STATE OF THE CALIFORNIA CURRENT 2009–2010: REGIONAL VARIATION PERSISTS THROUGH TRANSITION FROM LA NIÑA TO EL NIÑO (AND BACK?)

ERIC P. BJORKSTEDT
NOAA Fisheries Service
Southwest Fisheries Science Center
Fisheries Ecology Division and
Department of Fisheries Biology
Humboldt State University
P.O. Box 690
Trinidad, CA 95570

RALF GOERICKE
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093-0205

SAM MCCLATCHIE, ED WEBER,
WILLIAM WATSON, NANCY LO
NOAA Fisheries Service
Southwest Fisheries Science Center
8604 La Jolla Shores Drive
La Jolla, CA 92037-1508

BILL PETERSON, BOB EMMETT
NOAA Fisheries Service
Northwest Fisheries Science Center
Hatfield Marine Science Center
Newport, OR 97365

JAY PETERSON
Cooperative Institute for Marine
Resource Studies, Oregon State University
Hatfield Marine Science Center
Newport, OR 97365

REGINALDO DURAZO
UABC-Facultad de Ciencias Marinas
Km 107, Carret. Tijuana-Ensenada
Ensenada, B.C., Mexico

GILBERTO GAXIOLA-CASTRO
CICESE-Departamento
de Oceanografía Biológica
Carretera Ensenada-Tijuana # 3918
Zona Playitas, Ensenada, B.C., Mexico

FRANCISCO CHAVEZ,
J. T. PENNINGTON
Monterey Bay Aquarium Research Institute
7700 Sandholdt Road
Moss Landing, CA 95039

C. A. COLLINS
Naval Postgraduate School
Monterey, CA 93943

JOHN FIELD, STEVE RALSTON,
KEITH SAKUMA
NOAA Fisheries Service
Southwest Fisheries Science Center
Fisheries Ecology Division
110 Shaffer Road
Santa Cruz, CA 95060

STEVEN J. BOGRAD,
FRANKLIN B. SCHWING
NOAA Fisheries Service
Southwest Fisheries Science Center
Environmental Research Division
NOAA Fisheries Service
1352 Lighthouse Avenue
Pacific Grove, CA 93950-2020

YAN XUE
Climate Prediction Center
National Centers for Environmental Prediction
National Ocean Atmospheric Administration
National Weather Service
Camp Springs, MD

WILLIAM J. SYDEMAN,
SARAH ANN THOMPSON,
JARROD A. SANTORA
Farallon Institute for
Advanced Ecosystem Research
PO Box 750756
Petaluma, CA 94975

JOHN LARGIER, CHRIS HALLE,
STEVEN MORGAN
Bodega Marine Laboratory
P.O. Box 247
Bodega Bay, CA 94923

SUNG YONG KIM
Scripps Institution of Oceanography, UCSD
9500 Gilman Drive
La Jolla CA, 92093

KARLINA P. B. MERKENS,
JOHN A. HILDEBRAND
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093-0205

LISA M. MUNGER
NOAA Fisheries Service
Pacific Islands Fisheries Science Center
Coral Reef Ecosystems Division
1125-B Ala Moana Boulevard
Honolulu, HI 96814

ABSTRACT

This report summarizes observations of the California Current System (CCS) from Baja California, Mexico to Oregon for the period from spring 2009 through spring 2010. During this period, changes in the state of the CCS reflected a transition from cool La Niña conditions into and through a short-lived, relatively weak El Niño event. Weaker than normal upwelling and several extended relaxation events contributed to warming over much of the CCS during summer 2009, especially in the north. Moderation of La Niña conditions in the CCS coincided with the development of El Niño conditions in the equatorial Pacific, yet manifested well in advance of any evidence for direct effects of El Niño on the CCS. Responses to El Niño in fall 2009 and winter 2009–2010 appear to have varied substantially with latitude: conditions off southern California returned to near climatological values with the decline of La Niña, and did not indicate any subsequent response to El Niño, yet the northern CCS warmed subtantially following the decline of La Niña and was strongly affected by intense downwelling during winter 2009–2010. The 2009–2010 El Niño diminished rapidly in early 2010, and upwelling off central and southern California resumed unusually early and strongly for a spring following an El Niño, but recovery from El Niño in early 2010 appears to be less robust in the northern CCS. Thus, despite dynamic changes in the overall state of the California Current, 2009–2010 continued the recent pattern of strong regional variability across the CCS.

INTRODUCTION

This report reviews oceanographic conditions and ecosystem responses in the California Current System (CCS) from spring 2009 through spring 2010 based on observations collected and analyzed by a diverse range

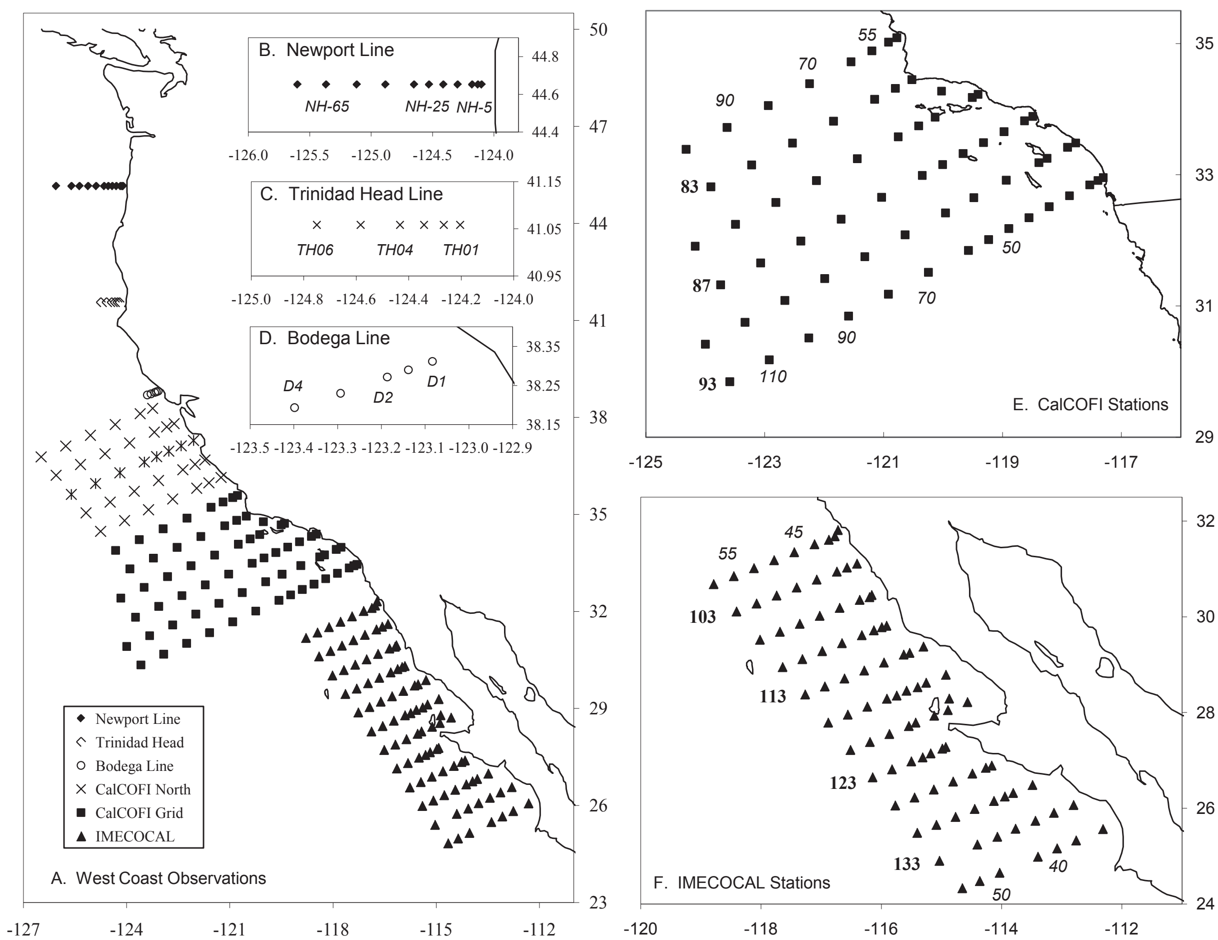

Figure 1. Location of stations for ship-based observing programs that contributed data to this year's report. Observational lines are labeled using bold numbers positioned west of the line terminus; stations are labeled using numbers in italics immediately below or above the respective stations. Line and station numbers for the IMECOCAL and CalCOFI programs are following the CalCOFI line and station nomenclature. The 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 St 25 and occasionally further offshore. The Trinidad Head Line is occupied at monthly or shorter intervals. The Bodega Line is occupied at quarterly or shorter intervals.

of government, academic, and private research programs. Programs or institutions that have contributed data and analysis to this and previous reports in this series include the Environmental Research Division, Fisheries Resources Division and Fisheries Ecology Division of the Southwest Fisheries Science Center (SWFSC) of NOAA's National Marine Fisheries Service (NMFS), Humboldt State University, the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program off southern California, the Investigaciones Mexicanas de la Corriente de California (IMECOCAL) program off Baja California, the Monterey Bay Aquarium Research Institute (MBARI) off central California, the NMFS Northwest Fisheries Science Center (NWFSC), and the Farallon Institute for Advanced Ecosystem Research. In keeping with the tradition of extending the scope of information brought to bear in evaluating the state of the CCS, this year's report includes for the first time observations of surface currents derived from a network of HF radar systems along the Oregon and California coasts, and data collected along the recently established Bodega Line by researchers at the University of California, Davis Bodega Marine Laboratory.

As in previous reports in this series, the focus here is on reviewing recent observations in the context of historical observations as a means of identifying changes in the state of the CCS ostensibly related to recent climatic conditions. This review emphasizes evaluation of augmented or new time series of observations. Where necessary for additional context, insights from spatial patterns are described in general terms in the text; supporting maps and other "snapshots" of the CCS, including more detailed information on specific cruises, are available online at observing programs' websites (indicated in footnotes). The data sets reviewed herein are the subject of ongoing research to understand links between climate and ecosystem processes, work that is well beyond the scope of the present paper. This review, therefore focuses on description and preliminary synthesis of available observations, and therefore offers only sparse information on methods related to data collection (primarily in footnotes). For many ongoing observing programs, more detailed descriptions of methods are available in previous State of the California Current reports or online.

The report is organized as follows. First, we review recent historical conditions and long-term indices of large-scale climate modes (e.g., the Pacific Decadal Oscillation or PDO), followed by more detailed, recent basin-scale information from the tropical and northern Pacific Ocean. This review provides a broad temporal and spatial context for observations that focus more specifically on patterns and structure in physical forcing and responses at scales that span the entire CCS. Second, proceeding from south to north, we summarize the state of the CCS based on physical, chemical and biological observations collected in the course of repeated ship-based surveys that occupy designated stations on a more or less regular schedule (fig. 1). Third, we summarize information on the status of higher trophic levels whether derived from data collected on one (or rarely two) targeted large scale surveys, in conjunction with ongoing large-scale surveys of the CCS, or aggregated from a suite of survey-based, fishery-based, and other sources. Finally, in the Discussion, we summarize the evolution of the state of the CCS through the last year, including the oceanographic and ecological consequences of the 2009–2010 El Niño, and peer briefly into the future.

Recent Evolution of the State of the California Current

A shift to cool conditions following the 1997–1998 El Niño (Bograd et al. 2000; Peterson and Schwing 2003) drove ecosystem responses consistent with those expected for such a transition, e.g., increased zooplankton production, as well as occasional shifts in zooplankton community structure (Brinton and Townsend 2003; Lavaniegos and Ohman 2003). Two events impinged on the CCS in 2002–2003: an intrusion of subarctic waters (the signature of which was detectable in parts of the CCS into 2007) and a mild tropical El Niño (Venrick et al. 2003). Strong ecosystem responses to the intrusion of anomalously cool, fresh, and nutrient-rich waters (e.g., enhanced productivity) were observed only in the northern CCS (e.g., off Oregon); it is thought that the effects of El Niño were likely to have countered any similar responses off southern California and Baja California (Venrick et al. 2003; Wheeler et al. 2003; Bograd and Lynn 2003; Goericke et al. 2004). Since 2004, regional variability has dominated over coherent CCS-wide patterns (Goericke et al. 2005, Peterson et al. 2006; Goericke et al. 2007; McClatchie et al. 2008; 2009). The late onset of upwelling in 2005 and 2006 led to delayed spin-up of productivity in coastal waters, with strongly negative consequences for higher trophic levels in the northern CCS (Peterson et al. 2006; Sydeman et al. 2006; Goericke et al. 2007; Lindley et al. 2009). Cool conditions associated with La Niña prevailed from mid-2007 through 2008 into early 2009, but regional variability was again dominant: increases in productivity in the northern CCS were not matched by similar responses off southern California and Baja California despite evidence of hydrographic effects of La Niña (McClatchie et al. 2008, 2009).

In contrast to the consistently warm conditions that dominated the CCS prior to the strong 1997–1998 El Niño, the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) index suggests that the North Pacific has since been in a generally cooler state. However, the PDO has been for the past decade fluctuating at intervals of approximately two to four years between cool states marked by negative values of the PDO index and associated negative anomalies in sea surface temperature throughout the CCS (e.g., 1998–2001, 2008–2009) and warmer states of positive PDO and positive SST anomalies (e.g., 2003–2006) (fig. 2, and see next page). Over this period, variability in PDO exhibits a high degree of coherence with the Multivariate El Niño Southern Oscillation Index (MEI) (fig. 2). Whether a sustained "cool regime" has been in place for the CCS remains an open question. The North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al. 2008) index declined in late 2008 and fell to values near zero for much of spring and summer 2009 before slowly increasing into early 2010 to levels comparable to those observed through much of 2008 (fig. 2).

BASIN-WIDE CONDITIONS

Equatorial Pacific

The 2009–2010 El Niño was preceded by weak La Niña conditions during the winter 2008–2009. The tropical Pacific returned to near-normal conditions during boreal spring 2009, but then transitioned into weak El Niño conditions (NINO3.4 > 0.5°C)[1] during boreal summer 2009. The evolutions of the equatorial sea surface temperature (SST), zonal wind stress, and heat content (upper 300 m temperature average) anomalies from spring 2009 to spring 2010 are shown in Figure 3. The June–July–August seasonal mean SST anomaly (SSTa) was about +1.2°C in the far eastern equatorial Pacific. The positive SSTa in the central-eastern equatorial Pacific strengthened rapidly in October–November

[1]The NINO3.4 index is the average sea surface temperature anomaly over a region of the equatorial Pacific bounded by 5°N–5°S latitude and 120°W–170°W longitude.

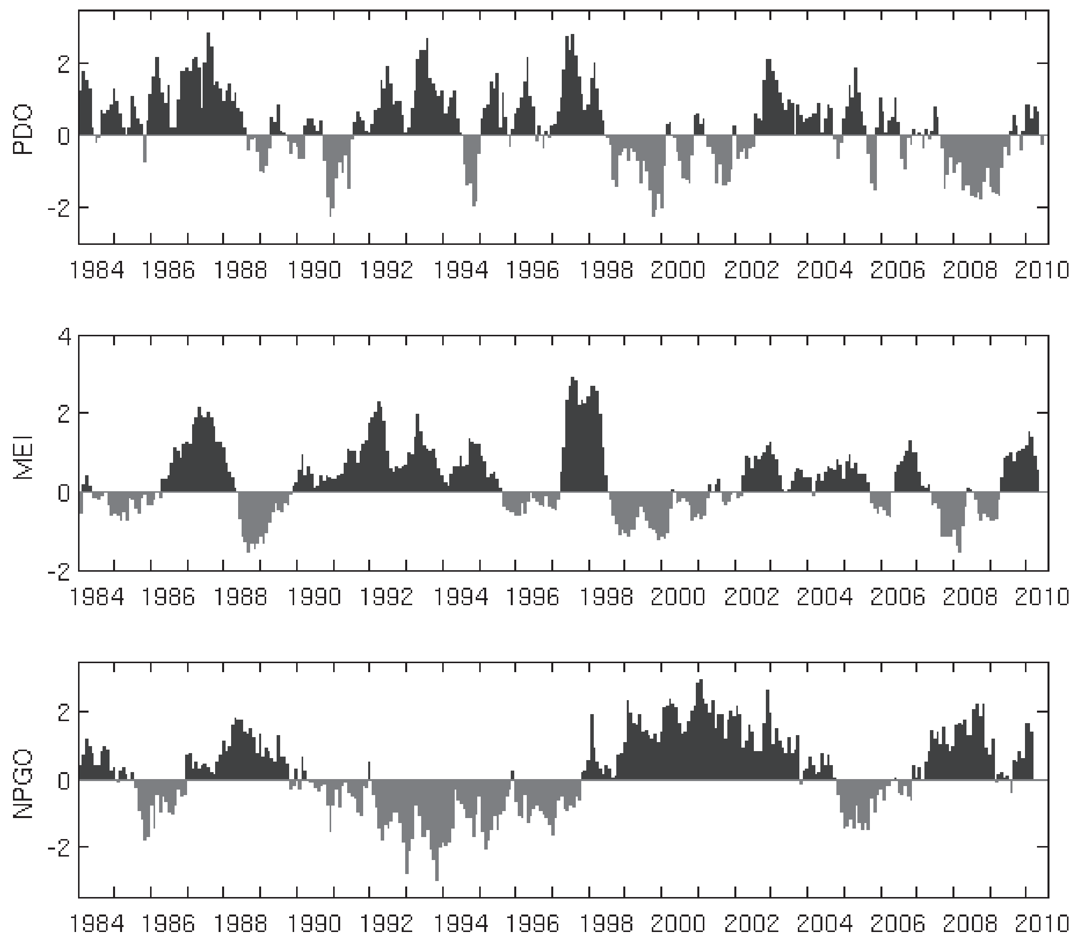

Figure 2. Time series of the Pacific Decadal Oscillation (PDO; top panel; data retrieved from http://jisao.washington.edu/pdo/PDO.latest), the Multivariate ENSO Index (MEI; middle panel; data downloaded from http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/table.html), and the North Pacific Gyre Oscillation (NPGO; bottom panel; downloaded from http://www.o3d.org/npgo/data/NPGO.txt) for January 1984–May 2010 (March 2010 for the NPGO).

2009, and the 3-month-running mean NINO3.4 SST was about 1˚C above-normal in September–November 2009, indicating a moderate strength of El Niño. Coincident with the positive SSTa, the positive zonal wind stress anomalies persisted in the western Pacific and positive heat content anomalies persisted across the equatorial Pacific (fig. 3).

Since June 2009 there have been five episodes of downwelling oceanic Kelvin waves associated with westerly wind burst events that are believed to have contributed to the maintenance and strengthening of the 2009–2010 El Niño (fig. 3)[2]. The El Niño reached a peak phase during December 2009, and the SSTa pattern since January 2010 falls into the category of the central-Pacific event or Modoki event (Ashok et al. 2007) in which the largest warming is centered near the Dateline. Niño indices continued to decline through winter and spring of 2010 and approached zero in May 2010.

