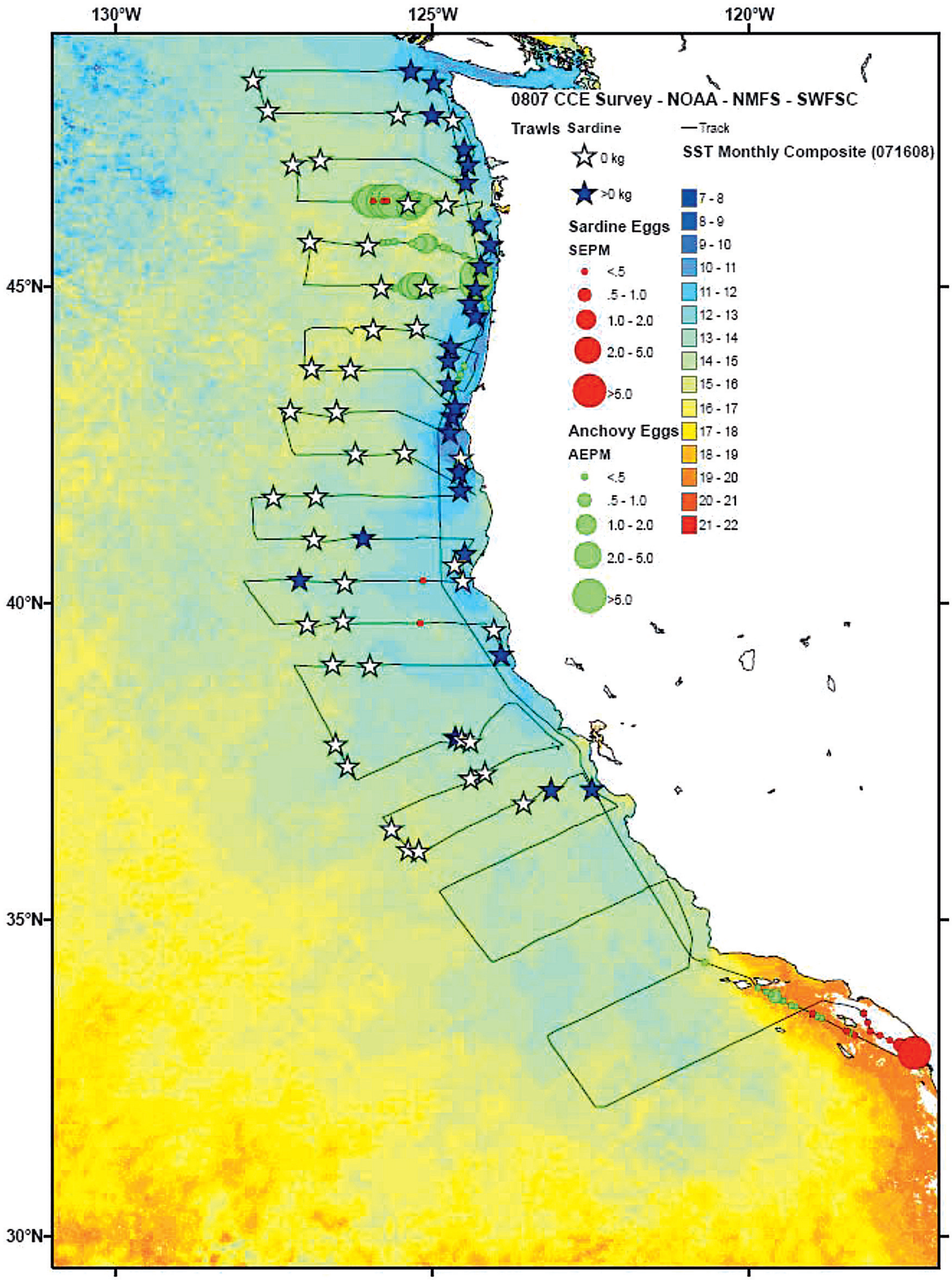

Figure 24. Egg distributions from CUFES and the locations and catches from surface trawls overlaid on a month-long composite of sea surface temperature (satellite SST) for the July/August 2008 survey. Blue stars indicate positive catches of Pacific sardine (*Sardinops sagax*), white stars indicate no catch of sardine.

