RECORD COASTAL UPWELLING IN THE CALIFORNIA CURRENT IN 1999

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ABSTRACT

An extremely unusual level of coastal upwelling in the spring and summer of 1999 over much of the California Current system (CCS) is described, based on direct and indirect observations. Wind and ocean anomalies in 1999, a period characterized by an equatorial La Niña, are compared to climate trends for the previous several years, and specifically contrasted with the extremes associated with the 1997–98 El Niño event. Conditions in the CCS during the spring and summer of 1999 were consistent with extremely high levels of sustained coastal upwelling. The Pacific Fisheries Environmental Laboratory (PFEL) upwelling indices reached record highs for a series extending back to 1946. Strong, sustained upwelling-favorable winds were measured at coastal buoys through late 1998 and much of 1999. Coastal sea-surface temperatures (SSTs) were 3°–4°C below their seasonal mean in spring 1999, and about 10° cooler than the region experienced in late 1997. Hydrographic surveys off central California suggest upwelling of water by 100 m or more relative to the long-term spring average. Coastal sea-level (CSL) anomalies in the northern CCS were the lowest in at least 65 years. Greater than usual southward transport by the California Current is implied. A number of population and ecological changes observed during this period may be linked to the unusual ocean conditions and the striking transition from El Niño to La Niña. Physical conditions in the CCS can change swiftly and dramatically, and its marine populations appear to respond nearly as rapidly. The large physical and biological changes that occurred in 1999 may signify the initiation of a new climate regime for the CCS.

INTRODUCTION

In less than two years sea-surface temperatures (SSTs) over much of the California Current system (CCS) dropped from the warmest on record during the height of El Niño in late 1997 (as much as 6°C above the seasonal mean; Lynn et al. 1998) to low temperatures in 1999 not seen in decades (more than 3° below normal). This rapid cooling is unprecedented, particularly in the context of the very warm regional ocean temperatures of the past decade, and is especially impressive given that the annual range of SST is about 3°C off central California, and its interannual variance is only 1°C.

Coastal upwelling is arguably the dominant process affecting the physical and ecological structure of the CCS and other eastern boundary current ecosystems. Upwelling in spring and summer significantly affects regional and local ocean circulation, thermohaline structure and stability, and water-mass exchange between the coastal and deep ocean. It drives the biological productivity and energetics of the system through the vertical transport of nutrients into the photic zone and the lateral advection of nutrients, primary and secondary producers, and larvae of higher predators. This process also contributes to the generation of ocean fronts, where organisms and material often aggregate.

Interannual variability in coastal upwelling is reflected in the physical, biochemical, and ecological nature of the CCS (Chelton et al. 1982). Much of the variability on this time scale is attributed to El Niño and La Niña; another major contribution is from longer-term climate change (Mantua et al. 1997; Schwing and Mendelssohn 1997; Schwing et al. 1997). Yet it is not always clear whether unseasonable levels of upwelling are locally or remotely forced. It is also noted that interannual fluctuations in CCS transport or biological character (e.g., population distribution or recruitment) do not always have a corresponding shift in coastal upwelling.

The goal of this paper is to describe the extremely unusual level of coastal upwelling that occurred in the spring and summer of 1999 over much of the CCS, based on direct and indirect observations. Anomalies of coastal winds, ocean temperature, structure, circulation, and coastal sea level are compared to coastal California climate trends for the previous several years, and specifically contrasted with the extremes associated with the 1997–98 El Niño event. We speculate on the impact of the resulting anomalous conditions on coastal marine populations. We also look at the possible role of 1999 in predicting future conditions. This paper complements the article on the status of the California Current in this volume (Bograd et al. 2000).

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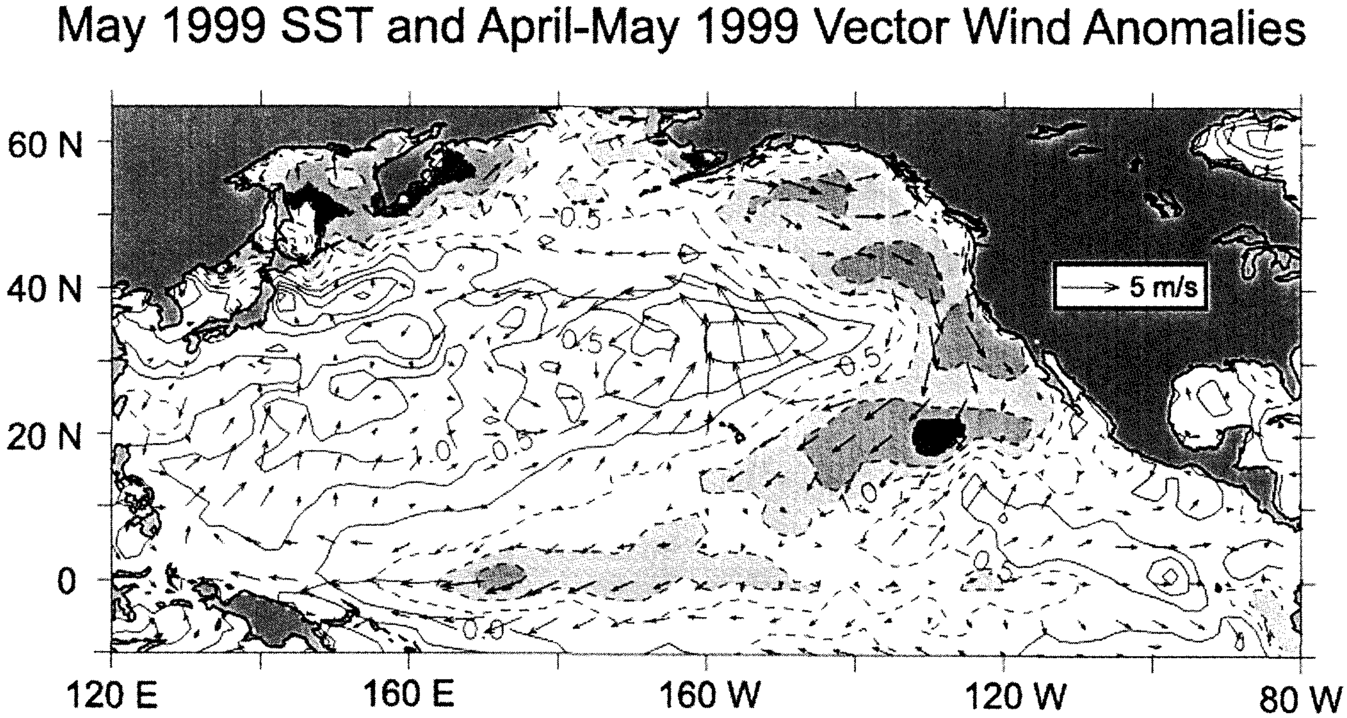

Figure 1. May 1999 SST anomalies and April–May 1999 wind anomalies for the North Pacific. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 0.5°C. Negative SST anomalies (dashed contours) less than −1.0°C are shaded. Anomalies computed on NOAA-CIRES/Climate Diagnostics Center Web site (*http://www.cdc.noaa.gov*).

LARGE-SCALE CONDITIONS AFFECTING THE NORTHEAST PACIFIC

The latter half of 1998 was marked by the rapid decay of one of the strongest El Niño events of this century and the equally sudden onset and intensification of La Niña conditions. The multivariate ENSO index (MEI; Wolter and Timlin 1998) dropped from an El Niño peak in spring 1998 to a minimum in late fall 1998 (*http://www.cdc.noaa.gov/~kew/MEI/mei.html*). This decline was unprecedented in the 50-year history of the MEI. The intensity of the 1998–99 La Niña, as indicated by the MEI, remained moderately strong from October 1998 through 1999 (Bograd et al. 2000).

Through much of the 1999 upwelling season, unusually high atmospheric pressure in the North Pacific High (35°N, 130°W) led to vigorous anticyclonic wind stress, including anomalously strong alongshore upwelling-favorable winds along the North American west coast. This pattern was at its strongest in early spring 1999 (fig. 1). This also contributed to stronger than normal trade winds, a typical feature of the La Niña phase of ENSO. The anomalous winds in 1999 were similar to those during the several years prior to the 1976 climate regime shift (Parrish et al., in press).

