

## STATE OF THE CALIFORNIA CURRENT 2010–2011: REGIONALLY VARIABLE RESPONSES TO A STRONG (BUT FLEETING?) LA NIÑA

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### ABSTRACT

The state of the California Current system (CCS) since spring 2010 has evolved in response to the development of cooler La Niña following the dissipation of the relatively weak and short-lived El Niño event of 2009–2010. The 2009–2010 El Niño appears to have dissipated quite rapidly in early spring 2010, yet the transition to anomalously cool conditions followed somewhat later with the onset of anomalously strong upwelling throughout the CCS in summer 2010 and the development of unusually—in some cases record—cool conditions throughout the CCS. However, following the fairly consistent emergence of cooler La Niña conditions across the CCS going into summer 2010, regional contrasts were apparent. Off southern California, the effects of both the 2009–2010 El Niño and subsequent return to La Niña conditions appear to have had modest effects on the system, and the patterns that attract interest appear to be unfolding over longer time scales (e.g., freshening of upper water column and trends in nitrate and oxygen concentrations). In contrast, the

northern California Current has exhibited much more dramatic short-term changes over the past two years, due in part to greater variability in environmental forcing affecting this region. Ecosystem responses also varied across the CCS. The pelagic ecosystem off central and southern California showed evidence of enhanced productivity, in terms of rockfish recruitment, seabird abundance and reproductive success, etc., and the planktonic assemblage off Baja California indicated a resurgence of crustacean zooplankton following a period dominated by gelatinous zooplankton. Off northern California and Oregon, however, the return to La Niña conditions did not entirely reverse changes in the copepod assemblage arising during the 2009–2010 El Niño, which may have contributed to low at-sea survival of juvenile salmon. At the time of writing, tropical conditions are ENSO-neutral and forecast to remain so into fall 2011 and possibly into early 2012, yet the PDO remained strongly negative into summer 2011. It is uncertain whether the return to cool conditions observed in the past year will continue to govern the state of the California Current.

## INTRODUCTION

This report reviews oceanographic conditions and ecosystem responses in the California Current system (CCS) from spring 2010 through spring 2011. This review is based on observations collected and analyzed by a diverse range of government, academic, and private research programs and voluntarily contributed in response to an open solicitation for contributions. 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 Naval Postgraduate School (NPS), the Fisheries Ecology Division of NOAA's Northwest Fisheries Science Center (NWFS), PRBO Conservation Science, the Farallon Institute for Advanced Ecosystem Research, and the Coastal Ocean Currents Monitoring Program (COCMP) which includes several academic institutions along the coast (see Acknowledgements). Data continue to be collected along the Bodega Line and will be included in future reports.

As in previous reports in this series, the focus here is on reviewing recent observations in the context of historical patterns as a means of identifying changes in the state of the CCS ostensibly related to changing 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' Web sites (indicated below). 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 focuses on description and preliminary synthesis of available observations, and 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 at more or less regular intervals throughout the year (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, as part of seasonal sampling programs, in conjunction with ongoing large-scale surveys of the CCS, or aggregated from a suite of survey-based, fishery-based, and other sources. In reviewing these diverse data sets, it is important to remember that responses to climate forcing may be relatively rapid or may include substantial lags, particularly in variables that require time to accumulate the effects of changes in forcing or in variables that scale with species' life histories or phenology. Finally, in the Discussion, we summarize the evolution of the state of the CCS through the last year.

## 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; Bjorkstedt et al. 2010). 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

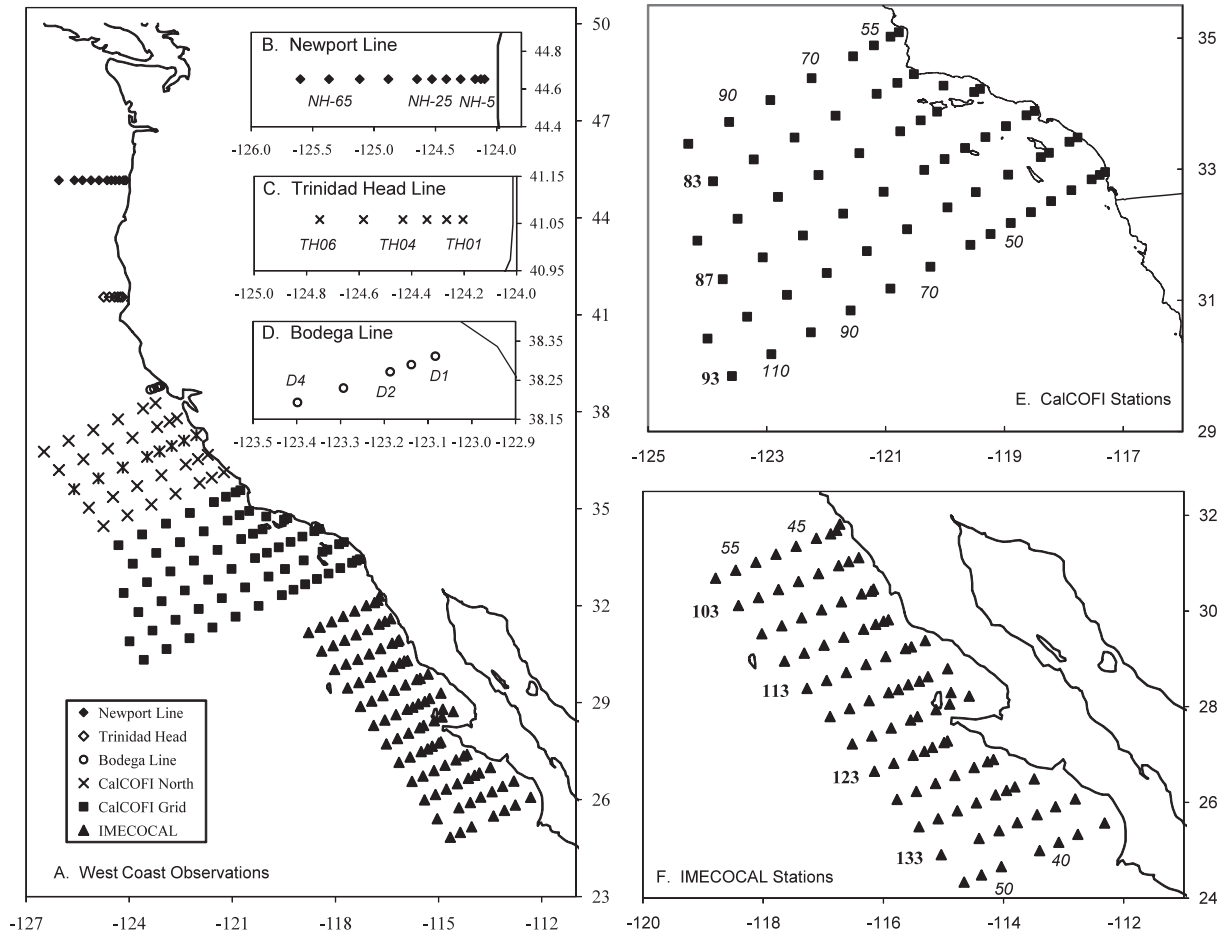


Figure 1. (Panel A) Location of stations for year-round ship-based observing programs that contributed data to this year's report. (Panel B–F) Exploded views of each region or line. Observational lines are labeled using bold numbers positioned west of the line terminus; stations are labeled using numbers in italics immediately below or above the respective stations. Line and station numbers for the IMECOCAL (panel F) and CalCOFI (panel E) programs follow the CalCOFI line and station nomenclature. The Newport Line (panel B) station names designate distance (nm) from shore. The 66 standard CalCOFI stations (black squares in A and E) 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 sampled biweekly out to St 25 and occasionally further offshore. The Trinidad Head Line (panel C) is occupied at monthly or shorter intervals. The Bodega Line (panel D) is occupied at quarterly or shorter intervals; data for the Bodega Line were not available for this year's report, but will be included in future reports.

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). The general pattern of substantial contrasts between the northern and southern regions of the CCS persisted into the short-lived, relatively weak El Niño event in late 2009 through early 2010 (Bjorkstedt et al. 2010). For example, whereas conditions off southern California returned to near climatological values with the decline of La Niña and did not indicate any substantial subsequent response to El Niño, the northern CCS warmed substantially following the decline of La Niña and was strongly affected by intense downwelling during winter 2009–10 (Bjorkstedt et al. 2010). Moreover, as the El Niño diminished rapidly in early 2010, 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 have been less robust in the northern CCS (Bjorkstedt et al. 2010).

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, 2008–09) and warmer states of positive PDO and positive SST anomalies (e.g., 2003–06) (fig. 2, and see below). This pattern appears to be continuing into spring 2011, with PDO declining to neutral values after recovering from the

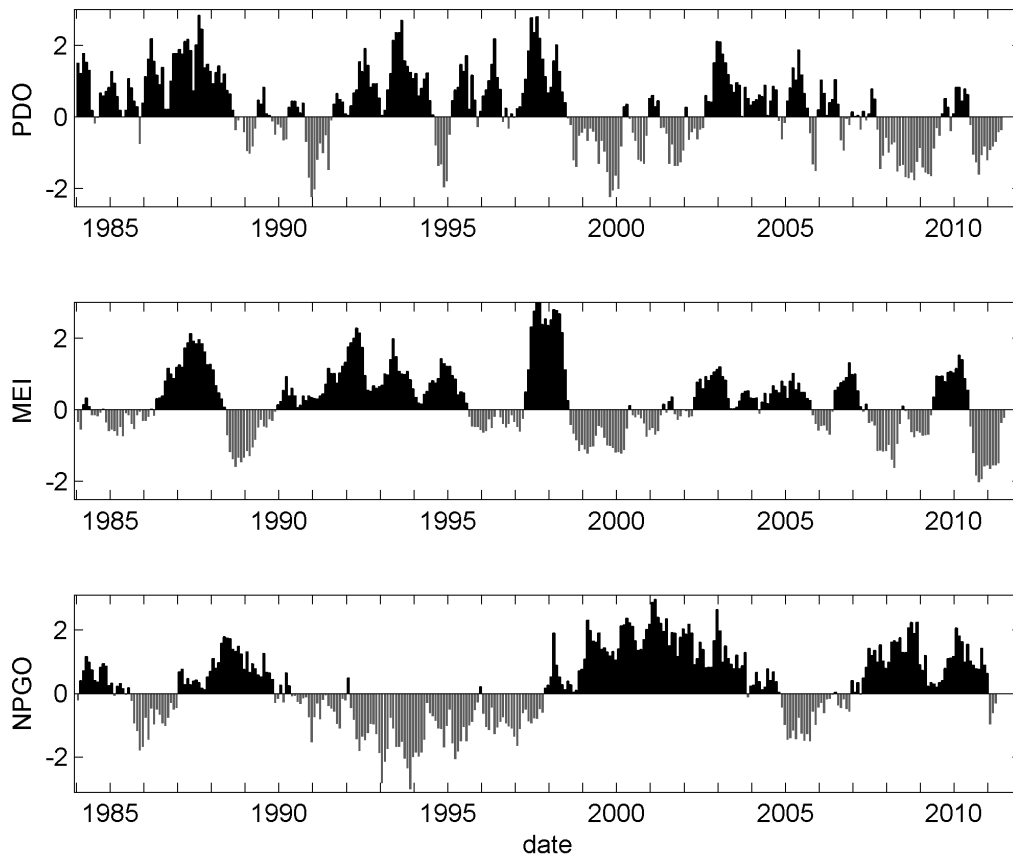


Figure 2. Time series of the Pacific Decadal Oscillation (PDO; top panel; data retrieved from <http://jisao.washington.edu/pdo/PDO.latest>), the Multivariate ENSO Index (MEI; middle panel; data downloaded from <http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/table.html>), and the North Pacific Gyre Oscillation (NPGO; bottom panel; downloaded from <http://www.o3d.org/npgo/data/NPGO.txt>) for January 1984–May 2011 (March 2011 for the NPGO).

effects of the 2009–2010 El Niño. Over this period, variability in PDO exhibits a high degree of coherence with the Multivariate El Niño Southern Oscillation Index (MEI; Wolter and Timlin 1998) (fig. 2). The MEI shifted dramatically from El Niño to La Niña conditions in early 2010 and remained in a strongly La Niña state until increasing rapidly towards neutral values in early 2011. 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), which is a measure of the strength of gyral circulation in the North Pacific, has been predominantly positive since the late 1990s indicating anomalously strong equatorward flow in the CCS (fig. 2); negative NPGO during 2005 and 2006 corresponds to the period of unusually low productivity observed through much of the CCS.

### NORTH PACIFIC CLIMATE PATTERNS<sup>1</sup>

In the extratropical Pacific, SST anomalies in summer 2010 were generally cool ( $-0.5$  to  $-1.0^{\circ}\text{C}$ ) around the North American coast and warm ( $>+0.5^{\circ}\text{C}$ ) in the

western and central North Pacific (fig. 3a), a pattern that has persisted in recent years. This pattern also reflects a negative phase of the Pacific Decadal Oscillation (PDO), which has been predominantly in the negative phase since 2007 (fig. 2; Peterson and Schwing 2003). The tropical El Niño that developed in summer 2009 and peaked in winter 2009–10 had largely dissipated by early spring 2010. This event appears to have been an El Niño Modoki marked by anomalous warming in the central, rather than western, equatorial Pacific (Ashok et al. 2007). By July 2010, La Niña developed in the tropical Pacific, with cooler SSTs (anomalies of approximately  $-1.0^{\circ}\text{C}$ ) extending from the South American coast to the dateline (fig. 3a). Strong anticyclonic wind anomalies dominated the northeast Pacific at this time, resulting in cooler SSTs throughout the Gulf of Alaska and California Current. La Niña conditions strengthened through autumn 2010 and into early winter 2011, during which unusually cool SSTs (anomalies of approximately  $-2.0^{\circ}\text{C}$ ) occurred in parts of the equatorial Pacific (fig. 3b,c). A brief period of warm SST anomalies in the eastern North Pacific in September–October 2010 transitioned back to cool SST anomalies in early winter 2010–11 (fig. 3c). By April–May 2011, tropical

<sup>1</sup>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>).

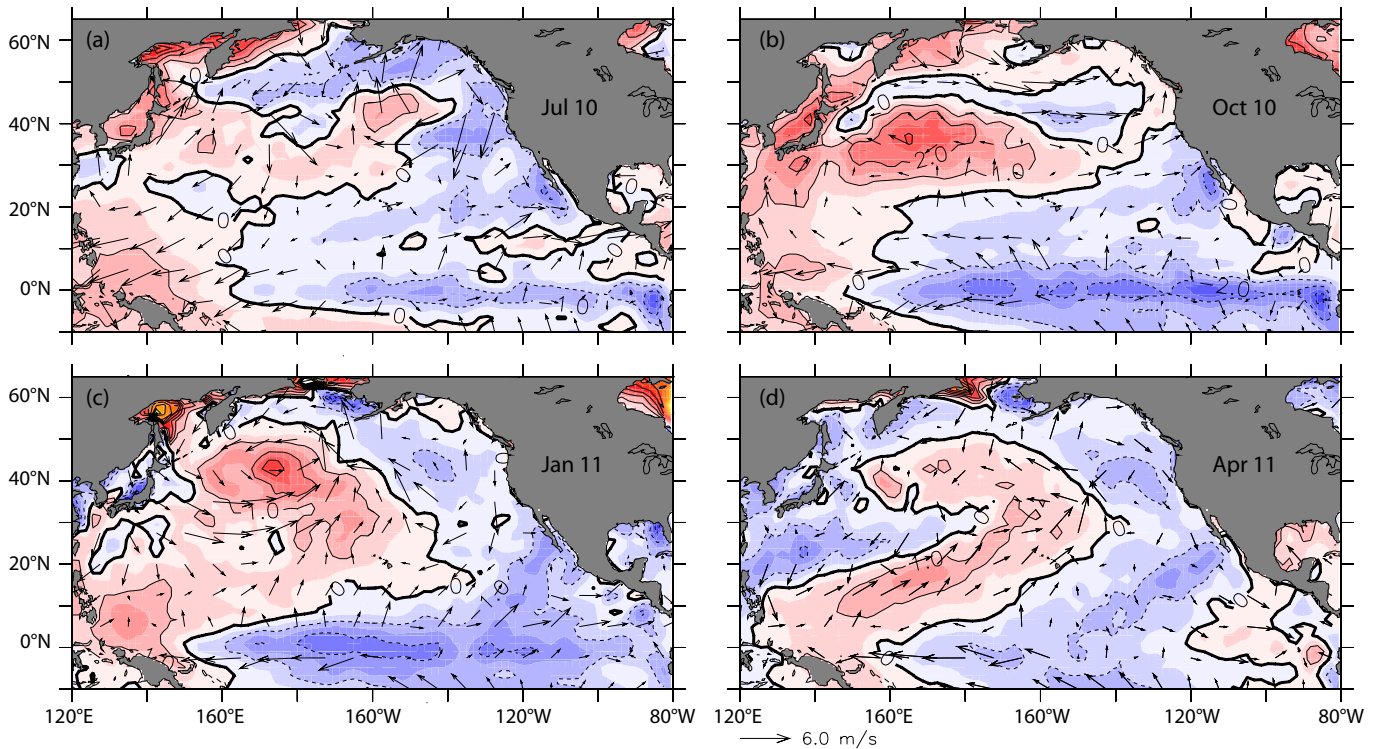


Figure 3. Anomalies of surface wind velocity and sea surface temperature (SST) in the north Pacific Ocean, for (a) July 2010, (b) October 2010, (c) January 2011, and (d) April 2011. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative (cool) SST anomalies are shaded blue; positive (warm) SST anomalies are shaded red. Wind climatology period is 1968–96. SST climatology period is 1950–79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

conditions had transitioned to ENSO-neutral, while the eastern North Pacific (NEP) was dominated by a strong North Pacific High (anticyclonic wind anomalies), strong upwelling in the California Current, and cooler than normal SST throughout the NEP (fig. 3d).

Recent trends and variability in major climate indices also reflect the development and decline of El Niño in the North Pacific. In spring 2010, cooling in the North Pacific is captured in the sharp transition of PDO back to strongly negative values comparable to those observed during cool conditions prior to the 2009–2010 El Niño. Following this transition, the PDO declined in magnitude more or less steadily (fig. 2). The Multivariate El Niño Southern Oscillation Index (MEI) also marked a sharp transition to strong La Niña conditions that has subsequently relaxed towards ENSO-neutral conditions (fig. 2). The North Pacific Gyre Oscillation (NPGO) index indicated a weakening of gyral circulation (i.e., a weakening of the California Current) coincident with the tropical signal of the 2009–2010 El Niño that recovered strongly in spring 2010, then gradually declined into negative anomalies in early 2011 (fig. 2). The NPGO signal associated with the 2009–2010 El Niño and its dissipation appears to lead that of the SST-based PDO (fig. 2).

## CALIFORNIA CURRENT

### Atmospheric Forcing, Upwelling, and Sea Surface Temperature Responses

Conditions in the North Pacific and California Current show clear responses to variability in the development and strength of seasonally dominant atmospheric pressure systems (e.g., the Aleutian Low in winter and the North Pacific High in spring and summer). Upwelling was anomalously strong throughout the California Current during midsummer 2010, reflecting persistently strong anticyclonic wind anomalies associated with a strong North Pacific High (figs. 3, 4). The rapidly changing atmospheric forcing in the northeast Pacific from autumn 2010 through winter 2011 is reflected in California Current upwelling. A strong Aleutian Low in December 2010 and March 2011 led to brief periods of anomalously strong downwelling in the northern California Current. In contrast the development of the North Pacific High in spring 2011 led to an early onset and relatively strong upwelling from Baja through central California.