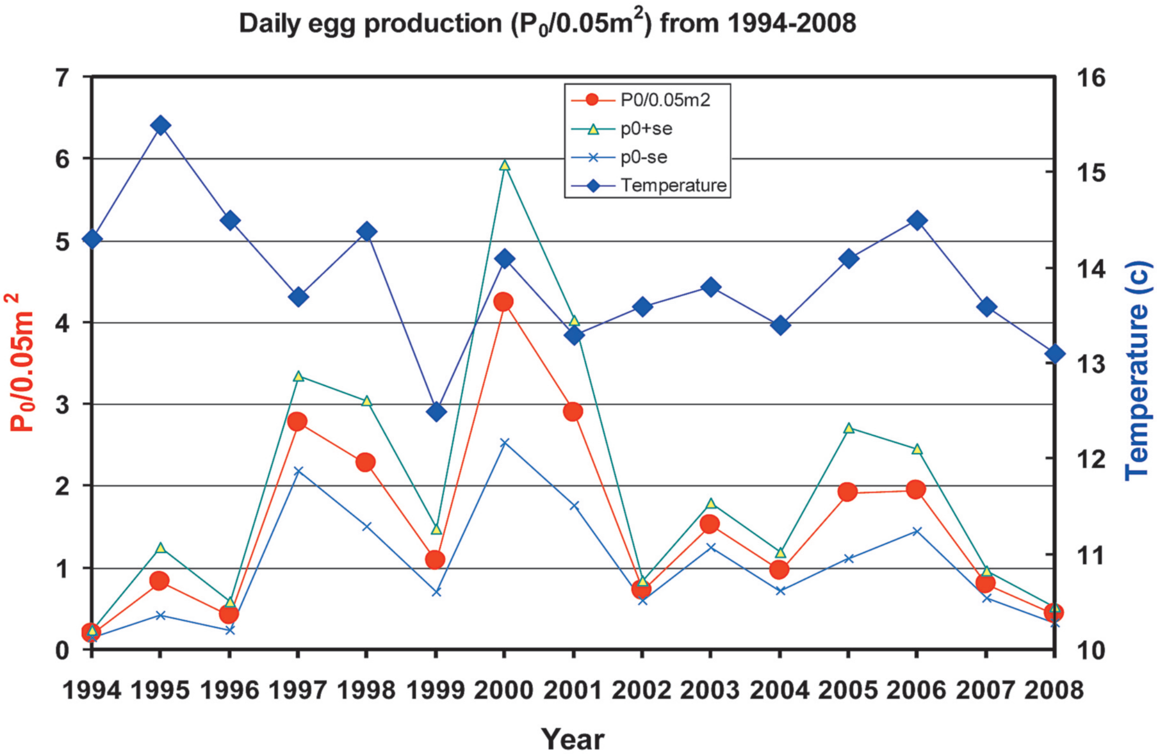

Figure 25. Daily egg production/0.05 m^2 of Pacific sardine (*Sardinops sagax*) (circle) with upper (triangle) and lower (cross) 95% confidence limits and average sea surface temperature (°C) weighted by egg abundance (diamond) during March–May CalCOFI cruises and DEPM surveys from 1994–2008 for the DEPM survey area between San Diego and San Francisco.

indicated that in most years, except 1997 and 2002, increased daily egg production coincides with increased sea surface temperature (fig. 25). This relationship is consistent with the assertion that warm temperature is favorable for the Pacific sardine (Jacobson and MacCall 1995).

Northern anchovy eggs were abundant in the Southern California Bight (SCB), inshore of the sardine eggs in April 2008; no anchovy eggs were found north of the SCB in April (fig. 23). During the July/August survey a few anchovy eggs were found in the SCB, but the highest concentrations were found off Oregon and Washington at 45°–46°N (fig. 24).