[2]See also "Monthly Ocean Briefing" PPT by Climate Prediction Center (CPC), NCEP, at http://www.cpc.ncep.noaa.gov/products/GODAS.

North Pacific Climate Patterns[3]

In the extratropical North Pacific, SST anomalies[4] in summer 2009 were generally cool (–0.5 to –1.0˚C) along the North American coast and warm (>+1˚C) in the central northeast Pacific (fig.4a), a pattern that had persisted through 2008 and into the first half of 2009. This pattern also reflects the negative phase of the Pacific Decadal Oscillation (PDO) in place during this period. Concomitant with the development of the tropical El Niño in summer 2009, the negative-PDO pattern broke down in the northeast Pacific. Typical of El Niño periods, the Aleutian Low deepened in autumn 2009, leading to anomalously strong cyclonic winds in the northeast Pacific (fig.4b). Cool SSTs remained in the

[3]Further details on month-to-month and interannual global ocean climate variability can be found at CPC's "Monthly Ocean Briefing" archive (http://www.cpc.ncep.noaa.gov/products/GODAS).

[4]Large-scale patterns are summarized from the National Center for Environmental Prediction reanalysis fields (Kistler et al. 2001) and from the NOAA-CIRES climate Diagnostics Center (http://www.cdc.noaa.gov/). The reanalysis fields are monthly-gridded (approximately 2˚ × 2˚) anomalies of sea surface temperature (SST) and surface winds. The base period is 1968–1996.

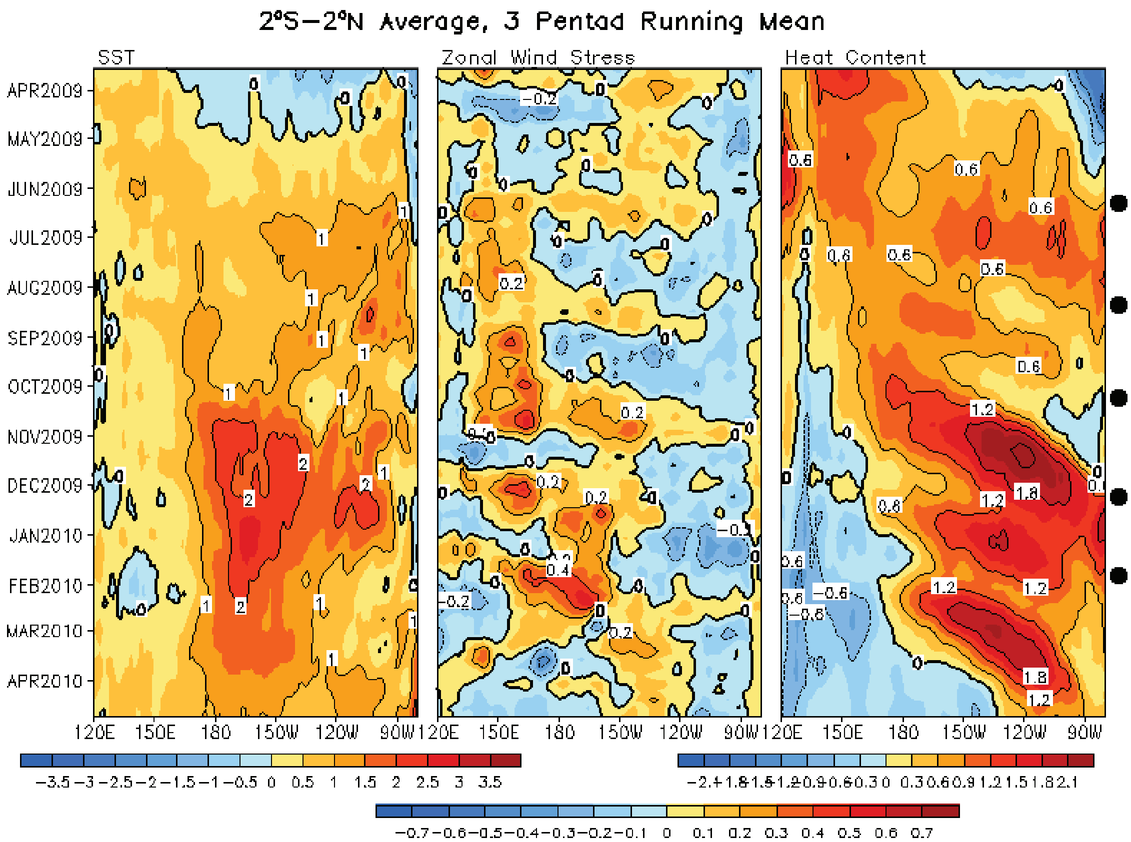

Figure 3. Time-longitude plots of 3-pentad-running mean of SST (left), zonal wind stress (middle) and heat content (upper 300 m temperature average, right) anomalies averaged in 2°S–2°N. SSTs are from the weekly 1° Optimum Interpolation (OI) analyses of (Reynolds et al. 2002), heat contents from the NCEP GODAS (Behringer and Xue 2004), and zonal wind stresses from the NCEP Reanalysis 2 (Kanamitsu et al. 2002). Anomalies for SST, zonal wind stress and heat content were calculated for the base periods of 1971–2000, 1982–2004, and 1982–2004 respectively. Black dots to right of plot indicate approximate timing of wind bursts and subsequent onset of downwelling Kelvin waves.

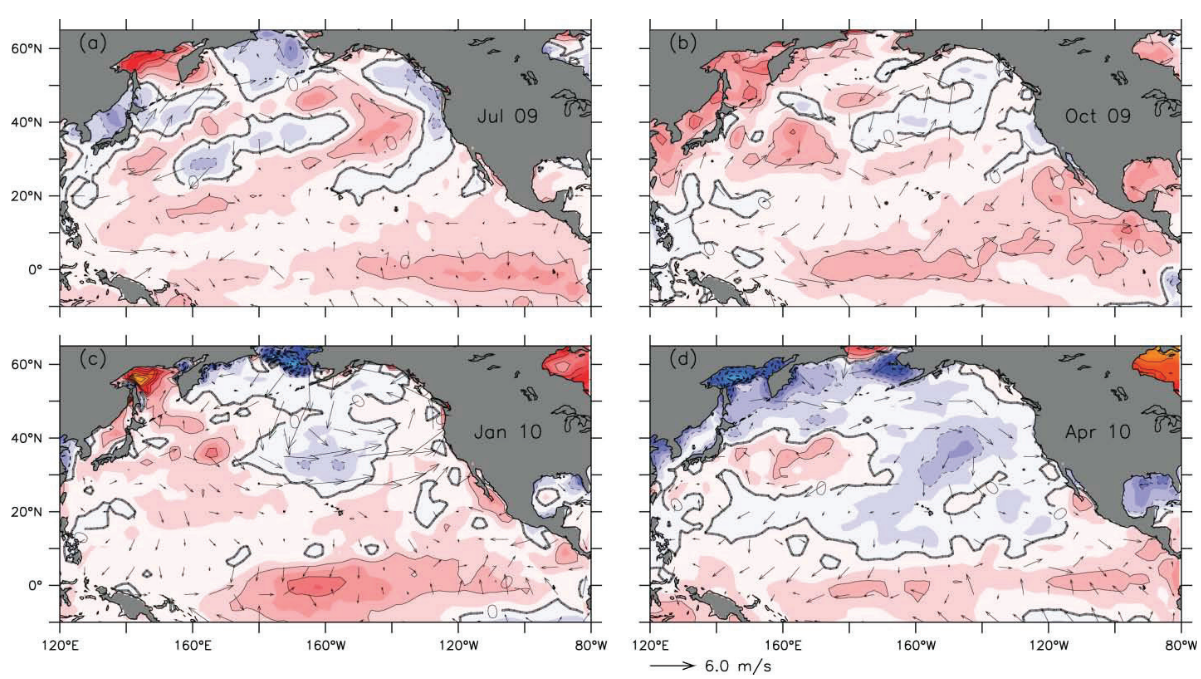

Figure 4. Anomalies of surface wind velocity and sea surface temperature (SST) in the north Pacific Ocean, for (a) July 2009, (b) October 2009, (c) January 2010, and (d) April 2010. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative (cool) SST anomalies are shaded blue; positive (warm) SST anomalies are shaded red. Wind climatology period is 1968–1996. SST climatology period is 1950–1979. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

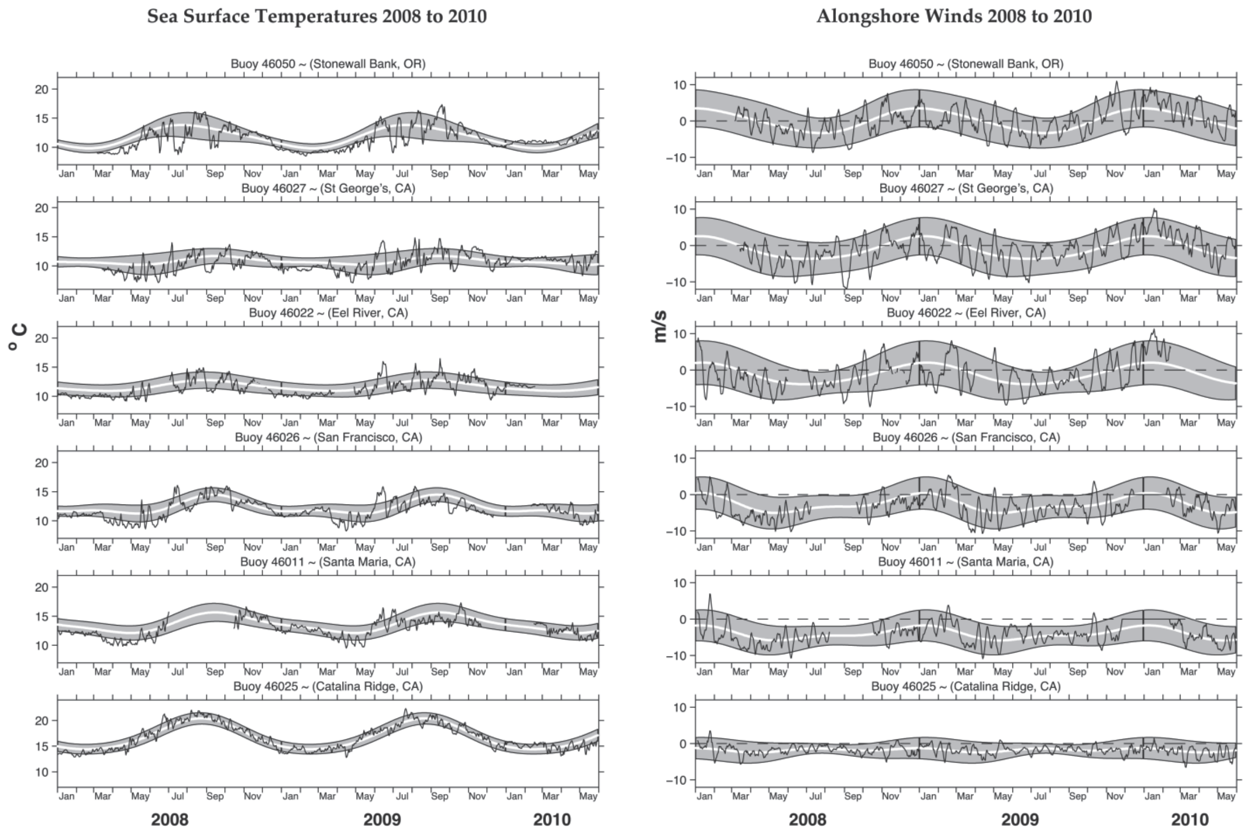

Figure 5. Time series of daily-averaged SST (left) and alongshore winds (right) for January 2008–April 2010 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a 7-day running mean. Data provided by NOAA NDBC. Coordinates for buoy locations are at http://www.ndbc.noaa.gov/to_station.shtml.

California Current, but anomalies were weaker than in the summer. At the time of peak tropical El Niño conditions (December 2009–January 2010), strong cyclonic wind anomalies dominated the northeast Pacific, resulting in warm SST anomalies (~0.5˚C) in the California Current and eastern Gulf of Alaska, and cool SSTs near the dateline (fig. 4c). This pattern changed rapidly in late winter and early spring 2010, as the North Pacific High developed unseasonably early and strong anticyclonic (upwelling-favorable) wind anomalies prevailed by March–April 2010, leading to a return to slightly cooler than normal SSTs in the California Current (fig. 4d).

CALIFORNIA CURRENT

Atmospheric Forcing, Upwelling, and Sea Surface Temperature Responses

In 2009, the spring transition to upwelling conditions, estimated from trends in cumulative upwelling indices and changes in sea level[5], occurred during the second half of March. Strong event-scale variability prevailed in summer 2009, as it had in 2008, with numerous upwelling and relaxation events and corresponding variations in SST. This strong cycle of upwelling/downwelling events has been evident since 2007, and might be linked to an active period of the intraseasonal Madden-Julian Oscillation[6], which is characterized by 30–60 day variability in the tropics. Conditions at coastal NDBC buoys[7] have reflected these large-scale patterns, with high volatility in both surface winds and SST (fig. 5).

The numerous extended relaxation events resulted in anomalous warming of nearshore waters (cf. SST at NDBC Buoy 46050 off Oregon, fig. 5), effects of which are apparent in the warm SST anomalies observed near the coast in the northern CCS (north of Point Arena) in summer 2009 (fig. 4a). An unusually late upwelling event in late September and early October generated the cool anomalies observed in fall 2009 (fig. 4b). Off central California, anomalously cool conditions prevailed in April and May, and transitioned to anomalously warm, fresh waters in June and July before conditions settled

[5]See http://www.cbr.washington.edu/data/trans.html for methods of estimating spring transition.

[6]http://www.cpc.noaa.gov/products/precip/CWlink/MJO/mjo.shtml.

[7]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.

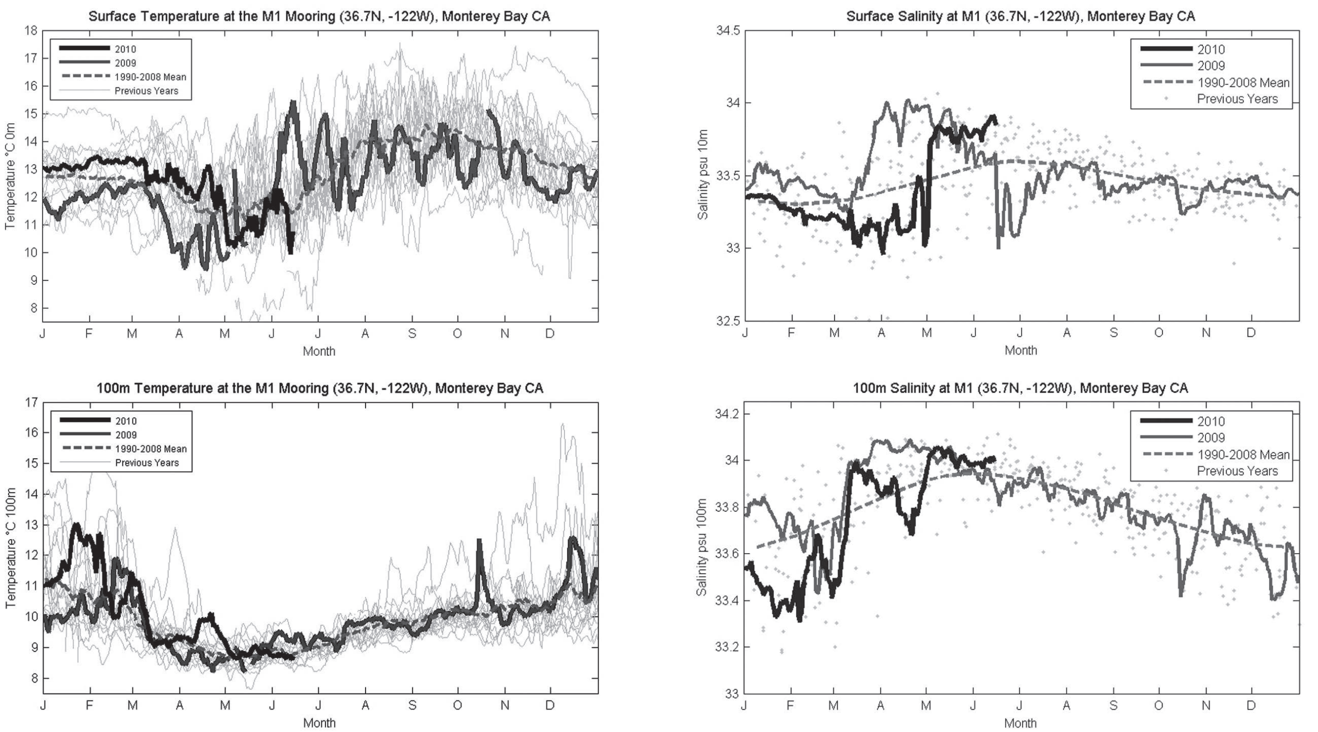

Figure 6. Daily 2009 (thick grey line) and 2010 (thick blue) temperatures (left hand panels) and salinities (right hand panels) at the surface (top panels) and at 100 m (bottom panels) measured by the M1 mooring in Monterey Bay compared to climatological values (grey) from shipboard measurements.

towards climatology in late summer (fig. 6; see also SST at NDBC Buoy 46026 off San Francisco, fig. 5). Overall, the highly variable upwelling and extended relaxation events yielded anomalously weak upwelling during the summer of 2009, particularly in the northern CCS. Coastal SSTs in the southern CCS were above normal (fig. 4a).

The rapidly changing atmospheric forcing in the northeast Pacific through winter 2009–2010 is reflected in California Current upwelling[8]. The strong Aleutian Low in winter 2009–2010 resulted in anomalously strong downwelling in the northern California Current, especially north of Point Arena (~39°N) where a series of intense winter storms contributed to downwelling comparable in magnitude to that observed during winters of 1997–1998 and 1998–1999 (fig. 7). SSTs in winter 2010 were anomalously warm, reflecting the strengthened Aleutian Low and strong downwelling. The generally weaker upwelling (and strong downwelling in the northern California Current) observed in 2009 is typical of an El Niño year.

Rapid development of a strong North Pacific High drove resumption of upwelling earlier and more strongly than is usual following an El Niño event, especially in the central California Current (fig. 7) and likely reflects the rapid decay of the tropical El Niño. Observations along the coast show that the water column remained anomalously warm and fresh at the surface from winter 2009–2010 until the spring transition to upwelling in late April/early May 2010 (approximately a month later than in 2009). Anomalously strong southward wind stress, associated with a well-developed North Pacific High, produced negative SST anomalies throughout most of the CCS. Observations off central California indicate that recovery from El Niño conditions may have begun earlier at depth: anomalies >2°C at 100 m in Monterey Bay (M1 mooring) had returned to normal by early March 2010 (fig. 6). Observations elsewhere in the northern CCS corroborate this pattern (e.g. Trinidad Head Line; data not shown). Moreover, observations in the northern CCS also also suggest that upwelling was weak and intermittent following the 2010 spring transition; upwelling has generally been weaker than normal through the spring of 2010 over much of the CCS (fig. 7).