The pattern of North Pacific sea-surface temperature (SST) anomalies during spring–summer 1999 (fig. 1) was similar to that seen during many past La Niña events. It also was similar to patterns of surface anomalies seen before the 1976 regime shift (Parrish et al., in press) and more generally during the negative phase of the Pacific Decadal Oscillation (Mantua et al. 1997). Positive anomalies extended from the western North Pacific to north of Hawaii. A region of cooler than normal SST stretched roughly along the axis of the North Pacific trade winds from the western equatorial Pacific to Baja California, and along the North American west coast into the Gulf of Alaska. This horseshoe-shaped region of negative SST anomaly developed in late 1998 and intensified in spring 1999, particularly in the CCS. At the same time, the anomalous anticyclonic atmospheric circulation over the northeast Pacific, and the associated southward wind stress along the west coast strengthened (fig. 1). The wind stress curl over this region of cool anomalies was higher than normal, reinforcing cool upper ocean temperatures via enhanced Ekman pumping (open-ocean upwelling). The implication is that regional wind anomalies led to the extreme SST anomalies in the CCS and northeast Pacific through Ekman processes in the upper ocean. No clear links between the wind or SST anomalies in the northeast Pacific and the equatorial Pacific are apparent for this period.

WEST COAST ANOMALIES 1998–99

Coastal Upwelling

The PFEL upwelling index (Bakun 1990; Schwing et al. 1996) estimates the intensity of large-scale, wind-

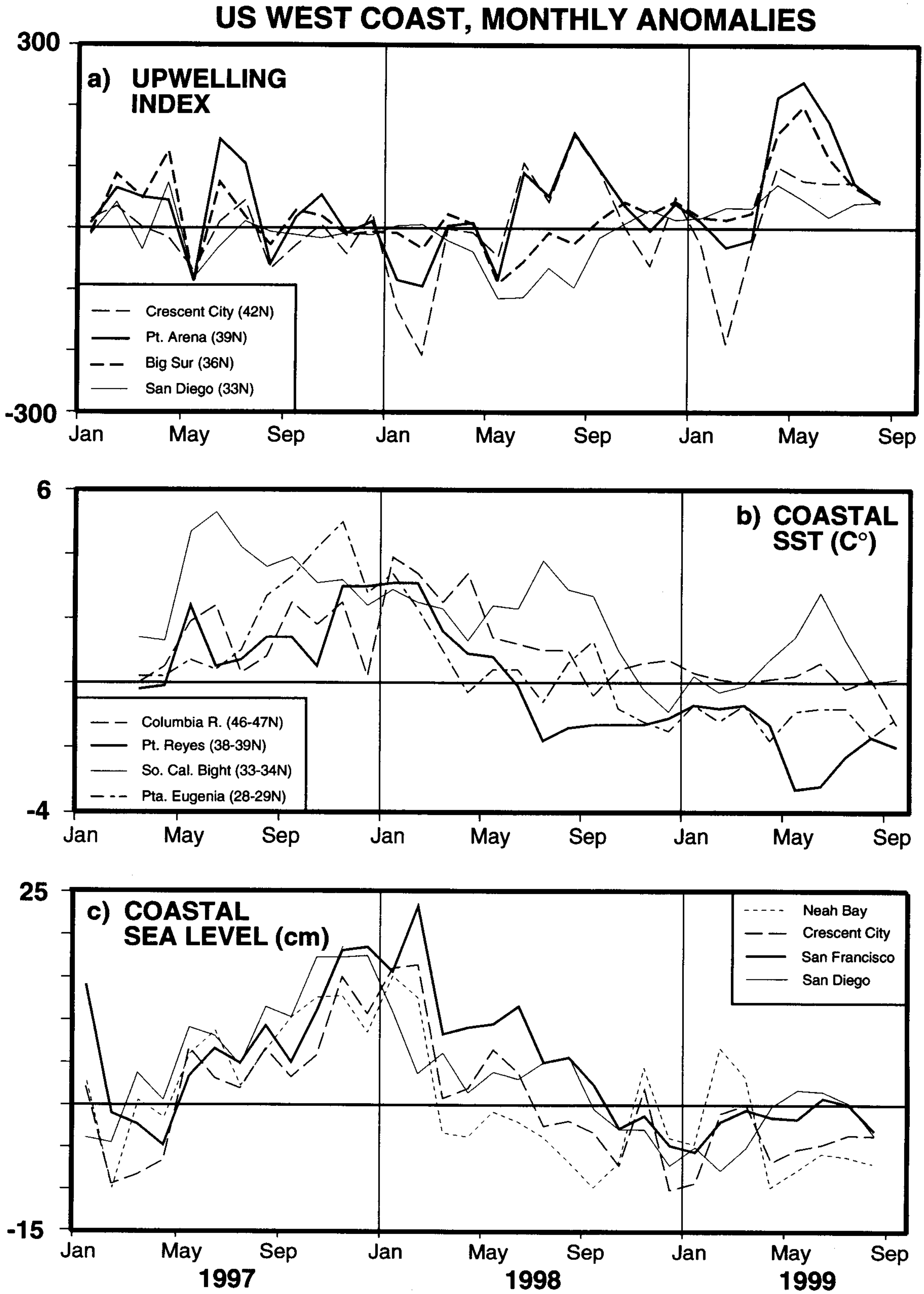

Figure 2. Monthly anomalies of (*a*) upwelling (m³/s along each 100 m of coastline; anomaly reference period, 1948–67); (*b*) SST (one-degree summaries of surface reports, ship reports, and buoy observations; anomalies calculated by using the climatology from the UWM/COADS analysis); and (*c*) coastal sea level (anomaly reference period 1975–95) at selected locations along the North American west coast, 1997–99.

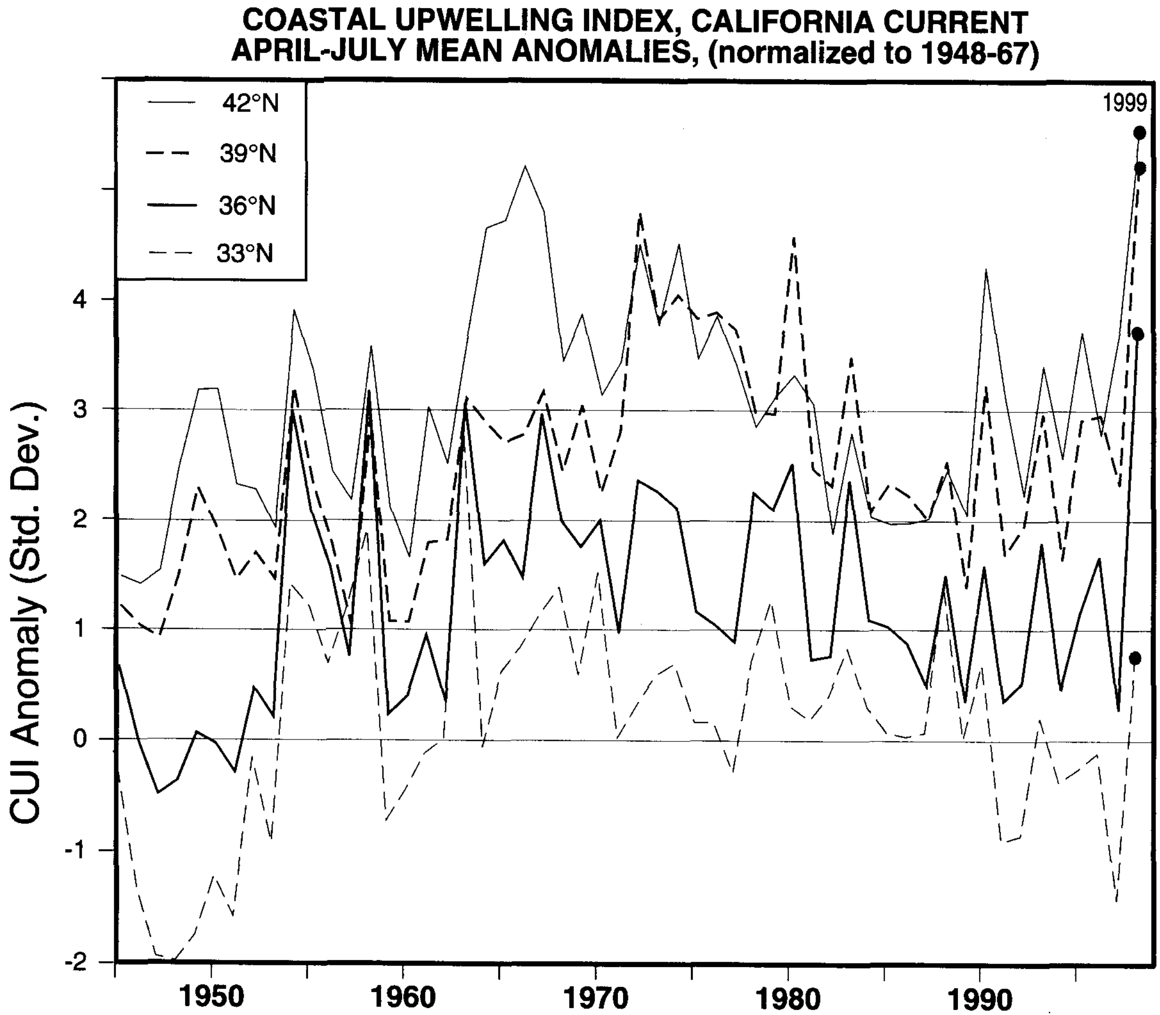

Figure 3. Anomalies of coastal upwelling index during the upwelling season (April–July), 1946–99 at four west coast locations. Each series normalized to 1948–67 period. Series from 36°N, 39°N, and 42°N offset by 1, 2, and 3 standard units. Horizontal lines denote mean of each series. Solid circles denote 1999 values.