Baja California

Off Baja California the effects of basin-wide La Niña conditions on SST were evident only during early 2008 (figs. 9 and 26); SSTs were close to long-term averages during the rest of 2008. None of the biological variables (Chl *a*, zooplankton biomass or the abundance of copepods or euphausiids – fig. 27) responded to the 2007/08 La Niña conditions. However, a strong covariation was observed between sea surface salinity (SSS) and Chl *a* (fig. 26) over the last decade. The exceptions are October 1997, January 1998 and the year 2007, due to invasion of equatorial water of a high salinity close to values of the undercurrent salinity (Durazo and Baumgartner 2002). The relationship between Chl *a* and zooplankton biomass has changed over the last two years. During 1999–2006 the two measures were negatively correlated (r^2 = 0.349). In contrast, anomalies for both measures have been positive during 2008.

Over the last decade zooplankton biomass covaried with the surface to 200 m salinity gradient (fig. 27), a proxy for stratification. The time series consists of two distinct periods, a period of weak stratification (and low zooplankton biomass) during July 1998 to January 2003 and a period of strong stratification (and high zooplankton biomass) during April 2003 to July 2008. Exceptions to these patterns were observed during the El Niño of 1997/98 and 2007 equatorial El Niño. The abundances of the main suspension-feeding crustaceans (copepods and euphausiids) were above long-term averages over the last four years (2004–08; fig. 26); these time series do not show a distinct response to basin-wide forcing, i.e., ENSO or salinity signals. The covariation between copepod abundance and the salinity gradient was not as strong as that observed for total zooplankton biomass but was still significant ($F = 5.0$, $p = 0.031$ when weak and strong stratification periods were compared). Euphausiids did not show significant differences between stratification periods and showed considerable variability.

