

# California's Variable Ocean Environment

The habitat of California's living marine resources is primarily the California Current system. This huge, open system is constantly changing in response to weather systems, seasonal heating and cooling processes, inter-annual episodes such as El Niño - La Niña events, and longer term or regime scale climatic changes.

Small organisms, and the young of most large ones, are impacted by the full temporal range of physical processes. Shorter time scale and local physical processes including intense wind storms, extended periods of calms, infusions of freshwater runoff, and shorter term variations in currents heavily impact the growth, survival, and distribution of most of these organisms. Short-term variations in primary production (e.g., diatom blooms) coincide with upwelling, but the scale of phytoplankton production relates to the history of water masses and weather conditions. Seasonal scale fluctuations are so important to many organisms that their life-cycle is often largely adapted to the seasonal cycle and their abundance is often heavily influenced by variations from the seasonal norm. Longer term events, El Niños and regime shifts, appear to be primarily dependent upon physical processes that are centered elsewhere in the Pacific and their effects include alterations in the physical, nutrient, and biological content of the waters entering the California Current system. These events also result in alterations in local physical processes such as currents and upwelling that control local inputs of nutrients. El Niño events and regime shifts have extensive effects on kelp forests and zooplankton populations.

The adults of larger fishes and other marine vertebrates are somewhat buffered from the effects of weather and other short-term physical fluctuations, and extremely long-lived organisms, such as many of the deep benthic fishes, may have populations that are nearly independent of normal short-term environmental fluctuations. Many of California's marine fishes have life history adaptations such as extended spawning seasons, multiple spawnings, migrations, and extreme longevity that reduce the harmful effects of short-term adverse environmental fluctuations and even limit the effects of El Niño events at the population level. In contrast, organisms with shorter life spans, such as the market squid, that may be only slightly affected by environmental fluctuations at the shorter time scales appear to have extreme population declines during El Niño events. Decadal or regime scale climatic fluctuations that alter the basic productivity of the California Current system are common, repetitive events readily observed in paleo-sediment analyses that extend back several thousand years. They are also clearly evident in time series analyses of physical factors (*i.e.*, ocean

temperatures) and indices of biological productivity (*i.e.*, zooplankton densities). These longer term events have been shown to greatly alter populations of the dominant pelagic fishes of the California Current and it is probable that they affect the populations of even long-lived benthic fishes and marine mammals.

A species physiology determines its preferred temperature range and its lethal temperature tolerances. The surface and bottom temperatures on the continental shelf off California make the northern portion of the state good habitat for sub-arctic and cold-temperate species (salmon, market crab, and petrale sole) and the southern portion good habitat for warm temperate and sub-tropical species (kelp bass, spiny lobster and California halibut). Many of the most abundant species of the California Current are transition-zone species that have the center of their distribution in California (Pacific sardine, Pacific hake, and northern anchovy). Temperature, like other physical oceanic factors, is highly variable on seasonal, annual, and longer time scales and it is the most easily studied. In addition, temperature is highly dependent upon large-scale ocean currents and local upwelling; it is therefore a rough index of the productivity of the lower trophic levels and an indicator of climatic processes that favor the colder or the warmer water faunas that occur in California. Temperature is thus the most commonly correlated climatic variable used to determine associations with biological processes. However, nearly any environmental factor that is associated with variations in the major currents will also be correlated with biological processes and temperature, and we do not know if alterations in currents or the resultant changes in temperature have the largest effect on biological processes in the California Current.

**Table 1**  
Average Monthly Sea Surface Temperatures  
Off San Francisco

Month	Warm Years <sup>1</sup> Temperature (°F)	Cold Years <sup>2</sup> Temperature (°F)
January	56.18	51.51
February	56.01	51.67
March	56.86	51.87
April	55.77	51.19
May	56.07	50.22
June	59.26	51.91
July	60.94	54.76
August	60.17	53.70
September	61.83	55.27
October	60.71	55.40
November	58.26	53.38
December	56.46	53.09
Average Temperature	58.24	52.83

<sup>1</sup> warm years: 1940, 1959, and 1992  
<sup>2</sup> cold years: 1910, 1929, and 1975

**Average Monthly Sea Surface Temperatures Off San Francisco**  
Sea surface water temperature offshore of San Francisco indicates a distinct summer upwelling pattern with cold sea surface temperatures nearshore, as well as large inter-annual variations. Within this strong upwelling cell, sea surface temperatures can be colder during the summer in cold years than they are during the winter in warm years.