HF Radar Surface Current Observations[9]

In spring 2009, enhancement of upwelling jets south of major capes was observed as regions of strong mean

[8]Monthly upwelling indices for the North American West Coast (21°–52°N) and methods for their calculation are available at http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html. Anomalies are calculated relative to 1948–1967.

[9]HF Radar currents presented herein are calculated hourly at 6 km resolution using optimal interpolation (Kim et al. 2008; Terrill et al. 2006) and further averaged to 20 kilometer resolution prior to display. Real-time displays of HF-Radar surface currents can be viewed at the regional association websites: http://www.sccoos.org/data/hfrnet/ and http://www.cencoos.org/sections/conditions/Google_currents/ and at websites maintained by the institutions that contributed data reported here (listed in Acknowledgments).

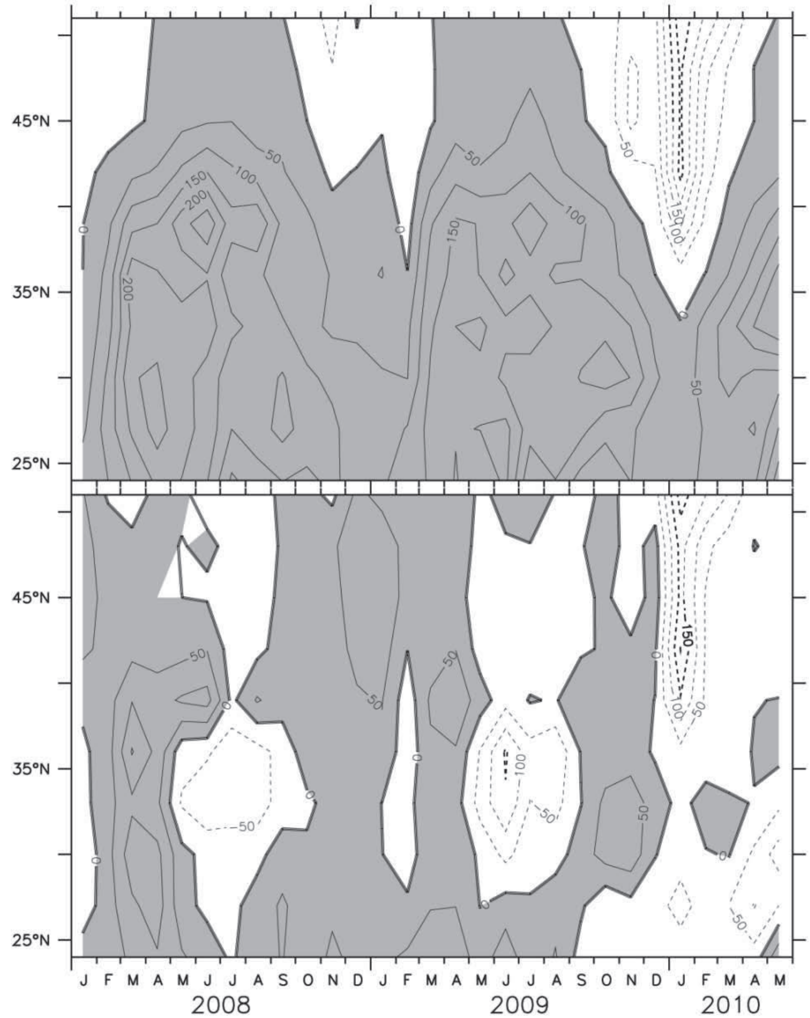

Figure 7. Monthly upwelling index (top) and upwelling index anomaly (bottom) for January 2008–April 2010. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–1967 monthly means. Units are in m^3/s per 100 km of coastline.

flow extending south from Cape Blanco, Cape Mendocino, Point Arena, Point Reyes and Point Sur (fig. 8). During summer 2009, the spatial extent of strong mean flow increased somewhat north of Cape Mendocino, but mean flows (and locally enhanced upwelling jets) generally weakened into summer and fall. Only the mesoscale feature south of Cape Mendocino persisted robustly through summer and into the fall, associated with the persistence of a clockwise mesoscale eddy (Halle et al. 2010). In the winter (December to February), northward mean flow was evident throughout the California Current region. Spatial variability in the magnitude of poleward surface currents corroborates the difference in intensity of downwelling between the northern and southern portions of the CCS (fig. 7; fig. 8).

Southward flow over the outer shelf off Point Reyes was strong in the summer of 2009 (comparable or greater in magnitude to that observed during the preceding two years, and clearly stronger than in 2005 and 2006), but anomalously strong in April 2009 with a monthly average of 0.7m/s (fig. 9). These flows reflect interactions between the California Current and wind-forced flow over the continental shelf in this region, and therefore provide an index of periods when the California Current has a more or less energetic influence on coastal waters (Largier et al. 1993; Kaplan et al. 2009; Halle and Largier 2010). Strong equatorward flows over the outer shelf were consistent with the strongly positive NPGO and negative PDO during winter 2008–2009 and associated large-scale circulation patterns. Strong poleward flow over the outer shelf in early 2010 coincided with downwelling in the northern CCS (fig. 9). In contrast, alongshore flow over the inner shelf, which generally repsonds more strongly to local wind forcing and includes poleward "relaxation" flows, diminished rapidly from spring 2009 and was weaker in summer

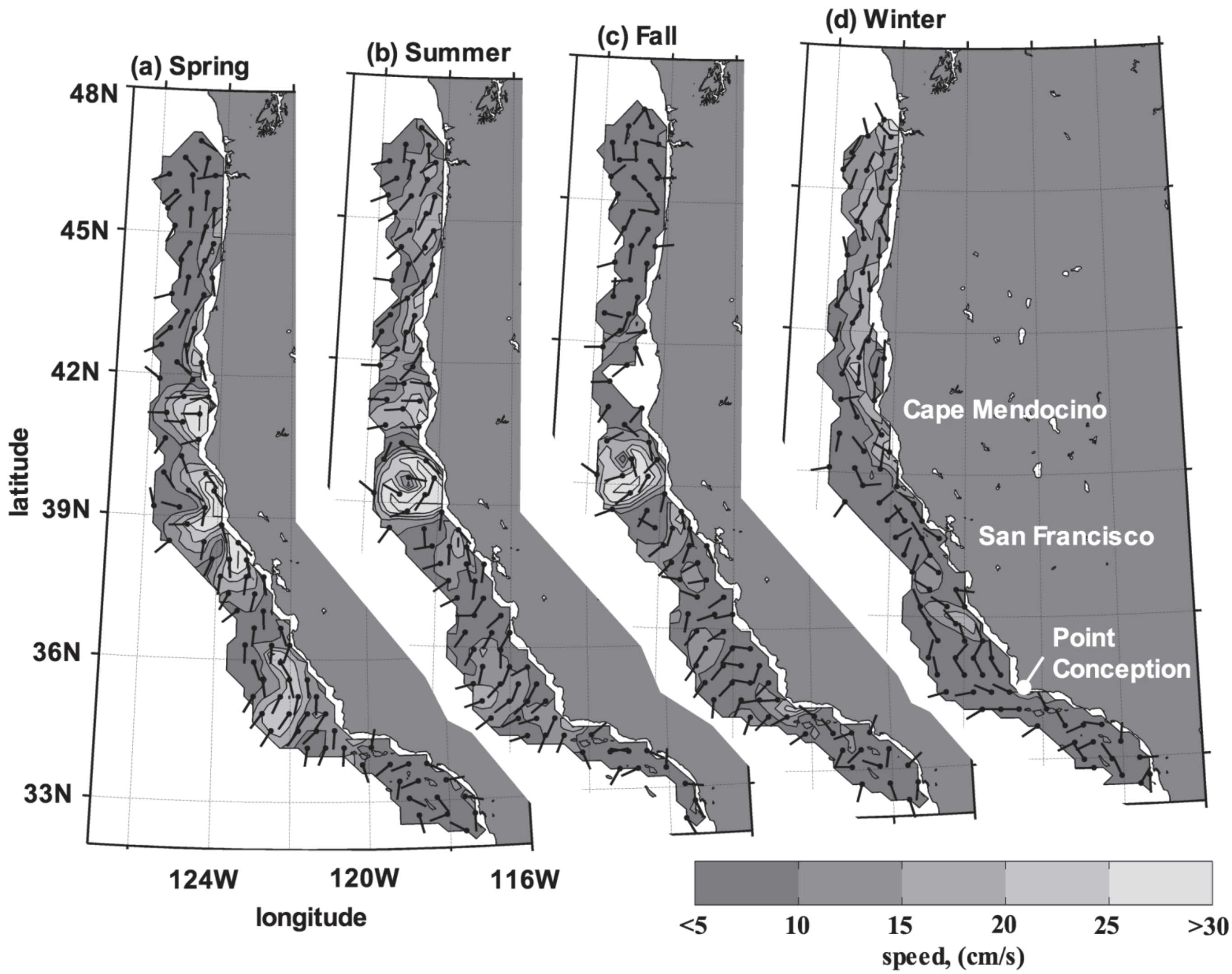

Figure 8. Mean seasonal maps of surface currents observed throughout the CCS with coastal HF radar for March 2009 through February 2010. The seasons are spring (March–May), summer (June–August), fall (September–November), and winter (December–February). Mean surface currents are calculated at 20 km resolution using hourly HF radar observations. Current speeds are indicated by shading. Current direction is given by direction of lines extending from black dots that indicate the location of the measured currents. For clarity, roughly one-sixth of the directions associated with the gridded 20 km currents are shown.

2009 than in the preceding two years (fig. 9). By 2010, strong southward flow had returned to the inner shelf, reflecting the resumption of upwelling winds along the north-central California coast (fig. 9).

El Niño Impacts in the California Current

Although the El Niño of 2009–2010 appears to have been relatively weak and short-lived, evidence of direct, physical effects was observed in the California Current. Time series of coastal sea level from Panama (Balboa) to Washington (Neah Bay) include a number of high sea level events (e.g., mid-October, late January) that plausibly indicate the propagation of coastally-trapped waves triggered by downwelling equatorial Kelvin waves (fig. 10). These events are corroborated by coincident pulses of anomalously warm, fresh water in the upper 100 m of the water column in Monterey Bay (fig. 7). The timing of these events is more or less consistent with the expected arrival of equatorial downwelling Kelvin waves on the coast of South America (cf. fig. 3) and subsequent poleward propagation of resulting coastally trapped Kelvin waves. However, coastal sea levels also vary in response to local wind forcing (e.g., storm passage) and additional work is needed to evaluate whether and to what degree the observed high sea level events did in fact mark the passage of coastally-trapped Kelvin waves. If these events are shown by subsequent analysis to represent the effects of Kelvin waves, they represent the in-water arrival of El Niño at various points along the west coast of North America.

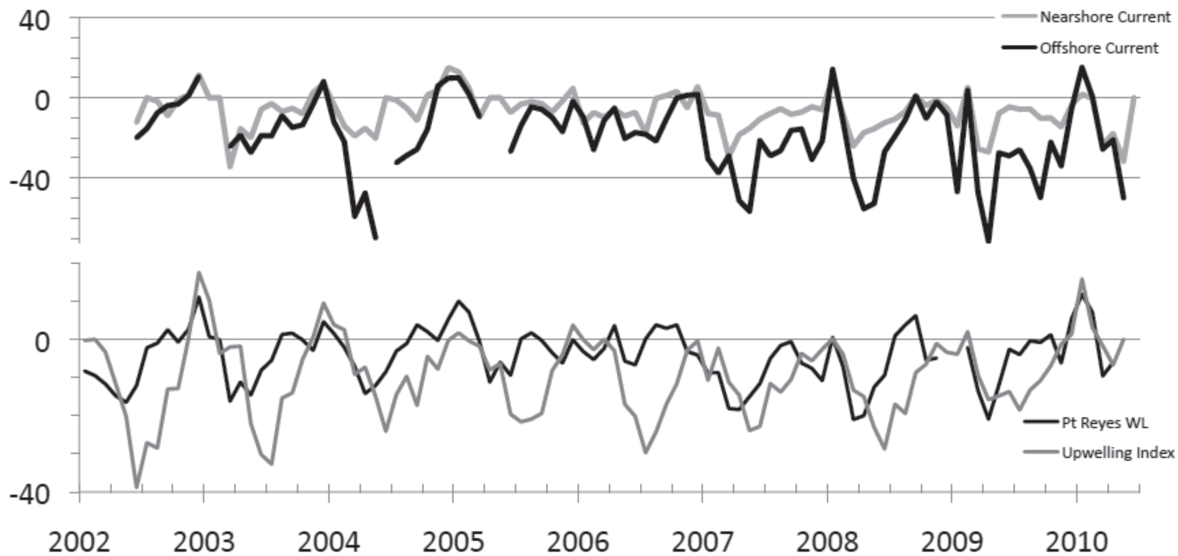

Figure 9. Upper panel: Monthly average surface flow past Point Reyes, CA (positive indicates northward flow, cm/s) between 0 to 15 km offshore (38°00' to 38°00'N and 123°00' to 123°10'W; grey line) and between 30 and 60 km offshore (38°00' to 38°00'N and 123°20' to 123°40'W; black line). Lower panel: Sea level at Point Reyes relative to 1 m above MLLW (units cm; black line) and negative upwelling index for 39°N, i.e., positive values indicate onshore Ekman transport (units m^3/s per 10 m of coastline; grey line).

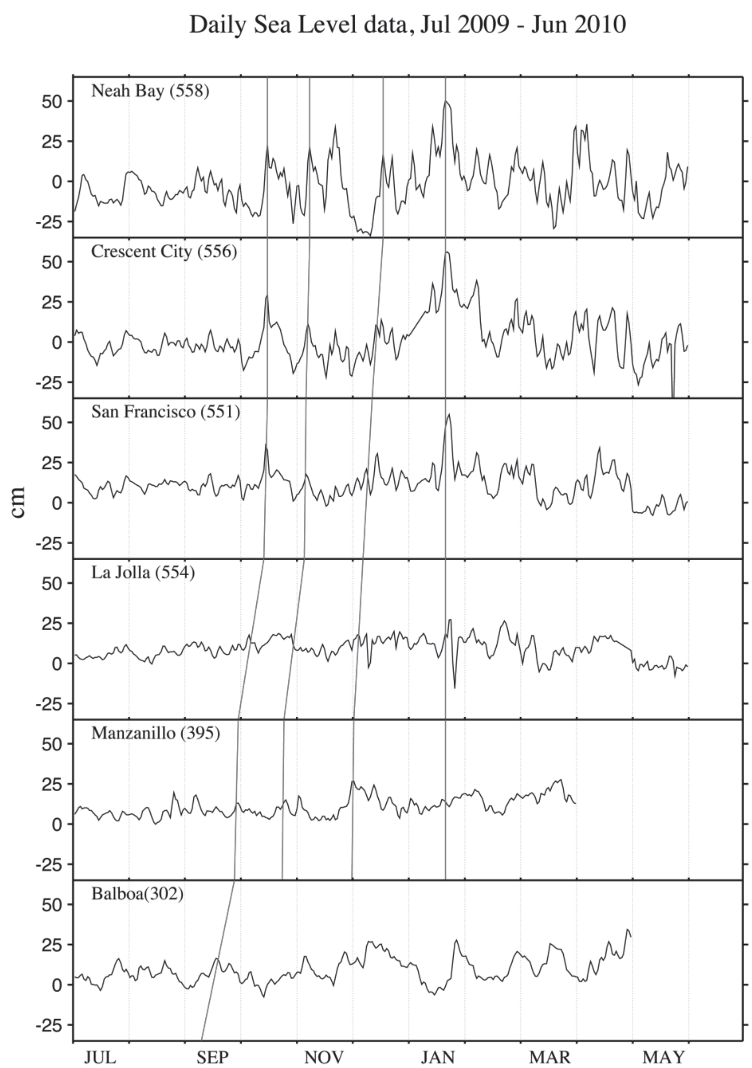

Figure 10. Daily adjusted sea levels (cm) at six locations along the North American continent. High sea level events that might correspond to passage of coastally-trapped Kelvin waves are indicated by lines connecting peaks across time series.

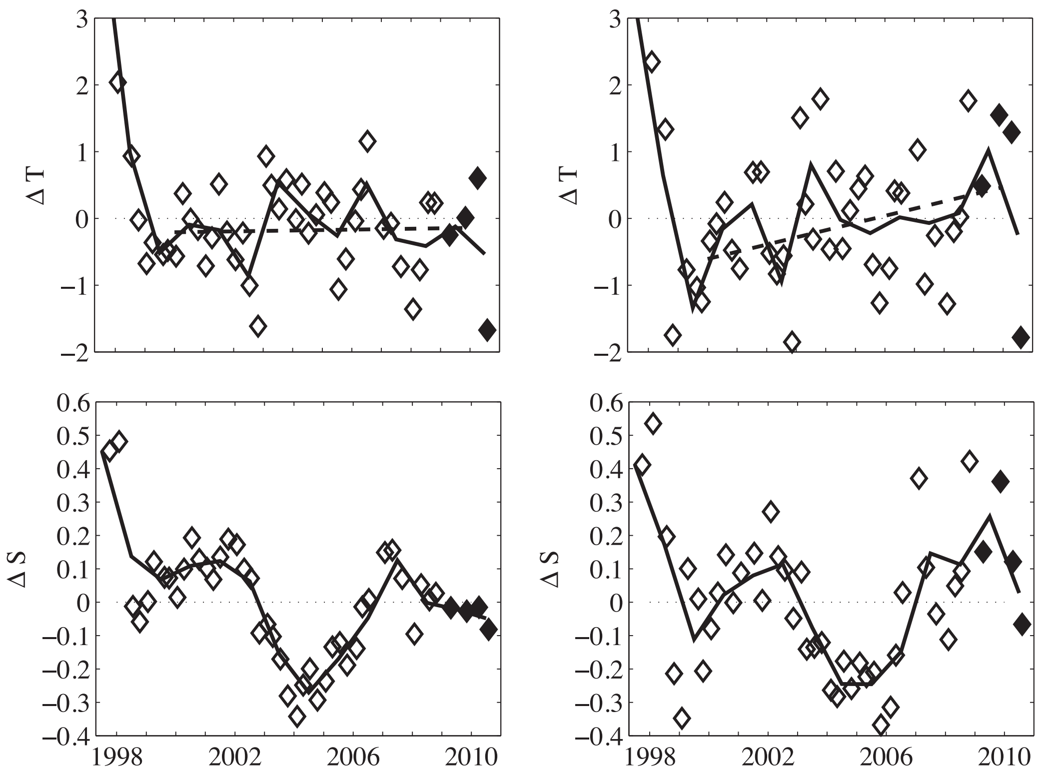

Figure 11. Time evolution of regional 10-m temperature (°C), salinity, and phytoplankton chl-a anomalies (mg m^{-3}). Northern region values were obtained by averaging anomalies from lines 103, 107, 110 and 113. Southern region values were obtained from observations along sections 123, 127, 130 and 133. Anomalies were computed by contrasting measured values at each depth/location to climatological means obtained from all available data (44 cruises) in the period 1998–2010.