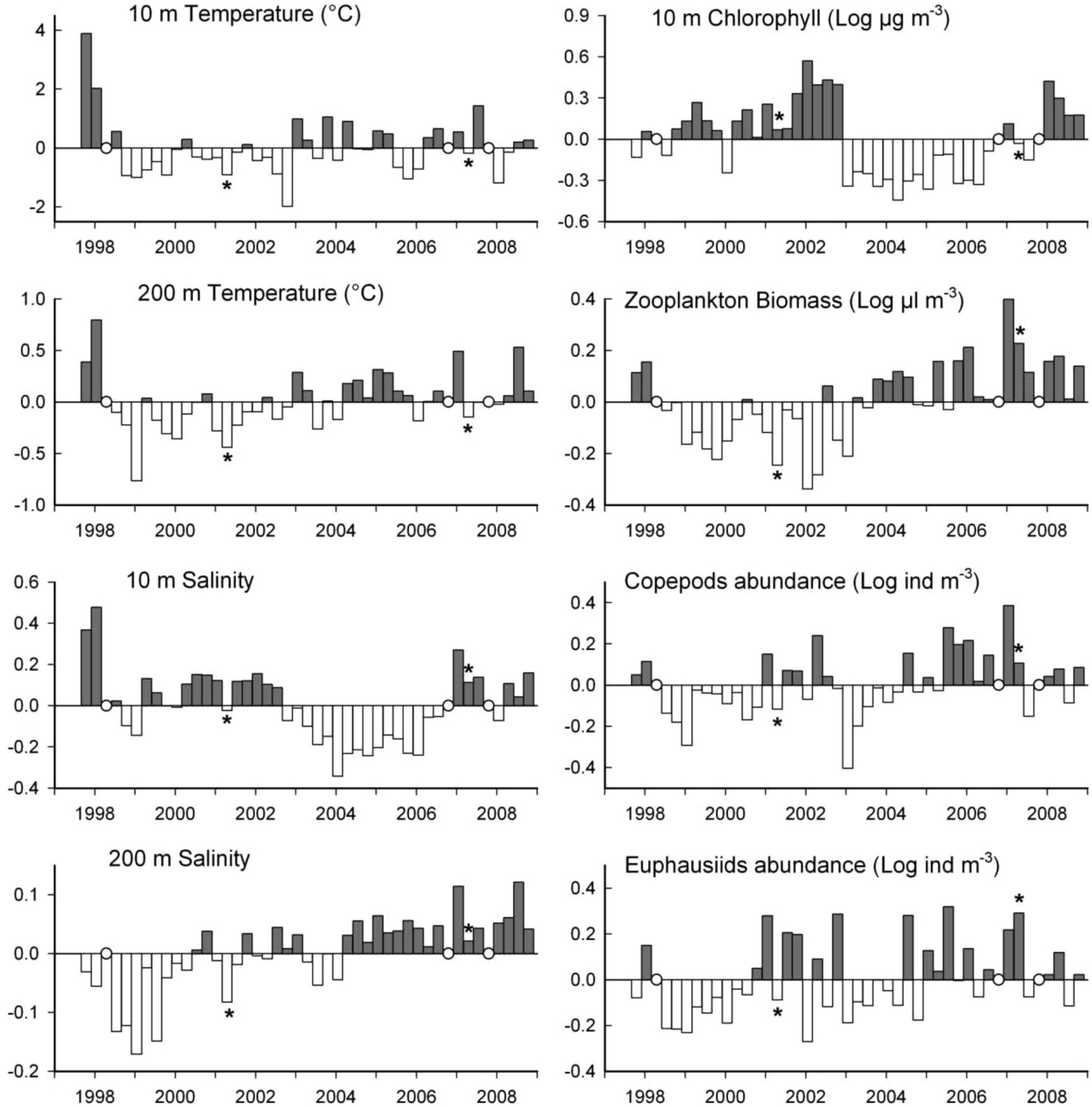

Figure 26. Time series anomalies of hydrological properties at two depths (temperature and salinity), plankton biomass (Chl *a* and zooplankton displacement volume), and nighttime zooplankton abundance (copepods and euphausiids) estimated for the entire area off Baja California. Open circles indicate missing cruises; the asterisks indicate data available only from north Baja California. Biological variables were previously transformed to logarithms.

DISCUSSION

The equatorial La Niña conditions and their extra tropical manifestations along the west coast of North America persisted from the summer of 2007 until the spring of 2009. As typical for these conditions, SSTs were generally lower than normal along the U.S. west coast and similar or even higher than the long-term average along the coast of Baja California, with the exception of January 2008. In most locations, upwelling was stronger than normal in the spring and early summer, slightly below normal in the summer and slightly stronger than normal in the fall. Thus, the years 2007 and 2008 differed dramatically from the years 2005 and 2006 when delayed and weak upwelling during the spring significantly reduced production off central California and Oregon (Sydeman et al. 2006). The delayed onset of seasonal upwelling in spring 2005 and 2006 (Schwing et al. 2006) has been blamed for poor ocean conditions and biological productivity, and recruitment failures in several populations (Sydeman et al. 2006). Extremely poor