Conditions at coastal NDBC buoys have reflected these large-scale patterns, with high volatility in both surface winds and SST (fig. 5). Strong event-scale vari-

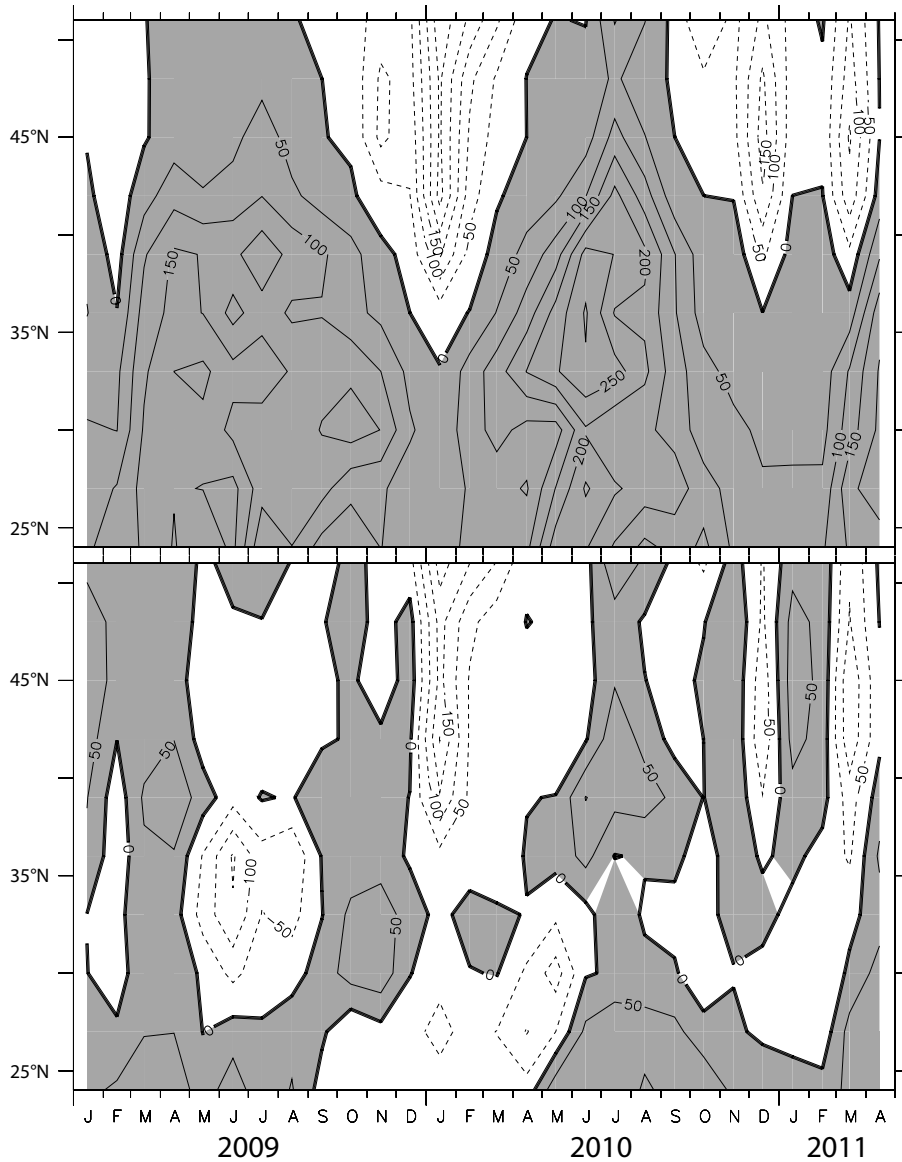


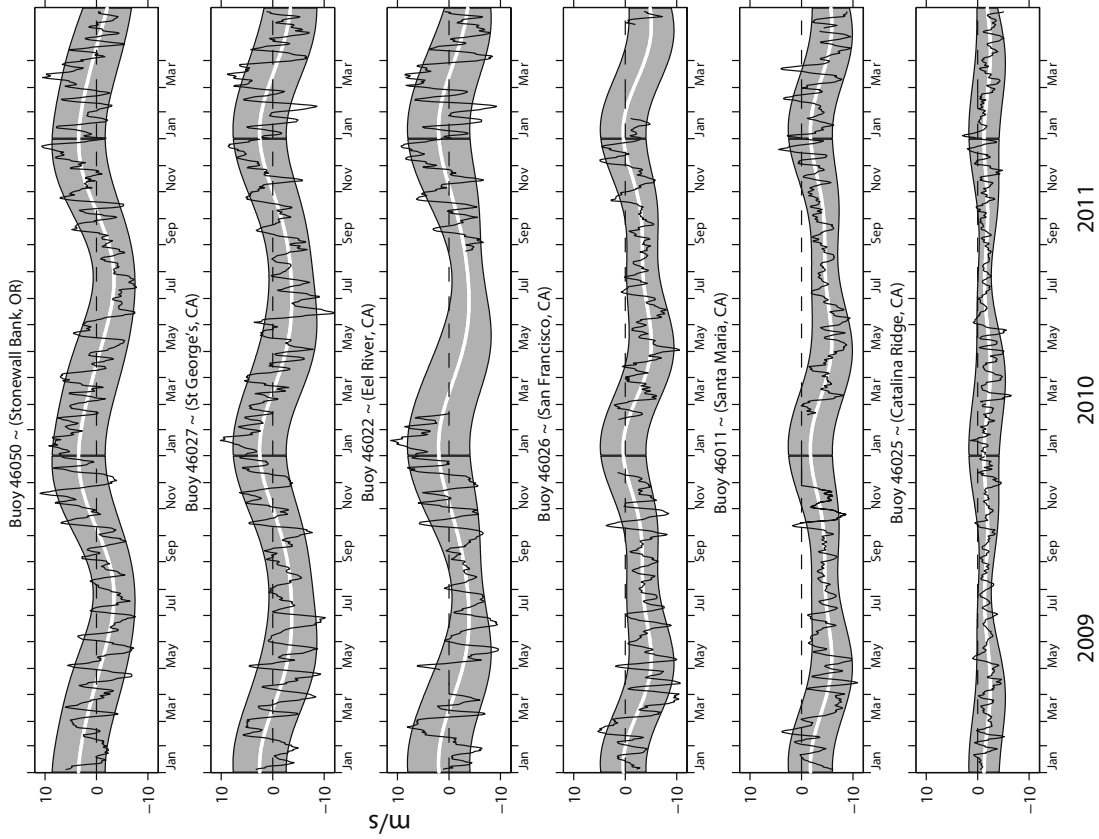
Figure 4. Monthly upwelling index (top) and upwelling index anomaly (bottom) for January 2009–April 2011. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in  $\text{m}^3/\text{s}$  per 100 km of coastline.

ability (i.e., variability over time scales of several days to weeks) prevailed in the summers of 2009 and 2010, as it has since 2007, with numerous upwelling and relaxation events and corresponding variations in SST, particularly in the northern California Current. Strong event-scale variability was also evident in nearshore winds during the winters of 2009–10 and 2010–11. While SSTs in winter 2009–10 were anomalously warm—a consequence of a strong Aleutian Low and intense downwelling associated with the El Niño—SSTs in winter 2010–11 were generally cooler than normal in the California Current. Strong upwelling in the southern California Current in April 2011 led to strong negative SST anomalies at the southern buoys.

Latitudinal variation in cumulative upwelling<sup>2</sup> further illustrates the contrasts in recent years (fig. 6). Off southern California, upwelling patterns have been quite similar and near average despite the transition from La Niña conditions through the 2009–2010 El Niño and back to La Niña. Moving north, however, differences between years become more apparent, to the point that off Oregon, cumulative upwelling in early 2009 was among the strongest observed, yet among the weakest in early 2010. Cumulative upwelling in 2011 showed a similar latitudinal pattern, with differences between northern and

<sup>2</sup>Cumulative upwelling was calculated from the 6-hourly Bakun Index obtained from the NOAA Fisheries Environmental Research Division obtained through <http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/PFELindices.html>.

Alongshore Winds 2009 to 2011



Sea Surface Temperatures 2009 to 2011

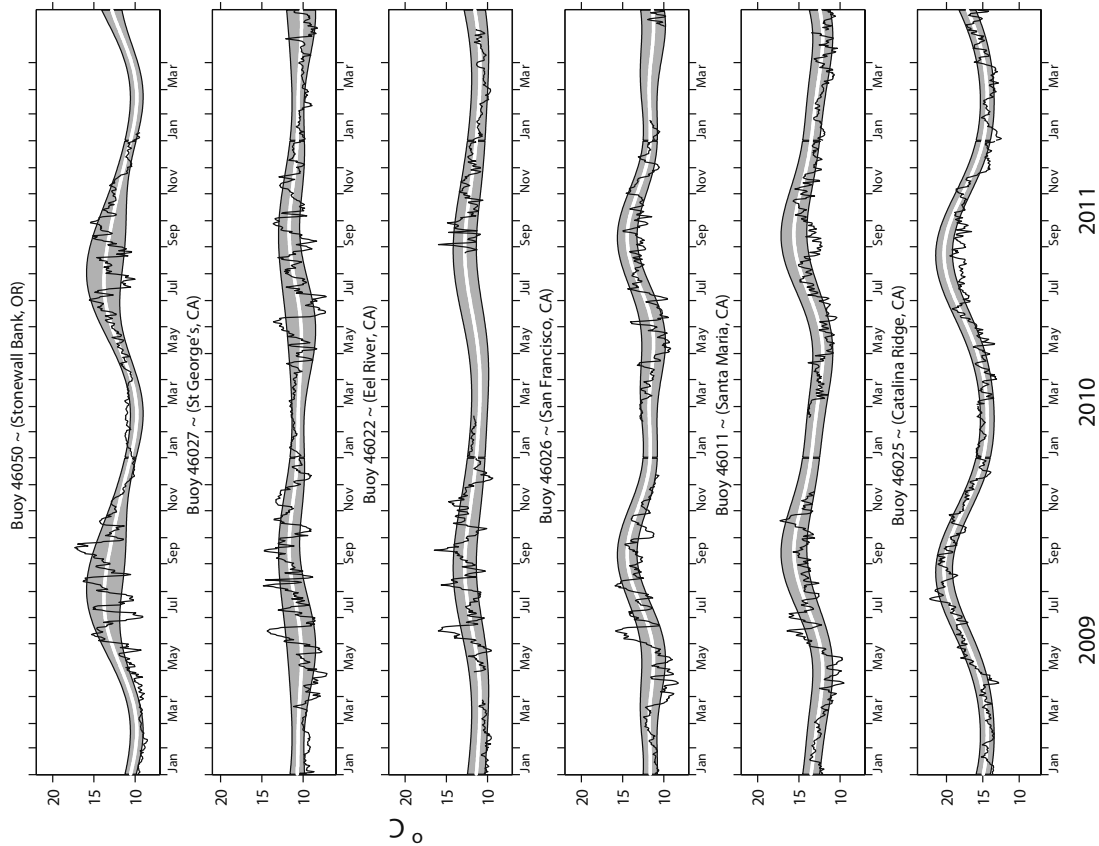


Figure 5. Time series of daily-averaged SST (left) and alongshore winds (right) for January 2009–April 2011 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. 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/fo\\_station.shtml](http://www.ndbc.noaa.gov/fo_station.shtml).

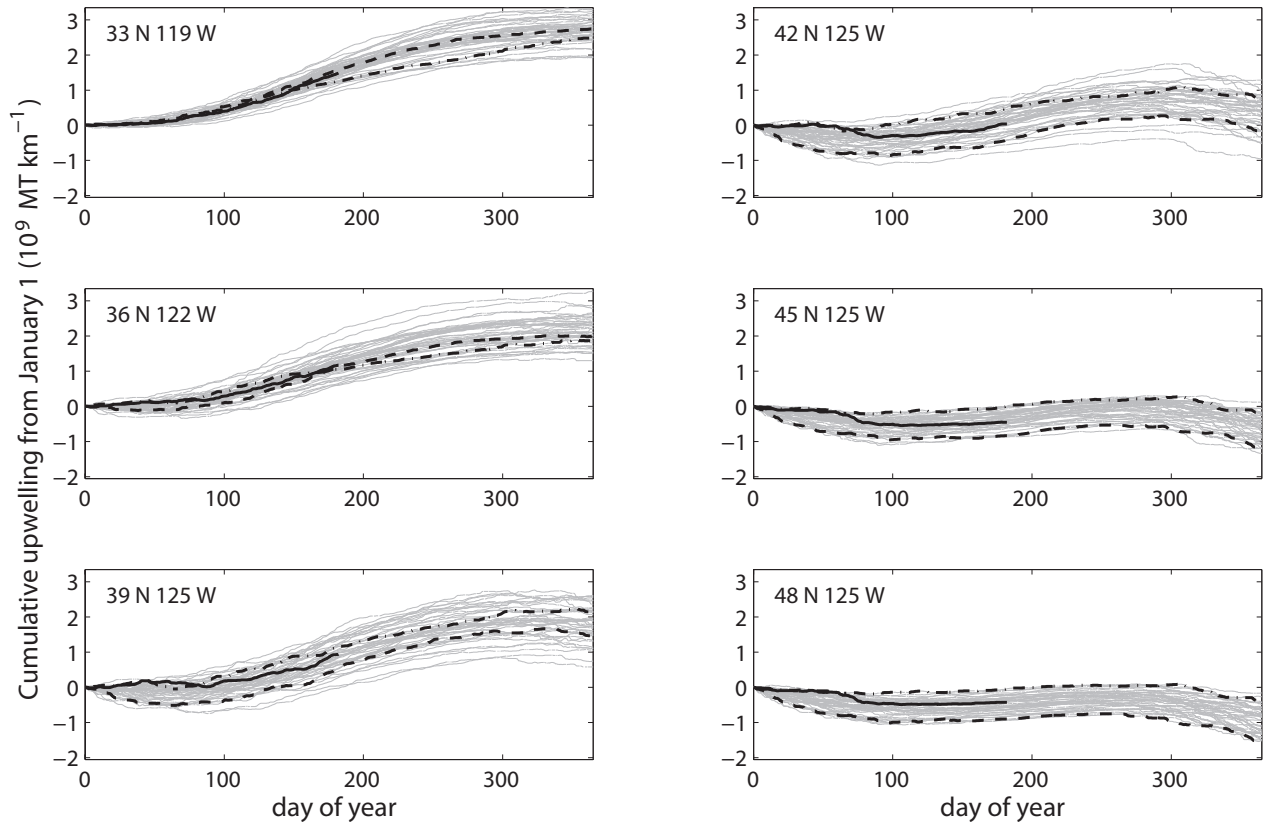


Figure 6. Cumulative upwelling from January 1 calculated from the Bakun Index at indicated locations along the West Coast of North America for 1967–2008 (grey lines), 2009 (dash-dotted line), 2010 (dashed line), and 2011 (solid line).

southern locations arising as a consequence of strong downwelling in the north in spring 2011. The prolonged sequence of downwelling events in early 2011 led to a slightly delayed spring transition<sup>3</sup> in the northern California Current (e.g., at 45°N; fig. 7).

#### HF Radar Surface Current Observations<sup>4</sup>

Seasonal mean surface currents observed with HF radar provide further evidence of the contrast between spring 2010 through spring 2011 and the previous year. In spring 2010 (March through May), mean currents are directed southward throughout the domain (including the Southern California Bight) and have a clear offshore component off central California (fig. 8). During the summer, a marked offshore orientation of mean flows

is evident throughout the upwelling region from Point Conception to the mouth of the Columbia River. In the Southern California Bight, flow is weaker and mostly poleward in summer and fall. In fall (September through November), currents weaken in the upwelling region and consistent upwelling is not evident north of Cape Mendocino.

Persistent enhanced offshore flow is evident in the seasonal mean as upwelling jets either at or just south of major capes (e.g., Cape Blanco, Cape Mendocino, Point Arena, Point Reyes, Point Año Nuevo, and Point Conception; fig. 8). These features varied in strength and structure between years. In contrast to 2009, during which strong features observed in spring weakened during summer (Bjorkstedt et al. 2010), these features were weaker in spring 2010, but strengthened through the summer (June through August), particularly off Cape Blanco and Point Arena. Also in contrast with observations from the previous year, the “Mendocino Eddy” (Halle et al. in review) is not evident as a closed circulation pattern in the mean flow patterns, yet mean flows do include a persistent offshore flow just north of Point Arena—most strikingly in fall, when wind forcing was relatively weak—that is consistent with the southern portion of the Mendocino Eddy (fig. 8).

<sup>3</sup>Spring transition date is based on the day on which cumulative upwelling reaches its most negative value immediately prior to the onset of sustained positive upwelling. Usually this corresponds to the lowest value of cumulative upwelling, but in some years the spring transition corresponds to a second-most negative value of cumulative upwelling following a weak upwelling event.

<sup>4</sup>High Frequency (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-km resolution prior to display. Real-time displays of HF-Radar surface currents can be viewed at the regional association Web sites: <http://www.sccoos.org/data/hfrnet/> and [http://www.cencoos.org/sections/conditions/Google\\_currents/](http://www.cencoos.org/sections/conditions/Google_currents/) and at Web sites maintained by the institutions that contributed data reported here (listed in Acknowledgments).



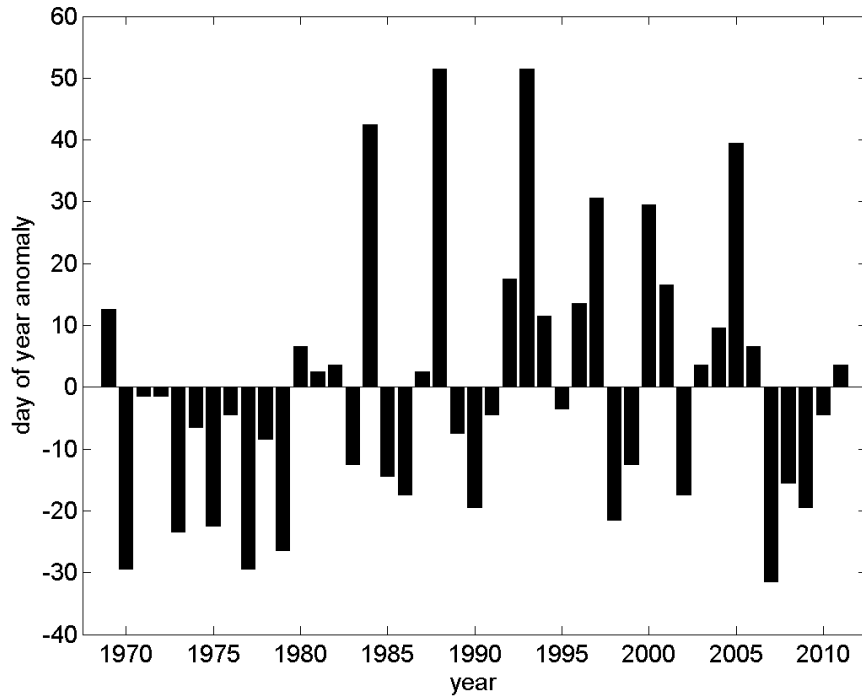


Figure 7. Variability in spring transition dates around the mean of observed transition dates calculated from the Bakun Index at 45°N 125°W. Negative anomalies indicate early spring transitions, positive anomalies indicate late transitions. Day of transition is from the most negative value of cumulative upwelling immediately prior to onset of sustained upwelling. Mean spring transition date is Day 103 (April 13).