induced coastal upwelling along the North American west coast. After a period of generally weaker than normal upwelling through late spring and summer 1998 from San Francisco to southern Baja California, the positive index anomaly indicates slightly above normal upwelling in late 1998 and early 1999 (Hayward et al. 1999). Extremely strong upwelling, centered near Point Arena and extending the length of the California coast, developed in April 1999 (fig. 2a). At the same time, upwelling anomalies were negative off Oregon and Washington. Upwelling off northern California during April–July 1999 (the peak of the upwelling season) was the strongest in the 54-year record of this index, 2.5–3.5 standard deviations above normal (fig. 3). Anomalies remained positive into the fall of 1999.

Large positive upwelling anomalies have been observed in the spring of other La Niña years (e.g., 1965, 1971, 1974). Conversely, weaker than normal upwelling followed the strong 1997–98 El Niño, a relationship seen in 1983 and 1992 as well. However, not all La Niña years feature anomalously strong coastal California upwelling (e.g., 1951, 1963), and some years of very strong upwelling (e.g., 1973) are not linked to equatorial La Niña events. Although there is a clear connection between tropical and extratropical variability on the interannual scale, anomalous conditions in mid-latitude regions such as the CCS cannot always be explained by an anomalous equatorial state.

Coastal Winds

Coastal winds off the western United States are linked to the Pacific basin-scale wind patterns. Winds measured at west coast NOAA National Data Buoy Center (NDBC) buoys are highly coherent over large alongshore distances (Dorman and Winant 1995), yet most of the buoy records from recent years feature large data gaps. Composite time series of available wind and SST observations for three geographical regions of the CCS

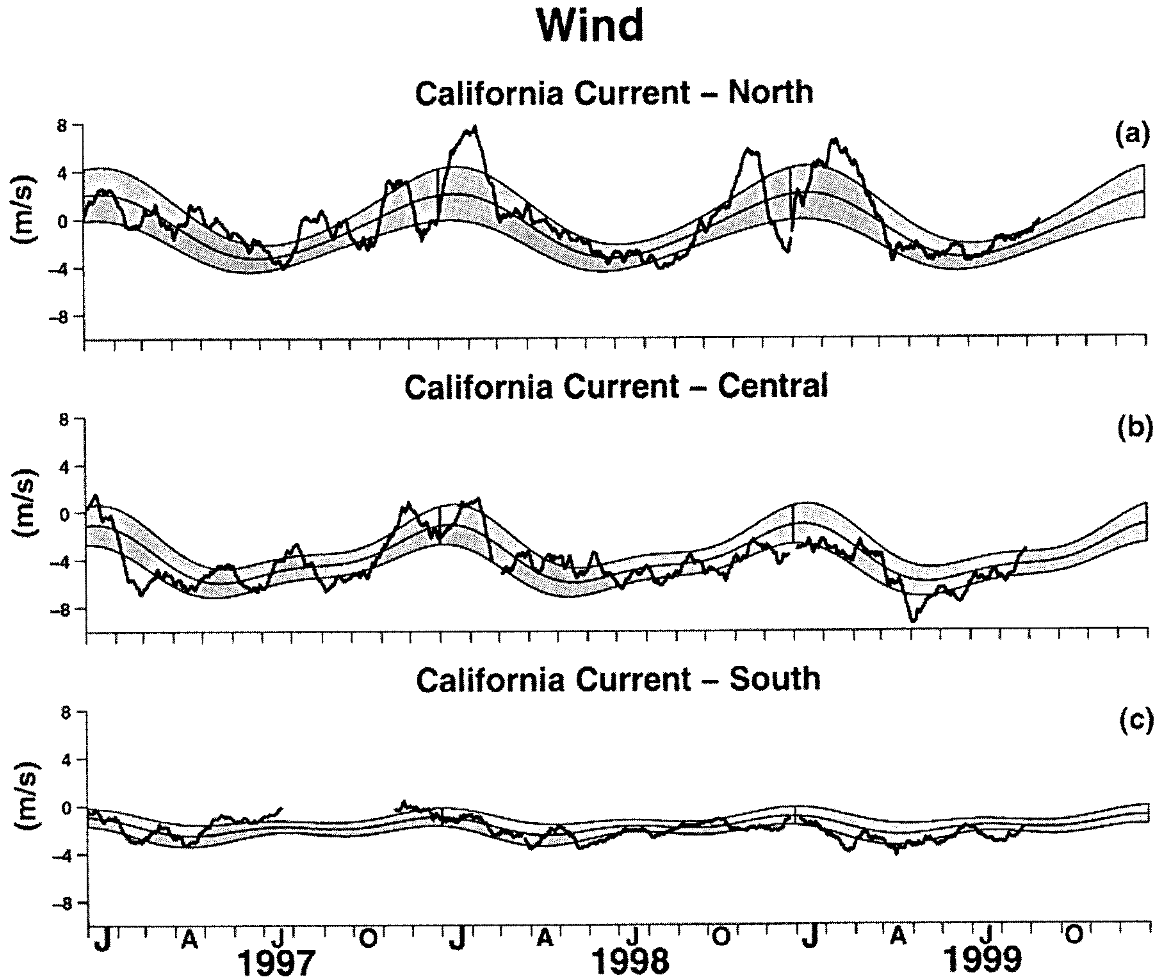

Figure 4. Regional composite series (1997–99) of NDBC buoy alongshore winds superimposed on long-term (1981–99) composite annual biharmonic mean and standard error envelope. Northern region is north of Cape Mendocino, southern region is south of Point Conception. Buoys used for each composite are listed in table 1.

are presented in figures 4 and 5, respectively. These represent the regions' patterns over the past three years. The buoys used in the creation of these composite series are listed in table 1.

Alongshore winds in the central and southern CCS were dominated by stronger than normal northerly (more upwelling-favorable) winds through the latter half of 1998 and much of 1999 (fig. 4b, c). A number of stronger than normal northerly wind events were observed coastwide during this period. Two particularly strong events occurred in February and April 1999 off southern California (fig. 4c) and in early May and June 1999 off central California (fig. 4b). Strong equatorward wind stress leads to low coastal sea level (CSL) and cool ocean temperatures due to offshore surface Ekman transport and subsequent coastal upwelling. North of 40°N, winds in late 1998 and again in early 1999 were unusually strong from the south (fig. 4a), an artifact of winter storms moving through the Pacific Northwest. Unlike the CCS regions to the south, this area did not experience unusually strong upwelling-favorable winds during the 1999 upwelling season. Buoy winds throughout the CCS weakened considerably in the late summer of 1999.