The living marine resources of California evolved in a dynamic and changing ocean and most populations undoubtedly fluctuated in response to environmental alterations long before man exploited them. Many of these resources are now heavily exploited and those in the near-shore environment are also impacted by human induced environmental changes. Some species, such as bocaccio and lingcod, have been heavily overfished, and their current populations are at very low levels. A few very highly overfished stocks, such as Pacific mackerel and Pacific sardine, have suffered nearly complete population collapses from which they have recovered after one or more decades of protection by harvest moratoriums. As discussed below, there is considerable evidence that regime shifts exacerbated the effects of fishing and delayed the effects of the moratoriums.

Fishery and marine resource management is presently in the middle of a change in philosophy. In the past, our management has been based on the view that the environment can be considered to be constant with only minor and temporary perturbations which introduce "random noise" into our population assessments and management policies. This has resulted in a management system that has failed to protect exploited populations during extended periods of adverse environmental conditions. The information in the following sections indicates that physical factors and biological productivity in the California Current system are not stationary. It is clear that variations in these processes must be monitored by our research programs and built into our management systems if we expect to maintain healthy and diverse nearshore and offshore ecosystems.

## Climatic Processes, El Niño Events and Regime Shifts

The California Current, one of the world's major eastern boundary currents, has its origin in the mid-latitude west-wind-drift region of the North Pacific, and it could be considered an equatorward flowing, surface extension of the North Pacific Current. The core of the California Current normally lies about 90 to 130 miles offshore of the shelf break or continental margin. The fauna and productivity of the California Current system are heavily dependent upon the input of cool, low-salinity, high nutrient and plankton-rich waters from the mid-latitude North Pacific.

The system also has a sub-surface, poleward current (the Davidson Current) that is often at a maximum just offshore of, and somewhat deeper than, the shelf break. In the fall, poleward flow often extends to the surface in the southern portion of the California Current and surface

poleward flow is not uncommon in the nearshore region over much of the system. The advection of warm, high salinity, low-nutrient and plankton-poor water from the sub-tropics is largely responsible for the warm water flora and fauna and lower productivity characteristic of the nearshore region south of Point Conception.

Like other eastern boundary currents, the California Current has extensive coastal upwelling that is primarily driven by spring and summer winds resulting from temperature gradients between the relatively cool sea surface and the warming continental land mass. Equatorward winds, offshore Ekman transport, and coastal upwelling occur nearly all year off of Baja California and the offshore region of southern California; however, within the Southern California Bight wind velocities are lower and offshore transport is much reduced. Wind velocities and upwelling are variable but tend to be at a maximum in the spring to early summer in the region between Point Conception (34.5°N) and the Oregon border (42°N). The duration and strength of upwelling-favorable winds diminishes northwards. Off the State of Washington (48°N) upwelling is relatively minor and is largely restricted to the late spring to early fall; winter storms there result in intense downwelling events. Downwelling events diminish in both magnitude and seasonal duration to the south, below Point Conception they are uncommon and usually of minor magnitude.

Climatic fluctuations ranging from strong storms to seasonal cycles to El Niño/La Niña events to decadal changes or regime shifts alter the physical, chemical, and biological environment of California's marine waters. Average monthly sea surface temperatures (SST) in California waters range from a minimum of about 52°F in February off northern California to a maximum of about 68°F in August off southern California. The pattern of sea surface temperatures in the California Current varies from a clearly latitude dependent situation in the late winter, with isotherms being nearly east-west in orientation, to the distinct upwelling pattern of cold water near shore and warmer water offshore in the late summer. Most of the area has mild winter SSTs, and cool summer SSTs caused by the summer upwelling. This results in a very small seasonal variation in SST, no more than 4 to 7° F during the year. In contrast, the inter-annual variation in SSTs can be as large as the normal summer/winter difference; off San Francisco SST is colder during the summer in cold years than it is during the winter in warm years.

## El Niño/La Niña Processes

El Niño is a term that describes large-scale changes in the atmospheric pressure system, trade winds, and sea surface temperatures of the entire tropical Pacific that

occur at approximately three to four-year intervals. The cold water portion of the cycle is now referred to as La Niña. This cyclic process has traditionally been measured by the southern oscillation index (SOI), which is the difference between the atmospheric pressure at Tahiti (an approximation of the South Pacific High) and the atmospheric pressure at Darwin, Australia (near the Tropical Pacific Low). The SOI is therefore a measure of the variability of the atmospheric circulation in the South Pacific. The effects of El Niño events in California include reduced input of cold, nutrient-rich waters from the north and increased advection of warm, nutrient-poor water of subtropical and tropical origin into the southern California area. There may or may not be a reduction in upwelling favorable winds; however, nutrient input to the surface waters from upwelling is decreased due to reduced nutrients in the subsurface waters and a depressed thermocline. Thus, during El Niños the California Current becomes more sub-tropical, and warm-water organisms enter the system in greater numbers. During La Niñas the environment is more sub-arctic and cold water organisms are favored.