REGIONAL SURVEY OBSERVATIONS

Baja California – IMECOCAL Surveys[10]

Time series of mixed layer temperature and salinity anomalies[11] illustrate the effects of El Niño in 1997–1998, La Niña 1999–2002, freshening of the upper layer in 2002–2006, and the short-termed La Niña event in late 2007–early 2008 throughout the IMECOCAL study region, and contrasting responses in the temperate and subtropical subregions north and south of 28°N, respectively (Durazo 2009) (fig. 11). Starting in late 2008, data in the northern region show slightly positive temperature anomalies and near normal salinities. For the southern region, the effects of El Niño are indicated by the larger positive anomalies ($\Delta T \sim 1$–2°C, $\Delta S \sim 0.4$), with peak values in October 2009.

[10]The IMECOCAL study region spans 93 stations off Baja California, México (fig. 1). IMECOCAL cruise schedules, data collection protocols, analysis methods, and additional substantiating data are fully described at http://imecocal.cicese.mx. Zooplankton data were not available at the time of writing, and will be presented elsewhere.

[11]Mixed layer temperature and salinity anomalies were calculated for regions north and south of 28°N using a method similar to that employed by CalCOFI (described below). Results for the southern region include some variability associated with inter-annual differences in station occupancy. Climatological means are computed from hydrographic data gathered by the IMECOCAL program in the period 1998–2010.

A dissimilar pattern was apparent in anomalies for chl a at 10-m (data not shown). In the northern region, chl a concentrations shifted from anomalously large values in spring 2009, through values very near the long term mean in autumn 2009, to large negative anomalies (~1.0 mg m^{-3}) in spring 2010. In the southern region, chl a values were near long term means throughout 2009, with slightly negative anomalies in spring 2010. The trend in chl a anomalies during 2002–2006 is related to patterns described by Gaxiola-Castro et al. (2008).

Analysis of cross-shelf sections (data not shown) shows that large positive salinity anomalies were most apparent near the coast in the southern region. These anomalies increased in strength between April 2009 to October 2009 (maximum anomalies $\Delta S \sim 0.5$ occured at southern nearshore stations in October 2009), but were replaced by negative anomalies ($\Delta S \sim -0.1$ to –0.5) near the coast by April 2010. Complex eddy structure was observed throughout the region during October 2009, and included features that are likely to have contributed to the strong nearshore salinity anomalies through entrainment of more saline water from south of the IMECOCAL region. These flows differ from circulation patterns observed during the 1997–1998 El Niño, during which waters of tropical and subtropical charac-

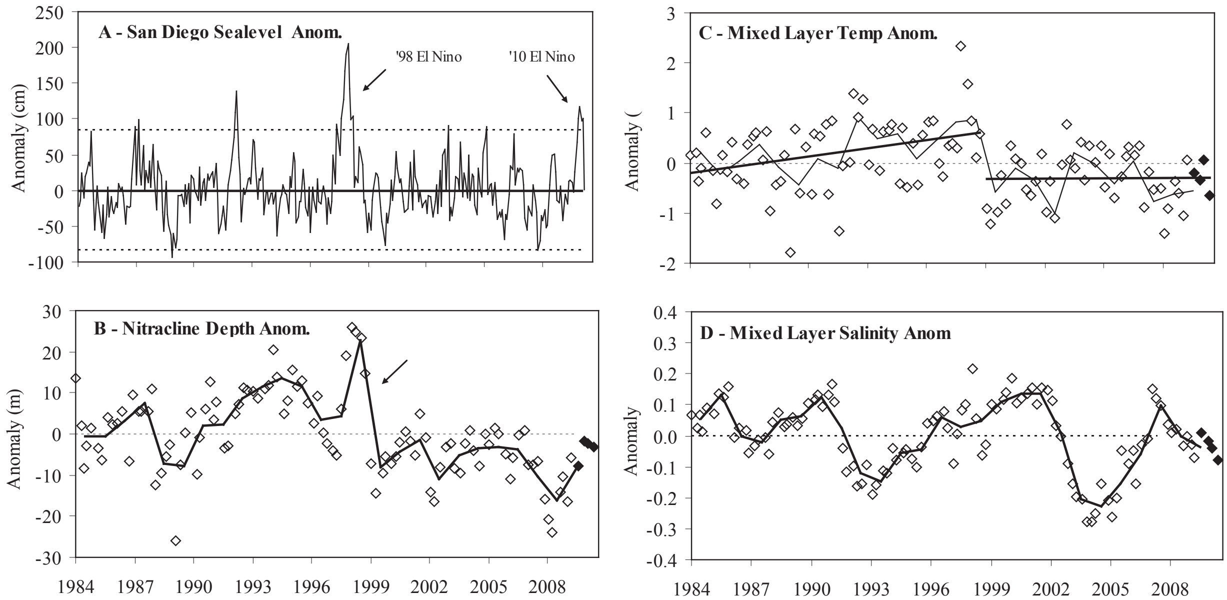

Figure 12. Anomalies of detrended San Diego sea level (A), nitracline depth (B), mixed layer (ML) temperature (C), and ML salinity (D) off Southern California (CalCOFI standard grid; fig. 10). Data from the last four CalCOFI cruises are plotted as solid symbols, data from previous cruises are plotted as open diamonds. The thin solid lines represent the annual averages, the dotted lines the climatological mean, which in the case of anomalies is zero and the straight solid lines long-term trends.

teristics coalesced into a coastal, poleward current north of Punta Eugenia (Durazo and Baumgartner 2002). In contrast, geostrophic circulation patterns in April 2009 and April 2010 were dominated by meandering equatorward flows.

Southern California – CalCOFI Surveys[12]

Sea level anomalies serve as useful indicators of local El Niño effects off southern California. The 2009–2010 El Niño started having an effect on local sea levels in the fall of 2009, reached its peak in late 2009 and by the spring of 2010 sea levels had receded to normal values (fig. 12a). Despite this clear signal of the El Niño event, no noticeable effects on mixed layer temperature or nitracline depth were observed (fig. 12b,c); values of both properties were close to their long-term means. Mixed layer salinity, which is not expected to be affected by ENSO, also was similar to long-term averages (fig. 12d).

Over the last year, temperatures and salinities at 200 m were slightly higher and lower, respectively, than long-term averages, similar to patterns observed during the 1997–1998 El Niño (fig. 13). However, these signals were driven by changing isopycnal depths (fig. 14) rather than changing properties on any isopycnal. Rather, in contrast to observations during the 1997–1998 El Niño, hydrographic and chemical properties did not change significantly at representative isopycnals during the 2009–2010 El Niño. Spatial patterns of isopycnal depth anomalies during the 2009–2010 El Niño were similar to those observed during 1997–1998, i.e. during the winter, deeper than normal isopycnal depths (positive anomalies), were observed primarily in the Southern California Bight (data not shown). In the spring, positive anomalies were primarily found in the offshore regions of the study area (data not shown). Averaged over the CalCOFI area, these spatial patterns contributed to the persistence of overall positive anomalies in isopycnal depth after the dissipation of El Niño conditions (fig. 14).

Temperature-salinity (TS) diagrams for different regions within the CalCOFI study area reflect these processes. During 2009, temperature and salinity differed from long-term averages only at intermediate depths. These patterns were consistent across all different regions of the study area (shown in Figure 15 for the edge of the central gyre, the southern California Current and the northern coastal region). The freshening of the thermocline at the edge of the Gyre, however, can not be attributed solely to the El Niño since a similar stratification was observed during 2008. This likely reflects the influence of the California Current which extended further offshore than usual (cf. McClatchie et al. 2009).

Nitracline depths in the CalCOFI area were similar to mean values observed since 1999. Thus, nitracline depth responded significantly to the La Niña conditions of 2007–2008 but not to the El Niño conditions of 2009–2010 (fig. 12b). Concentrations of nutrients in the mixed layer were likewise similar to long-term averages

[12]Results are presented here as cruise averages over all 66 stations (fig. 1C) or as anomalies with respect to the 1984–2008 time series to augment ongoing time series of observations. Detailed descriptions of the cruises and methods used to collect data and analyze samples are given in previous reports and are available at http://www.calcofi.org.

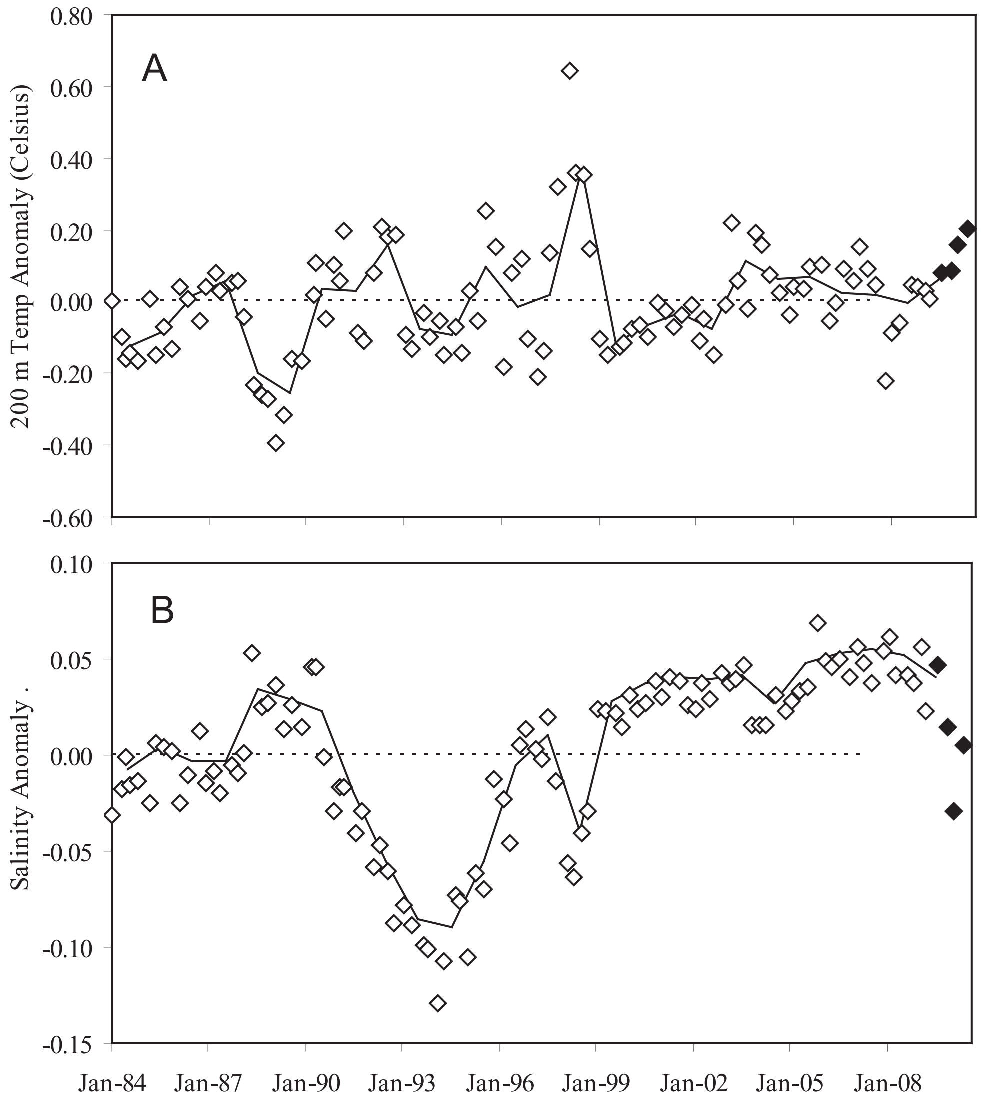

Figure 13. Anomalies of temperature (A) and salinity (B) at a depth of 200 m, calculated and presented as described at left for Figure 12.

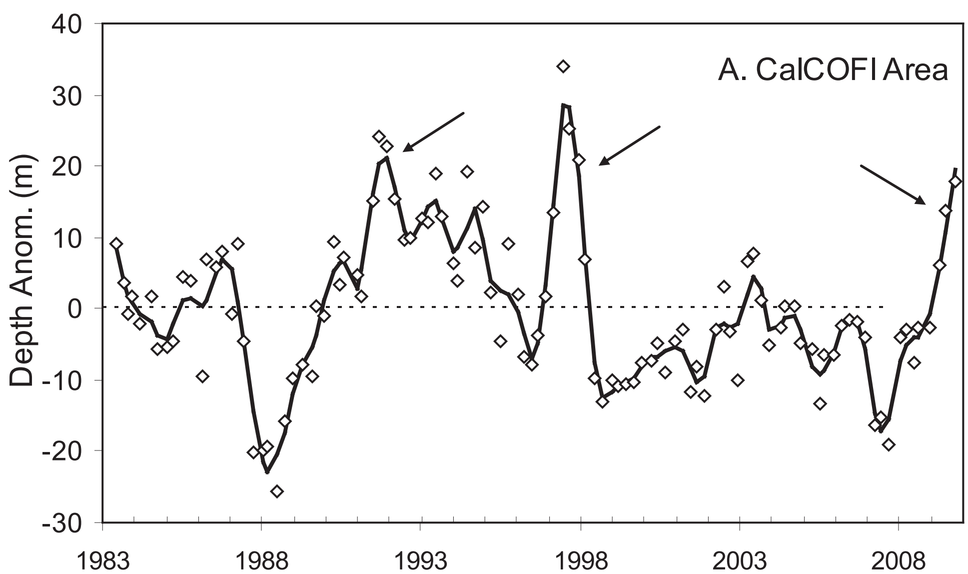

Figure 14. Depth anomalies of the σ_t 26.4 isopycnal calculated and presented as described at left for Figure 12. Arrows indicate the last three strong El Niños.

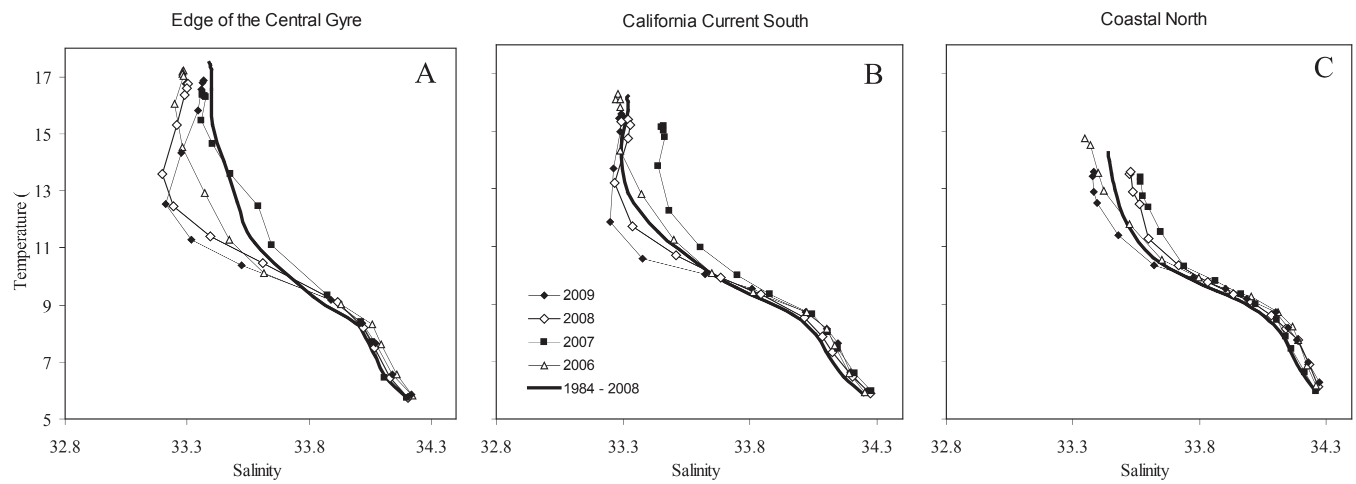

Figure 15. TS plots for three representative areas of the CalCOFI region. A. The edge of the central gyre (Lines 90–93, Stations 100–120), B. the southern California Current region (Lines 87–93, Stations 60–90) and C. the coastal areas in the north (Lines 77–80, Stations 60 and inshore). Each data point represents the average TS characteristic of one standard depth level for the specified time periods, i.e., 1984–2008, 2006, 2007, 2008 and 2009.

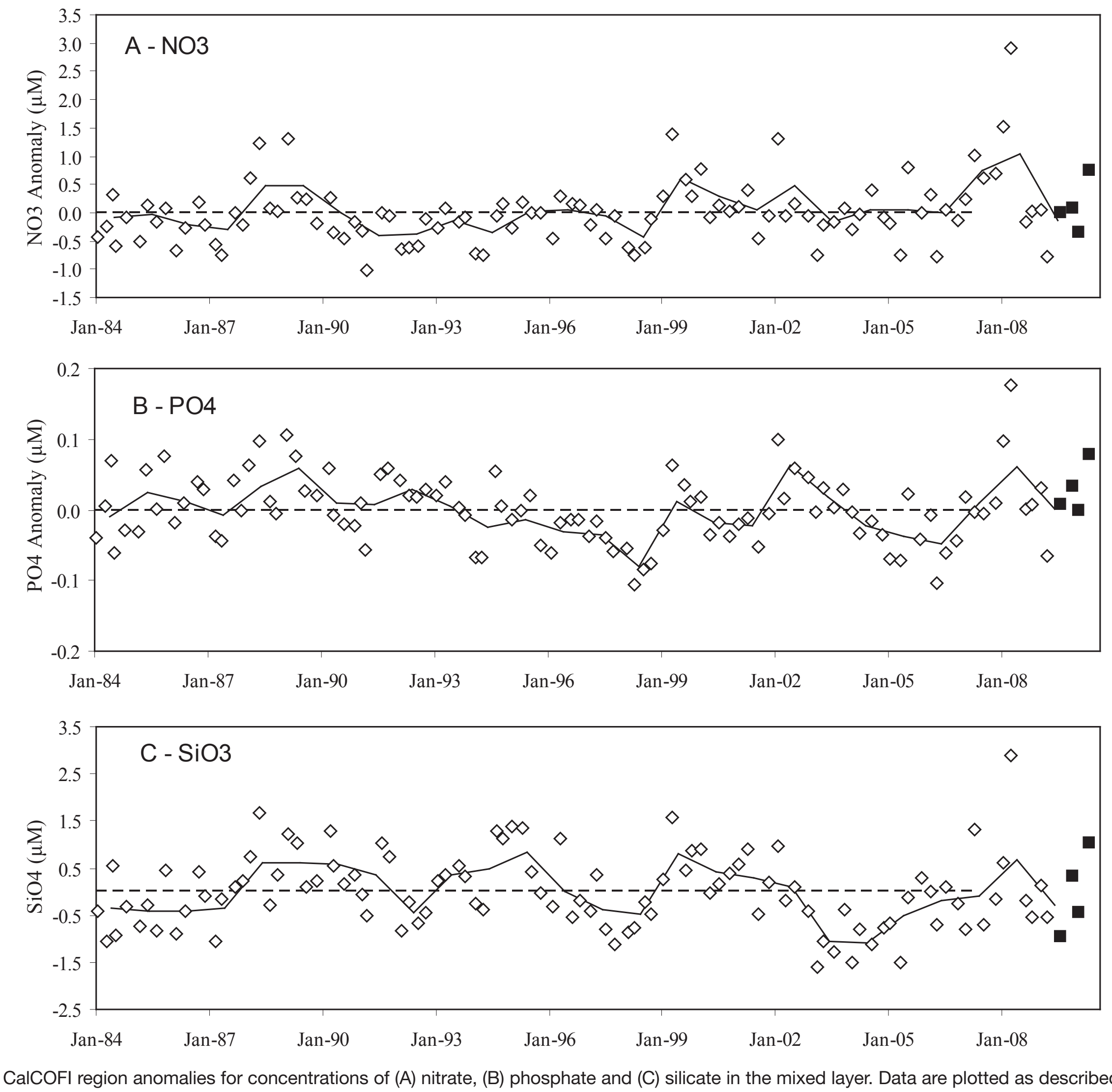

Figure 16. CalCOFI region anomalies for concentrations of (A) nitrate, (B) phosphate and (C) silicate in the mixed layer. Data are plotted as described in Figure 12.