Coastal SST

SST anomalies in the CCS reflect perturbations in local coastal upwelling, complicated by the effects of large-scale atmospheric forcing and regional anomalies in ocean circulation. After an extended period of above-normal coastal ocean temperature, west coast SST summaries show a steady, long-term decline in late 1998 following the mature phase of El Niño (figs. 2b, 5). SST anomalies became negative off California in early fall 1998. A series of strong northerly wind events affecting the central and southern CCS during late 1998 contributed to these dramatic drops in SST. A strong correlation between increased upwelling and lower SSTs existed after June 1998 (fig. 6). The most notable of

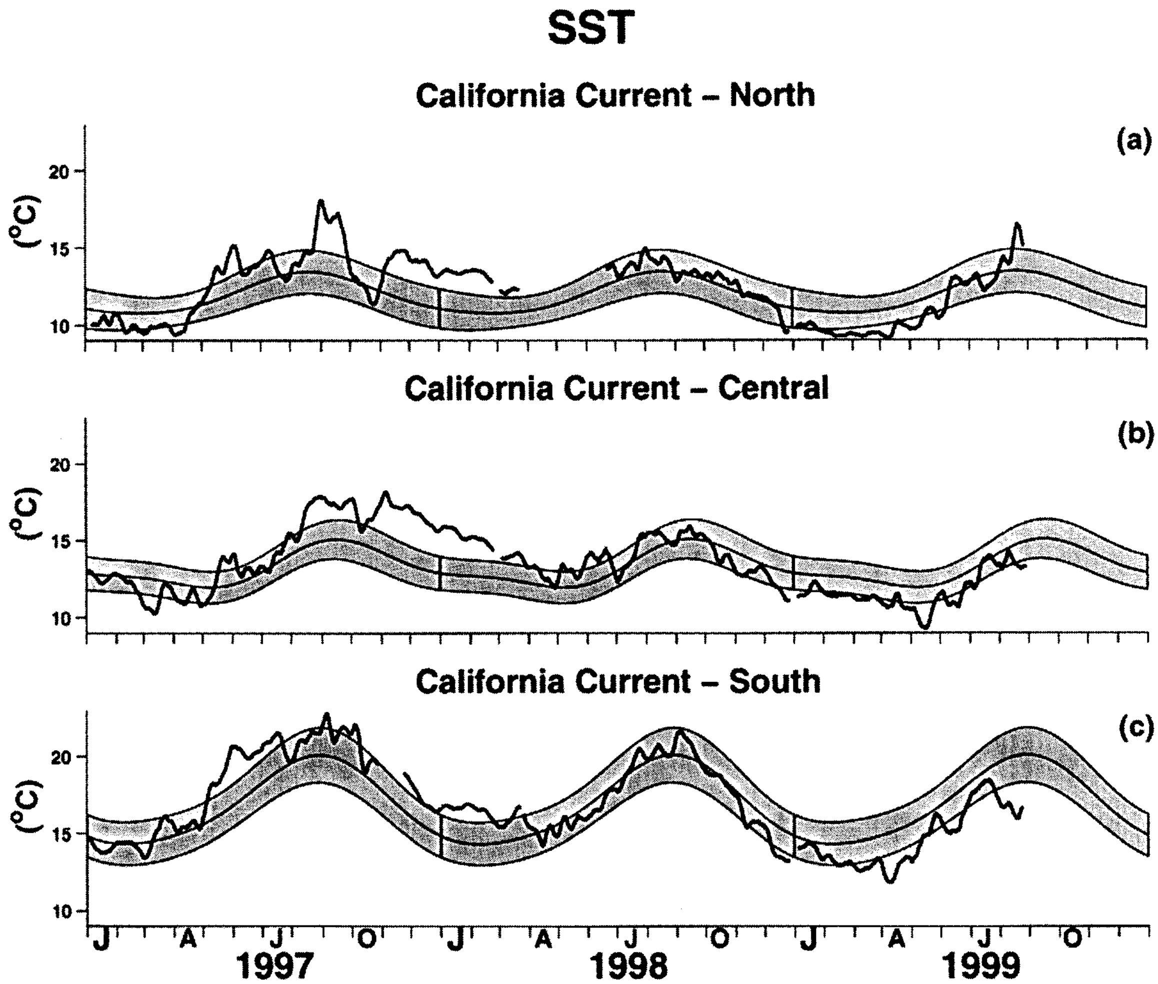

Figure 5. Regional composite series (1997–99) of NDBC buoy SST superimposed on long-term (1981–99) composite annual biharmonic mean and standard error envelope. Northern region is north of Cape Mendocino, southern region is south of Point Conception. Buoys used for each composite are listed in table 1.

these events were in early November and December. A similar cooling occurred at buoys in the northern CCS, despite the concurrent strong southerly winds during this period.

Unseasonably cool coastal SSTs dropped even further in April and May 1999 from Point Conception to the California-Oregon border, corresponding to the time and region of greatly enhanced upwelling (figs. 2a, 4). This led to very cool SSTs through the 1999 upwelling season. SST anomalies were as much as 3°–4°C below normal during this time. The coolest SSTs during May–July 1999 followed the strongest upwelling rates (lower right corner of fig. 6). Near Point Reyes, SSTs were about 7.5° during much of May.

Localized warm areas were seen during the summer of 1999 in the Southern California Bight (inshore of the Channel Islands) and along the Oregon coast (fig. 2b). Warm SSTs in the Pacific Northwest were associated with weaker than normal northerly winds and negative upwelling anomalies. Southern California shore temperatures were actually warmer than normal during much of this time (Bograd et al. 2000). Positive anomalies in the inner Southern California Bight may have been due to a combination of reduced upwelling, a lack of ocean mixing, and transport of warm water from the south.

A major difference in the atmospheric forcing of upper ocean temperature in the past three years is that the very cool conditions in 1999 developed in situ adjacent to the coast, and can be attributed directly to strong coastal upwelling. Positive SST anomalies during the 1997–98 El Niño were a product of large-scale atmospheric conditions (e.g., open-ocean upwelling in the outer CCS) and ocean transport in addition to reduced local upwelling at the coast. This is especially clear during fall 1997 along central California (fig. 5b). This distinction is illustrated by the relationship of SST with upwelling off Point Reyes (fig. 6). During the 1998–99 La Niña there was a strong negative correlation between monthly

TABLE 1
National Data Buoy Center (NDBC) Buoys in the California Current Used to Calculate Composite Climatologies for Figures 4 and 5

Region	Location	NDBC buoy no.	Lat./lon. (°N/°W)
North	Columbia River Bar	46029	46.2/124.2
	Eel River, CA	46022	40.8/124.5
Central	Bodega, CA	46013	38.2/123.3
	San Francisco, CA	46026	37.8/122.8
	Santa Cruz, CA	46012	37.4/122.7
	Monterey, CA	46042	36.8/122.4
	Cape San Martin, CA	46028	35.8/121.9
	Santa Maria, CA	46011	34.9/120.9
	Point Conception, CA	46023	34.3/120.8
South	Santa Barbara, CA	46053	34.2/119.8
	Long Beach, CA	46045	33.8/118.4
	Catalina Ridge, CA	46025	33.7/119.1

anomalies in local upwelling and coastal SST (fig. 6, solid squares); no relation was seen during the 1997–98 El Niño (open squares). However, both regressions have a non-zero intercept, suggesting that monthly variations in SST due to upwelling occurred on a warmer than normal background during El Niño and on a cooler than normal background during La Niña.

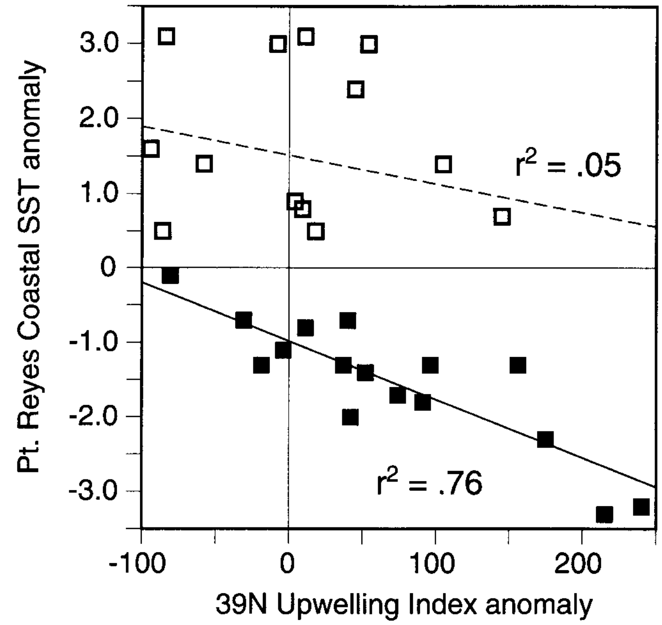

Figure 6. PFEL monthly upwelling index anomaly at 39°N plotted against monthly SST anomalies off Point Reyes (38°–39°N, 123°–124°W). SST lags upwelling index by one month. Both series were detrended to remove long-term climate variability. Open squares denote monthly anomalies during El Niño (May 1997–May 1998). Solid squares denote monthly anomalies during La Niña (June 1998–September 1999). Periods based on Southern Oscillation Index. Dashed line is regression for El Niño; solid line is regression for La Niña.