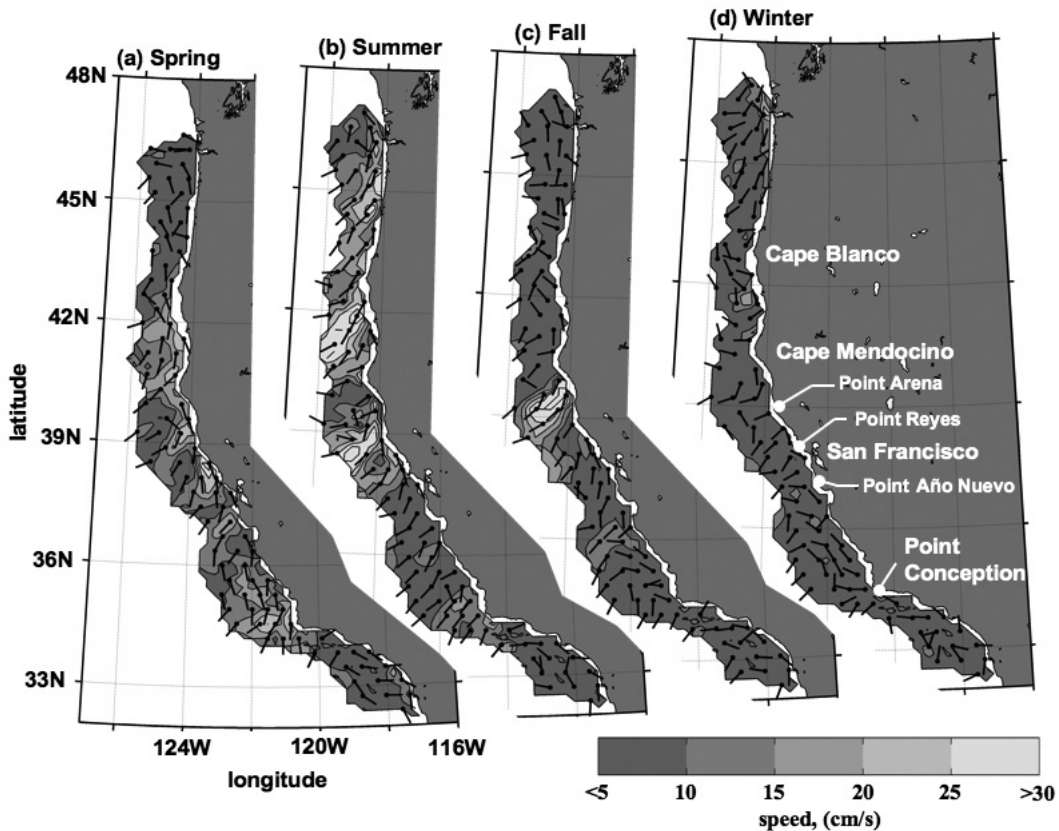


Figure 8. Mean seasonal maps of surface currents observed throughout the CCS with coastal HF radar for March 2010 through February 2011. The seasons are spring (March–May), summer (June–August), fall (September–November), and winter (December–February). Mean surface currents are calculated at 20-km resolution 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.

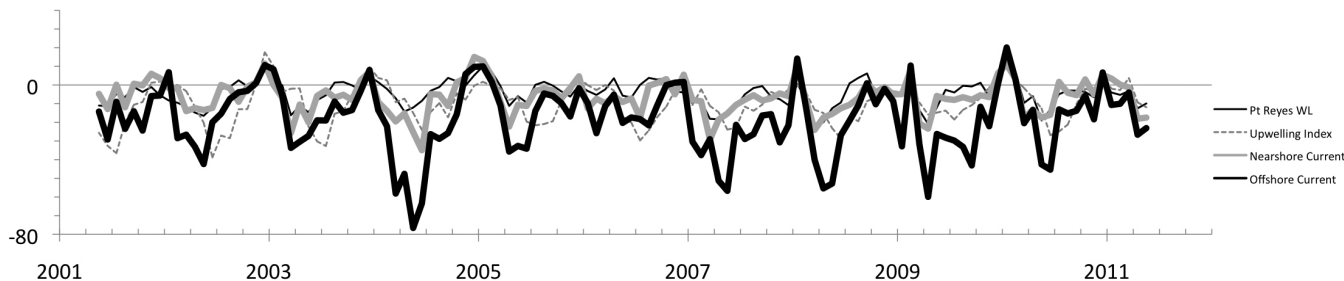


Figure 9. Monthly averages of spatially averaged surface flow past Point Reyes, CA between 30 and 60 km offshore (38°00' to 38°10'N and 123°20' to 123°40'W; thick black line) and between 0 and 15 km offshore (38°00' to 38°10'N and 123°00' to 123°10'W; thick grey line). Positive values indicate poleward flow in cm/s. Fine, grey dashed line: cross-shelf Ekman transport indexed as the negative Upwelling Index at 39°N (i.e., positive values indicate onshore Ekman transport in units of 10 m<sup>3</sup>/s per 100 m of coastline). Fine black line: sea level at Point Reyes relative to 1 m above MLLW (units cm).

Following strong northward flows during the 2009–10 winter, southward flow off Point Reyes returned to moderate levels in 2010 and exhibited greater correlation between nearshore (0–15 km) and offshore (30–60 km) flows than was observed in 2009 (fig. 9). These flows were strongest during May and June 2010, but relatively weak earlier in the spring and later in the summer. In fact, mean flow past Point Reyes near the coast was approximately zero from July onward. Flows were variable and weak during the 2010–11 winter and continued to appear weak into early 2011 (fig. 9). As in previous years, the seasonal development of alongshore flow past Point Reyes leads that of local wind forcing as indicated by the Upwelling Index (fig. 9; see Garcia-Reyes and Largier (in review) for further discussion). Indeed, alongshore flow is better correlated with monthly mean water level at the Point Reyes tide gage, which reflects both wind forcing and forcing related to offshore eddies (e.g., Kaplan et al. 2009).

## REGIONAL SURVEY OBSERVATIONS

### Baja California—IMECOCAL Surveys<sup>5</sup>

Within the IMECOCAL study region off Baja California, temporal variability in both temperature and salinity (expressed in terms of mean 10 m anomalies) effectively capture climate events and clearly illustrate the onset and dissipation of the recent 2009–2010 El Niño event (fig. 10). In Spring 2010, colder, fresher conditions developed, eventually leading to the coldest (October 2010) and freshest (January 2011) conditions recorded in time series (fig. 10). The 2010–11 freshening event exceeds the 2002–03 event in scale, which had been the result of an anomalous intrusion of subarctic waters into the CC (Venrick et al. 2003; Gómez-Valdes and Jeronimo

2009). Subsequent observations show both temperature and salinity reverting to long-term mean values.

Temporal variability in chl *a* (expressed as anomalies of chlorophyll integrated over the upper 100 m of the water column) also capture the consequences of climate variability off Baja California at interannual to decadal scales, including El Niño–La Niña cycles (Gaxiola-Castro et al. 2008). These patterns show a positive relationship with the NPGO (North Pacific Gyre Oscillation) index, but low relation to MEI (Gaxiola-Castro et al. 2010). Positive chl *a* anomalies were present off Baja California from 2008 to 2011 (April), except for the spring 2010 survey, which is likely to have been a consequence of the 2009–2010 El Niño in the region (fig. 11). Anomalous high concentrations of chl *a* were observed off Baja California from the second half of 2010 through spring 2011, but remain lower than those observed in 2002 (Gaxiola-Castro et al. 2008).

During 2010 and into early 2011, zooplankton displacement volumes were relatively high, which is consistent with patterns observed since 2004 (fig. 12; Lavaniegos 2009). In early 2010, however, crustacean zooplankton grazers were relatively rare and high indices of zooplankton abundance reflected the high abundance of gelatinous groups (not shown). Indeed, abundance of medusae reached a record value for the IMECOCAL series (1998–2010) in early 2010. In contrast, copepods and euphausiids returned to relatively high abundance during July and October 2010 (fig. 12), presumably as a consequence of cool water and enhanced production associated with La Niña.

### Southern California—CalCOFI Surveys<sup>6</sup>

Unusually high sea levels associated with the 2009–2010 El Niño cycle returned to normal and slightly negative values by the summer of 2010 (fig. 13a). Mixed

<sup>5</sup>The IMECOCAL study region spans 93 stations off Baja California, Mexico (fig. 1). IMECOCAL cruise schedules, data collection protocols, analysis methods, and additional substantiating data are fully described at <http://imecocal.cicese.mx>. Note that results from the present analysis based on 10 m anomalies have been corroborated and correlate well with patterns in anomalies based on analysis of mixed layer properties (Durazo 2009; Gómez-Valdes and Jeronimo 2009; Bjorkstedt et al. 2010).

<sup>6</sup>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>.

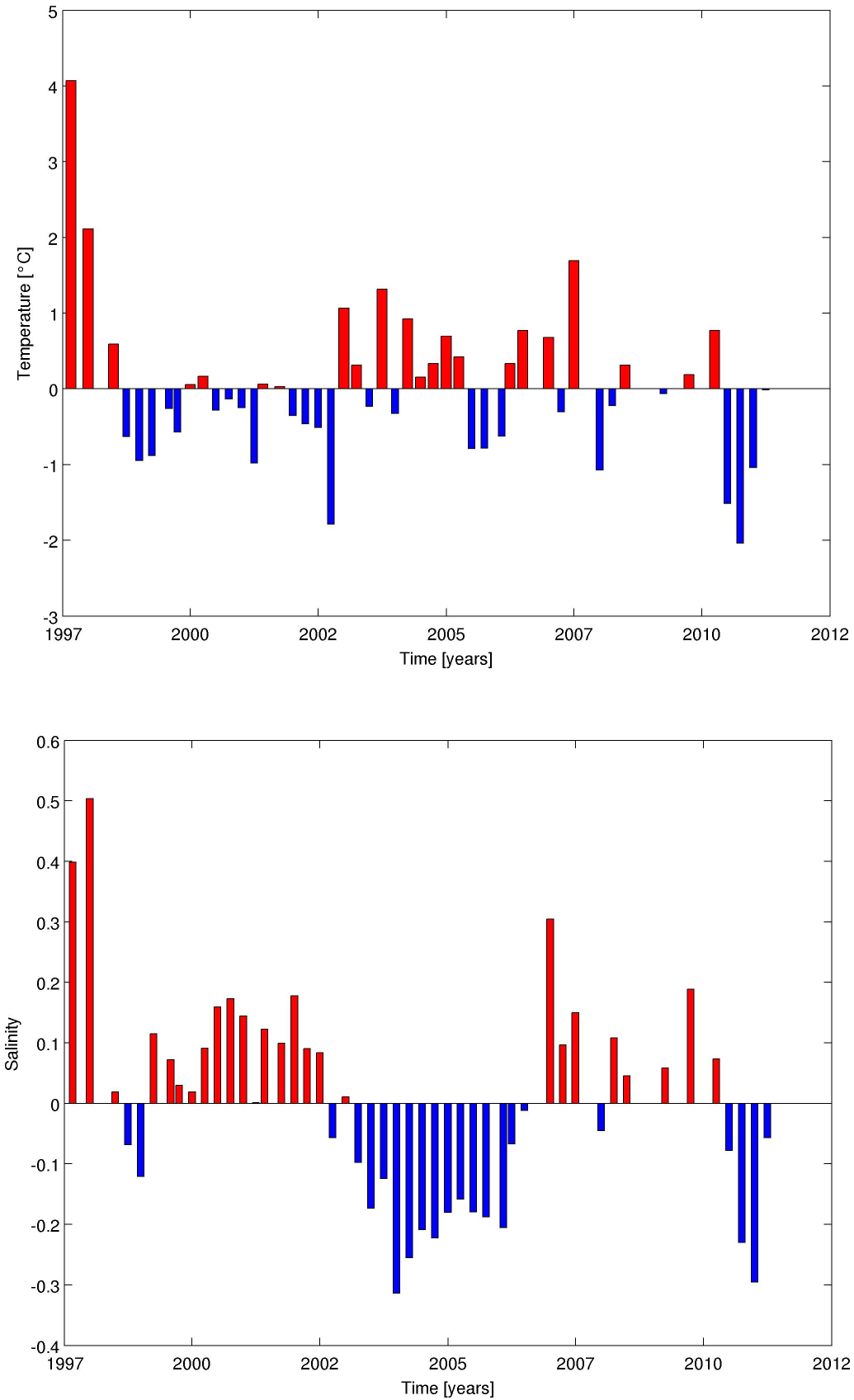


Figure 10. Mean anomalies of temperature (upper panel) and salinity (lower panel) at 10 m over the IMECOCAL study region for the period 1997–2011.

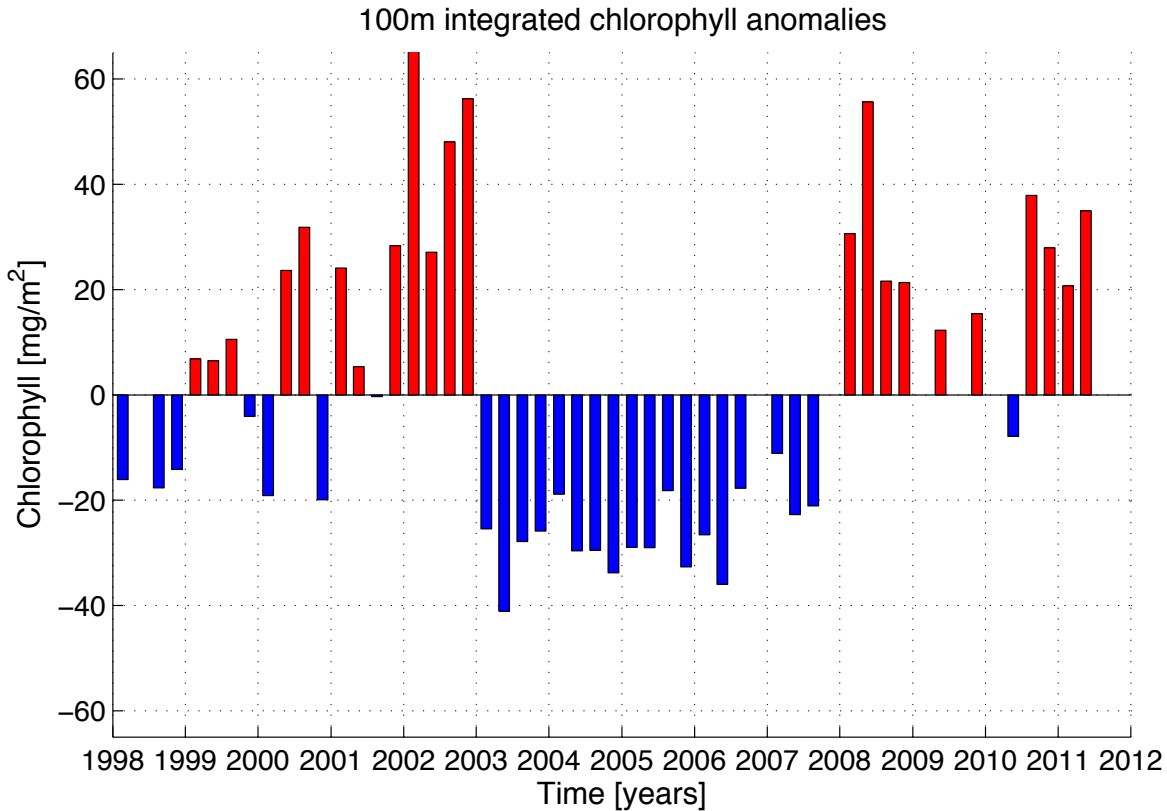


Figure 11. Anomalies of average water-column integrated chl *a* in the IMECOCAL study region off Baja California from 1998 to spring 2011.

layer temperature continued to remain slightly cooler than the long term average, continuing a trend established after the 1998–1999 El Niño. Mixer layer temperature was substantially cooler than normal during summer 2010, reflecting the strong equatorial La Niña conditions, but subsequently returned towards recent mean values (fig. 13c).

Values of mixed layer salinity, which is not expected to be affected by ENSO cycles, continued to decline through 2010 and into 2011 (fig. 13d). This pattern is reflected in many regions within the CalCOFI study area that continue to exhibit freshening of the upper water column, as has been observed over the last few years (Bjorkstedt et al. 2010). Indeed, this freshening trend either persisted or became stronger in the case of the southern California Current (fig. 14), and likely reflect a general strengthening of the California Current.

During the 2009–2010 El Niño, the  $\sigma_t$  26.4 isopycnal<sup>7</sup> was deeper than usual (i.e., exhibiting a positive depth anomaly), but returned to depths similar to those observed over the last decade following the development of La Niña (fig. 15a). Temperature and oxygen anoma-

lies at the  $\sigma_t$  26.4 isopycnal did not change substantially over the last ENSO cycle (fig. 15), suggesting that water masses at the isopycnal did not change substantially during this time. Considering these rather subtle changes in properties, the large observed increase in nitrate concentrations over the last years is surprising (fig. 15). Although the increasing trend in nitrate concentration since 2000 coincides with a decline in oxygen concentration (to levels that have persisted into 2011), the sharp increase in nitrate over the past two years is not matched by a corresponding additional decrease in oxygen concentrations. Thus, it appears that the increase of nitrate over the last two years can not have been driven by increased local remineralization without some other mechanism present to offset the expected draw down of dissolved oxygen. The largest anomalies in nitrate concentration at the  $\sigma_t$  26.4 isopycnal were observed along the offshore sections of lines in the northern (lines 77 and 80) and southern (lines 90 and 93) of the CalCOFI grid (fig. 1). This nitrate concentration anomaly also does not appear to be related to the freshening of the upper water column since analogous trends in nitrate and oxygen concentrations are not observed higher in the water column (e.g., at the  $\sigma_t$  25.6 isopycnal which is located at a depth of about 90 m with a temperature of about 11°C, data not shown).

<sup>7</sup>The  $\sigma_t$  26.4 isopycnal is located within the pycnocline, at an average depth of about 200 m off S. California, and is largely independent of processes affecting the mixed layer (i.e., local forcing).

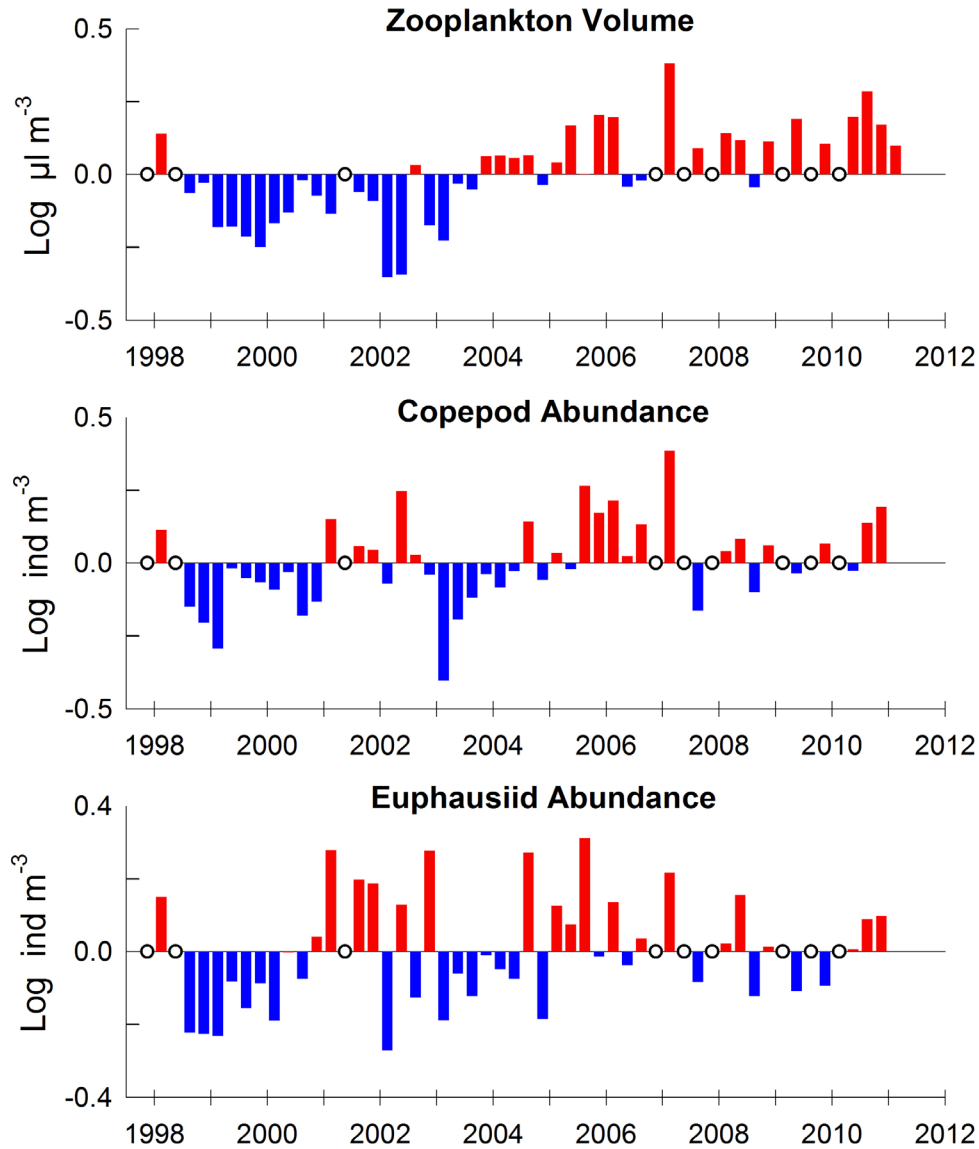


Figure 12. Anomalies of average zooplankton densities observed in the IMECOCAL study region off Baja California from 1998 to fall 2010. Top panel: Anomalies of zooplankton displacement volume. Middle panel: Anomalies in estimated copepod abundance based on nighttime samples. Bottom panel: Anomalies in estimated euphausiid abundance based on nighttime samples. Open circles indicate missing cruises or cruises with reduced area coverage that were excluded from calculation of anomalies. Zooplankton data for January 2011 are not yet available.