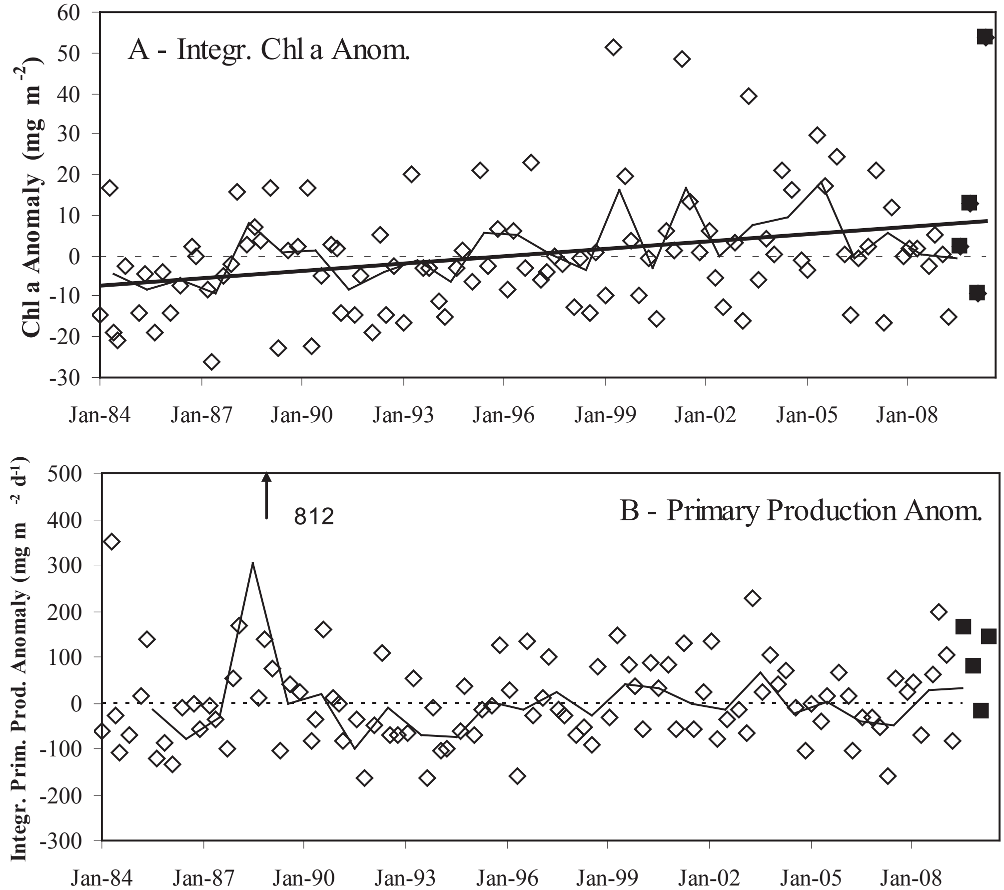

Figure 17. CalCOFI region averages for standing stocks of Chl *a* (A) and rates of primary production (B) both integrated to the bottom of the euphotic zone, plotted against time. Data and symbol codes are the same as those in Figure 13.

(fig. 16). The slightly elevated concentrations observed during the April/May 2010 cruise were due to strong upwelling observed west and southwest of Point Conception during the cruise. Strong upwelling also contributed to the very high chl a concentrations observed during the April/May 2010 cruise (fig. 17a), a signal primarily driven by enhanced phytoplankton growth in the coastal areas. Coincident observations of extremely low zooplankton displacement volumes southwest of Pt Conception on the April/May 2010 cruise are also likely to reflect the effects of transport associated with this upwelling event (data not shown). With the exception of those observed during the winter of 2009–2010, rates of primary production were slightly above long-term averages (fig. 17b).

Zooplankton displacement volumes over the past 12 months have been similar to long-term averages for the respective months (fig. 18a). Anomalies of zooplankton displacement volumes are consistent with the long-term trend of declining values observed since 1999 (fig. 18b). Spatial patterns in zooplankton displacement volume anomalies[13] suggest that recent trends of declining zooplankton displacement in the CalCOFI study area are due to trends of increasing zooplankton biomass in the offshore areas, declining biomass in the California Current regions and stable biomass in the Southern California Bight; this pattern continues to hold, with smaller average anomalies, in data from the past 12 months. What factors control zooplankton biomass in these different areas are currently not known.

[13]Anomalies of zooplankton displacement volumes are calculated relative to the base period 1984 to 2008.

Central California: Monterey Bay and Line 67[14]

The 2009 spring transition to upwelling conditions occurred in the later half of March at the surface in both temperature and salinity and seems to have been anticipated at 100 m. Anomalously cool, salty conditions in April and inconsistently May 2009 were somewhat cooler and saltier than normal, whereas summer

[14]Data on temperature and salinity at the surface and 100 m for Monterey Bay are based on MBARI monthly cruises and mooring data. CalCOFI Line 67 was occupied three times in 2009 and twice so far in 2010; three of these occupations were regular CalCOFI cruises and the data have not been included here.

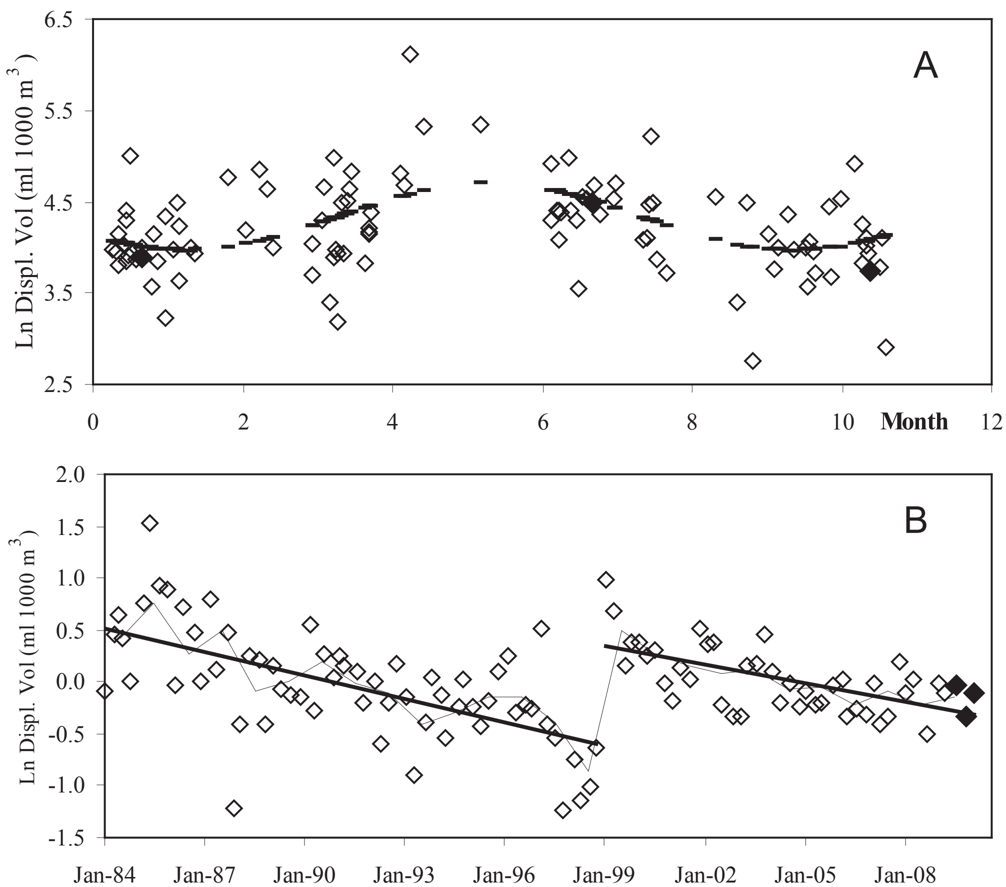

Figure 18. CalCOFI log cruise-mean macrozooplankton displacement volumes plotted against the month of the year (A) and time (B). Symbols are as described for Figure 12, except that data for cruise 2010-04 are not yet available. The dashed line in A is the harmonic fit to the data. Straight lines in B represent long term trends for the periods 1984 to 1998 and 1999 to 2009.

was close to climatology (fig. 6). In both 2009 and 2010, spring chl a[15] concentrations were lower than average, but 2009 summer chl a concentrations were close to climatology, although still lower than during the most recent 4–5 years (fig. 21). Five warm, fresh pulses were observed in the upper 100 m of the water column in winter 2009–2010, and the water column remained anomalously warm and fresh at the surface until the spring transition occurred in late April/early May (fig. 6). It appears, however, that the conditions began to return to normal earlier at depth: anomalies >2˚C at 100 m had disappeared by early March 2010.

NORTHERN CALIFORNIA CURRENT

Newport Hydrographic Line

Observations along the Newport Hydrographic Line[16] reveal that bottom waters over the inner- to mid-shelf were on average warmer and fresher during summer 2009 than in the previous two summers (data averaged over May to September; fig. 19) and relatively fresh in fall 2009 (October to December; fig. 20) compared to recent fall conditions. Further offshore, mid-water salinity anomalies do not indicate any influx of subtropical water related to the El Niño event (fig. 22). Except for observations on two separate cruises (6 March 2009 and 19 March 2010), salinity anomalies were small during 2009 and early 2010, in contrast to the strong, sustained freshening observed during the 1997–1998 El Niño.

Monthly averaged values of copepod species richness off Oregon[17] continue to track the PDO and SST quite closely, with cold conditions dominated by a few sub-

[15]Chlorophyll concentrations reported here are based on measurements at major stations (C1, H3, M1, 67–50, M2, 67–55) occupied at approximately 3 week intevals. The data have been averaged by day, gridded to 14 days, and smoothed with a 9-point moving average. Climatology is based on observations from 1990–2008.

[16]Regular sampling of the Newport Hydrographic (NH) line along 44.65˚N continued on a biweekly basis along the inner portions of the line, at seven stations ranging from 1 to 25 nautical miles from shore. Details on sampling protcols are available in previous reports and at http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/ka-hydrography-zoo-ichthyoplankton.cfm. Temperature anomalies along the Newport line are based on the Smith et al. (2001) climatology.

[17]Samples were collected with a 0.5 m diameter ring net of 202 µm mesh, hauled from near the bottom to the sea surface. A TSK flowmeter was used to estimate distance towed.

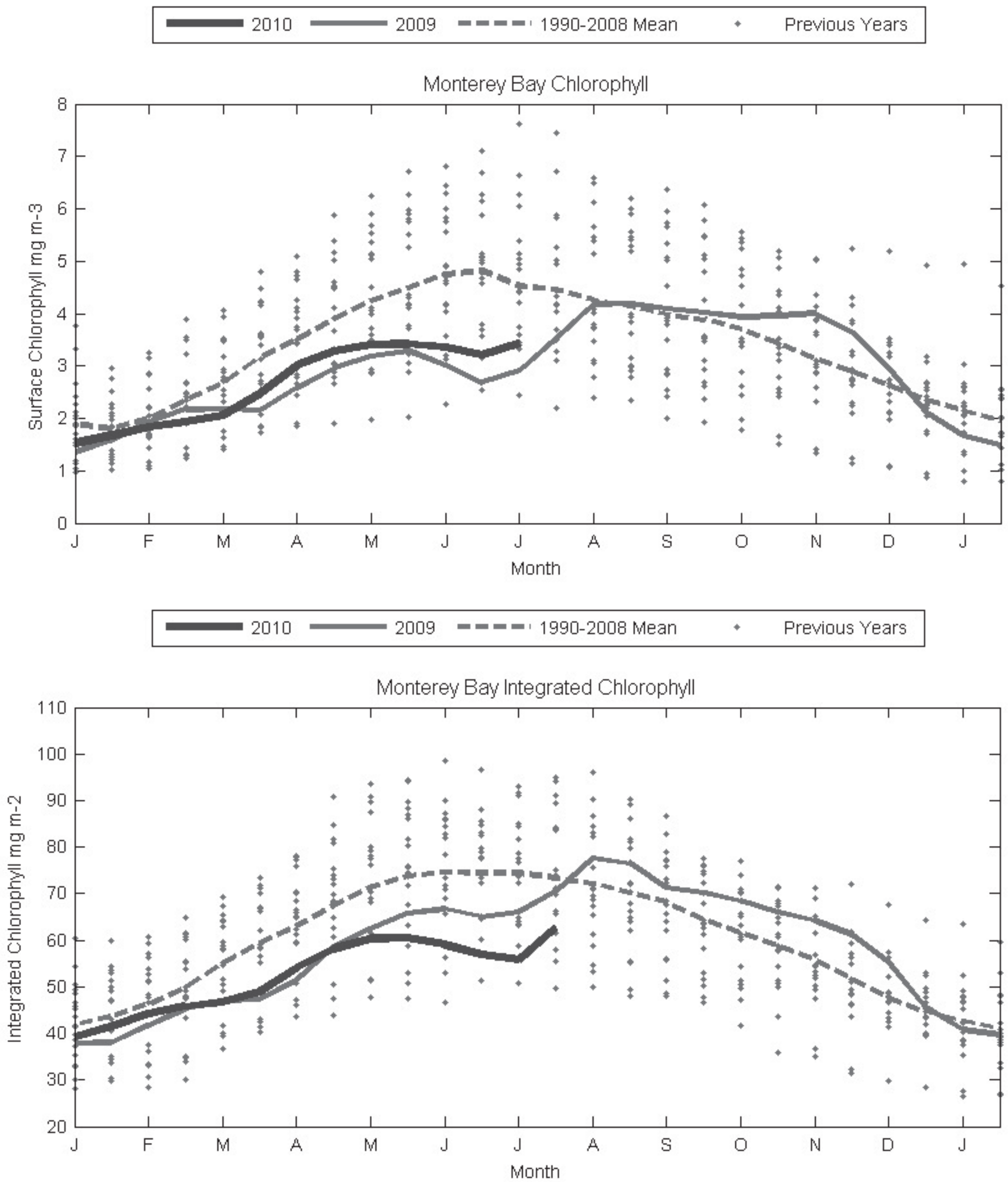

Figure 19. Surface (upper panel) and water column (lower panel) chlorophyll concentrations from Monterey Bay, California for 2009 and 2010 compared to the 1990–2008 seasonal mean.

arctic taxa and warmer conditions dominated by a more speciose subtropical assemblage (fig. 23). Moderately low species–richness values were observed during 2009 but not as low as during 2008. The winter and early spring of 2010 show anomalously high values of species richness, comparable to values observed during 1997–1998 El Niño and most of 2003 through 2006.

Trinidad Head Line[18]

Observations along the Trinidad Head Line indicate similar patterns to those reported above for the Newport Hydrographic Line. Specifically, available data show a greater degree of warming and freshening over the mid-shelf during winter in 2009–2010 than had been observed in the previous three winters, and indicate that warming of coastal waters began to develop in the late summer and early fall of 2009 and persisted until the transition to upwelling observed in April 2010. Salinity measurements at depths of 120–150 m at station TH04 (410 m depth) corroborate patterns in salinity observed over the slope off Oregon (data not shown).

[18]Details on sampling protocols for the Trinidad Head Line are available in previous reports and at http://swfsc.noaa.gov/HSU-FisheriesOceanography.

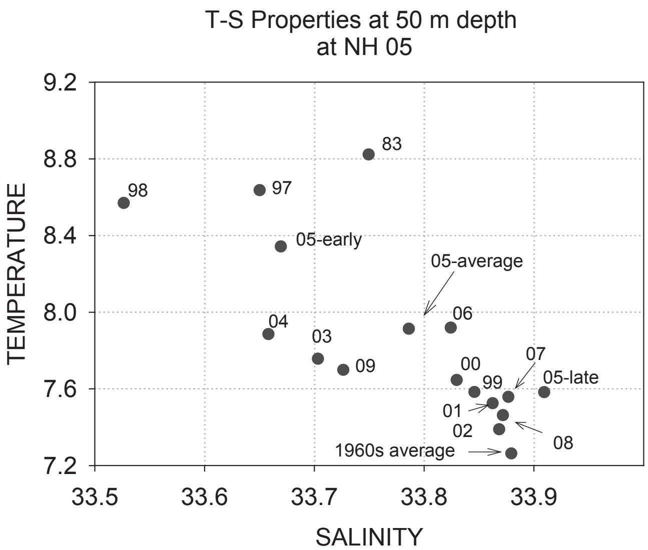

Figure 20. T-S characteristics at a depth of 50 m at a mid-shelf station (NH-05) off Newport OR, averaged over cruises in May through September.

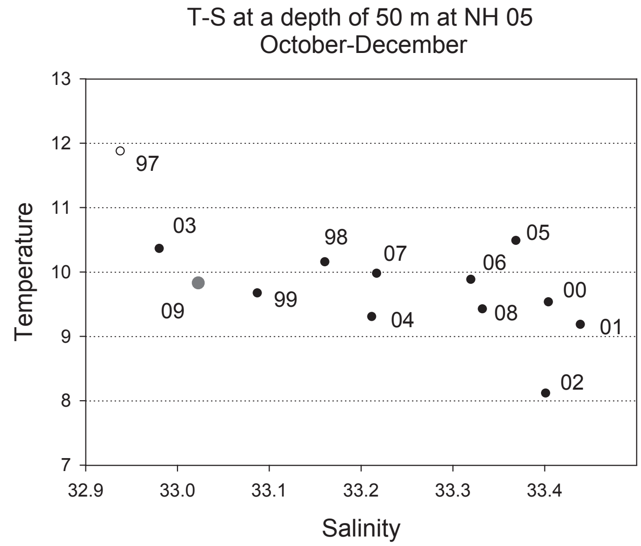

Figure 21. T-S characteristics at a depth of 50 m at a mid-shelf station (NH-05) off Newport OR, averaged over cruises in October through December of the year indicated. Autumn 2009 was characterized by the presence of relatively cool but fresh water, although temperature was similar to that observed in most other years.