Coastal Sea Level

Consistent with strong coastal upwelling, coastal sea level (CSL) was uncharacteristically low along the west coast during the 1999 upwelling season (fig. 7). Detrended CSL means for this season at Crescent City and Neah Bay were the lowest since at least 1934, and the third lowest at San Francisco since 1975 (*http://uhslc.soest.hawaii.edu/*). Although San Diego CSL anomalies were negative in 1999 as well, they were not highly unusual in the context of the past few decades. The observed drop in CSL during 1999 is consistent with theoretical estimates for the magnitude of the observed wind and upwelling index anomaly (Brink et al. 1987).

As the 1997–98 El Niño developed and dissipated, CSL rose and fell uniformly (fig. 2c). West coast anomalies became negative in the latter half of 1998, approximately at the time that the northerly winds strengthened. They remained near or below their seasonal means into late 1999. The greatest negative anomalies in CSL developed north of San Francisco in spring 1999, at the time of very strong upwelling. San Francisco and San Diego levels were less responsive to the positive upwelling anomalies. In spring and summer 1999, CSL sloped downward toward the north, reversing the southward sea-level slope of late winter. The coastwide low in winter is not clearly related to unusual coastal winds or upwelling. It is possibly linked to the concurrent anomalous clockwise atmospheric circulation over the North Pacific, which may not be displayed by the nearshore winds, or to a steric response to the rapid cooling shown by SST.

The rise in CSL during the 1997–98 El Niño was probably a reflection of steric expansion of the water column and increased poleward transport of the California Current. Anomalous coastal upwelling (fig. 2a) was probably not the major factor in the high CSLs during 1997. Large positive west coast CSL anomalies generally follow El Niño events (e.g., 1983, 1993, 1998; fig. 7). But previous low extremes in summer CSL anomalies (e.g., 1977, 1991, 1994) were not associated with equatorial La Niña events.

An example of the long-term relation between CSL and coastal upwelling is shown in figure 8. Lower sea level generally accompanies years of higher upwelling, with 1999 being the most extreme case in the past 54 years. The highest CSL anomalies occur during strong El Niño years, but are not necessarily related to unusually weak upwelling. This finding supports the contention that large-scale and remote processes contribute substantially to variability in the CCS during El Niño events. Also noteworthy is that the best statistical relationship for Crescent City CSL is not with local upwelling, but with upwelling south of Crescent City. This is true for San Francisco and Neah Bay as well.

The spatial coherence of CSL is much more extensive than for SST, suggesting that sea level is less affected

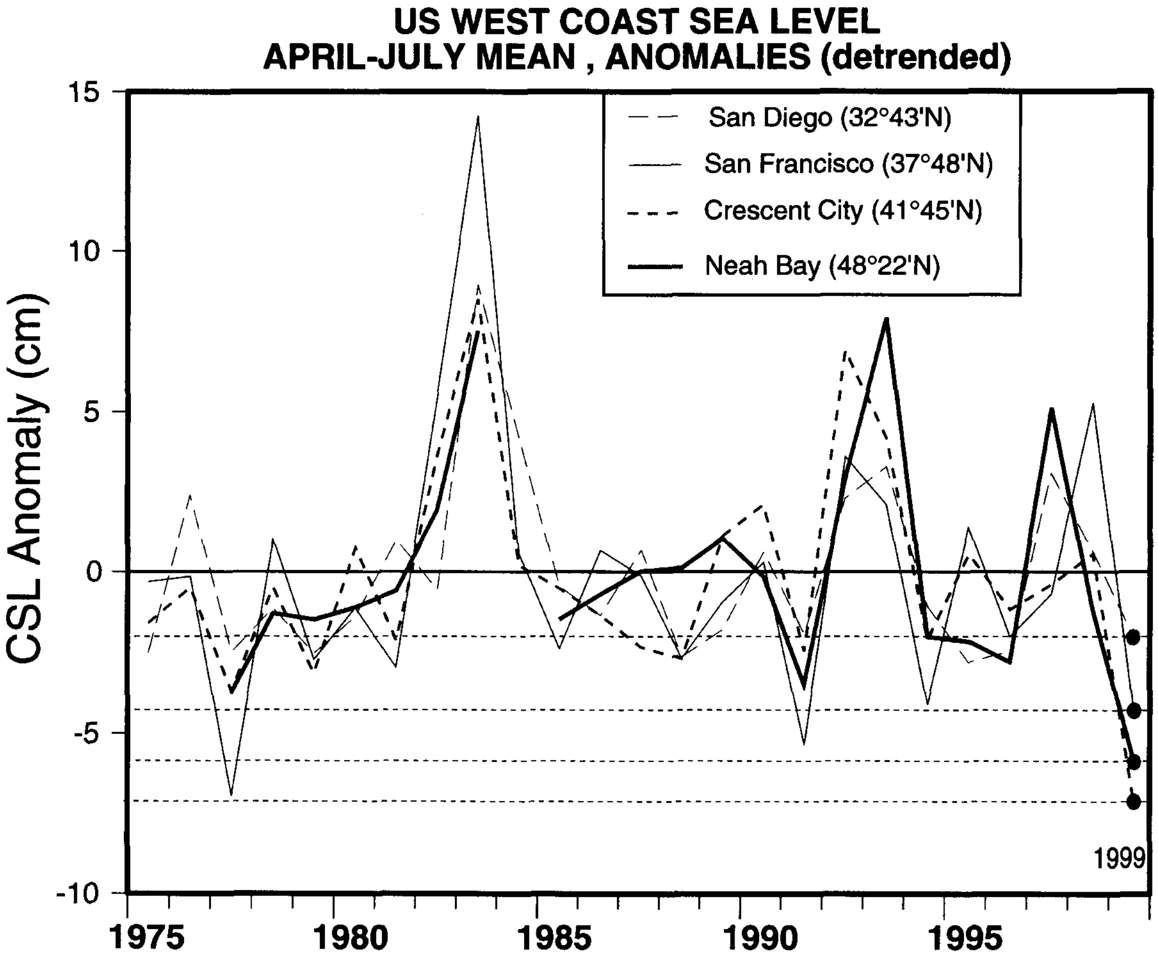

Figure 7. Coastal sea-level anomalies, annual April–July means. Series were detrended to remove long-term climate variability. Solid circles and horizontal dashed lines denote 1999 anomalies.

by local and regional differences in seasonal forcing (fig. 2). It also implies that CSL integrates the west coast climate signal, including El Niño and La Niña, to a greater degree than other ocean variables.

Subsurface Temperature and Salinity

Thus far the description of strong upwelling in 1999 has been based on surface observations. Perturbations in subsurface conditions confirm the significant impact of anomalous coastal upwelling on ocean conditions. Stronger upwelling is reflected in an uplifting of isotherms and isohalines toward the coast, identified by cooler temperatures and higher salinities at a given depth. The discussion here will focus on central California. The coverage of southern California by the CalCOFI surveys is detailed in Bograd et al. 2000.

In May 1999 the Tiburon Laboratory (NMFS-SWFSC) examined ocean structure off central California as part of the annual pelagic juvenile rockfish surveys. Strong upwelling was indicated at that time by very low temperatures and high salinities throughout the upper water column (figs. 9 and 10). The Point Reyes upwelling filament was the coldest observed in the 17-year history of the Tiburon spring surveys. Mixed layer (upper 50 m) measurements were 1–2 s.d. (1°–2°C cooler and S = 0.2–0.4 higher) outside the long-term (1987–96) means for this area (Baltz 1997). Vertical sections off Point Reyes show robust coastal upwelling and very cool, saline water on the shelf (fig. 10). Temperature and salinity values observed in the upper 50 m indicated an upwelling of water on the order of 100–150 m in response to the unusual coastal upwelling of 1999, relative to typical spring ocean conditions. This corresponds dynamically to a 10–15 cm drop in CSL, as noted in figure 2c. Upwelled isohalines that normally outcrop near the coast surfaced 50 km offshore. This helped produce a strong ocean front at the surface convergence of offshore-flowing upwelled water with the warmer California Current.