Nitracline depths in the CalCOFI area were similar to values observed since 1999 (fig. 13b). Whereas nitracline depth responded significantly to the La Niña conditions of 2007–2008 it did not respond strongly to the El Niño conditions of 2009–2010, as it had during previous El Niños (fig. 13b). Consistent with the observation of nitracline depth, concentrations of mixed layer nitrate were slightly above long-term averages and concentrations of silicic acid and phosphate were similar to long-term averages over the last decade (fig. 16). Concentrations of nitrate and N-P ratios have been increasing slightly over the last decades, but no such trend can be detected for concentrations of silicic acid and phosphate.

The spatially-averaged concentration of mixed layer chl *a* observed over the last year was similar to long-term averages (fig. 17a). These trends for the whole region reflect processes in specific areas as well. Concentrations of chl *a* have been higher than normal at the edge of the central gyre and in the California Current in past years and these have been lower than average in the northern coastal areas. In 2010, concentrations of chl *a* returned to average values in these areas. (fig. 18). The exception is the southern coastal region where exceptionally high concentrations of chl *a* were observed this year. Rates of primary production were slightly above long-term averages (fig. 17b), a trend possibly related to the slight increase in nitrate concentration over the last year. Zoo-

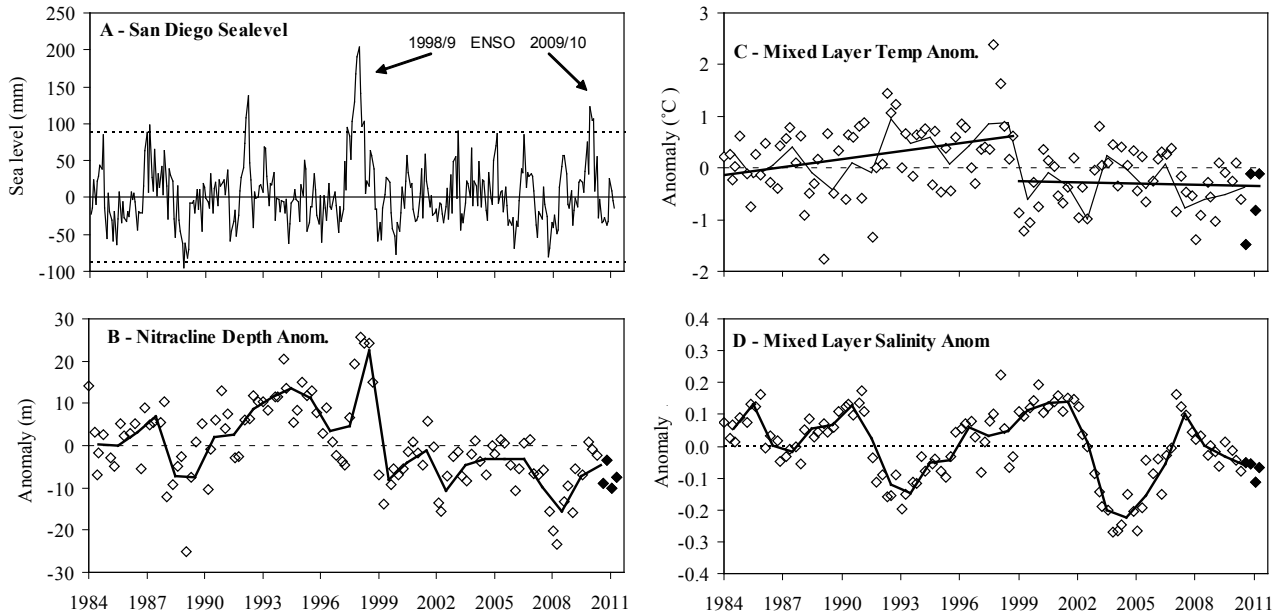


Figure 13. Anomalies of detrended San Diego sea level (A), nitracline depth (B), mixed layer (ML) temperature (C), and ML salinity (D) off southern California (CalCOFI standard grid, CalCOFI fig. 1). Data from the last four CalCOFI cruises are plotted as solid symbols, data from previous cruises are 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, when present, long-term trends.

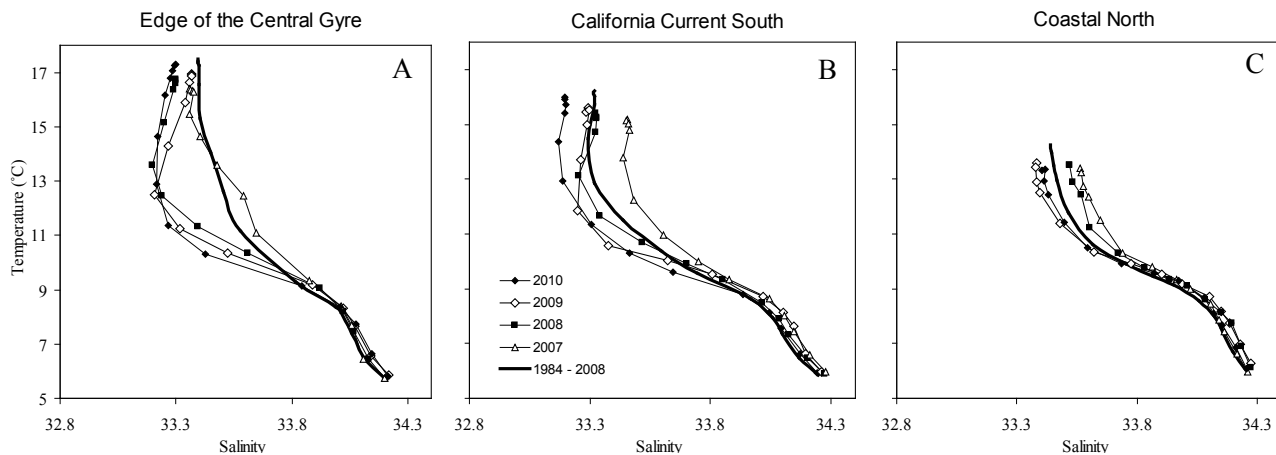


Figure 14. TS plots for three representative areas of the CalCOFI region. A. The edge of the central gyre (Lines 90–93, Stations 100–120); B. the southern California Current region (Lines 87–93, Stations 60–90); and C. the coastal areas in the north (Lines 77–80, Stations 60 and inshore). Each data point represents the average TS characteristic of one standard depth level for the specified time periods, i.e., 1984–2008, 2007, 2008, 2009 and 2010.

plankton displacement volume, a proxy for zooplankton biomass, has not been affected by the last ENSO cycle, in contrast to the 1998–99 ENSO cycle when zooplankton biomass decreased by 70%.

### Central California—Monterey Bay and Line 67<sup>8</sup>

Observations off central California also reflected the decline of the 2009–2010 El Niño event in mid-spring 2010 and the transition to La Niña conditions which have persisted into spring 2011 (fig. 19). In the outer reaches of Monterey Bay, the upper water column was unusually warm during January 2010 (anom-

alies greater than 0.8°C extended from the surface to a depth of 100 m), but by November 2010, this pattern had completely reversed: the upper water column was unusually cool (anomalies of approximately –0.8°C at 100 m) and salty (salinity anomaly of 0.2 S). These changes were in part explained by changes in regional Ekman transports and were also consistent with Monterey sea level measurements (data not shown). The development and persistence of La Niña conditions was also evident in the development of anomalously high chl *a* concentrations in the upper 100 m of the water column during summer 2010. In contrast to the preceding summer, when phytoplankton were both less abundant and concentrated at depth (as is more typi-

<sup>8</sup>Data on temperature and salinity at the surface and 100 m for Monterey Bay are based on MBARI monthly cruises and mooring data.

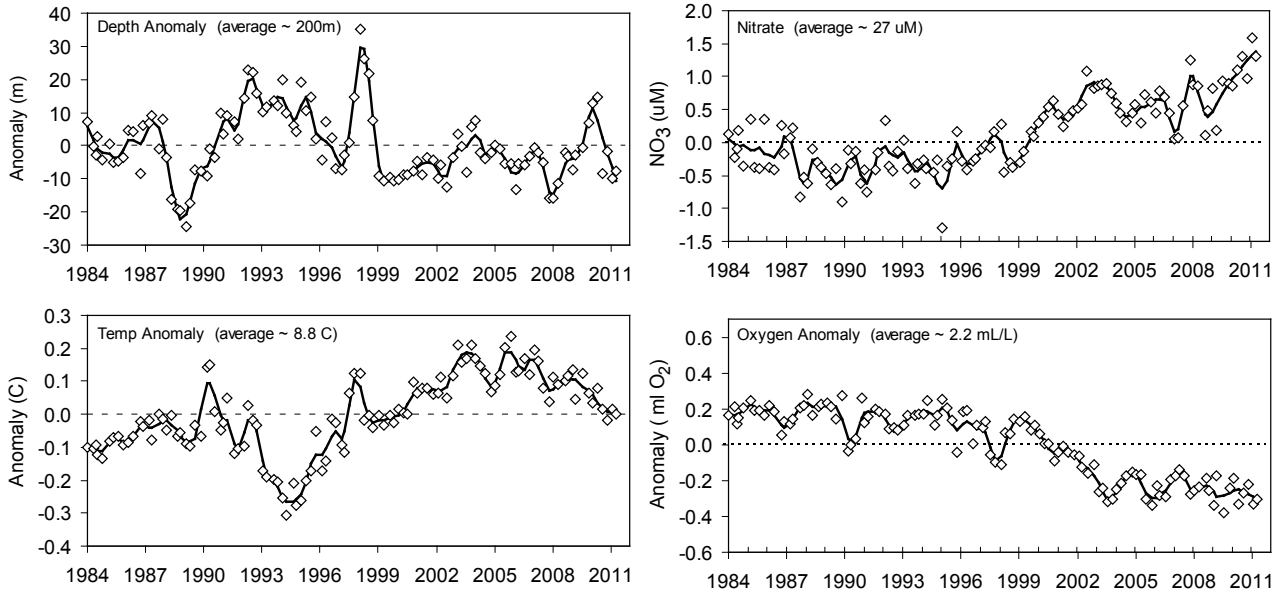


Figure 15. Property anomalies of the  $\sigma_t$ , 26.4 isopycnal calculated and presented as described above for Figure 13. Shown are anomalies of the isopycnal depth anomaly, concentrations of nitrate, temperature and oxygen. Average values for the properties are given as well.

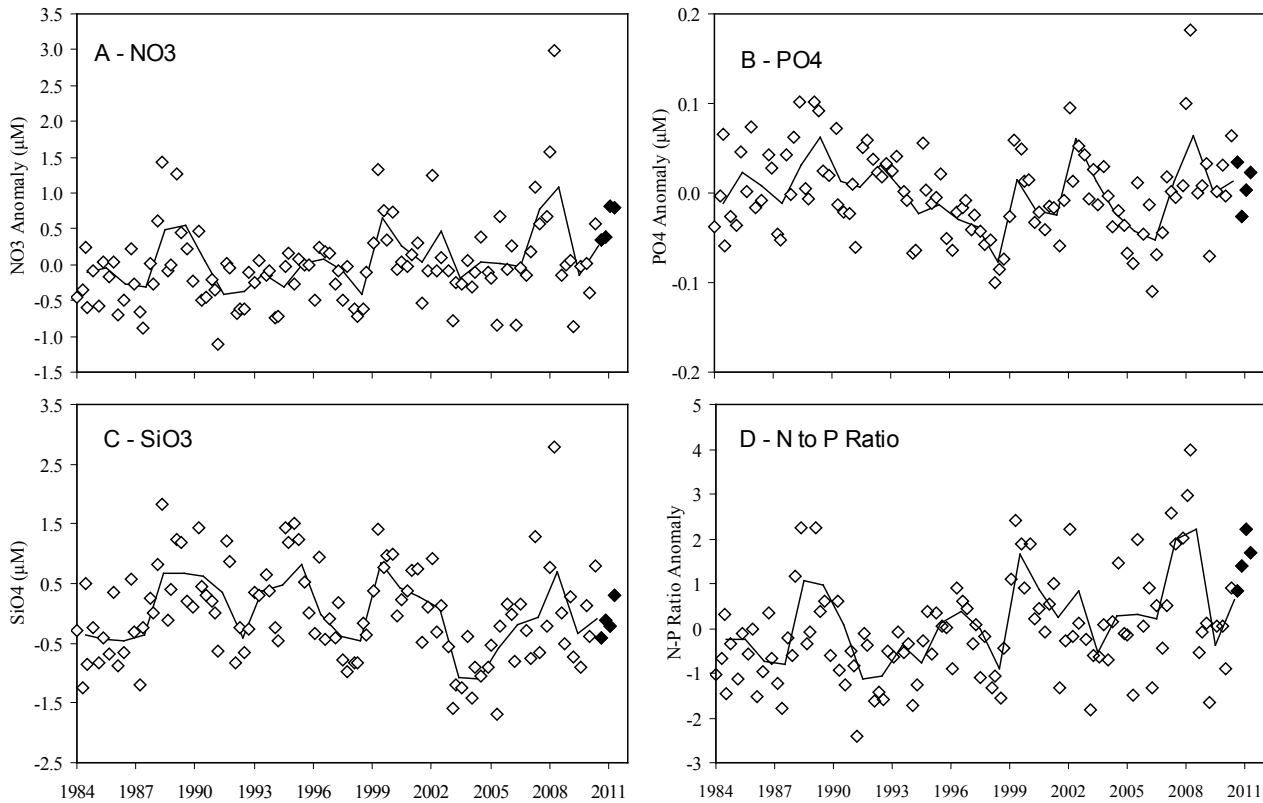
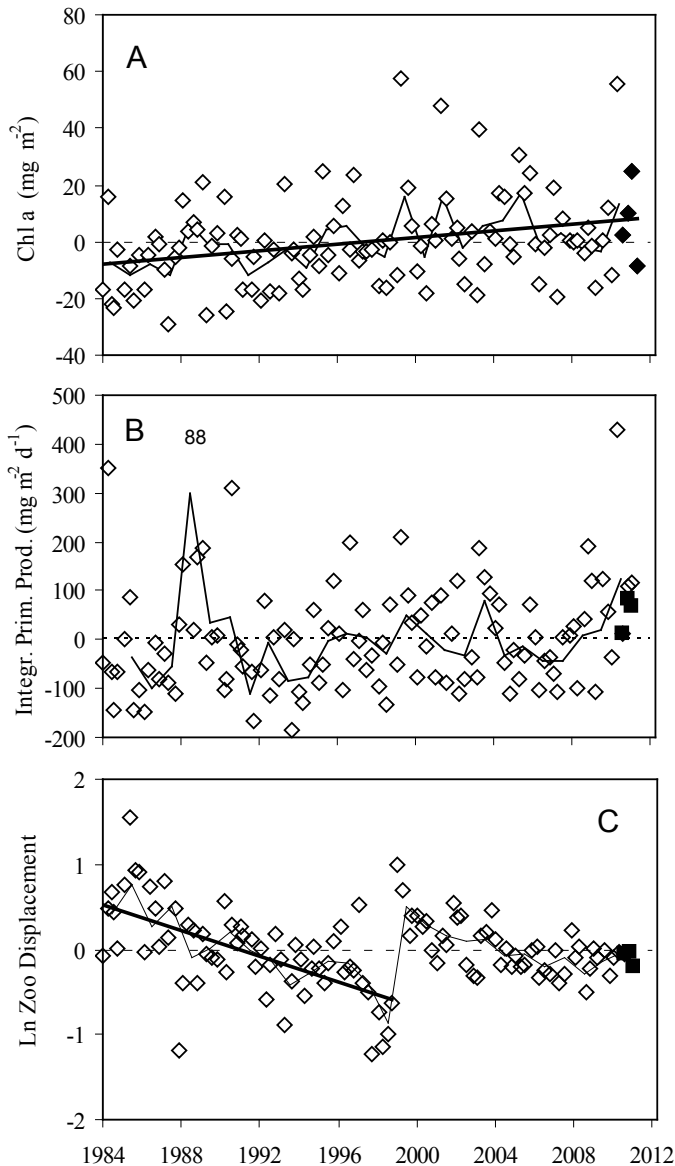


Figure 16. CalCOFI region anomalies for mixed layer concentrations of (A) nitrate, (B) phosphate, (C) silicic acid and nitrate to phosphate ratio. Data are plotted as described in Figure 13.

cal of locations far from the coast), much of the phytoplankton was concentrated towards the surface (a more typical nearshore pattern).

Observations along Line 67 during late July and early November 2010 likewise encountered cold conditions

following the development of La Niña (fig. 20). Mean temperature of the halocline was the lowest observed, continuing the long-term trend since the section began in 1997 (fig. 19). In both July and November, the inshore edge of the California Current was observed between



stations 67–70 and 67–65 (approximately 110–150 km nm off the mouth of Monterey Bay). Seasonal salinity anomalies in the upper 200 m on the offshore (inshore) side of the front were  $-0.4$  ( $+0.4$ ) in both July and November. The pattern of seasonal temperature anomalies associated with the salinity anomalies was complex but with generally warmer (cooler) waters on the offshore (inshore) side of the front with anomalies about  $\sim 1^\circ\text{C}$  ( $-1^\circ\text{C}$ ). These patterns suggest an intensification of flow in the upper ocean along the front.

### Northern California Current—Newport Hydrographic Line and Trinidad Head Line

Observations along the Newport Hydrographic Line<sup>9</sup> indicate a strong transition from El Niño to La Niña conditions from spring 2010 to summer 2010. Spring 2010 was marked by some of the the warmest and freshest waters observed in the time series, similar to 1997 and to other warm ocean years (1998, 2003, 2005 and 2006). In strong contrast, deep midshelf waters in summer 2010 were the coldest on record (fig. 21).

Monthly average values of copepod species richness off Oregon continue to track the PDO and SST quite closely, with cold conditions (negative PDO) dominated by a few subarctic taxa and warm conditions (pos-

<sup>9</sup>Regular sampling of the Newport Hydrographic (NH) line along  $44.65^\circ\text{N}$  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 protocols are available in previous reports and at <http://www.nwfc.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. Copepod data are based on samples collected with a 0.5 m diameter ring net of 202  $\mu\text{m}$  mesh, hauled from near the bottom to the sea surface. A TSK flowmeter was used to estimate distance towed.