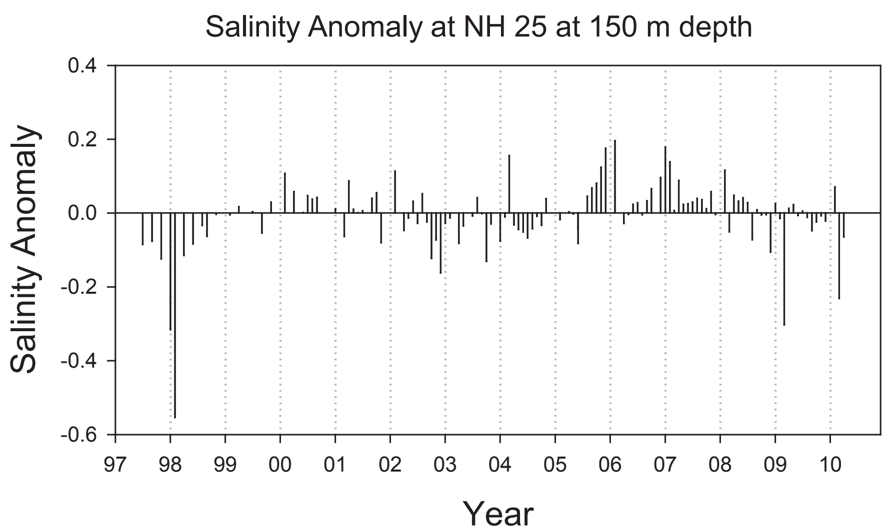

Figure 22. Time series of salinity anomalies at a depth of 150 m at a slope station, NH 25, 25 miles from shore in 300 m of water.

Comparison of copepod assemblages off northern California and Oregon. Copepod assemblages observed at mid-shelf stations off northern California[19] and Oregon continued to show marked seasonal variation, with high abundances developing over the summer and into the fall and subsequently declining over the winter (fig. 24). Total abundance of copepods over the shelf appears to have been lower or later in developing in summer 2009 than in 2008 in sampled areas of the northern CCS.

Patterns in assemblage structure, as indicated by the abundance of species particular biogeographic affinities (e.g., southern (warm) v. northern (cold), neritic v. oceanic; Hooff and Peterson 2006), show a substantial degree of coherence since 2008, particularly at stations north of Cape Mendocino. Compared to winter 2009, the composition of copepod assemblages off Oregon and northern California shifted strongly towards being dominated by southern and oceanic species by winter 2010 (fig. 23). Southern taxa were abundant off Bodega in late 2008, coincident with warm temperatures, but largely disappeared from mid-shelf waters in early 2009, possibly as a consequence of intense transport

[19]Zooplankton samples were collected along the Trinidad Head Line and Bodega Line following protocols as implemented on the Newport line. Prior to October 2008, samples off Trinidad Head were collected using a 0.25 m PairoVET net fitted with 202 μm mesh and a General Oceanics flowmeter.

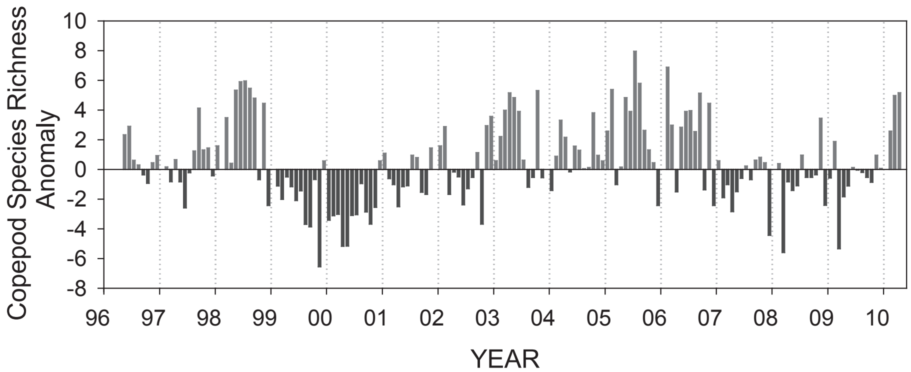

Figure 23. Monthly averaged copepod species richness anomalies at Station NH-5 off Newport, OR.

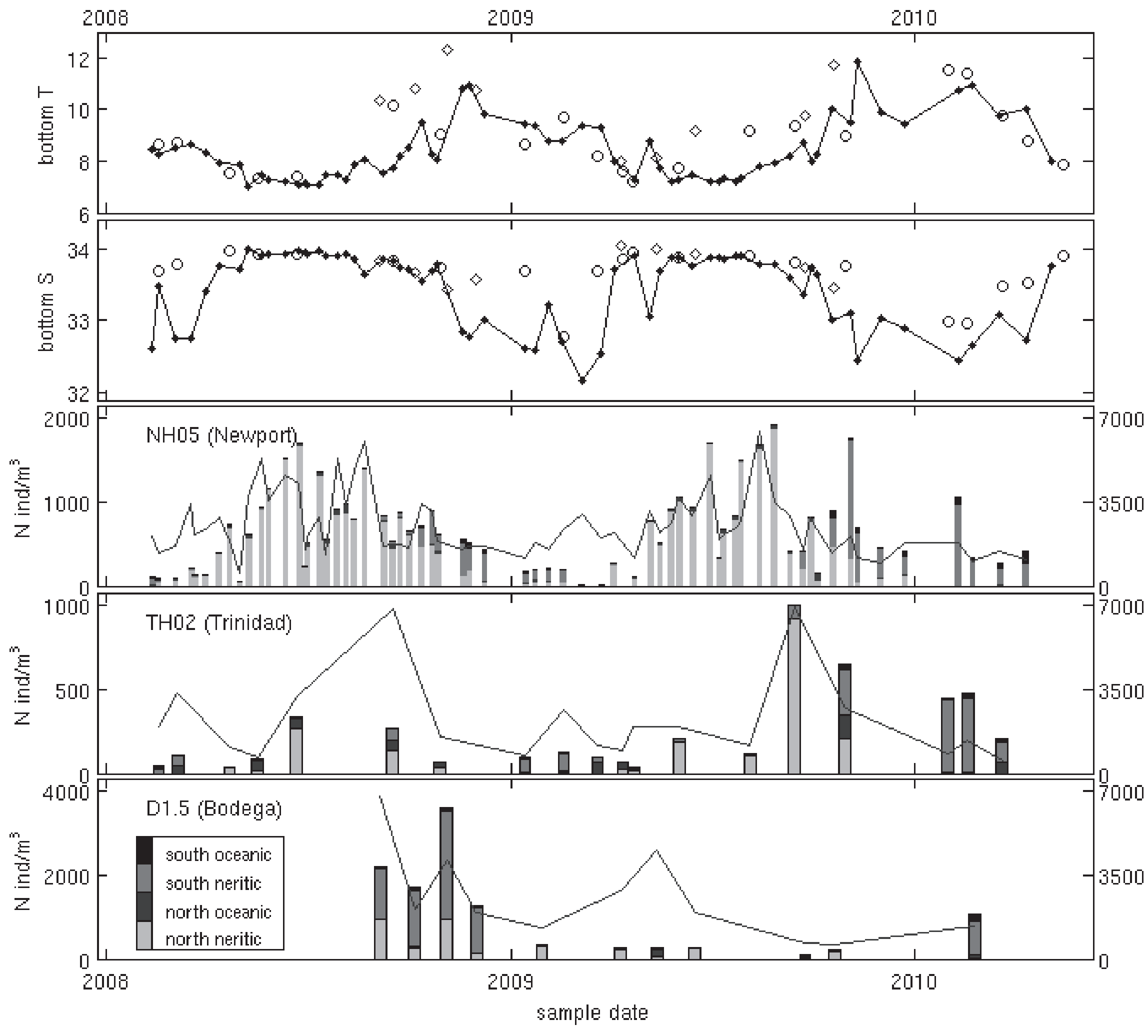

Figure 24. Top two panels: near-bottom temperature and salinity for stations NH05 (solid line with dots), TH02 (open circles), and D1.5 (open diamonds). Bottom three panels: copepod density in vertical ring-net samples collected at stations NH05 (Newport Line, 44.65°N, 124.18°W, 77 m), TH02 (Trinidad Head Line, 41.06°N, 124.27°W, 77 m) and D1.5 (Bodega Line, 38.29°N, 123.20°N, 83 m), respectively. Shaded bars (left hand y-axis) indicate density of selected species indiciative of assemblages identified in Hooff and Peterson (2006): northern neritic (*Calanus marshallae, Acartia longiremis, Acartia hudsonica, Centropages abdominalis*), northern oceanic (*Metridia pacifica, Microcalanus pusillus*), southern neritic (*Acartia tonsa, Ctenocalanus vanus, Paracalanus parvus, Corycaeus anglicus*), southern oceanic (*Acartia danae, Calanus pacificus, Clausocalanus spp, Eucalanus californicus*). Lines (right hand y-axis) indicate total copepod density.

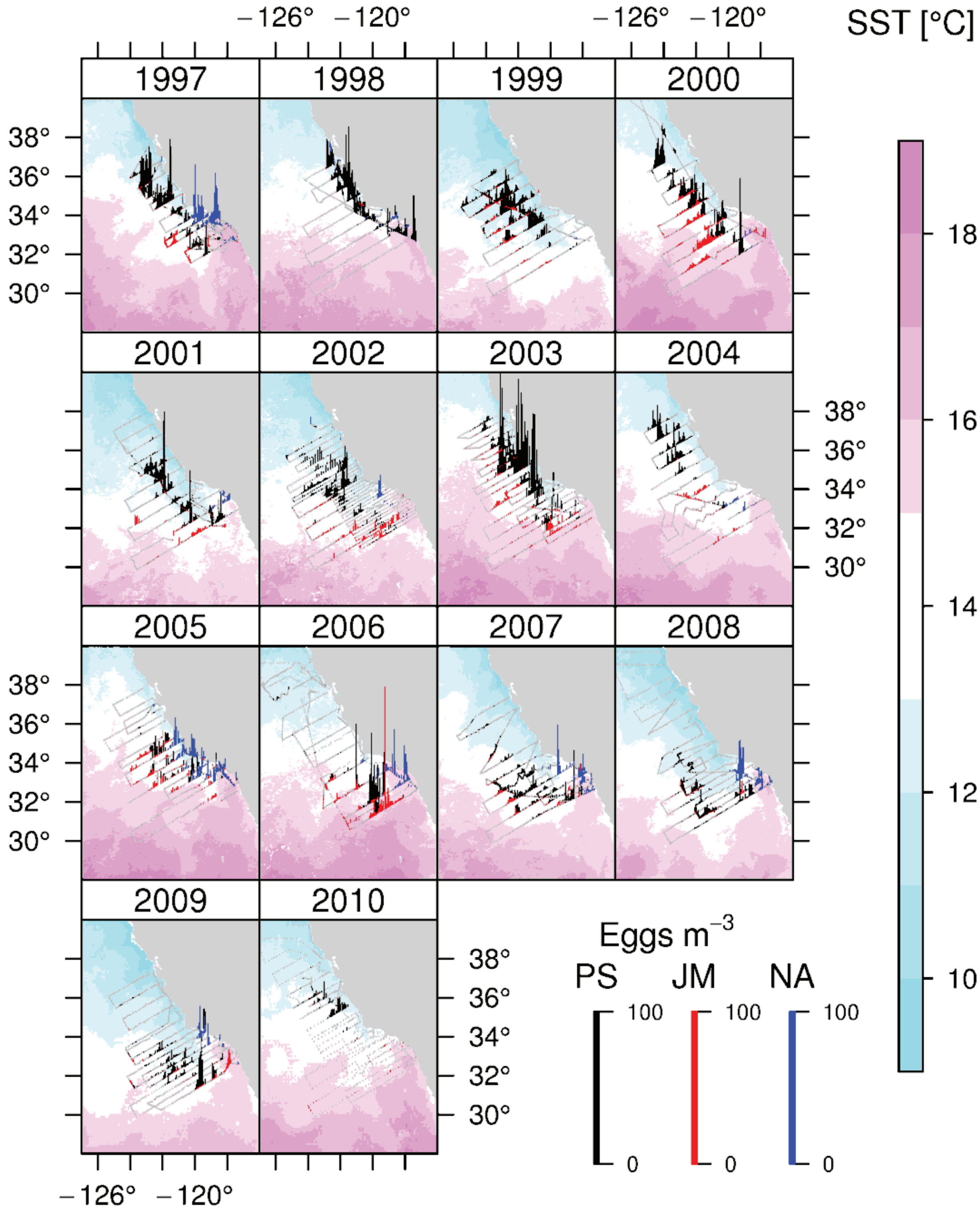

Figure 25. Density of eggs from Pacific sardine, northern anchovy and jack mackerel collected with CUFES (all on the same scale) overlaid on satellite SST derived from a monthly composite of April AVHRR Pathfinder imagery (1997–2008) and a blended SST product (2009–2010). PS = Pacific sardine (*Sardinops sagax*), JM = jack mackerel (*Trachurus symmetricus*), and NA = northern anchovy (*Engraulis mordax*).

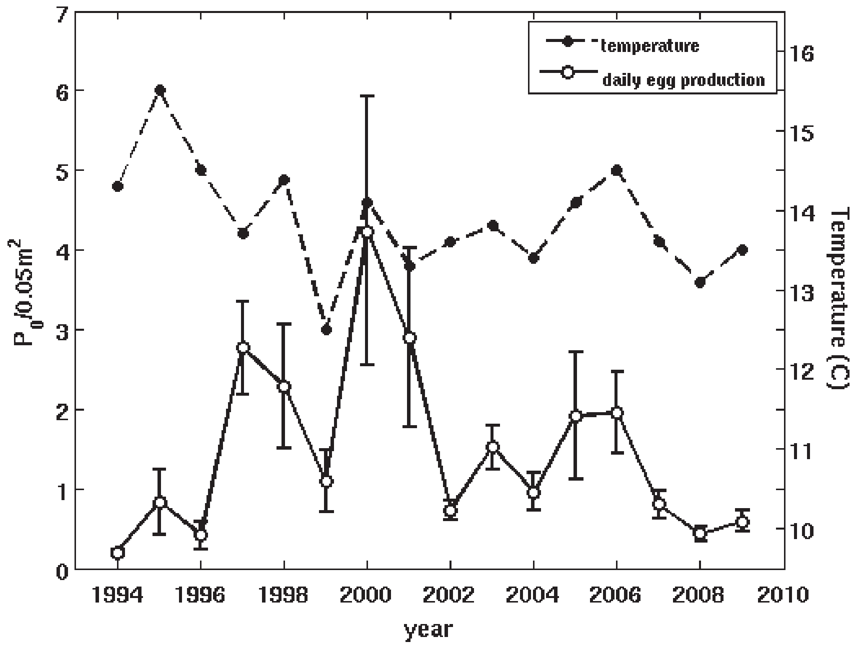

Figure 26. Daily egg production/0.05m^2 of Pacific sardine (open circles, solid line; error bars indicate +– 1 SE) and average SST (°C) (closed circles, dashed line) during March–April DEPM-CalCOFI cruises from 1994–2009.

(fig. 9). Although warm water and reduced flows were observed in summer 2009 off Bodega, total copepod abundance did not reach high abundances and southern taxa did not assume a dominant place in the assemblage until winter 2010.

ECOSYSTEM SURVEYS & HIGHER TROPHIC LEVELS

Small Pelagic Fish Spawning

The spatial distribution of sardine (*Sardinops sagax*) eggs with respect to sea surface temperature varies substantially from year to year in the CCS (fig. 25)[20]. In 2009, the concentration of sardine eggs off southern California indicated that the spawning ground was similar to 2006–2008 when the distribution of sardine spawning was almost entirely restricted to latitudes south of Point Conception (Lo et al. 2007a, 2007b, 2008; McClatchie et al. 2009). By contrast, in 2010 the distribution of sardine spawning was similar to 2004, being well north of Point Conception. The early part of the time series shows sardine spawning at latitudes from San Diego to San Francisco. Northerly extension of sardine spawning out of the Southern California Bight to along the central California coast does not appear to be consistently related to variation in temperature. Qualitative examination of sardine egg distributions suggests that 5 of 8 anomalously warm years (1998, 2000, 2003, 2004 and 2010) showed northern extension of sardine spawning; the remaining 3 years (1997, 2005, 2006) were ambiguous or contradicted the expected pattern (fig. 25).

Spawning grounds of northern anchovy (*Engraulis mordax*) and jack mackerel (*Trachurus symmetricus*) also exhibit substantial variation over time as indicated by the spatial distribution of their eggs (fig. 25). In spring 2009, anchovy eggs appeared to be concentrated in the Southern California Bight, and in spring 2010, anchovy eggs were nearly absent from the study region (fig. 25). These patterns contrast sharply with the broader extent of anchovy spawning grounds observed in 2005–2008 (fig. 25). In spring 2009, jack mackerel eggs were broadly distributed throughout the southwestern area of the survey at low densities, showed an unusual degree of overlap with the distribution of sardine eggs, and occurred in high densities inshore of the sardine spawning grounds in the southern portion of the survey region (fig. 25). The latter pattern was also observed in 2000, and substantial overlap between sardine and jack mackerel spawning also occurred in 2005,

[20]During spring cruises from 1997–2010 fish eggs were collected from 3 m depth with the Continuous Underway Fish Egg Sampler (CUFES), manually identified and counted, and converted to densities (eggs m^{-3}). Temperature anomalies were calculated from monthly composites of April SST for each year using AVHRR Pathfinder v5 (4.4km resolution) for the years 1997–2008, and a blended SST product (0.1° resolution) for 2009 and 2010. The imagery were gridded to the same resolution (Weber and McClatchie 2009), and an SST anomaly at each pixel location was calculated by subtracting the monthly mean of all years at each location from the monthly mean for each year at that location. We overlaid densities of sardine, anchovy and jack mackerel eggs on both the SST and the SST anomalies.