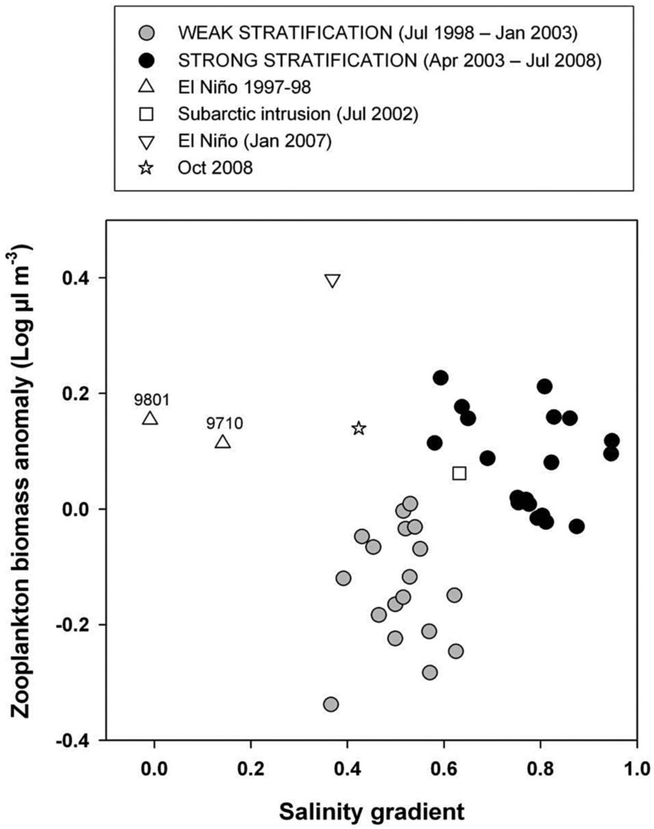

Figure 27. Zooplankton biomass anomaly as a function of the salinity gradient, estimated as the difference between the salinity at 200 and 10 m depth. Symbols indicate two long periods of different stratification conditions and particular events.

returns of fall Chinook salmon stocks in California, which triggered a closure of much of the West Coast salmon fishery, has been attributed to poor production.

In contrast, in 2008 production off central California and Oregon was higher than normal, likely driven by the higher than normal rates of upwelling. The upwelling season began early and remained unseasonably strong through at least April 2007–09 (fig. 5). Cumulative upwelling off central and northern California was particularly high throughout 2008 (fig. 5), and started early in 2009. An implication of this is greater ecosystem production and reproductive success for many populations. In fact, record or near-record returns are expected for Columbia River Chinook Salmon in 2010 (for fish that went to sea in 2008).

However, production off southern California and Baja California over the last four years appeared less affected by coastal upwelling or SST since neither concentrations of Chl *a* nor zooplankton biomass covaried with either variable. Off southern California, concentrations of Chl *a* have been increasing since 1984 and zooplankton displacement volume has been decreasing since the 1950s. Decadal-scale variations in Chl *a* concentrations off southern California have been linked to the North Pacific Gyre Oscillation index (NPGO, Di Lorenzo et al. 2008). As the NPGO reflects changes in large-scale winds and advection, this suggests that off southern California production depends more on basin-scale forcing than coastal upwelling. Observations off Baja California and the analysis provided by the IMECOCAL group (fig. 27) suggest that this is also true for those areas since both Chl *a* and zooplankton biomass covaried strongly with variations of sea surface salinity and salinity gradients, parameters which are driven by forcing associated with the NPGO. To summarize, the data presented in this and previous reports suggest that production north of Point Conception, i.e., in the horseshoe-shaped area characterized by negative SST anomalies during La Niñas, is significantly affected by local SST and coastal upwelling. Areas south of Point Conception appear to be less affected by La Niña conditions and more strongly by basin-scale forcing as reflected by the NPGO.

NOAA Climate Prediction Center (CPC) issued an assessment in July 2009 that El Niño conditions are developing. The criteria used by the CPC for El Niño conditions is a +0.5°C anomaly in the Niño3.4 index, along with consistent atmospheric features, both forecast to persist for three months or more. Since May 2009, positive SST anomalies were recorded across the equatorial Pacific Ocean. While the Niño3.4 index indicates El Niño conditions in the equatorial Pacific Ocean, the criterion for fully fledged El Niño conditions used by NOAA is a +0.5°C anomaly in the Oceanic Niño Index (ONI) sustained over five consecutive overlapping three-month periods. This has not yet occurred. The April–June 2009 ONI value is +0.2°C. Most ENSO models predict that El Niño will continue to intensify through the northern hemisphere summer, and persist through the winter of 2009–10. The models disagree on the predicted strength of the El Niño, but most predict a moderate to strong episode. See http://www.cpc.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf for more details. We conclude, based on these projections, that change is once again about to come to the state of the California Current.

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