Figure 17. CalCOFI region averages for standing stocks of chl a (A) and rates of primary production (B) and zooplankton displacement volume (C). Data and symbol codes are the same as those in Figure 13.

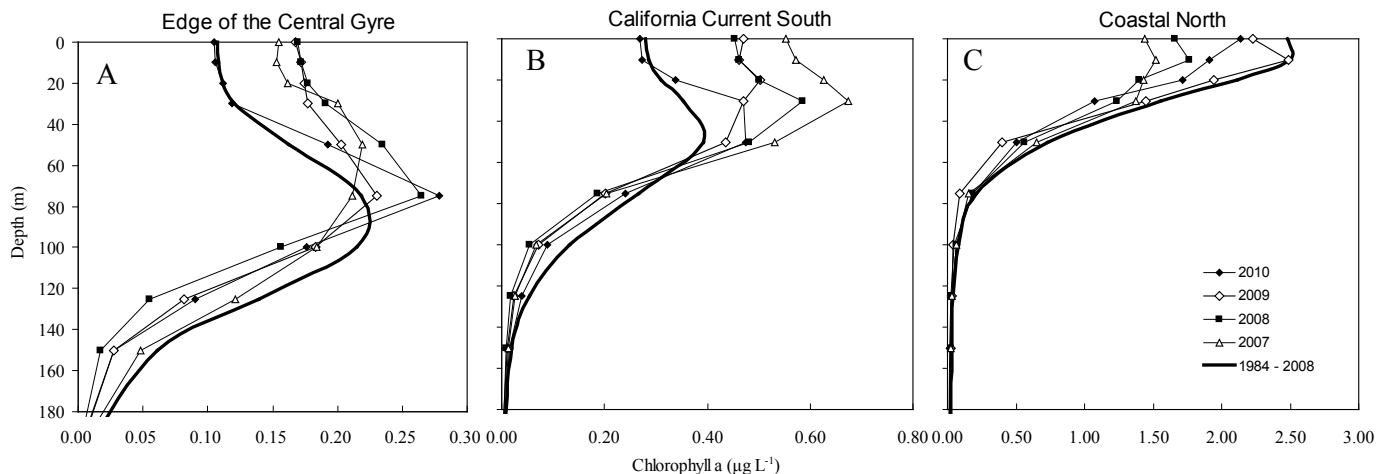


Figure 18. Average annual chl a profiles at standard depths for the three regions defined in Figure 14.



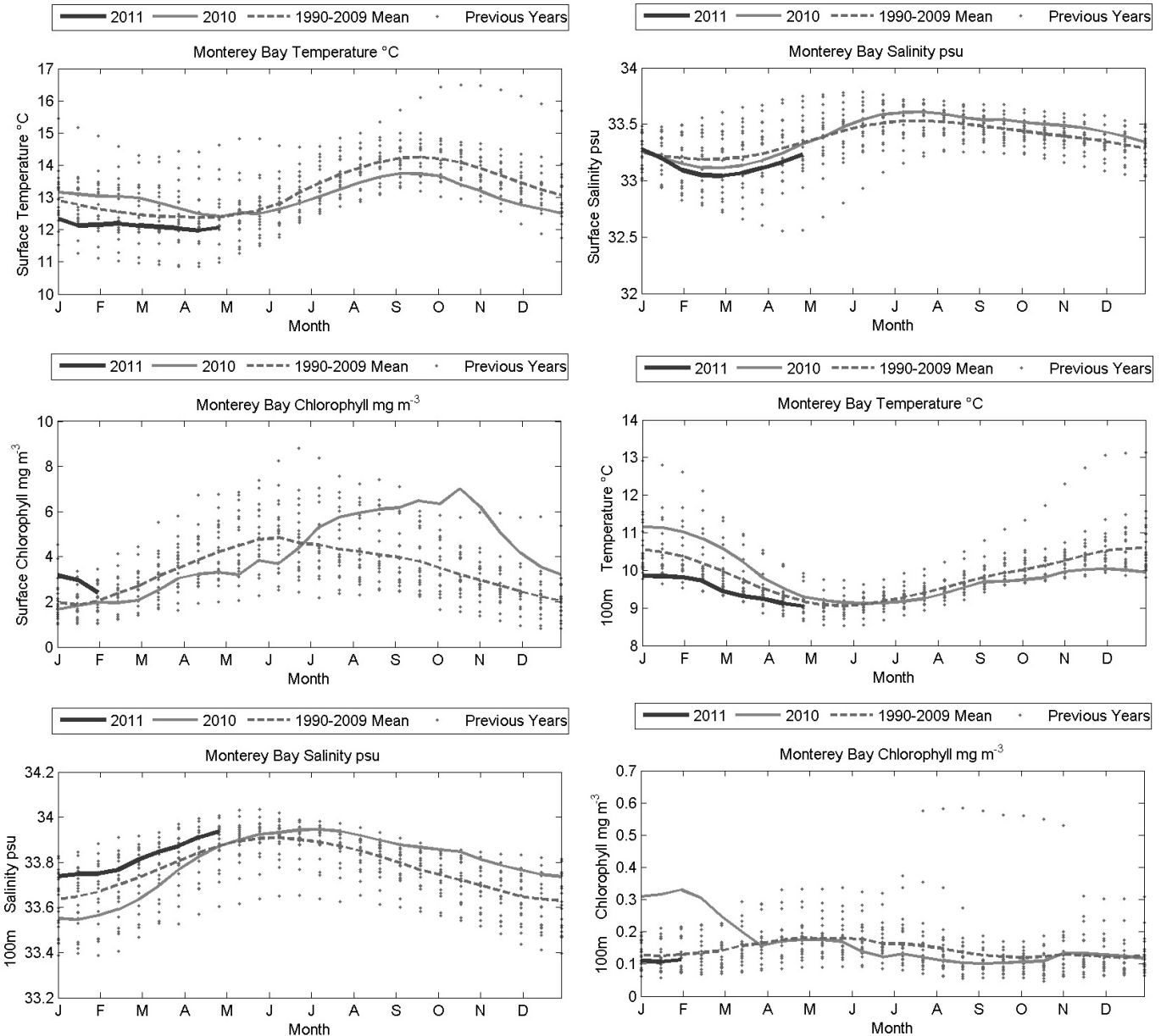


Figure 19. Temperature (top panels), salinity (middle panels) and chl a concentration (bottom panels) at the surface (left hand column) and at 100 m (right hand column) observed at the M1 mooring.

itive PDO) dominated by a more speciose subtropical assemblage. The copepod assemblage observed throughout much of 2009 was relatively depauperate, but species richness increased in response to the 2009–2010 El Niño event to reach anomalously high values by summer 2010 that persisted throughout the year (fig. 22). Copepod species richness reached the same magnitude as that observed during the 1998 El Niño event and the period between 2003 and 2006 marked by a consistently positive PDO. Species richness declined in early 2011, save for during March, when anomalously strong downwelling appears to have driven a temporary enrichment of the

copepod assemblage over the Oregon shelf with southern and oceanic species (fig. 22).

The response of the plankton ecosystem to seasonal and climate variability is also indicated by the relative biomass of several copepod species with northern biogeographic affinities (*Pseudocalanus mimus*, *Calanus marshallae* and *Acartia longiremis*) to total copepod biomass (fig. 23). Biomass of northern copepods declined in response to the 2009–2010 El Niño, and this change in assemblage structure persisted well into summer 2010 before recovering to moderately high levels in late 2010 (fig. 23).

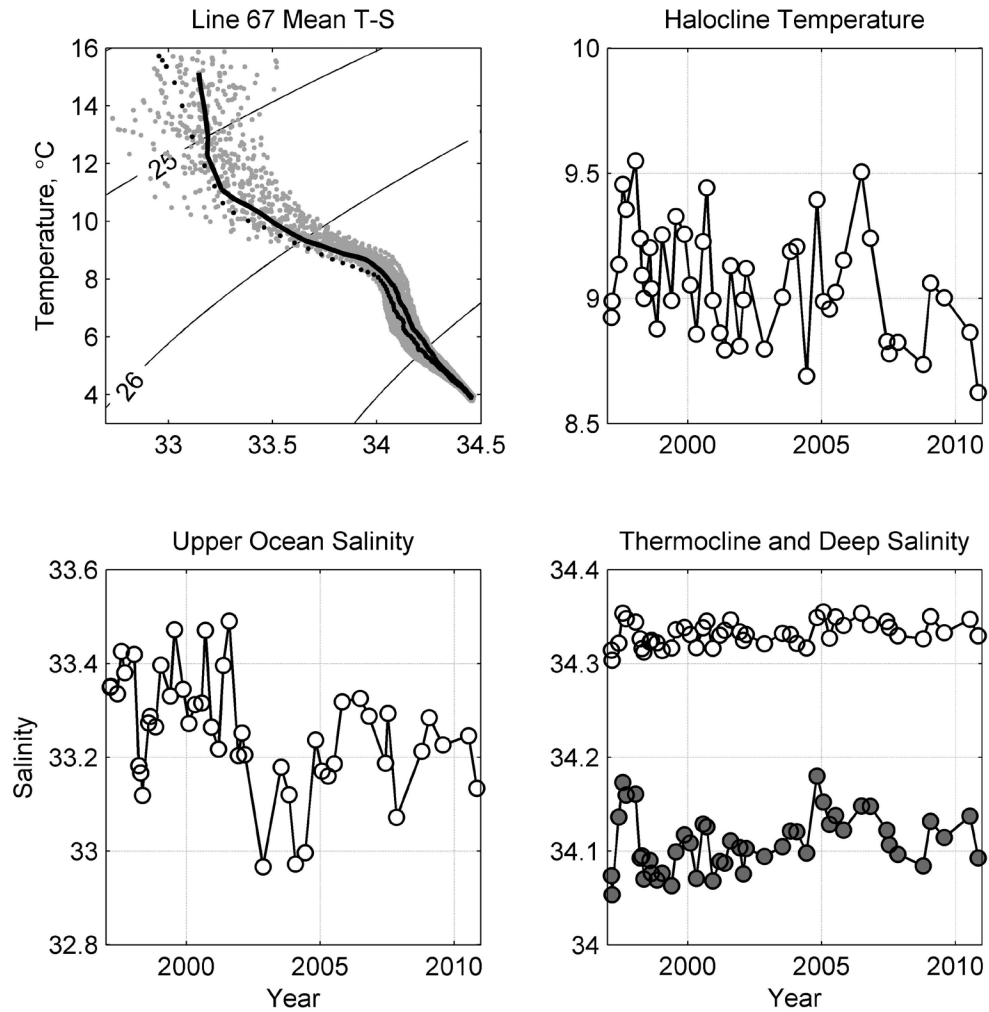


Figure 20. Hydrographic properties along Line 67 from 1997 to 2010. Each cruise included 17 stations along line 67 spaced 20 km apart from H3 (at the entrance to Monterey Bay) to station 67-90 (located 320 km offshore of H3). Data for 47 cruises are shown. (upper left) Mean T-S properties for each cruise. The July 2010 cruise is a solid black line and the November 2010 cruise is a black dotted line. Isopycnals are spaced at 1 kg/m<sup>3</sup> intervals. (upper right) Mean temperature of halocline waters, 33.6<S<34.0. (lower left) Mean salinity of upper ocean waters (waters whose temperature is greater than 10°C). (lower right) Mean salinity of the thermocline, 6°C<T<8°C (closed dots), and deeper waters, T<6°C.

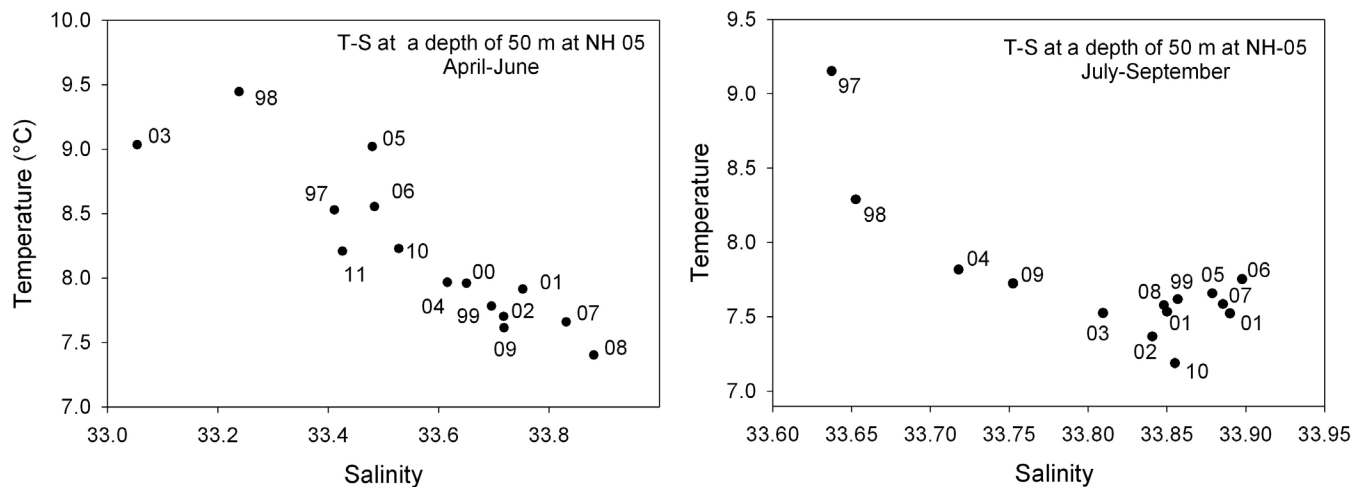


Figure 21. Seasonal mean temperature and salinity at 50 m depth at NH-05 along the Newport Hydrographic Line for spring (left panel) and summer (right panel). Note changes in scale on both temperature and salinity axes. Numbers next to points indicate year of observations.

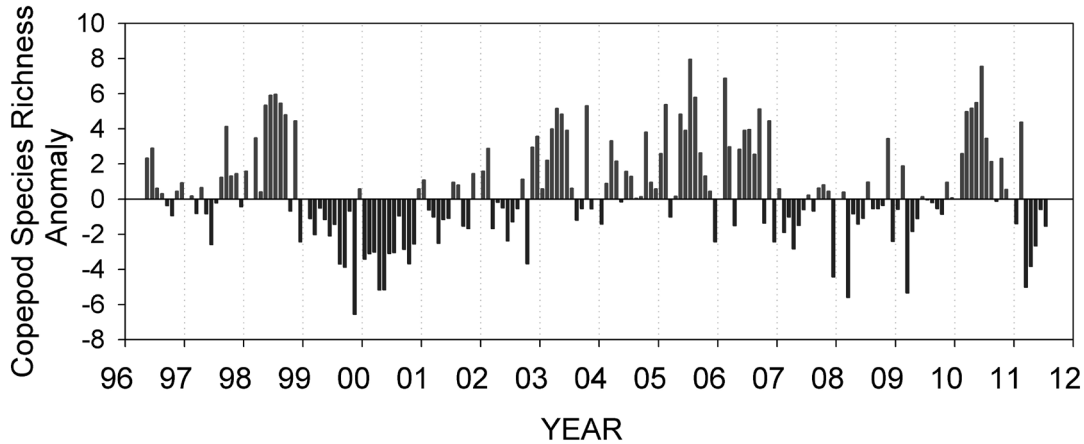


Figure 22. Monthly averaged copepod species richness anomalies at station NH 05 off Newport, Oregon.

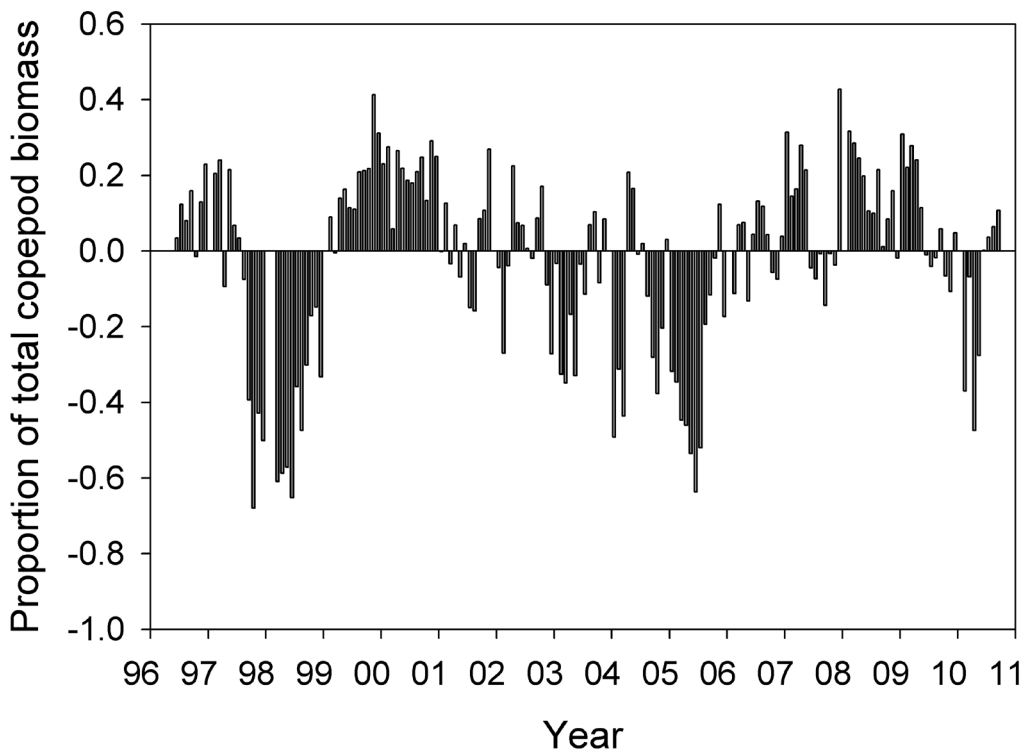


Figure 23. Monthly anomalies in proportion of copepod biomass in samples from the Newport Station 5 [NH05] biweekly time series that was made up by the three dominant northern copepod species (*Pseudocalanus mimus*, *Calanus marshallae* and *Acartia longiremis*; upper panel).

Observations along the Trinidad Head Line<sup>10</sup> indicate a similarly strong reversal from El Niño conditions to La Niña conditions as indicated by the properties of deep, midshelf waters, but also indicate that water properties over the narrow shelf in this region are highly dynamic and respond rapidly to short term variability in wind forcing. In winter 2010, these waters were the warmest observed and nearly the freshest observed (fig. 24). Some of the the coldest, saltiest deep midshelf water was

observed during one cruise in July 2010, but this cold water was replaced by moderately cool waters within a few weeks, so that an unambiguous signal of unusually strong, sustained upwelling was not apparent in the ship-based observations (fig. 24, see also upper panels of fig. 25). Anomalously warm, fresh waters comparable to those observed in winter 2010 were observed in December 2010, but were quickly replaced by cooler, saltier water during active upwelling in early 2011 (figs. 24, 25). Concentrations and distributions of chl *a* at midshelf in summer 2010 were somewhat less than those observed in summer 2008 yet were much greater than in 2009 (data

<sup>10</sup>Details on sampling protocols for the Trinidad Head Line are available in previous reports and online at <http://swfsc.noaa.gov/HSU-CFORT/>.