Robust and sustained upwelling in 1999 led to stronger net offshore Ekman transport, particularly with respect

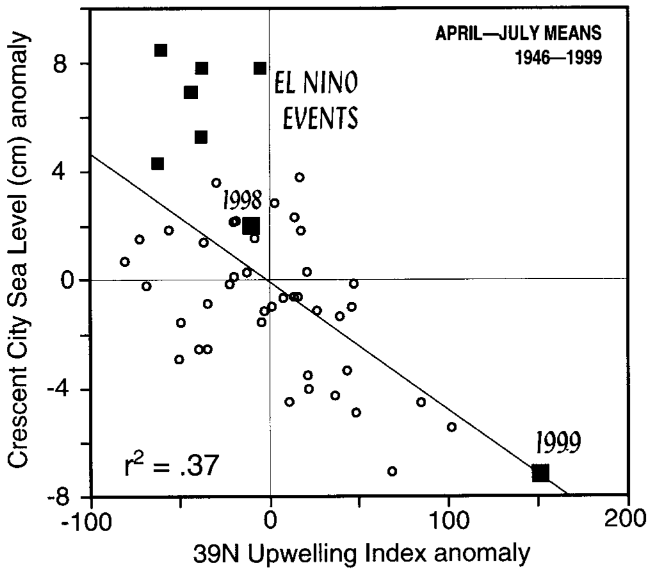

Figure 8. Annual April–July anomalies of PFEL monthly upwelling index (39°N, 125°W) versus Crescent City coastal sea level, 1946–99. El Niño years denoted by gray squares. Regression shows effect of very strong upwelling on sea level in 1999 (labeled). Sea level is higher than expected during El Niño because of thermal expansion of water column and higher northward transport of California Current.

to the upwelling jet at Point Reyes and elsewhere. This resulted in an unusual offshore displacement of the upwelling front and the maximum of chlorophyll (fig. 11). It also contributed to an unusually strong southward geostrophic surface flow in association with the upwelling front, and a reduction and even reversal of the poleward California Undercurrent at 200 m off central California. The low dynamic thickness of the upper 200 m in 1999, 5–10 dyn. cm lower than in 1998, indicates anomalously dense water in the upper ocean. This would be true in the case of strong coastal upwelling. It also implies a strong southward flow (Ramp et al. 1995). Anomalous southward transport in the CCS is consistent with the very low CSLs at this time. The relative alongshore CSL gradient between Crescent City and San Francisco (fig. 2c) is equivalent to an approximately 10 cm/s greater southward geostrophic current.

BIOLOGICAL CONSEQUENCES OF STRONG UPWELLING

Although the mechanisms linking climate change to biological variability are not fully understood, a number of correlations between interannual and longer physical changes and marine organisms have been identified (cf. Chelton et al. 1982; Hollowed and Wooster 1992). In general, swings in population growth, abundance, distribution, and ecosystem structure accompany shifts in climate patterns. For example, the collapse of the California sardine fishery in the 1940s is now believed to have been at least partly due to a shift to cooler ocean conditions, whereas a revival in this species has accompanied ocean warming since 1976. A five-fold drop in macrozooplankton off southern California over the past 50 years has been attributed to long-term warming (Roemmich and McGowan 1995). Interannual variability, such as El Niño and La Niña, is linked to changes in the species assemblage of phytoplankton, and to latitudinal shifts in the distribution of zooplankton such as euphasiids and copepods.

Interannual fluctuations in coastal upwelling can affect marine populations in three major ways. First, organisms are metabolically sensitive to thermal extremes and may migrate into or out of a region if it becomes too cool. Development, growth, and feeding rates are influenced by temperature as well. Second, the ecosystem is nutritionally enhanced by higher upwelling. Primary production increases, providing grazers and ultimately higher consumers with more food. Third, upwelling-related advective processes transport zooplankton and pelagic larval stages. Many species are adapted to use upwelling circulation patterns for recruitment. Upwelling jets also represent a transport of nutrients, prey, and larvae out of the coastal zone into the deep ocean.

The speed at which the Pacific transitioned from a very strong El Niño state to a moderately strong La Niña is illustrated by indices such as the multivariate ENSO index (Wolter and Timlin 1998). The sudden transition from one climate extreme to the opposite is evidenced by the dramatic changes seen in the northeast Pacific as well. Climate models currently forecast a continuation of La Niña well into 2000. Thus the present coastal anomalies may be sustained into the 2000 upwelling season. If this is the case, a transition to a different marine ecosystem structure than seen for most of the 1990s is likely.

Of relevance to the physical changes in the CCS in 1999 are a number of biological observations that appear to go against recent and long-term ecosystem patterns. Most of these latest observations are consistent with those historically identified with a cooler regional ocean climate.

Chlorophyll concentrations off central California were greatest nearly 50 km offshore in May 1999, in association with the position of the upwelling front (fig. 11). Typically, the highest chlorophyll levels are immediately next to the coast. However, synoptic variability within a season is too high to allow an interannual difference to be determined. Chlorophyll, as indicated by SeaWiFS, increased significantly off coastal California, with 1999 concentrations much higher than typical (Bograd et al. 2000).

The zooplankton communities off Oregon (W. Peterson, pers. comm.) and British Columbia (D. Mackas, pers. comm.) shifted from a structure dominated by a

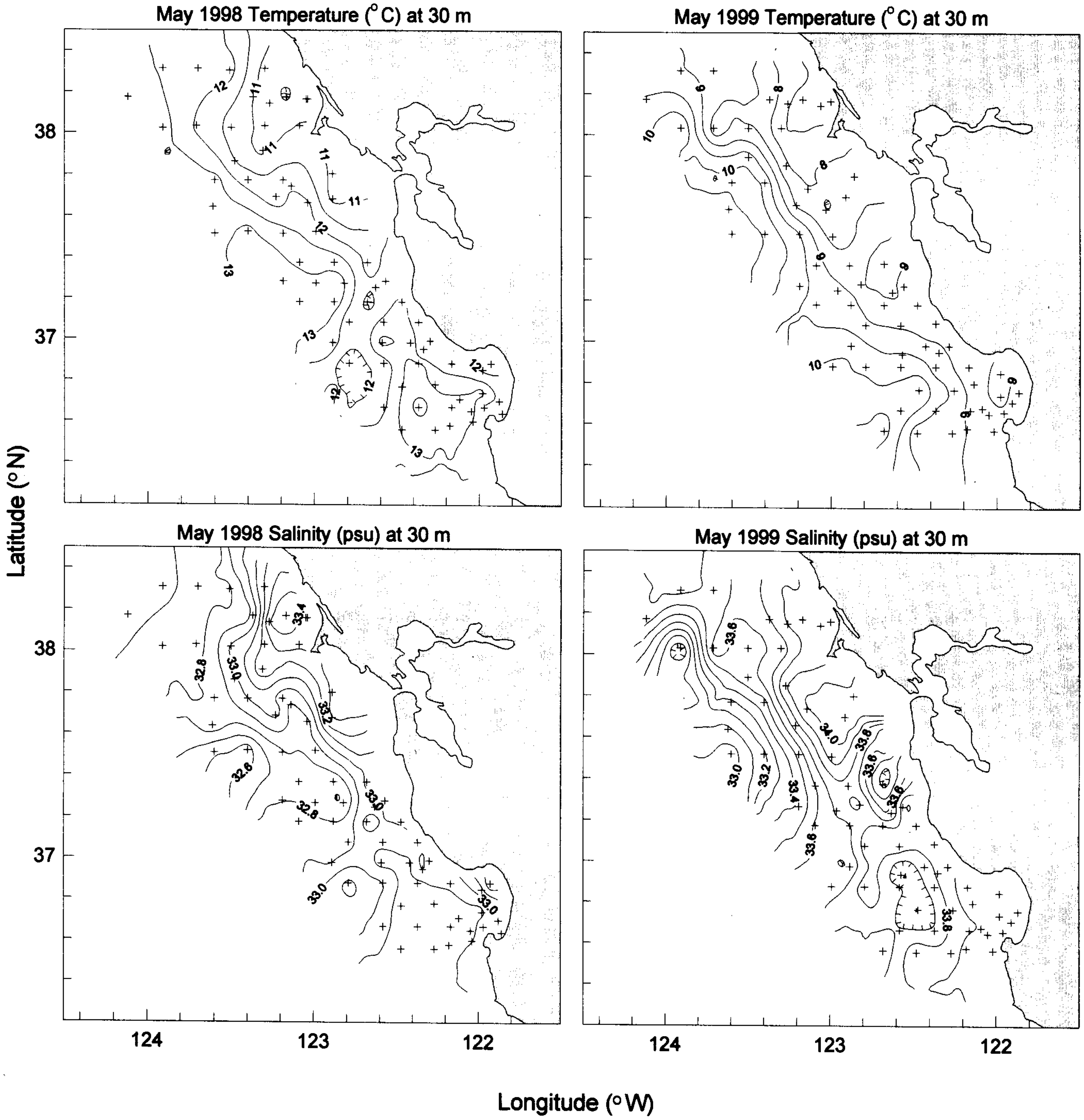

Figure 9. Temperature and salinity at 30 m depth off central California during early May of 1998 and 1999. Crosses show CTD stations.

mixture of warm water and oceanic species to one comprising exclusively subarctic species. Macrozooplankton biomass levels off southern California in early 1999 were very high relative to the past 15 years (S. Bograd, pers. comm.). The January 1999 biomass was the highest in this period, representing a potential change in the long-term decline described by Roemmich and McGowan (1995). The lowest biomass levels in the past 15 years were observed in 1998. The zooplankton displacement volume, estimated from acoustic returns, was much higher than usual in April 1999 off southern and central California (R. Lynn, pers. comm.).