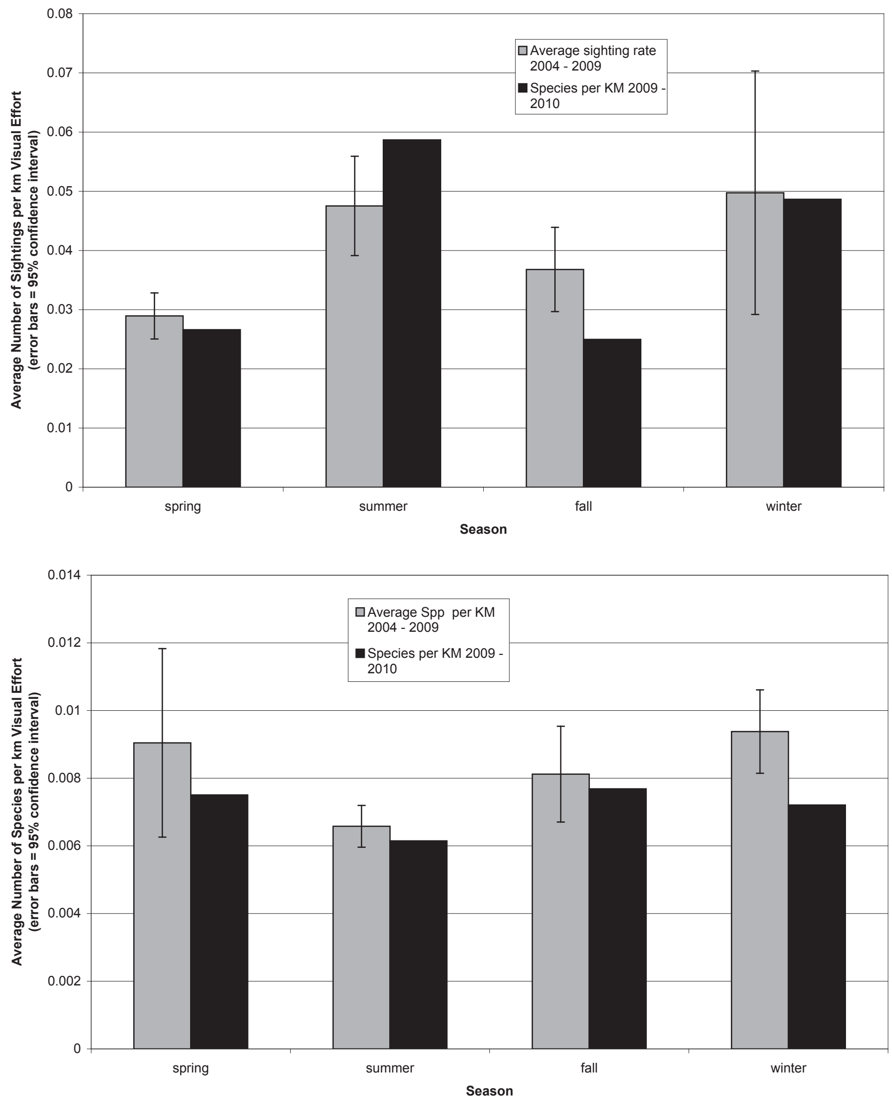

Figure 27. Comparison of the average sighting rates (top panel) and average species richness (bottom panel) for July 2004–January 2009 (grey) and for Spring 2009–Winter 2010 (black). Error bars indicate 95% confidence interval.

2007, and 2008. Jack mackerel eggs occurred only south of Point Conception in 2010.

These patterns need to be quantified for all three species, but pose possible challenges to three commonly held views. Specifically, these data suggest that sardine spawning does not necessarily shift northwards in warmer years, that anchovy spawning is not always associated with coastal upwelling areas, and that jack mackerel do not always spawn further offshore than sardine.

Based on analysis of data and samples from the 2009 survey, estimated daily egg production rates suggest a slight increase in 2009[21], coincident with overall warmer temperatures than the preceding year (fig. 26). The relationship between sea surface temperature and changes in estimated daily egg production rates remained consistent over the period 1994 to 2009, with the exception of 1997 and 2002. Given that the spawning biomass of Pacific sardine is positively related to the daily egg production, in particular if the number of oocytes per biomass weight remains constant (Lo et al. 2009), estimated daily egg production rates suggest that spawning biomass of Pacific sardines is presently at relative low levels compared to recent historical estimates (fig. 26). The extent of spawning south of San Diego depends on the local environmental conditions (Baumgartner et al. 2008) and will not be known until

[21]In 2009, the spring CalCOFI cruise was conducted from March 7–22, 2009, and so estimates of daily egg production of Pacific sardines were estimated using only data from the April 15–May 9 2009 sardine biomass survey. Sardine eggs were collected aboard the chartered fishing vessel F/V *Frosti* using CalVET, CUFES, and Bongo nets during the April 15–May 9 2009 sardine biomass survey. The survey was conducted south of San Francisco down to San Diego (CalCOFI lines 63.3 to 95.0) and extended offshore to CalCOFI station 90 and 100 in the areas north and south of Point Conception, respectively (fig. 1).

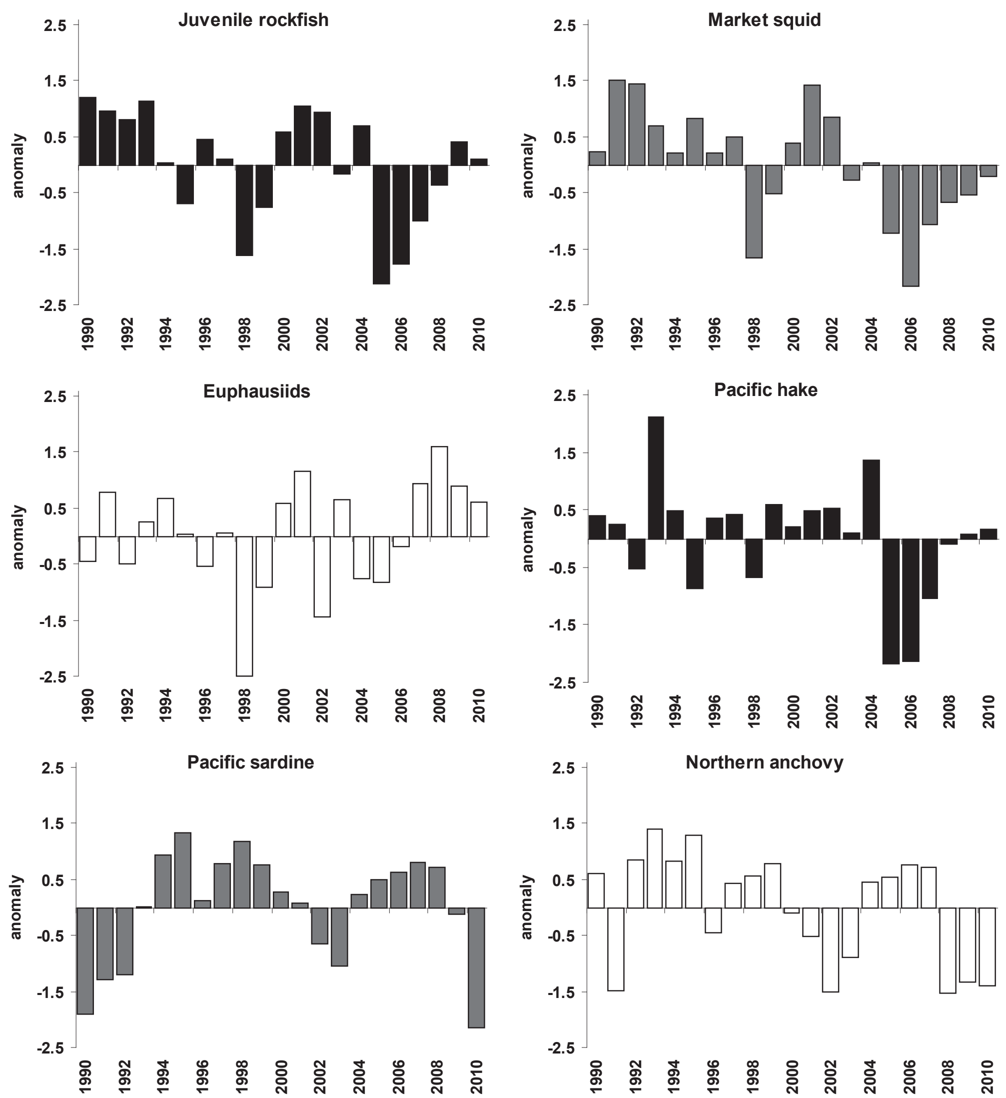

Figure 28. Long-term standardized anomalies of several of the most frequently encountered pelagic forage species from the central California rockfish recruitment survey in the core region (1990–2010 period only).

information from Mexican surveys, i.e. IMECOCAL becomes available for recent years. To update previous reports, we note that analysis of CUFES samples collected during IMECOCAL survey 0804 suggests that little sardine spawning occurred in the IMECOCAL area in April 2008.

Southern California Cetaceans

Visual surveys[22] for cetaceans on quarterly CalCOFI cruises did not detect changes in the cetacean assemblage off southern California. Species richness (average number of species per km of effort) of cetaceans observed on all four cruises for 2009–2010 was similar to richness in all previous years (not shown); however, species richness observed during the winter 2010 cruise was lower than in previous winters despite a relatively high sighting rate (fig. 27). For most species, 2009–2010 was not unusual. Relative to other cetaceans, Dall's porpoise (*Phocoenoides dalli*), which is generally restricted to cold/temperate waters, were abundant in the spring 2009 and winter 2010 cruises. During the summer cruise we observed remarkably high numbers of blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whales, and common (*Delphinus* spp.), striped (*Stenella coeruleoalba*) and bottlenose (*Tursiops truncatus*) dolphins. Northern right whale dolphins (*Lissodelphis borealis*), gray whales (*Eschrichtius robustus*) and sperm

[22]Marine mammal surveys have been carried out as part of quarterly Southern California CalCOFI cruises since 2004. Methods are standard across years: two trained marine mammal observers use binoculars (7X and 18–25X) and the naked eye to scan the area forward of the ship's beam for marine mammals during daylight hours while the ship is underway (~10 km). Opportunistic sighting data are also recorded.

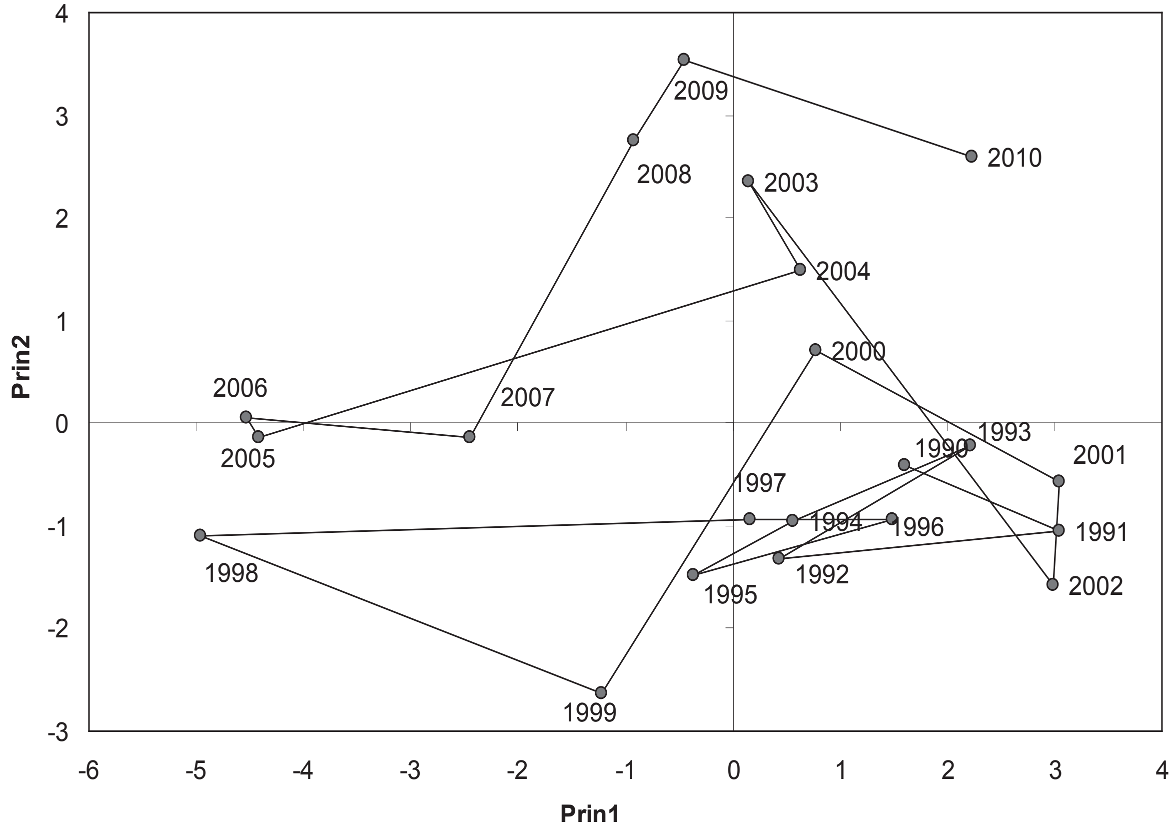

Figure 29. Phase plot of first two principal component scores for the fifteen most frequently encountered species groups captured between 1990 and 2010 in the core area of the Fisheries Ecology Division Midwater Trawl Survey off central California.

whales (*Physeter macrocephalus*) were unusually abundant during the winter 2010 cruise.

Central California Pelagic Ecosystem

Analysis of catch composition and abundance of key taxa from annual mid-water trawl surveys off central California[23] indicated that trends in 2009 and 2010 were of increasing abundance for the species and assemblages that tend to do better with cool, productive conditions, including juvenile rockfish, juvenile Pacific hake, market squid and krill (fig. 28). However, while the trend in relative abundance for rockfish and squid has been increasing since record low values in the 2005–2006 period, this increase has been only to levels close to the long term mean, and has not continued into 2010 for all taxa (fig. 28). Of the taxa favored by cool conditions, only krill appear to have recovered strongly, with very high catches in recent years. By contrast, the coastal pelagic forage species (adult life history stages of northern anchovy and Pacific sardine) typically observed in greater numbers during warmer, less productive periods were at low levels in 2009 and 2010, either as a result of lower abundance, a more offshore or southerly distribution, or both (fig. 28).

Trends observed in these six indicators are consistent with trends across a number of other taxa within this region. Results from a Principal Components Analysis of annual catch data[24] highlight changes in the midwater assemblage over time: the clupeoid-mesopelagic group was prominent during the 1998 El Niño and during the anomalously warm years 2005–2007, while the groundfish group prospered during the early 1990s, the cool-phase between 1999 and 2003, and most recently from 2009 through 2010 (fig. 29). As with the 2009 data, results from 2010 continue to represent a return towards

[23]Observations reported here are based on midwater trawl surveys conducted off central California (a region running from just south of Monterey Bay to just north of Point Reyes, CA, and about 60 km offshore) since 1990 (see Sakuma et al. 2006 for methods and details on spatial extent of survey). Most cruises have been conducted on the NOAA ship *David Starr Jordan* (1990–2008), the NOAA Ship *Miller Freeman* (2009) and the 2010 cruise took place on the F/V *Frosti* (2010). Data for the 2010 survey presented here are preliminary, and neither 2009 nor 2010 data account for potential vessel-related differences in catchability. Data are reported as standardized anomalies from the log of mean catch rates. Most taxa reported are considered to be well sampled, but the survey was not designed to accurately sample krill.

[24]Principal Components Analysis (PCA) was applied to the covariance among fifteen of the most frequently encountered species and species groups, yielding strong loadings for various young-of-the-year groundfish taxa (rockfish, Pacific hake, rex sole and sanddabs), cephalopods, and euphausiids, with slightly weaker (and inverse) loadings for Pacific sardine, northern anchovy, and several species of mesopelagic fishes. The first and second components explain 39% and 14% of the variance in the data respectively.

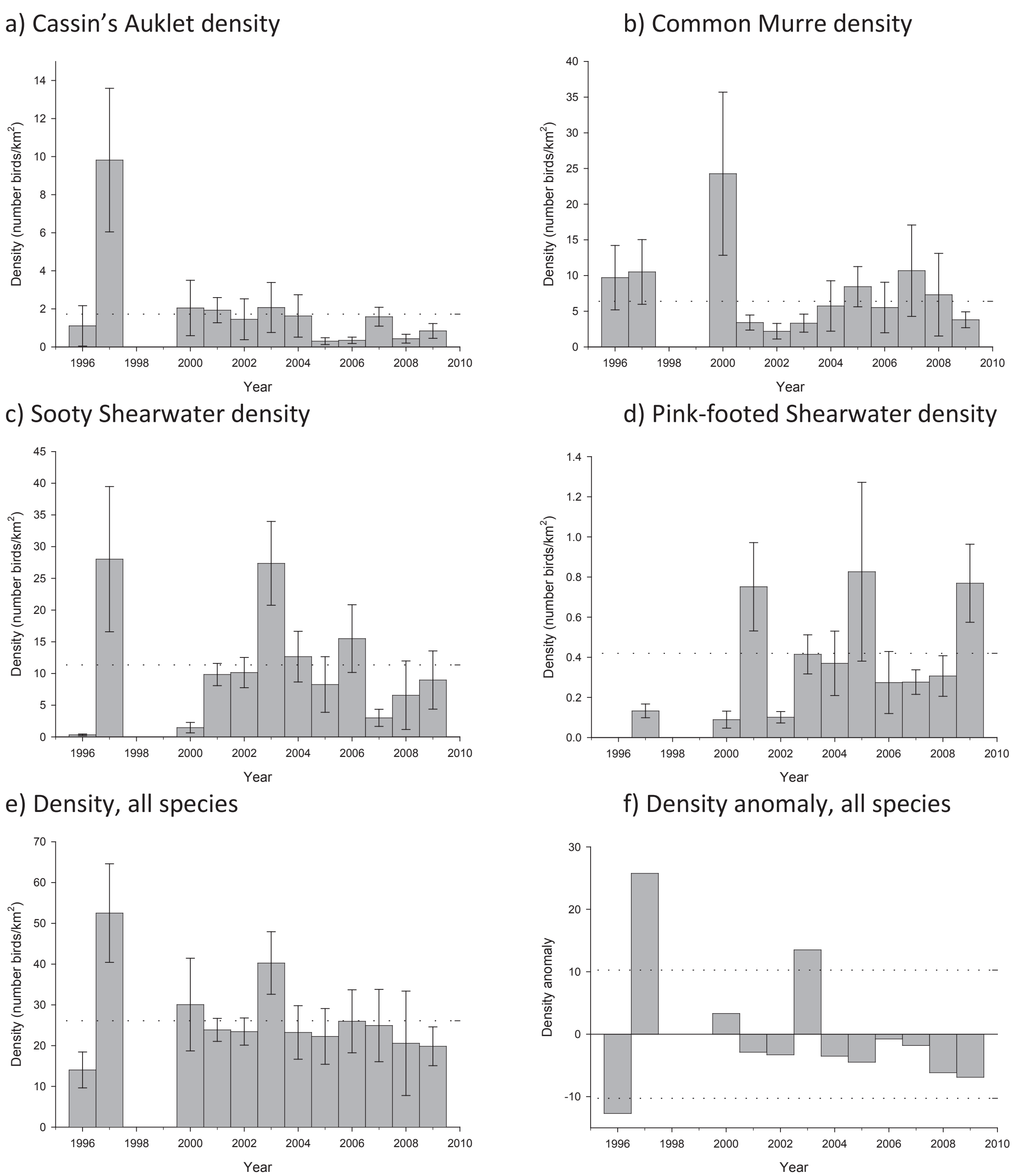

Figure 30. Variation in density of seabirds in the greater Gulf of the Farallones region (Pt. Sur to Pt. Arena), May–June, 1996–2009. Annual mean at-sea density (birds km^{-2} day^{-1}) of (a) Cassin's auklet, (bb) common murre, (c) sooty shearwater, (d) pink-footed shearwater and (e) combined avifauna, and (f) anomaly for combined avifauna of 'all species' (a), and anomaly in annual mean at-sea density (birds m^{-2} day^{-1}) of all species (b), CAAU (c), COMU (d), SOSH (e), and PFSH (f) are illustrated. Dashed lines in (a–f) show the long-term average density for each species and the overall seabird community.

conditions similar to the 1999 to 2003 period for many groups, while others are at moderate levels that approximate long term mean conditions.