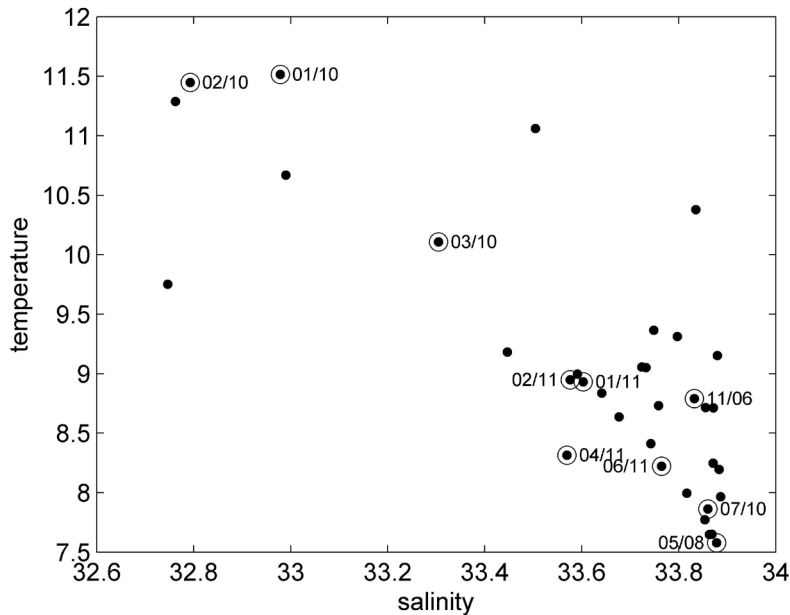


Figure 24. Temperature and salinity at 60 m depth at midshelf (station TH02) along the Trinidad Head Line. Most points represent observations from a single monthly cruise, but several represent average observations from two closely spaced cruises. Date (month/year) labels apply to circled points.

not shown). Observations in early 2011 indicate small blooms, presumably in response to upwelling events in January and February, but high concentrations of phytoplankton over the shelf had not yet been observed.

The copepod assemblage at midshelf along the Trinidad Head Lines continues to have a more southern, more oceanic composition than is observed off Newport, which is consistent with the location of the Trinidad Head Line relative to Newport and the narrow shelf off Trinidad Head (fig. 25). In contrast to the coherent seasonal signals in copepod abundance observed in previous years (Bjorkstedt et al. 2010), copepod densities were low off Trinidad in summer 2010, yet quite high off Newport (fig. 25). This may reflect differences in circulation related to the narrow shelf off Trinidad Head, which might favor (temporary) export of copepods during periods of intense upwelling and offshore Ekman transport. Off Trinidad Head, the copepod assemblage during winter 2010–11 was similar to that observed during the weak 2009–2010 El Niño, in that the assemblage was dominated by more southern taxa. Southern taxa remained common throughout 2010, despite the dissipation of El Niño. In contrast to spring 2010, northern, neritic species had returned in abundance by spring 2011.

## ECOSYSTEM SURVEYS & BIOLOGICAL RESPONSES OF HIGHER TROPHIC LEVELS

### Southern California Pelagic Ecosystem

Spawning of small pelagic fish, such as Pacific sardine (*Sardinops sagax*), northern anchovy (*Engraulis mordax*),

and jack mackerel (*Trachurus symmetricus*), is sensitive to temperature, among other factors, with individual species responding differently to a particular suite of environmental conditions. Information on spawning distributions provides an integrated picture of the CCS from the perspective of these important fishes, and is important to the design of fisheries surveys used to estimate spawning stock biomass from daily egg production.

Comparisons of the spatial distribution of eggs<sup>11</sup> among years with “warm” or “cool” SSTs in April<sup>12</sup> showed that sardine changed their spawning distribution during warm years more than did anchovy or jack mackerel (fig. 26). Sardine moved the furthest north in the warm springs of 2006 and 2010 (fig. 26). The coordinates of the median egg density for April 2011 are also highlighted for comparison. Spawning sardine occurred 30–60 miles northwards and shoreward in warm years. Greater numbers of sardine eggs to the east (shoreward) during warm years may have been caused by movement of spawning sardine into coastal waters during warm Aprils marked by reduced upwelling (fig. 26).

<sup>11</sup>The distribution and density of eggs was determined from the Continuous Underway Fish Egg Sampler (CUFES) using standard methods documented for ichthyoplankton surveys. The data were restricted to latitudes between San Diego and San Francisco to avoid bias by the few surveys that sampled the entire U.S. West Coast (2006, 2008 and 2010).

<sup>12</sup>Monthly Sea Surface Temperature (SST) data (centered on mid-month) were obtained from the Pathfinder v.5 sensor at 5.5 km resolution for each April (approximate center of spawning for Pacific sardine) from 1997 to 2010 between 20–40°N and 116–127°W. SST anomalies at each pixel were calculated by subtracting the mean April value at that pixel for all years, thereby creating an anomaly image. Boxplots centered on the median anomaly value for each anomaly image (i.e., April 1997, April 1998, etc.) were used to create a time series of April SST anomalies which were used to characterize warm and cool years. Eight of the 14 years were warm (1997, 1998, 2000, 2003–2006, and 2010) in April whereas there were 6 cool April years (1999, 2001–2002, and 2007–2009).

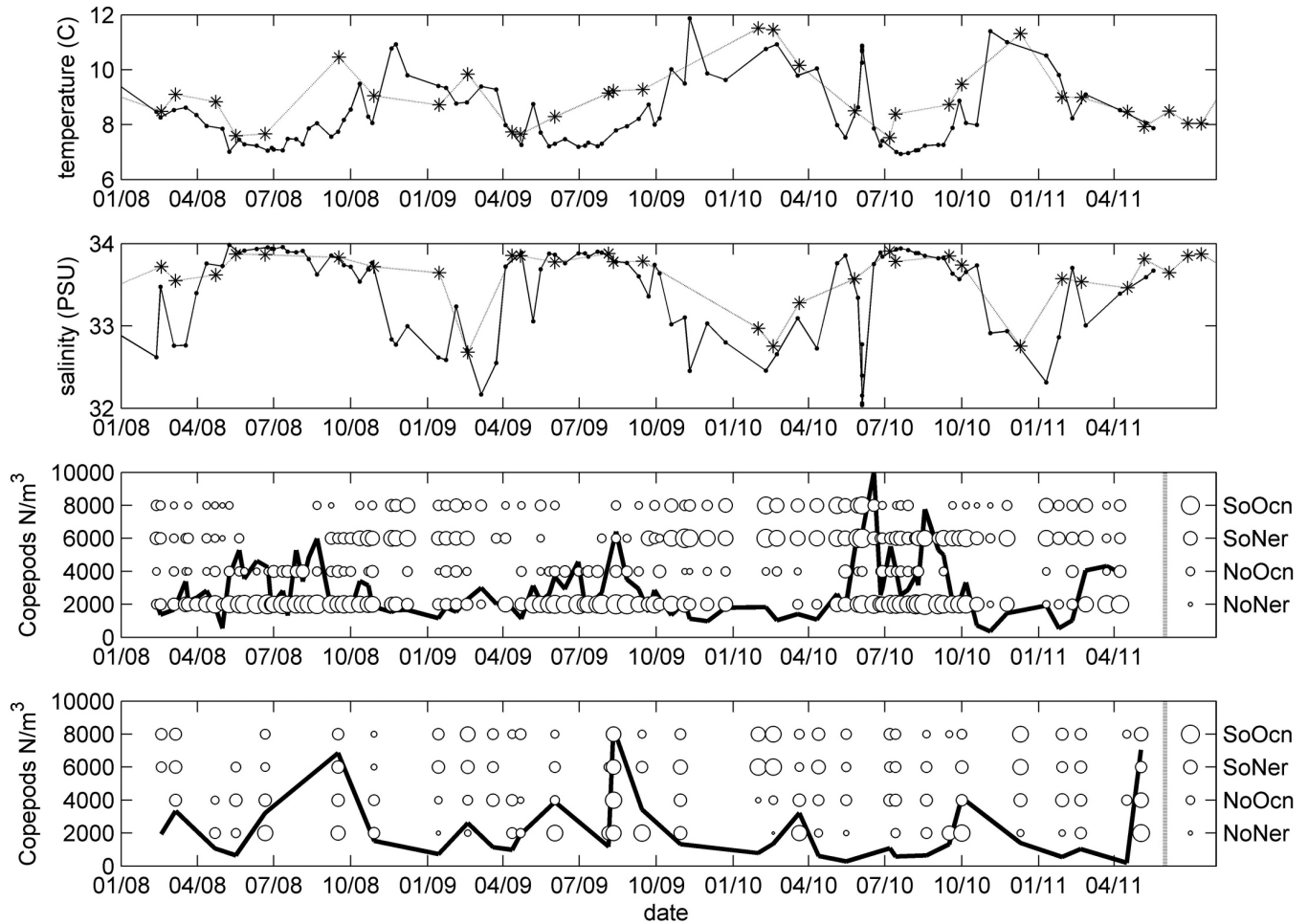


Figure 25. Top two panels: cruise-specific near-bottom temperature and salinity for stations NH05 (solid line with dots) and TH02 (dotted line with asterisks). Bottom two panels: copepod density in vertical ring-net samples collected at stations NH05 (Newport Line, 44.65°N, 124.18°W, 77 m) and TH02 (Trinidad Head Line, 41.06°N, 124.27°W, 77 m), respectively. Dark lines indicate total copepod density. Horizontal series of circles indicate pooled density of selected species from 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*). Density scale for assemblage data is given by symbols to the right of the grey line, which represent densities (from bottom to top) of 1, 10, 100, and 1000 copepods  $m^{-3}$ .

Spawning anchovy also moved eastward in warmer years, but the spawning range did not move toward shore. In contrast to sardine, anchovy did not show any detectable northward shift in warm years (fig. 26). Jack mackerel appear to have expanded their range of spawning northwards in warmer years, yet did not exhibit a corresponding move closer to shore (fig. 26).

It is important to note that this analysis is for an operationally defined region (San Francisco to San Diego) for which the most extensive time series data (14 years) are available. A similar analysis of data from the three coastwide surveys (2006 warm, 2008 cool and 2010 warm years) suggests that northward shifts of both sardine and anchovy are enhanced (and detected) during warm years, but change little for jack mackerel. These patterns are consistent with observations of considerable spawning of sardine off Oregon in some years, and

the presence of anchovy eggs off the Columbia River mouth. We anticipate that future analysis of coastwide data sets will resolve responses of spawning distributions to ocean conditions in greater detail as the time series of coastwide surveys continues to grow.

Spawning distributions observed in spring 2011 present a mixed picture of ocean conditions. The distribution of sardine eggs resembles that of warm years, in that the position of median egg density was coincident with that observed for warm years (fig. 26). There was almost no spawning of sardine in the Southern California Bight in April 2011, and instead sardine spawned off the southern part of Central California (south of San Francisco), including areas near to shore. This pattern was similar to that observed in the warm years of 2004 and 2010, yet differs from other years (e.g., 2002–05) during which sardine spawned in the northwest portion of the survey

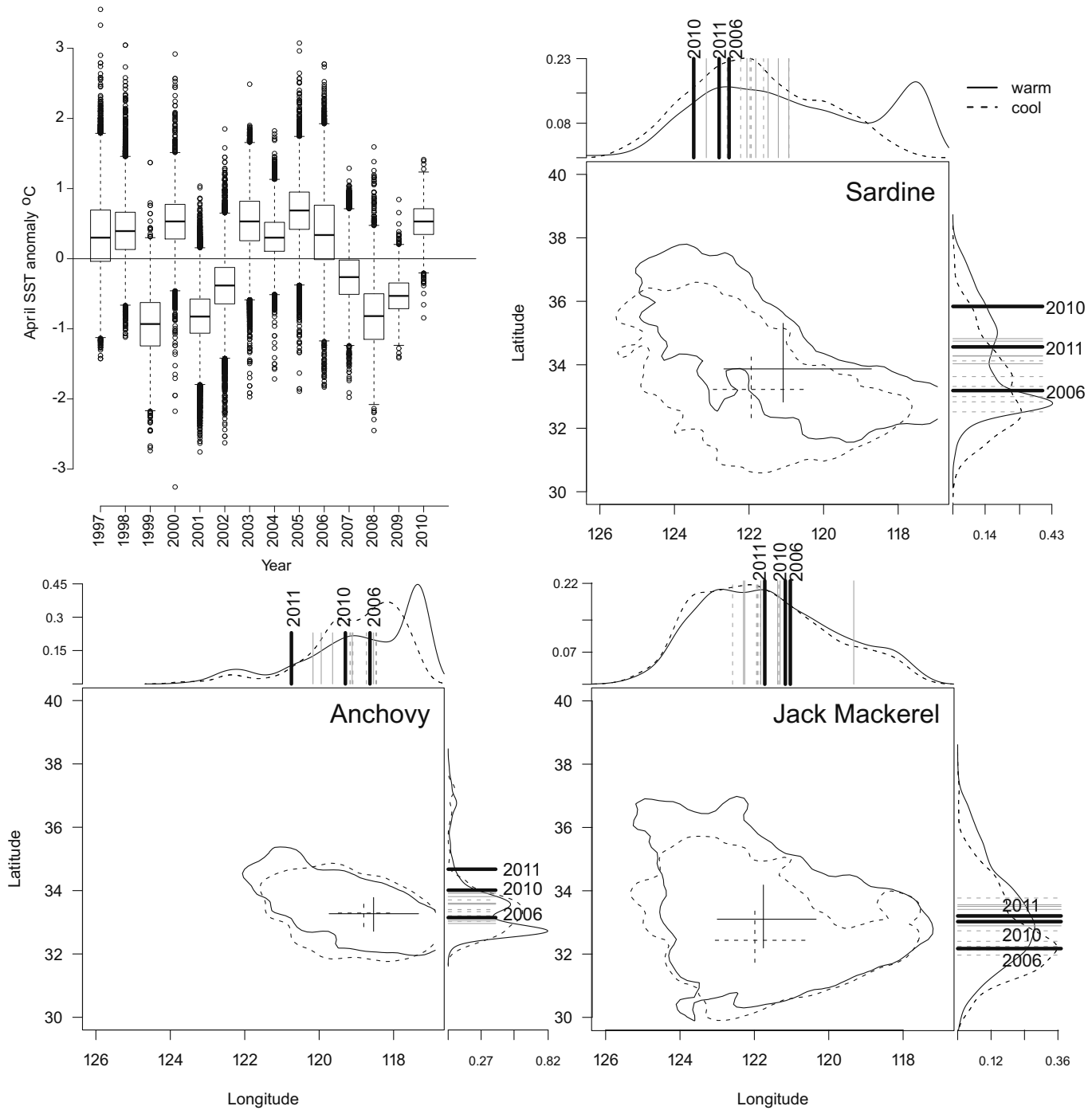


Figure 26. Upper left panel: boxplots of satellite SST anomalies used to characterize spring temperatures as either warm or cool. Distributions of sardine (upper right panel), anchovy (lower left panel) and jack mackerel (lower right panel) spawning observed between San Francisco and San Diego in anomalously warm compared to anomalously cool years ( $n = 14$  years). Marginal plots show the density distribution of sardine eggs in relation to latitude and longitude. Heavy black lines show the position of the median density distributions in April 2006, 2010 and 2011. Cross hairs on the main plot show the location of the median density and the 25th and 75th inter-quartile range for the latitude and longitude. Ellipses show the 99% confidence interval for the bivariate density distribution of the eggs (i.e., 0.5% of the distribution at the tails of each of the marginal plot density distributions are outside the ellipse).

region. In contrast, jack mackerel spawned to the west of  $122^{\circ}\text{W}$  at  $34\text{--}35^{\circ}\text{N}$ , which is about 60 miles south of where they usually spawn in warm years. Patterns of sardine and jack mackerel spawning are consistent with intermediate April conditions (i.e., neither notably

warm or cool). There was little anchovy spawning in April 2011, consistent with expected timing of anchovy spawning in late winter rather than coincident with the spring survey.

In spring 2010, sardine eggs remained far less abun-

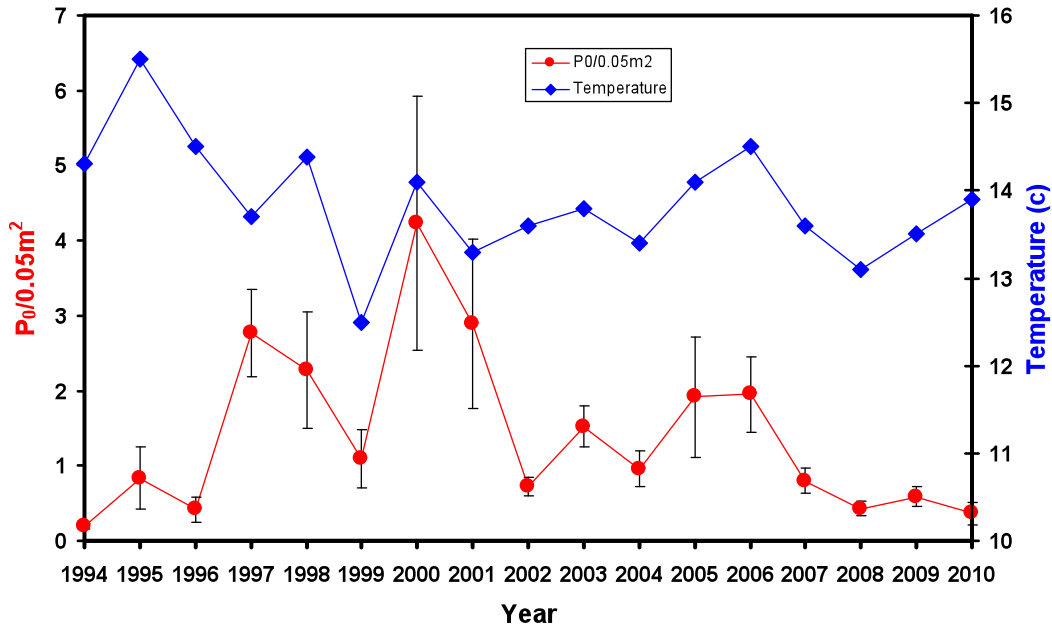


Figure 27. Daily egg production/0.05m<sup>2</sup> of Pacific sardine (circle) (+ and – one standard error) and average sea surface temperature (°C) (diamond) during March–April DEPM cruises from 1994–2010.

dant than in years prior to 2007. Spawning biomass Pacific sardine<sup>13</sup> based on analysis of these data using daily egg production methods suggests that Pacific sardine biomass remains small relative to the late 1990s and early 2000s (fig. 27). There is no evidence for an increase in daily egg production in relation to increased average sea surface temperatures observed in 2010.

### Southern California Cetaceans

Visual surveys for cetaceans on quarterly CalCOFI cruises found that the relative abundance of various species of small cetaceans in 2010–11 was similar to that observed for previous years with the exception of Dall’s porpoise (*Phocoenoides dalli*) which exhibited the second highest sighting rate observed for this species across the seven-year sampling period. Colder than average water temperatures in 2010–11 may have contributed to the increased relative abundance of Dall’s porpoise as this species is generally restricted to cold/temperate waters. Relative abundance of baleen whales also increased from previous years for three of four common baleen whale species, fin whales (*Balaenoptera physalus*), humpback

whales (*Megaptera noveangliae*) and gray whales (*Eschrichtius robustus*), all of which were sighted at rates nearly double the average, representing the second highest levels observed for the three species across the seven-year study period. The increase in sighting rates of large planktivorous whales is likely to reflect behavioral responses abundant prey resources in the region.

Despite the increase in sighting rates for several taxa, the visual surveys did not detect substantial changes in the cetacean assemblage off Southern California. While annual species richness (average number of species per km of effort) of cetaceans was similar to that observed during previous years, species richness was higher in spring 2010 and lower in summer 2010 relative to the seasonal averages since 2004, despite sighting rates were consistent with previous years’ efforts (data not shown).