Strong and sustained upwelling may have had a negative effect on recruitment of benthic nearshore species (e.g., urchins, barnacles, crabs) that rely on "relaxations" in upwelling to transport larvae onshore for settlement.

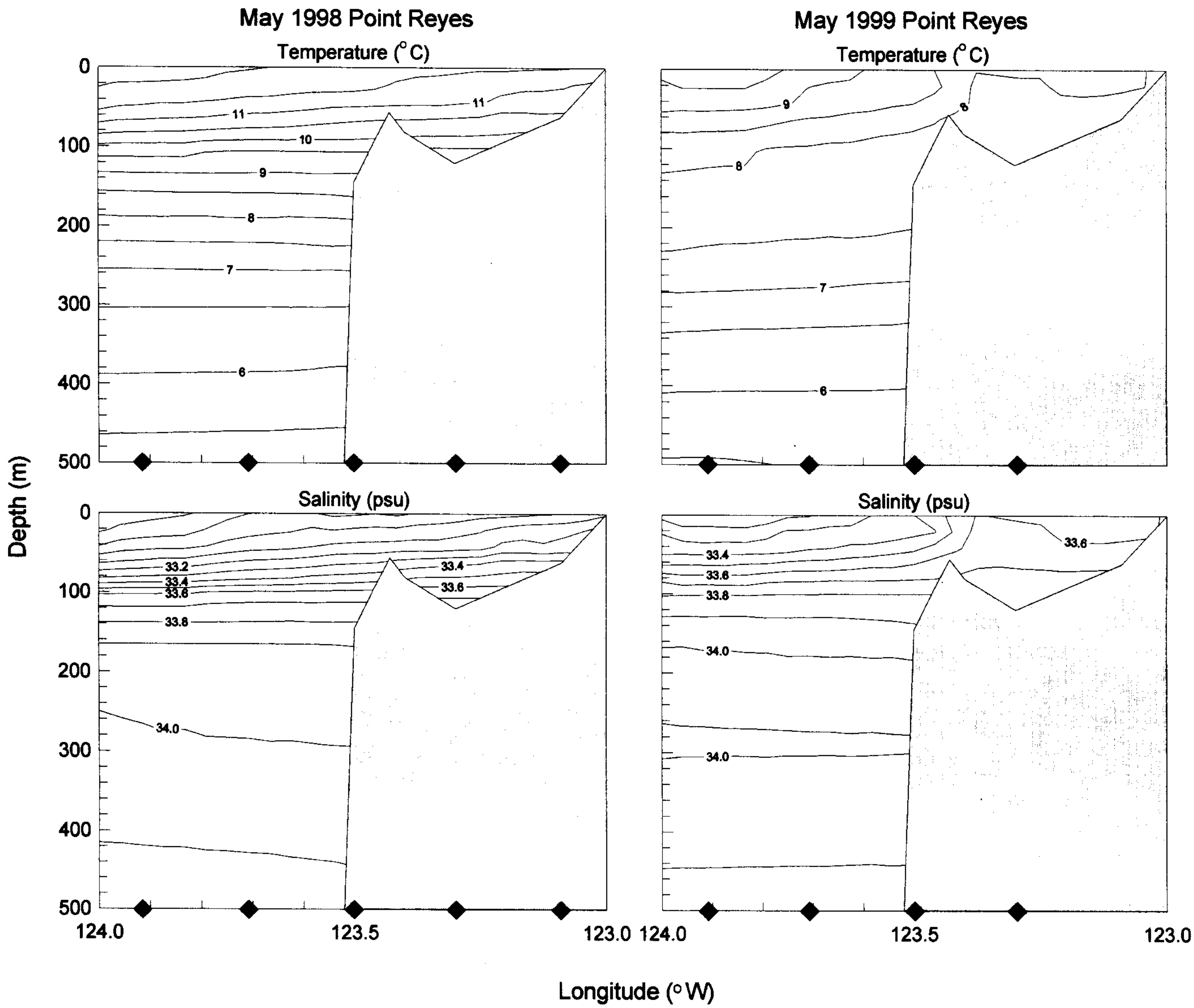

Figure 10. Vertical sections of temperature and salinity off Point Reyes, Calif. (38°10'N) during early May of 1998 and 1999. Diamonds show CTD stations.

Returns of northern and central California populations were very low in 1999 (C. Lundquist, pers. comm.). This may be due to the unusual offshore extent of the upwelling front, combined with the relative lack of onshore transport events.

Sardine eggs off southern California, an indicator of the spawning biomass of sardines and the likely recruitment to the future population, occurred in higher densities in 1999 and were dispersed farther offshore (R. Lynn, pers. comm.). Pelagic juvenile rockfish off central California continued a decade-long trend of low abundance over the continental shelf and slope. However, juveniles were found farther offshore than in the past, probably because of the very high and sustained offshore Ekman transport.

Adult bocaccio rockfish, normally a northerly distributed species in the CCS, were caught in unusually high numbers south of Point Conception. Adult rockfish off central California were full of euphasiids and had high levels of stored fat (Hayward et al. 1999). In 1999, six times as many juvenile coho salmon were caught in NMFS surveys off Washington/Oregon as in 1998 (W. Peterson, pers. comm.).

A switch in marine bird populations was noted in 1999 (Hayward et al. 1999). Total abundance was up over 1998, and the community shifted from a prevalence of subtropical to subarctic species. Hayward et al. (1999) reported higher *Macrocystis* growth in 1999, relative to the previous year, a result of higher upwelling (Tegner et al. 1997).