Seabirds Off North-Central California

Analysis of at-sea counts of seabirds off central California[25] indicated significantly greater densities of pink-footed shearwater (*Puffinus creatopus*) in 2009 than in the previous three years (fig. 30). Pink-footed shearwater tend to be associated with warmer water, which suggests that this increase may be associated with warming of surface waters observed in summer 2009. Trends in at-sea counts of other seabirds (fig. 30) corroborate observations made at breeding colonies on the Farallon

[25]In conjunction the NOAA NMFS mid-water trawl survey, seabirds are are identified and enumerated as they enter a 300-m arc from the bow to 90° amidships while the vessel is underway at speeds >5 k per standard techniques (Tasker et al. 1984). Here, we report on seabird counts made in May and June of 1996–1997 and 2000–2009 for a "core" area between Point Sur (36° 18'N, 121° 53'W) and Point Arena (38° 57'N, 123° 44'W). Seabird counts are expressed as a density function per day (birds km^{-2} day^{-1}) and each day is considered the sampling unit.

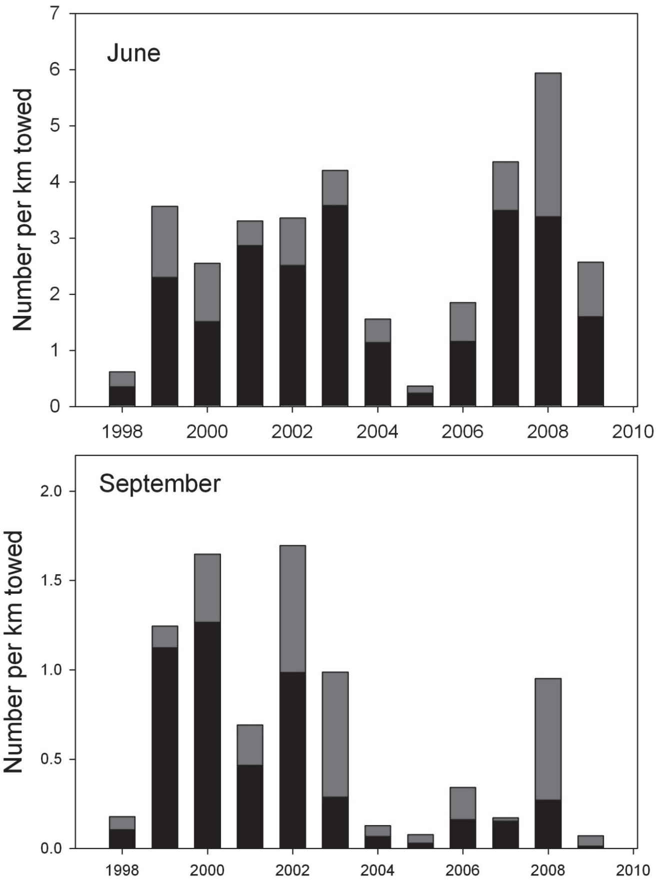

Figure 31. Average catches per unit effort of juvenile salmon partitioned among coho salmon (*Oncorhynchus kisutch* in black) and Chinook (*O. tshawytscha* in red) during June (upper panel) and September (lower panel) trawl surveys off the coast of Washington and Oregon from 1998 to 2009.

Islands (e.g., for murres and auklets; Warzybok and Bradley 2009), and support conclusions that abundance of sooty shearwaters has declined as has been observed for many years off southern California (Hyrenbach and Veit 2003; Sydeman et al. 2009) and more recently in central-northern California (Ainley and Hyrenbach 2010).

Breeding success of seabirds roosting on the Farallon Islands was mixed across species, with some species showing average to above average productivity while others showing diminished productivity and even complete failure in breeding (Warzybok and Bradley 2009). The breeding success of common murre (*Uria aalgae*) and Brandt's cormorant (*Phalacrocorax pennicillatus*) was essentially zero for 2009 (Warzybok and Bradley 2009). Interestingly, Brandt's cormorant breeding success was also near zero in 2008, a year of strong upwelling and cold SST (Warzybok and Bradley 2009). In both of these years, the abundance of northern anchovy (*Engraulis mordax*) was greatly reduced (fig. 28), which may have contributed to the cormorants' poor productivity. Thus, the decline in breeding success of Brandt's cormorant in 2009 may not have been related to the impending ENSO event, but rather factors that began to impact the birds in a previous year or during a time of the year well before any manifestation of El Niño was apparent off central California. In contrast, breeding success of Cassin's auklets (*Ptychoramphus aleuticus*) in 2009 was well above average (Warzybok and Bradley 2009). Hydroacoustic surveys in the greater Gulf of the Farallones indicated relatively high abundances of krill in the region (data not shown, but see fig. 28), which may have contributed to auklet breeding success.

Juvenile Salmon and Other Pelagic Fishes Off Oregon and Washington

Catches of juvenile salmonids in pelagic surface trawl surveys[26] were unusually low during September 2009. The fewest juvenile coho salmon (*Oncorhynchus kisutch*; 2 compared to maximum catch of 158 in 1999) and subyearling Chinook salmon (*O. tschawytschwa*; 2 versus 465 in 2001) were caught since the beginning of the time series in 1998 (fig. 31). Overall spring 2009 appeared to be relatively good for salmon marine survival but oceanographic conditions appear to have deteriorated for salmon by late summer 2009.

In 2009, annual average forage fish densities[27] off the Columbia River and Willapa Bay were the highest since 2005 (fig. 32). Northern anchovy (*Engraulis mordax*) and whitebait smelt (*Allosmerus elongates*) densities were the highest since 2004 which indicates successful recruitment in 2008. Pacific sardine (*Sardinops sagax*) and Pacific herring (*Clupea pallasi*) also made up a substantial portion of the catch. Overall forage fish densities were higher in 2009 than observed in 1998, 1999, 2006, 2007, and 2008 but still much lower from their very high abundance years 2000–2005.

In contrast, annual average predatory fish densities in 2009 were the lowest observed during the 12 year study period, in part because the abundant juvenile (yearling) Pacific hake (*Merluccius productus*) were too young to be counted as piscivores (fig. 32). Adult Pacific hake and jack mackerel (*Trachurus symmetricus*) were the two most abundant predatory fish taxa captured and were most abundant in July and August, respectively. Humboldt squid (*Dosidicus gigas*) were also present in appreciable numbers off northern Oregon/southern Washington during summer 2009 (see next page).

Humboldt Squid

Prior to the 1997–1998 El Niño, Humboldt squid was an infrequent visitor to the U.S. waters of the Cali-

[26]For information on methods and sampling locations see http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm.

[27]These results are based on ongoing bi-monthly surface trawls conducted from May to August off the Columbia River and Willapa Bay. As part of a broader sampling program, nektonic fishes are sampled using a Nordic 264 rope trawl (Net Systems, Bainbridge Island, WA) fished at the surface directly astern.

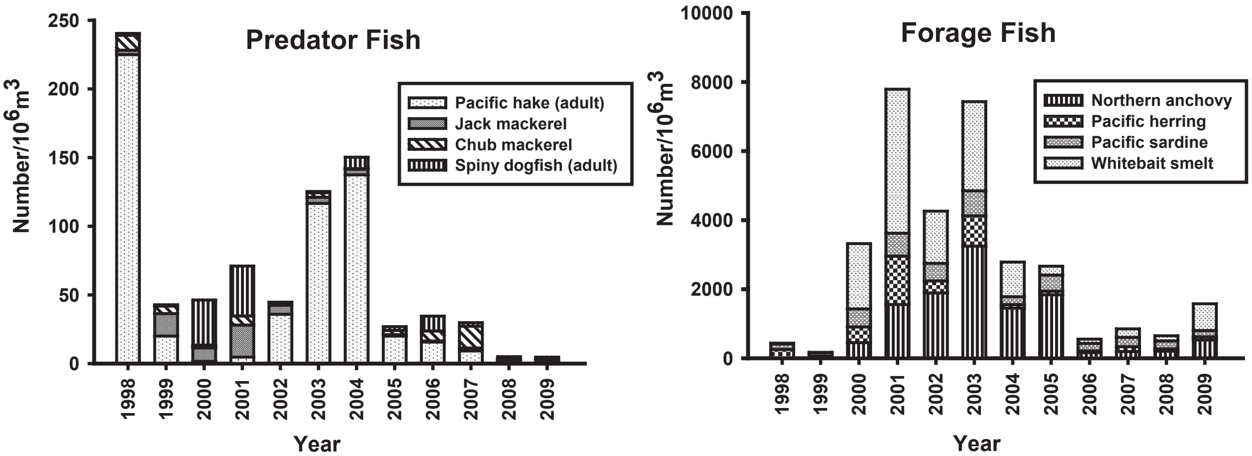

Figure 32. Annual average densities of predatory fishes (left panel) and forage fishes (right panel) captured off the Columbia River/Willapa Bay by bi-monthly surface trawling between May and September.

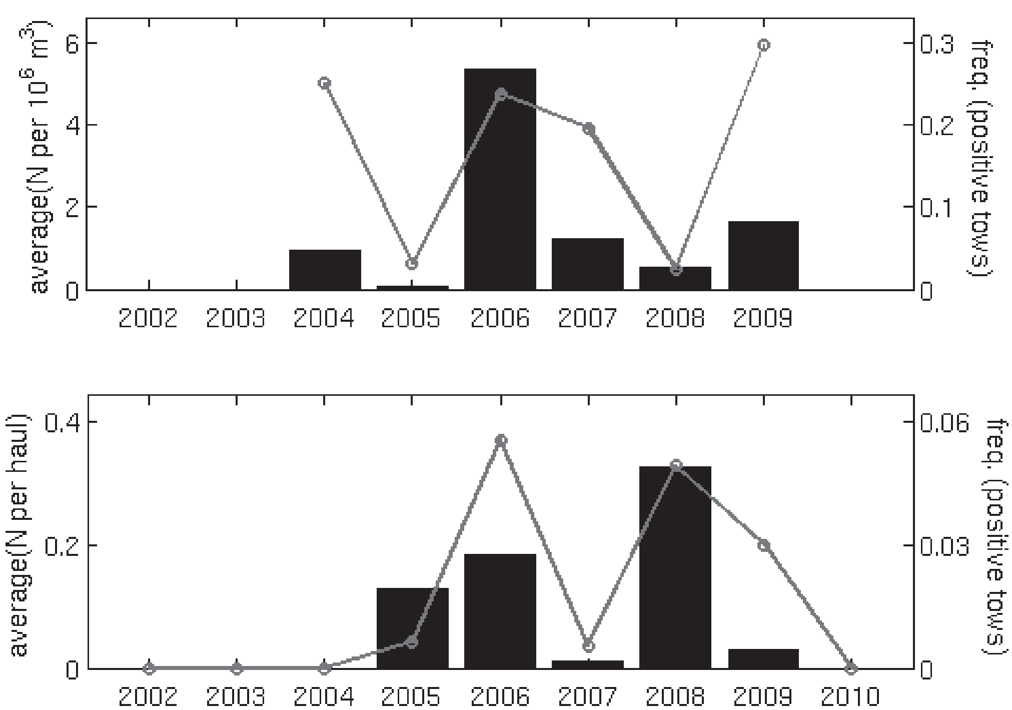

Figure 33. Indices of abundance for Humboldt squid (*Dosidicus gigas*) captured during surface trawl surveys in summer-fall surveys off Oregon and Washington (upper panel) and in mid-water trawl surveys during late spring-early summer off central California (lower panel). Bars indicate average density of squid. Lines indicate percent tows that captured at least one squid.

fornia Current System (CCS), yet since 2003 these animals have been regularly encountered in large numbers throughout the CCS in both the U.S. and Canada, and as far north as Southeast Alaska (Wing 2006; Zeidberg and Robison 2007; Field et al. 2007; fig. 33). The spatial and temporal extent of the present range of Humboldt squid is unprecedented in the historical record and may be related to an apparent expansion of the oxygen minimum zone (OMZ) throughout the CCS and elsewhere in the Northeast Pacific (Bograd et al. 2008).

Available data suggest that the movements and distribution of Humboldt squid in 2009 were consistent with general trends observed since 2003. Squid were encountered in both trawl and ROV surveys off of central California in modest numbers in spring and early summer 2009. Few squid were observed in the Pacific Northwest through the summer, however unusually large numbers of squid were observed in this region beginning in August 2009 in both commercial and recreational fisheries, various resource surveys and beach strandings. Strandings continued through the fall and winter of 2009. From November through December of 2009, squid were again abundant off of northern and central California, and in late December 2009 squid were again present off of San Diego (southern California), consistent with the proposed general southward migration during winter. By contrast, from spring through early summer (July) of 2010, Humboldt squid have been virtually absent from surveys and fisheries throughout the California Current, suggesting that cool conditions may be having an effect on squid abundance or distribution.

DISCUSSION

Changes in the state of the California Current System (CCS) since spring 2009 reflected a transition from cool La Niña conditions into and through a short-lived El Niño event. Responses to this climate sequence exhibited some consistent patterns across the CCS, but regional differences noted in recent State of the California Current reports appear to have persisted along the west coast of North America (cf. Goericke et al. 2007; McClatchie et al. 2009).

The transition from La Niña conditions appears to have unfolded well in advance of the arrival of direct effects of El Niño in the CCS in late 2009. Cool conditions related to the 2007–2008 La Niña abated in summer 2009, and, in general terms, hydrographic and ecological conditions from southern California north approached climatological values during summer 2009. Warmer than usual conditions had already developed off Baja California in 2008 and persisted into the current year, but showed similar directional responses to climate variability as did regions to the north. Overall, changes in the state of the CCS during 2009 coincide with the decay of La Niña conditions in the tropical Pacific.

In the context of the general pattern of transition from La Niña to El Niño, differences between the northern and southern regions of the CCS are readily apparent. Off southern California, the general trend was for mean hydrographic, chemical, and biological properties of the system to return to long-term average conditions during summer 2009. In contrast, the northern CCS, especially the region north of Point Arena, experienced anomalous warming of coastal waters and associated ecosystem responses, presumably as a consequence of anomalously weak and intermittent upwelling during 2009.

Likewise, regional differences and similarities are apparent from late fall 2009 through spring 2010, the period during which El Niño conditions propagated into the CCS and subsequently diminished. Off southern California, the arrival of El Niño was clearly indicated by anomalously high sea level, but responses to El Niño were limited to changes in isopyncnal depth—presumably related to the passage of poleward-propagating Kelvin waves and their lingering consequences. Coastal waters off Oregon and northern California were affected by unusually strong downwelling during winter 2009–2010. In neither case, however, was there any evidence for intrusion of unusual water masses such as had been observed during the strong 1997–1998 El Niño. Relatively strong positive anomalies in temperature and salinity off southern Baja California suggest that the 2009–2010 El Niño influenced the southern extent of the CCS, but these changes appear to have been a consequence of local circulation patterns rather than anomalous poleward flows.

Ecosystem observations offer further suggestion of regional variation in responses to El Niño, but it must be noted that such comparisons are limited by disparity in available data sets. Off southern California, estimates of nutrient concentrations, chl a standing stock, primary productivity, and zooplankton displacement volumes returned to "normal" levels, and did not show evidence for any decline associated with El Niño. In contrast, anomalies in chl a concentration shifted from positive to negative off Baja California, especially north of Point Eugenia, despite the lack of concomitantly strong changes in hydrographic conditions.

Responses at higher trophic levels are much more difficult to connect to simple indices of climate variability, but provide insight to the potential magnitude of ecosystem responses to conditions leading into spring 2009 and the consequences of the 2009–2010 El Niño relative to previous El Niños. Positive shifts in indices of abundance for the juvenile groundfish assemblage off central California and breeding success of Cassin's Auklet in 2009 are consistent with the persistence of cool conditions into spring 2009. Interestingly, the pelagic juvenile groundfish assemblage did not appear to collapse in 2010, suggesting that El Niño conditions did not substantially diminish productivity available to these taxa during critical life history stages during winter and early spring. In contrast, juvenile salmonids at sea in the northern region of the CCS appear to have fared poorly during the warmer than usual conditions of summer and fall 2009. Changes in the copepod assemblage off Oregon were consistent with warmer conditions that do not favor salmon production (Peterson and Schwing 2003; Peterson et al. 2010). Warmer conditions were also reflected in shifts in the marine avifauna off central California (i.e., elevated abundances of Pink-Footed Shearwaters, a species with warm-water affinities) and a northerly distribution of sardine spawning, although the latter observation may not represent a consistent response to temperature variability in the CCS. Humboldt squid (*Docidicus gigas*) continue to be seasonally common throughout the CCS, although it is not clear whether this pattern will persist into 2010.

In summary, the significant changes in the state of the CCS during 2009 and early 2010 appear to have been more closely associated with diminishment of La Niña conditions than direct effects of El Niño. The signature of the 2009–2010 El Niño throughout much of the CCS was substantially weaker than that of the strong 1997–1998 El Niño when influxes of more tropical waters were observed throughout the CCS. While the 2009–2010 El Niño is perhaps most comparable to the mild 2002–2003 El Niño, direct comparisons between the two events are confounded by the interaction of the 2002–2003 El Niño with a coincident intrusion of subarctic water that affected much of the CCS (Venrick et al. 2003). Indeed, the more dramatic changes observed during 2009–2010 in the northern CCS might reflect responses to atmospheric forcing favoring coastal warming absent countervailing subarctic influences. At the time of writing, a transition to moderate La Niña conditions is forecast for summer 2010.[28] It therefore appears that the past year might represent a temporary interruption of an otherwise cool period in the California Current.

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[28]http://www.cpc.noaa.gov/products/analysis_monitoring/enso_advisory.

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