### Central California Pelagic Ecosystem

Analysis of catch composition and abundance of key taxa from annual midwater trawl surveys<sup>14</sup> off Central California indicated that 2011 continues the trend observed in recent years towards increasing abundance of species and assemblages that tend to thrive under cool,

<sup>13</sup>The spring 2010 California Current Ecosystem (CCE) survey was conducted aboard one NOAA research vessel: *Miller Freeman* and a chartered fishing vessel: *F/V Frosti*. *Miller Freeman* (April 2–22) covered the area off California from San Diego to Monterey Bay (CalCOFI lines 95 to 66.7) and the *F/V Frosti* (March 28–April 28) covered the area from just south of Cape Flattery, Washington to just south of Monterey Bay, California (48.07°N to 34.88°N, i.e., CalCOFI line 70). During the CCE surveys, CalVET tows, bongo tows, CUFES and trawls were conducted aboard both vessels. After the CCE survey, the routine spring CalCOFI survey was carried out aboard *Miller Freeman* from April 26–May 17 to cover six lines from 93.3 to 76.6 and CalVET and bongo tows were taken. Only data from CCE survey were included in estimation of spawning biomass of Pacific sardines. Data from all spring cruises were used to examine the spatial distributions of Pacific sardine, northern anchovy and jack mackerel.

<sup>14</sup>Observations reported here are based on midwater trawl surveys that target small (1–20 cm) pelagic fishes and invertebrates conducted off central California (a region running from just south of Monterey Bay to just north of Point Reyes, CA, and from near the coast to about 60 km offshore) since 1990 (see Sakuma et al. 2006 for methods and details on spatial extent of survey). Cruises have been conducted on the NOAA ship *David Starr Jordan* (1990–2008), the NOAA Ship *Miller Freeman* (2009), the *F/V Frosti* (2010), and the *F/V Excalibur* (2011). Data for the 2011 survey presented here are preliminary, and data collected since 2009 do not 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.

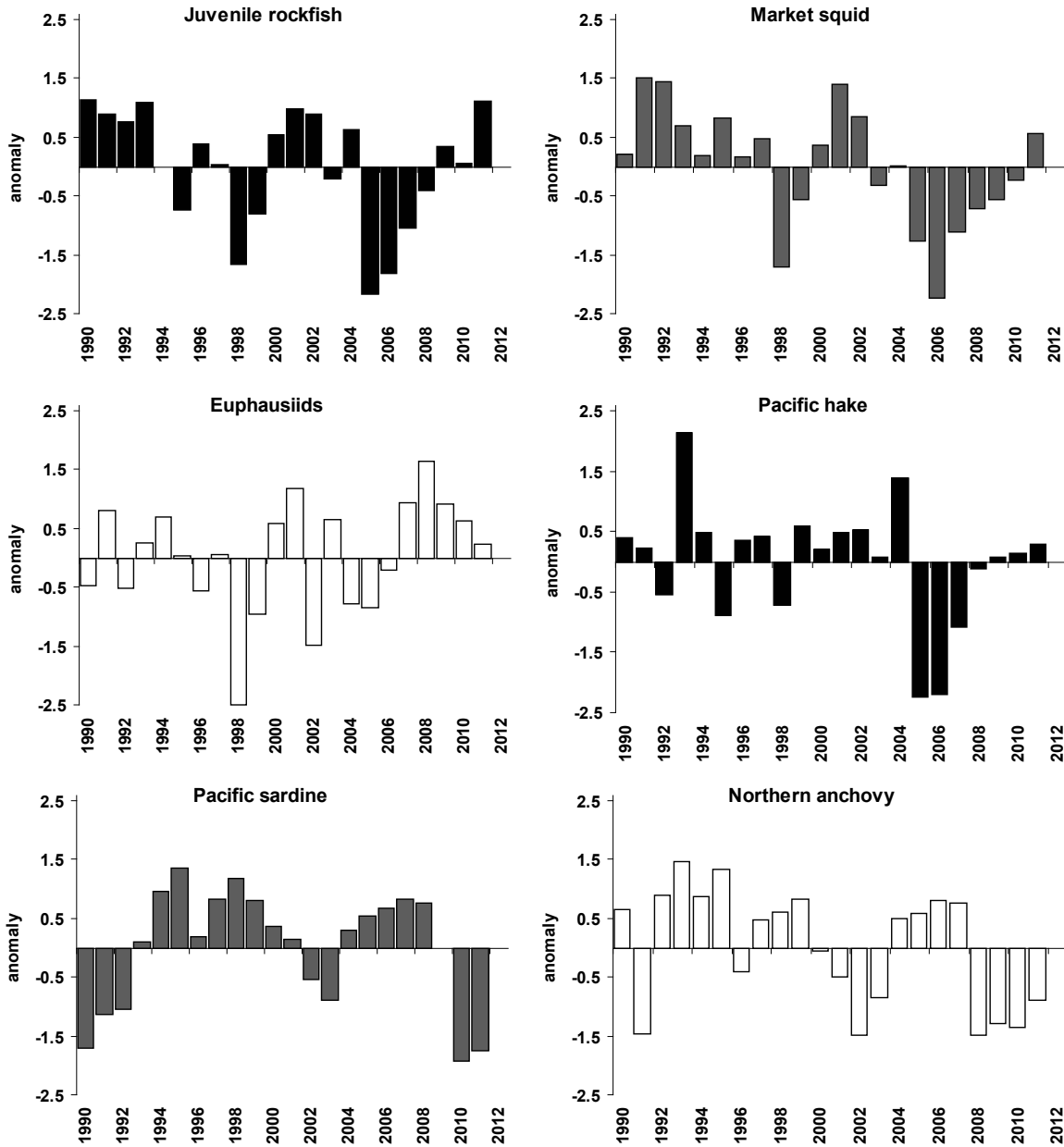


Figure 28. Long-term standardized anomalies of several of the most frequently encountered pelagic forage species from the central California rockfish recruitment survey in the core region (1990–2011 period only, not all taxa were recorded from 1983–89).

productive conditions, and a return to ecosystem characteristics similar to those seen in the early 1990s and early 2000s (fig. 28). In 2011, juvenile rockfish (*Sebastes* spp.), market squid (*Loligo opalescens*), and other groundfish (such as Pacific hake [*Merluccius productus*], shown, and Pacific sanddabs [*Citharichthys sordidus*], not shown) were at their highest levels since the early 2000s and early 1990s. By contrast, the coastal pelagic forage species (adult northern anchovy and Pacific sardine) were at low levels in 2010 and 2011, although this is likely a greater reflection of their local availability and ocean conditions rather than their coastwide or regional abundance. Euphausiids continued to be abundant, but less so

than in 2008–10. For the second year in a row, no Humboldt squid were captured during the survey.

Trends observed in the six indicators shown in Figure 28 are consistent with trends across a number of other taxa within this region. Results from a Principal Components Analysis of annual catch data<sup>15</sup> highlight

<sup>15</sup>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 (representing strong covariance among young-of-the-year groundfish, cephalopods and euphausiids, which in turn tend to be negatively correlated with coastal pelagic and mesopelagic fishes).



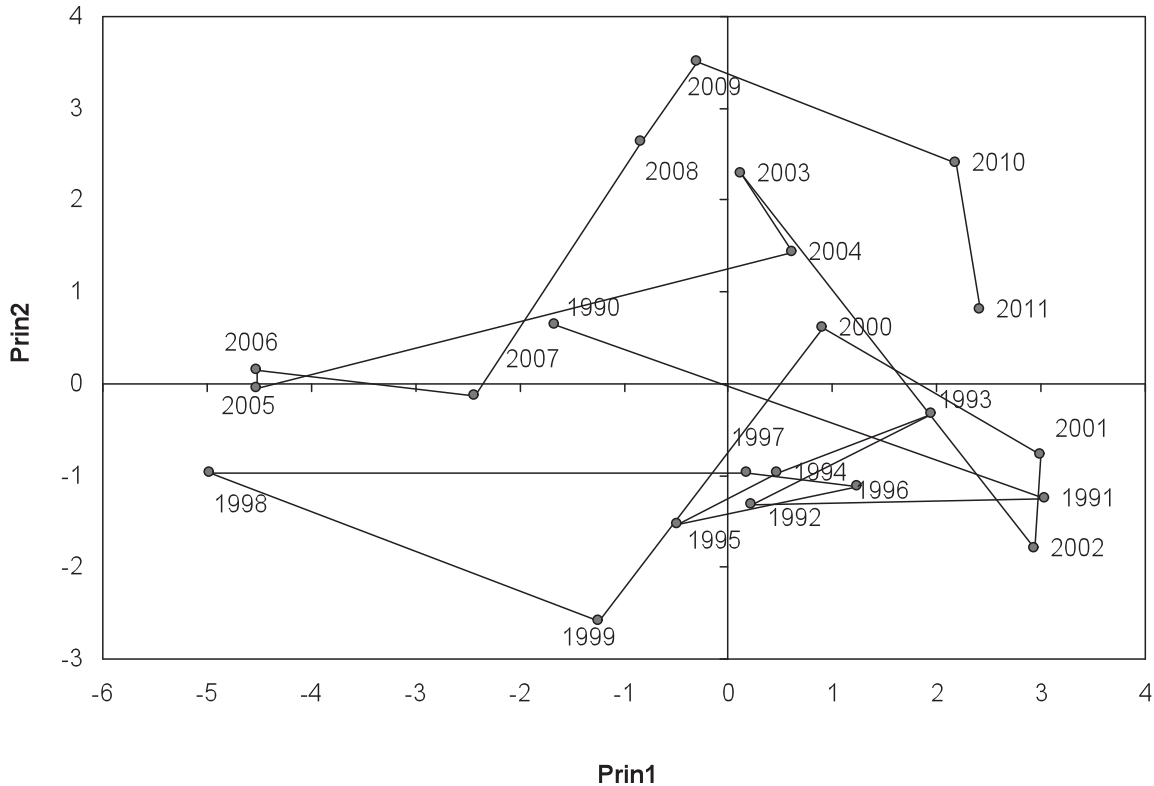


Figure 29: Temporal changes in pelagic ecosystem structure off central California based on PCA of the fourteen most frequently encountered species groups in the NMFS midwater trawl survey. Data are taken from stations in the core area (Point Reyes to Monterey Bay) from 1990–2011.

changes in the midwater assemblage over time: the clupeoid-mesopelagic group was prominent during the 1998 El Niño and during the anomalously warm years 2005–07, while the groundfish group prospered during the early 1990s, the cool-phase between 1999 and 2003, and most recently from 2009 through 2011 (fig. 29). As with the 2009 and 2010 data, results from 2011 continue to represent a return towards 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 Central and Southern California

Two data sets provide observations on seabirds off the California coast: estimates of reproductive success of seabirds on the Farallon Islands<sup>16</sup>, a major breeding colony for several seabird species, and at-sea densities of seabirds from ship surveys off southern California<sup>17</sup>. Observations from SE Farallon Island indicate that the 2010 breeding season was extraordinarily successful for most seabirds on the Farallon Islands, with many species having their best

breeding year since 2004 (Warzybok and Bradley 2010). Productivity of Cassin's auklets (*Ptychoramphus aleuticus*) was the highest ever recorded for this species, due in part to unprecedented high rates of successful double brooding (the fledging of a second chick after a successful first attempt) (fig. 30). Among the piscivorous seabirds, common murre (*Uria aalge*) and rhinoceros auklets (*Cerorhinca monocerata*) had their highest level of breeding success in the last 20 years (fig. 30). Productivity of pigeon guillemots (*Cepphus columba*) exceeded the long term mean for the first time since 2004 (fig. 30). Pelagic cormorants (*Phalacrocorax pelagicus*) showed a second year of strong productivity after 4 years of near breeding failure (fig. 30). The high productivity of these species is likely to reflect elevated productivity in the Gulf of the Farallones during spring and summer 2010: euphausiids and juvenile rockfish were both highly abundant. In contrast, western gulls (*Larus occidentalis*) had their poorest year on record, and Brandt's cormorants (*Phalacrocorax penicillatus*) continued to suffer very low reproductive success though they did manage to fledge a small number of young this season after two years of near complete breeding failure (2008–09) (fig. 30).

Off southern California, at-sea densities of sooty shearwater (*Puffinus griseus*) showed an increase in relative abundance in 2009 and 2010, despite a long-term decline that has persisted across seasonal and multiyear

<sup>16</sup>See Warzybok and Bradley 2010 for a description of methods.

<sup>17</sup>Surveys of marine birds have been conducted in conjunction with seasonal CalCOFI/CCE-LTER cruises since May 1987 (84 surveys through July 2010). Observations are collected by experienced observers, who identify and count seabirds within a 300 m wide strip transect while the ship is underway at speeds >5 k (see Yen et al. 2006 for details). Relative abundance is expressed as density of birds at sea (birds km<sup>-2</sup>).

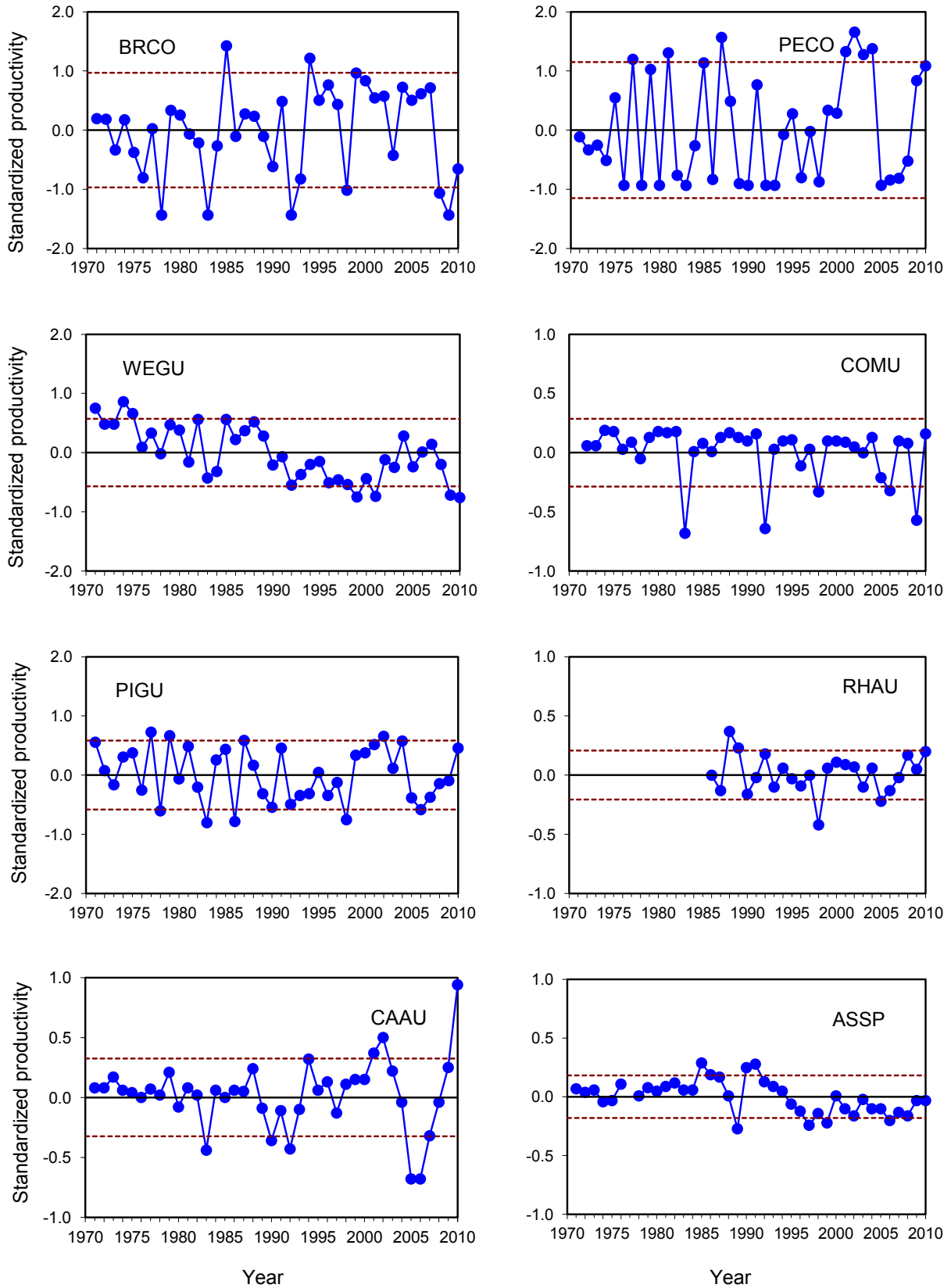


Figure 30. Anomalies of productivity (annual productivity—long-term mean) for 8 species of seabirds on SE Farallon Island, 1971–2010. Dashed lines represent 80% confidence intervals for the long-term means. Species are Brandt's cormorant (*Phalacrocorax penicillatus*; BRCO), western gull (*Larus occidentalis*; WEGU), pigeon guillemot (*Cepphus columba*; FIGU), Cassin's auklet (*Ptychoramphus aleuticus*; CAAU), pelagic cormorant (*Phalacrocorax pelagicus*; PECO), common murre (*Uria aalge*; COMU), rhinoceros auklet (*Cerorhinca monocerata*; RHAU), and ashy storm petrel (*Oceanodroma homochroa*; ASSP).

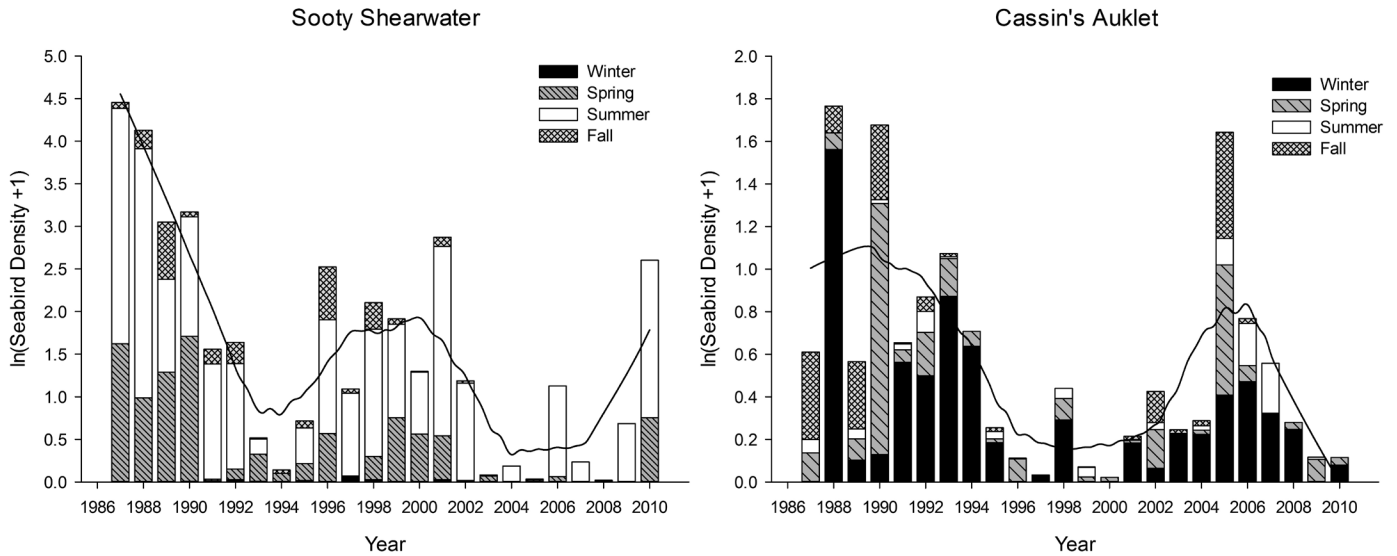


Figure 31. Changes in relative abundance (birds km<sup>-2</sup>) of sooty shearwater (*Puffinus griseus*) and Cassin's auklet (*Ptychoramphus aleuticus*) observed during CalCOFI surveys, May 1987–July 2010. Bars denote summed seasonal density estimates (stacked bars), with a Lowess smoothing (bandwidth=0.3) line shown for each species.