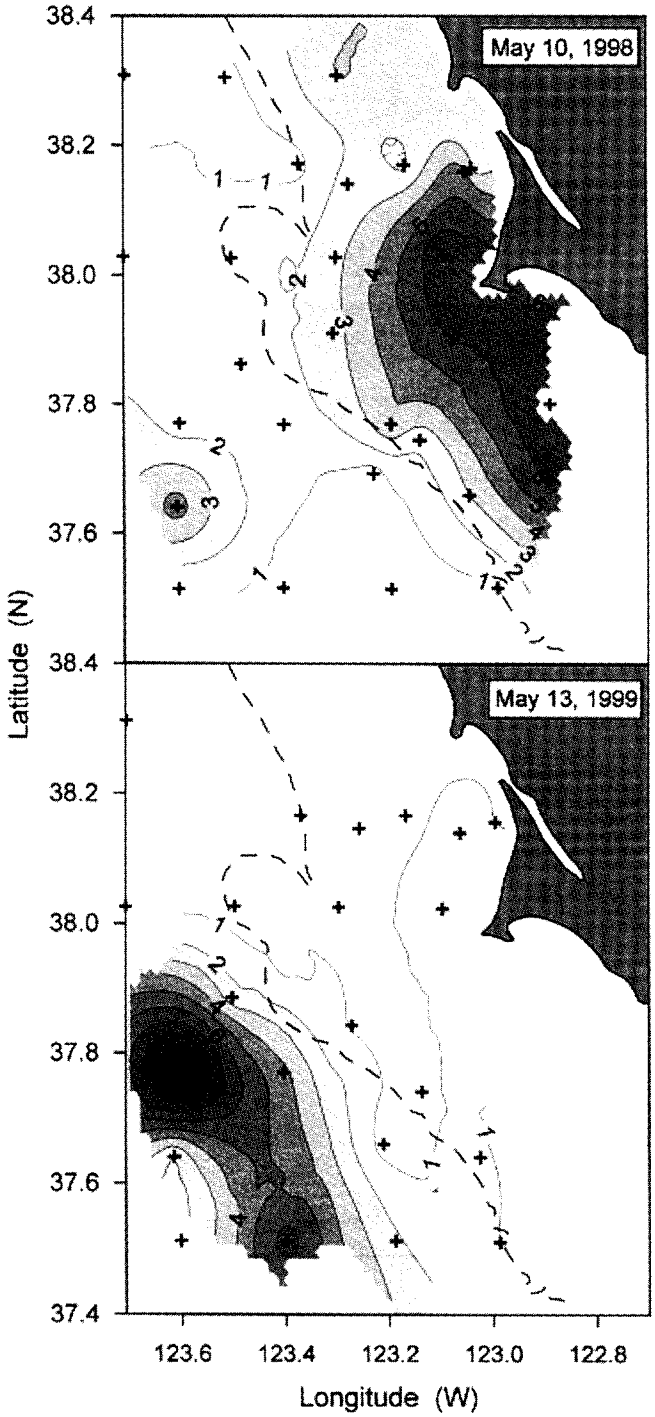

Figure 11. Chlorophyll concentrations (mg /m^3) at 10 m depth near Point Reyes, Calif., in early May of 1998 and near Point Reyes in May of 1999. Crosses denote sampling locations.

CONCLUSIONS

Conditions in the CCS during the spring and summer of 1999, a period characterized by an equatorial La Niña, were consistent with extremely high levels of sustained coastal upwelling. The PFEL upwelling indices were record highs for a series extending back to 1946. Strong, sustained upwelling-favorable winds were measured at coastal buoys through late 1998 and much of 1999. Coastal SSTs were 3°–4°C below their seasonal mean in spring 1999, and about 10° cooler than the region experienced in late 1997. Hydrographic surveys off central California suggest upwelling of water by 100 m or more relative to the long-term spring average. Coastal sea level in the northern CCS was the lowest in at least 65 years. Direct and indirect current measurements indicate greater than usual southward transport by the California Current.

The anomalous ocean conditions typically observed along the North American west coast during El Niño events (warm SST, high CSL) are the combined result of local and remote atmospheric and oceanic processes. In previous years, and specifically during the 1997–98 El Niño, ocean temperature anomalies were linked to regional and large-scale processes, and were less affected by local wind forcing. The upwelling season of 1999, however, shows a close relation between local wind and SST anomalies, indicating that local upwelling processes controlled coastal ocean conditions.

For much of California, the summer of 1999 was one of the coolest on record. From February through late 1999, sustained cool air temperatures along the central coast of California set numerous records (R. Renard, pers. comm.). The mean temperature at Monterey for March–July 1999 was 1.4°C cooler than the long-term average for these months. March and May tied and set 48-year records for their respective low mean and minimum average temperatures.

The relatively cool waters of the Pacific exert a strong maritime influence on the western United States. Unusually cool ocean conditions contribute to cooler than normal land temperatures. The west coast's weather is colored considerably through the development of a daily sea breeze and frequent coastal stratus and fog. Even the track and intensity of winter storms, as well as the amount of moisture they carry over the continental United States, are affected by upper ocean conditions.

It is too early to say for certain, but the unusual physical and biological conditions of 1999 may be the first signs of a shift in climate. Decadal-scale climate shifts, often referred to as regime shifts in the literature, have been described in a number of articles (cf. Mantua et al. 1997; Parrish et al., in press). The most familiar shift in the North Pacific occurred about 1977. Increasing recent evidence suggests that another significant climate shift occurred around 1990. Minobe (1999) has identified interdecadal oscillations in the Aleutian Low as a possible mechanism for climate shifts, and suggests that a phase reversal could occur as early as 1999–2000. The recent situation off California is reminiscent of the climatic and ecological patterns common in the years prior to 1977. Conditions in 1999 also appear to be an extreme case of the relatively cool state of the CCS for several years after the strong El Niño events of 1957–58 and 1982–83. Perhaps the Pacific climate has undergone a new, analogous transition, returning to a former environmental and ecological state. Or the unusual physical and biological conditions of 1999 may be merely a brief reaction to a strong, extended La Niña, a hiatus in the recent trend toward a warmer climate. In either case, recent months have revealed that the CCS can change swiftly and dramatically, and that its marine populations appear to respond nearly as rapidly.

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LITERATURE CITED

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science 247:198–201.

Baltz, K. A. 1997. Ten years of hydrographic variability off central California during the upwelling season, M.S. thesis, Naval Postgraduate School, Monterey, Calif., 319 pp.

Bograd, S. J., P. M. DiGiacomo, R. Durazo, T. L. Hayward, K. D. Hyrenbach, R. J. Lynn, A. W. Mantyla, F. B. Schwing, W. J. Sydeman, T. Baumgartner, B. Lavaniegos, and C. S. Moore. 2000. The state of the California Current, 1999–2000: forward to a new regime? Calif. Coop. Oceanic Fish. Invest. Rep. 41 (this volume).

Brink, K. H., D. C. Chapman, and G. R. Halliwell Jr. 1987. A stochastic model for wind-driven currents over the continental shelf. J. Geophys. Res. 92:1783–1797.

Chelton, D. B., P. A. Bernal, and J. A. McGowan. 1982. Large-scale interannual physical and biological interaction in the California Current. J. Mar. Res. 40:1095–1125.

Dorman, C. E., and C. D. Winant. 1995. Buoy observations of the atmosphere along the west coast of the United States, 1981–1990. J. Geophys. Res. 100:16,029–16,044.

Hayward, T. L., T. R. Baumgartner, D. M. Checkley, R. Durazo, G. Gaxiola-Castro, K. D. Hyrenbach, A. W. Mantyla, M. M. Mullin, T. Murphree, F. B. Schwing, P. E. Smith, and M. Tegner. 1999. The state of the California Current, 1998–1999: transition to cool-water conditions. Calif. Coop. Oceanic Fish. Invest. Rep. 40:29–62.

Hollowed, A. B., and W. S. Wooster. 1992. Variability of winter ocean conditions and strong year classes of Northeast Pacific fish stocks, ICES Mar. Sci. Symp. 195:433–444.

Lynn, R. J., T. Baumgartner, C. A. Collins, J. Garcia, T. L. Hayward, K. D. Hyrenbach, A. W. Mantyla, T. Murphree, A. Shankle, F. B. Schwing, K. M. Sakuma, and M. Tegner. 1998. The state of the California Current, 1997–1998: transition to El Niño conditions. Calif. Coop. Oceanic Fish. Invest. Rep. 39:25–49.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production, Bull. Am. Meteorol. Soc. 78:1069–1079.

Minobe, S. 1999. Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: role in climate regime shifts. Geophys. Res. Lett. 26:855–858.

Parrish, R. H., F. B. Schwing, and R. Mendelssohn. In press. Mid-latitude wind stress: the energy source for climatic regimes in the North Pacific Ocean. Fish. Oceanogr.

Ramp, S. R., N. Garfield, C.A. Collins, L. K. Rosenfeld, and F. B. Schwing. 1995. Circulation studies over the continental shelf and slope near the Farallon Islands, CA, executive summary. Naval Postgraduate School, Monterey, Calif. Tech. Rep. NPS-OC-95-004, 40 pp.

Roemmich, D., and J. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. Science 267:1324–1326.

Schwing, F. B., and R. Mendelssohn. 1997. Increased coastal upwelling in the California Current system. J. Geophys. Res. 102:3421–3438.

Schwing, F. B., M. O'Farrell, J. M. Steger, and K. Baltz. 1996. Coastal upwelling indices, west coast of North America, 1946–95. U.S. Dep. Commer., NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-231, 207 pp.

Schwing, F. B., R. H. Parrish, and R. Mendelssohn. 1997. Recent trends in the spatial variability of the SST and wind fields of the California Current system. *In* Global versus local changes in upwelling systems: proceedings. First Intl. CEOS Workshop, M. H. Durand et al., eds. Paris: ORSTOM, pp. 101–125.

Tegner, M. J., P. K. Dayton, P. B. Edwards, and K. L. Riser. 1997. Large-scale, low-frequency oceanographic effects on kelp forest succession: a tale of two cohorts. Mar. Ecol. Prog. Ser. 146:117–134.

Wolter, K., and M. S. Timlin. 1998. Measuring the strength of ENSO—how does 1997/98 rank? Weather 53:315–324.