Although California occupies a large geographical area, surface temperature anomalies on scales greater than a few weeks are common over the entire region. Time series of SST from northern, central and southern California are characterized by strong El Niño events such as those occurring in 1940, 1958, 1983, 1992, and 1997. In addition, there are decadal scale events where surface temperatures are above or below average for extended periods. Cold periods occurred prior to 1925, from about 1946 to 1956, and from 1962 to 1976. Warm periods occurred from 1938 to 1945, 1957 to 1961, and from 1977 to 1998. Waters of the Central Pacific, however, tend to vary in the opposite direction from the California Current system.

Surface temperature is not necessarily a good indicator of temperature below the upper mixed layer. In 1972, at the onset of a major El Niño, the surface temperature at Point Conception was the lowest since 1951, whereas the temperature at 330 feet was among the warmest recorded.

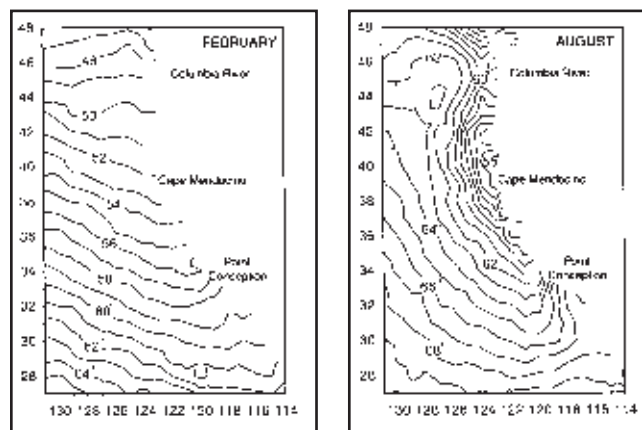
The 50 year time series of the California Cooperative Oceanic Fisheries Investigations (CalCOFI) is probably the world's best data set for determining the effects of inter-annual physical variability on zooplankton populations, the primary food for larger stages of larval and some adult fishes. As with temperature, strong interannual signals occur over a very large spatial scale. Anomalies of zooplankton abundance, 10m temperature, 10m salinity, and southward transport are highly correlated in time from southern Baja California to north of San Francisco. On interannual time scales, zooplankton abundance is pri-

marily influenced by large-scale variations in flow of the California Current. Increases in southward transport are associated with increases in zooplankton production, cold temperatures, and low salinity (La Niña events), whereas decreases in this transport result in unusually low zooplankton biomass, warm temperature, and high salinity (El Niño events).

In addition to substantial declines in zooplankton abundance during El Niño events, analysis of the samples taken during the years 1955 to 1959 showed a large rearrangement of the dominance structure of functional groups of macrozooplankton. The rank order of abundance for 18 groups, containing an estimated 546 species, changed over this period. Plankton community structure was similar in 1955 to 1957 but underwent an abrupt and dramatic change coincident with strong El Niño conditions in 1958-1959. In addition to changes in zooplankton, other characteristics of strong El Niño events include deepening of thermocline and nitricline by some 165 feet, and redistribution of phytoplankton biomass from the upper layers of the ocean to a deep chlorophyll maximum. Quarterly patterns of environmental variables and zooplankton biomass are now reported annually in the State of the California Current in CalCOFI Reports.

## Decadal/Regime Scale Processes

During the last decade it has become increasing apparent that longer term decadal to multi-decadal climatic cycles are impacting populations of a wide variety of marine organisms in the California region, and that all trophic levels are affected. Analyses of fish scales in anaerobic sediments have shown that these cycles have been occurring for thousands of years (*i.e.*, independent of fishing), and that the most abundant fish stocks have



**Winter and Summer Pacific Coast Sea Surface Temperatures**  
Average (1920-1992) February and August sea surface temperatures (°F). A cold summer upwelling core is apparent in northern California. Data extract from COADS as monthly means.

fluctuations which occur over an average period of about 60 years. The implications from a number of these paleo-sediment studies are that large-scale physical processes are forcing the biological fluctuations. Recent results from ocean/atmosphere models suggest that decadal climatic cycles are forced by air/sea interactions in the higher latitude North Pacific. Observed decadal to multi-decadal fluctuations in the mid-latitude atmospheric circulation in the Central Pacific have also been suggested to have physical and biological effects that appear to affect a large proportion of the North Pacific basin. A major regime shift occurred in 1976-1977 and the surface waters of the entire eastern Pacific Ocean from Mexico to Alaska became warmer. Since 1976, there has also been an increase in the frequency, duration and intensity of El Niño events in California waters.