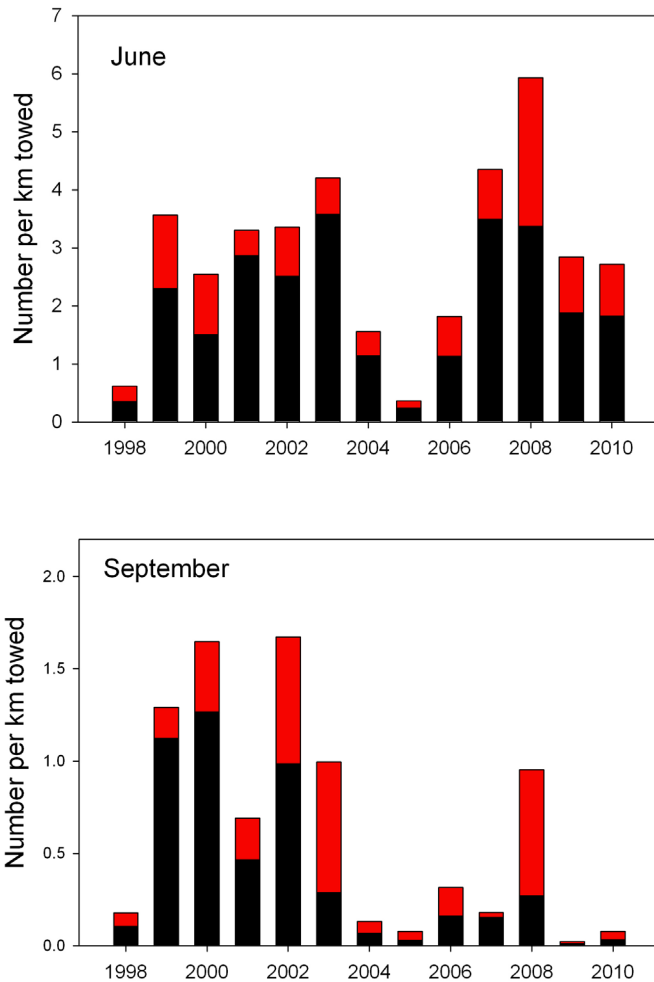


Figure 32. Catches of juvenile coho (black bars) and Spring Chinook (red bars) salmon off the coast of Oregon and Washington in June and September, from 1998–2010.

(e.g., peak-to-peak) temporal scales (fig. 30). In contrast, at-sea densities of Cassin's auklet (*Ptychoramphus aleuticus*) off southern California were observed to decline in 2009 and 2010 (fig. 31). Although both shearwaters and auklets are species with cold-water affinities (Hyrenbach and Veit 2003) that have spatial associations with euphausiids (Santora et al. 2011), these divergent temporal patterns are consistent with differences in life history of the two species. Shearwaters are (austral) wintering migrants from southern hemisphere (Shaffer et al. 2006), and are likely to respond more directly, in terms of abundance and distribution, to the distribution and density of local prey resources. Auklets breed in the CCS (Abraham and Sydeman 2004) and thus can be expected to have a more complex response to changes in prey availability. For example, in years when auklet breeding effort was compromised by poor prey availability in the Gulf of the Farallones (e.g., 2005 and 2007), auklets abandoned their major breeding site on SE Farallon Island and may have moved south in search of prey (Sydeman et al. 2006, 2009). In contrast, the high abundance of euphausiids and other prey in the Gulf of the Farallones during 2009 and 2010 would not force such emigration.

### Pelagic Fishes Off Oregon and Washington<sup>18</sup>

Catches of juvenile salmonids in pelagic rope trawl surveys were about average in June 2010 but very low by September 2010, including the second lowest num-

<sup>18</sup>For information on methods and sampling locations for the juvenile salmon surveys, see <http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm>. Data on pelagic predatory and forage fishes are from ongoing bimonthly surface trawls conducted from May to August off the Columbia River and Willapa Bay. See Phillips et al. 2009 for details on methods used for sampling larval and juvenile fishes.

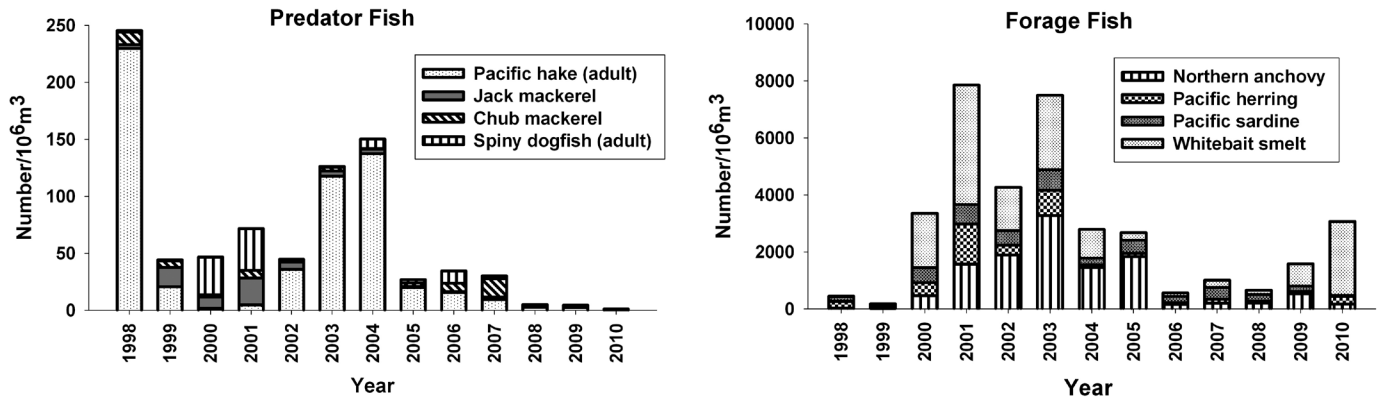


Figure 33. Annual average densities of predatory fishes (left panel) and forage fishes (right panel) captured off the Columbia River/Willapa Bay by nighttime surface trawling between May and September.

ber of coho salmon (*Oncorhynchus kisutch*) caught in the 13 year time series (fig. 32). This pattern is similar to that observed in 2009, in which moderately high abundances of juvenile salmonids in summer appear to have not carried through into the fall.

In 2010, average densities of predatory fishes<sup>19</sup> between May and September off Oregon and Washington were the lowest observed during the 13 year study period (fig. 33a). In contrast, average density of aggregate forage fishes off Willapa Bay (north of the Columbia River) in 2010 reached its highest value since 2003, and fourth highest overall (fig. 33b). This pattern was not consistent across species. Whitebait smelt (*Allosmerus elongatus*) and Pacific herring (*Clupea pallasii*) were both abundant. Migratory species with more southern affinities showed a different pattern: Pacific sardine (*Sardinops sagax*) catches were the lowest in the 13-year time series, and those of northern anchovy (*Engraulis mordax*) were the lowest since 2006 (the fourth lowest overall; fig. 32b).

Along the Newport Hydrographic Line, nearshore concentrations of larvae were higher in winter 2010 than in any winter since 1998 (data not shown; Auth et al., in prep.). This concentration of larval fishes near the coast during the early (El Niño) period of 2010 (including offshore taxa) was also marked by unusual onshore distributions of offshore taxa and the presence of taxa with more southern affinities, but these patterns were strongly reversed following the transition to La Niña later in spring 2010 during which low nearshore concentrations of larval fishes occurred (Auth et al., in prep.).

The transition from El Niño to La Niña also influenced the distribution and structure of the ichthyoplankton assemblage in the northern California Current. Surveys off Oregon and Washington encountered rela-

tively low concentrations of larval fishes (primarily rockfishes *Sebastes* spp.) in June and September 2010 (fig. 34). Among the assemblage of juvenile fishes, rockfishes and flatfishes showed a marked increase from low numbers in June to the highest catches recorded, but Pacific hake were notably rare in 2010 (fig. 34). Moreover, the mean size of juvenile rockfish caught in September was the highest recorded in this survey, suggesting that growth was strong during the spring and summer. Juvenile northern anchovy were relatively abundant in June 2010 (similar to levels observed in 2005), but, in contrast to 2009, made up only a minor component of the assemblage in September 2010 (fig. 34).

### Humboldt Squid

The presence of Humboldt squid (*Dosidicus gigas*) in the CCS appears to have declined to trace levels. In contrast to the record numbers encountered in 2009, no squid were captured by either of the two trawl surveys reported above, and relatively few squid were captured during fall sampling and in the hake fishery.

### DISCUSSION

The state of the California Current system (CCS) since spring 2010 has evolved in response to the development of cooler La Niña following the dissipation of the relatively weak and short-lived El Niño event of 2009–2010 (Bjorkstedt et al. 2010). The 2009–2010 El Niño appears to have dissipated quite rapidly in early spring 2010, yet the transition to anomalously cool conditions followed somewhat later with the onset of anomalously strong upwelling throughout the CCS in summer 2010. Patterns in winds and sea surface temperature reported at several moorings along the coast were corroborated by remotely sensed surface current fields that captured the signature of intense upwelling throughout much of the CCS in the spring and summer of 2010. Moreover, the broad patterns discerned from coastwide observations were also reflected in the unusually cool

<sup>19</sup>This analysis focuses on four common species of predatory fishes: chub mackerel (*Scomber japonicus*), jack mackerel (*Trachurus symmetricus*), adult Pacific hake (*Merluccius productus*), and spiny dogfish (*Squalus acanthias*). Juvenile (yearling) Pacific hake are not yet piscivorous at the ages and sizes present in the collections, and so are not included in the estimates of predatory fish density.

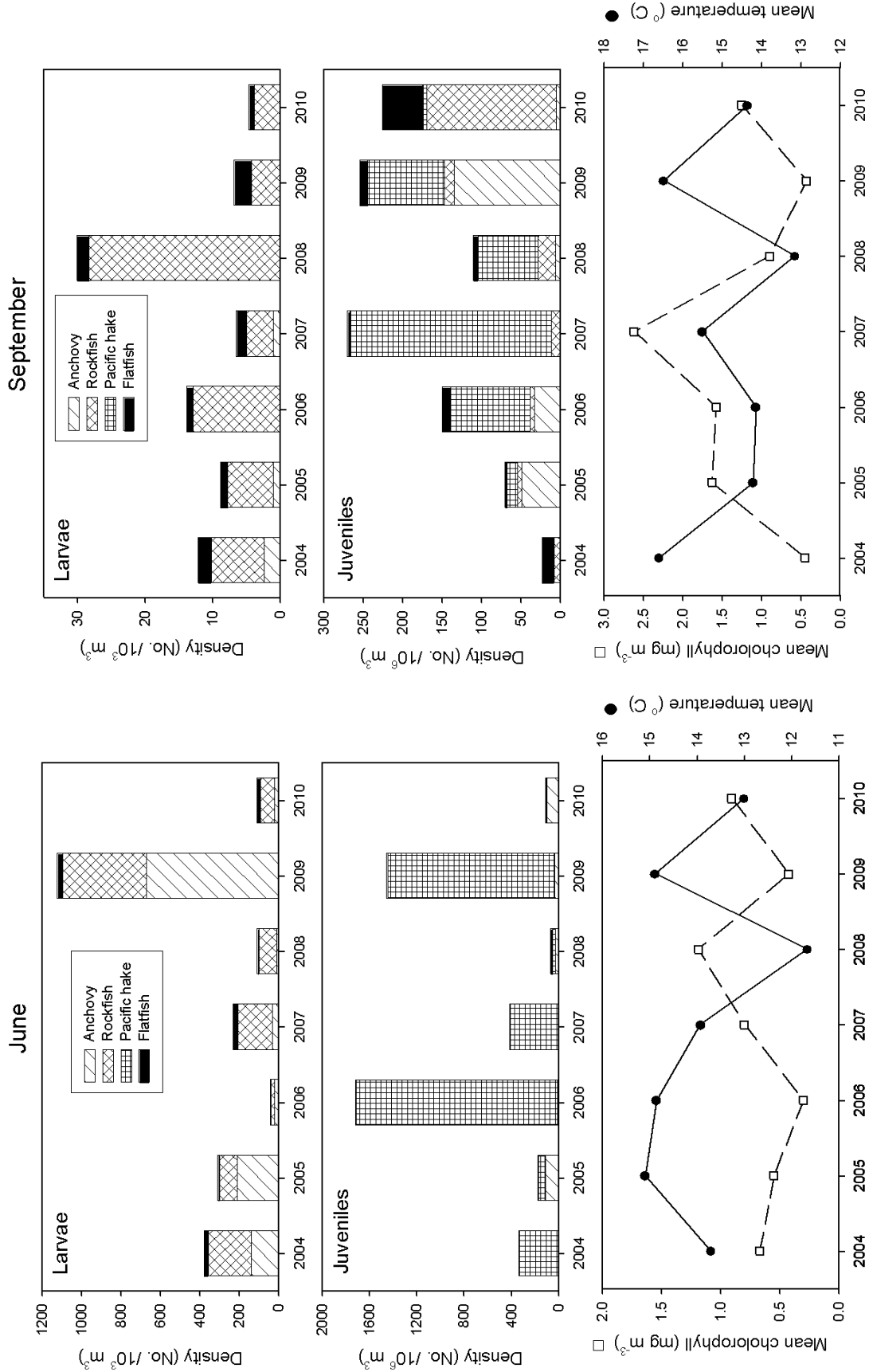


Figure 34. Mean densities of the dominant taxa for larval (top) and juvenile (middle) fish densities and mean temperature and chlorophyll concentrations (bottom) from the upper 50 m of the water column collected concurrently with the fish data for cruises conducted in June (left hand column) and September (right hand column) of each year (2004–10). See Phillips et al. 2009 for sampling details.

conditions observed during ship surveys throughout the CCS in summer 2010 (off Oregon and California) and fall 2010 (Baja California), some of which encountered the coldest (spatially averaged) conditions within the respective surveys' observational record.

Although the transition to cooler conditions was reported throughout the CCS, several factors contributed to continued regional variability in the response of the CCS to climate forcing. In particular, important differences continue to be observed between the northern and southern portions of the CCS, which appear to be related to regional differences in the timing, direction, and magnitude of climate forcing. For example, whereas the return to cooler conditions in spring and summer 2010 was fairly general across the CCS, regional variability was clearly evident in the fall when anomalously warm SST emerged briefly in the northern CCS while temperatures remained anomalously low in the southern portion of the CCS. This pattern corresponds with the decline from strong positive to moderately negative anomalies in upwelling, such that upwelling persisted in the south, but effectively relaxed in the north. Regional variability was also apparent during winter 2010 and into early 2011. During this period, the northern CCS was affected by highly variable winds, including strong downwelling events associated with winter storm activity that persisted well into spring 2011 and a prolonged period of quiescent winds in midwinter 2011. In contrast, the southern CCS appears to have experienced more consistent upwelling at near normal levels throughout the year.

Ecosystem responses to the transition from El Niño to La Niña follow some predictable patterns, such as the increase in phytoplankton (as indexed by chl *a*) in several regions, particularly those areas most directly influenced by coastal upwelling. Observations of zooplankton and higher trophic levels in several regions suggest responses that are also consistent with cooler, presumably more productive, conditions. Interestingly, however, the regional variability observed in the strength and timing of the transition from El Niño to La Niña and subsequent evolution of climate forcing and responses across the CCS appears also to manifest in the several different ecosystem data sets that were considered here. For example, off central California, the nektonic assemblage continued its trend towards a "cool conditions" assemblage into 2010 and 2011, and several species of seabirds that depend on this euphausiid-groundfish rich nektonic assemblage fared exceedingly well in 2010 despite the El Niño. Likewise, the recent resurgence of crustacean zooplankton off Baja California points to increased enrichment and productivity. A similar response was not apparent in spatially averaged zooplankton data for southern California, but increased

densities of migratory seabirds and planktivorous cetaceans are consistent with a more productive ecosystem. In contrast, the copepod assemblage off Oregon, which is a useful indicator for salmon productivity, did not recover rapidly and retained some characteristics of the assemblage observed during the transition from La Niña to El Niño in 2009, despite the onset of strong upwelling in early summer 2010. Juvenile salmon off Oregon also showed a sharp decline in abundance over the summer comparable to that observed during the onset of the 2009–2010 El Niño, yet, this occurred under consistently cool conditions, suggesting that prey availability and quality may have affected survival, with temperature proving less useful than prey data as an indicator of salmon productivity.

Interpretation of ecosystem responses to climate variability is likely to be confounded by inertia in ecosystem dynamics related to population dynamics and persistent effects of transport that preclude or blur "instantaneous" response to climate forcing. For example, while phytoplankton may respond rapidly to enrichment events, zooplankton and higher trophic levels may be as or more sensitive to "pre-conditioning" of the ecosystem during the winter (Black et al. 2010), to the standing stock based on productivity or transport events during the previous year, or to dynamics unfolding over longer time scales. For example, the persistence of copepod species with southern affinities in the northern CCS into 2010 may reflect lingering effects of poleward transport, and changes in distributions of pelagic fishes throughout the CCS may integrate the consequences of and responses to conditions in previous years. The potential role of unusual species interactions in the dynamics of higher trophic levels must also be considered, e.g., the potential effects of high abundances of Humboldt squid (*Dosidicus gigas*) in recent years may have contributed to reductions in pelagic fishes (Litz et al., this issue).

Several recent trends or novel observations warrant further consideration and closer examination in future reports. For example, data from the southern regions (CalCOFI and IMECOCAL surveys) have indicated a freshening trend in the upper water column. How pervasive this trend might be throughout the CCS is of interest, as it may be indicative of recent strengthening of the California Current and enhanced equatorward transport of subarctic water. Likewise, the unusual increase in nitrate concentration within the CalCOFI region requires additional consideration and, ideally, comparison to analogous data sets elsewhere along the coast. Trends in the composition of the zooplankton community (e.g., changes in the dominance of gelatinous taxa, as reported off Baja California) also bear further examination to determine the scale at which such dynamics unfold in the CCS.

To summarize, observations of the state of the CCS during 2010 and early 2011 capture the development of cooler La Niña conditions throughout the CCS, but continue to indicate substantial regional variability in how climate variability measured by basin-scale indices manifest locally. Off southern California, the effects of both the 2009–2010 El Niño and subsequent return to La Niña conditions appear to have had modest effects on the system, and the patterns that attract interest appear to be unfolding over longer time scales (e.g., freshening of upper water column and trends in nitrate and oxygen concentrations). In contrast, the northern California Current has exhibited much more dramatic short-term changes over the past two years, due in part to greater variability in environmental forcing affecting this region. At the time of writing, tropical conditions are ENSO neutral and forecast to remain so into fall 2011 and possibly into early 2012<sup>20</sup>, yet the PDO remained strongly negative into summer 2011. It is therefore uncertain whether the return to cool conditions observed in the past year will continue to govern the state of the California Current.

Looking forward, we note that several questions are raised by the recent perception of regional structure in the way the CCS responds to climate variability, a perception supported by several data sets reviewed in this paper and in previous reports in this series (Goericke et al. 2005; Peterson et al. 2006; Goericke et al. 2007; McClatchie et al. 2008, 2009; Bjorkstedt et al. 2010). Moreover, of the several spatial and temporal modes of climate variability that influence the CCS (Mantua et al. 1997; Wolter and Timlin 1998; Ashok et al. 2007; Di Lorenzo et al. 2008), some, particularly those associated with El Niño Modoki, have been strengthening in recent decades, and exhibit spatial patterns that vary within the domain of the CCS (Messié and Chavez 2011). The possibility for emergent or enhanced regional variability in the CCS to be a consequence of climate forcing clearly warrants closer scrutiny. Ideally, these questions will be amenable to more comprehensive analysis of data sets from established research and observing programs, but are also likely to profit greatly by integrating data from the several coastwide surveys that have been established in recent years. Such efforts should yield deeper insight to the scale and magnitude of regional variability in responses to climate forcing. Just as importantly, we expect that such efforts will also provide greater opportunity for connecting to ongoing efforts to develop and enhance ecosystem assessments for the California Current.

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