The 1976 climatic shift is clearly seen in time series of California sea surface temperatures. Decadal and regime shift processes both are evident in a newly proposed index for the North Pacific, the northern oscillation index (NOI). This index is analogous to the southern oscillation index used to describe and predict El Niños. However, it is a better measure of the atmospheric circulation in the North Pacific because it is based on the difference between the average position of the North Pacific High (35°N: 130°W) and the Tropical Low near Darwin. When the three to four year scale El Niño processes are filtered out, using a 36-month moving average, the NOI exhibits the decadal cycles that researchers have predicted and the widely observed climatic shift that occurred in 1976-1977.

Zooplankton populations also exhibit strong interdecadal variability. CalCOFI data showed a 70 percent decrease in the biomass of macrozooplankton associated with warming of surface layers between 1951 and 1993. Averages of zooplankton biomass over the initial and final seven-year periods of this interval were computed for southern California grid lines. The differences between the two periods appeared to be uniform in space and at least twice the standard deviation of the seven-year mean at each station. Over this time period, lines 80 and 90 surface temperatures warmed by an average 2.2 and 2.8°F, respectively, but thermal changes at depth were small. Therefore, the vertical stratification of the thermocline substantially increased, resulting in a reduction in the transfer of nutrients to the surface.

Long-term trends in temperature and salinity of the upper 100m, zooplankton biomass, and transport from north to south through the present day CalCOFI grid indicate that interdecadal changes apparently have different physical forcing mechanisms than those associated with El Niño events. Because the surface layer has become warmer and fresher, the increase in stratification apparently results

in reduced displacement of the thermocline and thus a shoaling of the source of upwelled waters. The effect is to decrease the fraction of the year when wind stress is strong enough to lift nutrient-rich waters to the surface near the coast. Because the increased stratification essentially insulates nutrient-bearing waters from the surface, a moderate degree of heating can greatly reduce the surface nutrient supply. These trends appear to be related to the strengthening of the North Pacific wintertime atmospheric circulation associated with the regime shift that began in 1976-1977.

Fish eggs and larvae are also sampled in CalCOFI zooplankton collections. Although both total larval fish and zooplankton abundance exhibit substantial interannual variability, there is no clear relation between the two time series. There are weak time-lagged correlations when zooplankton leads fish larvae by four to five months in three of four regions of the California Current, which would be expected if poor nutrition of adult fish has affected their reproductive success. Although zooplankton is well correlated with temperature, salinity, and transport, total fish larvae are poorly related to these physical parameters. Nor are larval fish clearly related to anomalies in longshore winds, the basis of coastal upwelling. Analyses of both larval fish and zooplankton data suffer from the obvious complications of lumping large numbers of taxa; studies of individual species may offer better opportunities of relating oceanographic variability to recruitment success. For example, there are inverse trends for northern anchovy and Pacific sardine spawning biomass and larval standing crop; the declines for anchovy and increases for sardines took place during a period of declining zooplankton abundance and warming temperatures associated with the regime shift. Clearly fishes are long-lived organisms with complicated life histories; mortality in poorly assessed stages such as juveniles may account for the poor relationships between physical parameters, larval abundance, and adult stocks.

## Implications for Nearshore Ecosystems

The flora and fauna of California's nearshore communities are strongly affected by interannual variability in the physical environment including both El Niño-Southern Oscillation events and the regime shift that began in 1976-1977. Furthermore, large wave events in this region are highly correlated with strong El Niño events, so these two forms of disturbance often co-occur. Thus, in the southern and central regions of the state there has been considerable interdecadal-scale wave variability, with greatly increasing numbers of episodes with significant wave heights greater than 12 feet in recent years.

The most dramatic benthic effects of El Niño events are on kelp forests, ecosystems organized around the structure and productivity provided by giant kelp (*Macrocystis*) and bull kelp (*Nereocystis*). The two-fold effects include extreme winter storm waves, which may decimate kelp populations along the entire exposed coast, and anomalously-warm, nutrient-depleted waters, whose effects increase in severity with decreasing latitude. With their high growth rate, southern California *Macrocystis* populations depend on nutrients supplied by upwelling or internal waves. When these sources are rendered ineffective by depression of the thermocline, growth ceases, tissue decay leads to the loss of the surface canopy, and considerable mortality may follow. Kelp forests from the warmest regions of the state, Orange County south along the mainland and the southeastern Channel Islands, suffer massive losses. Further to the north, the addition of the El Niño temperature anomaly to normal summer-fall temperatures apparently maintains the environment within the range of suitability (*i.e.*, nutrients did not become limiting), although growth may be reduced.

Sea surface temperature is the best predictor of kelp harvest and areal extent. The increase in mean SST since the 1976-1977 regime shift has been associated with large decreases in the size of *Macrocystis* plants as measured by number of stipes per individual. Furthermore, this secular increase in SSTs means that each El Niño event is adding to a higher temperature base; thus, successive events are characterized by increasingly severe temperature anomalies. Poor conditions for *Macrocystis* growth are associated with enhanced understory algae and reduced drift kelp production.

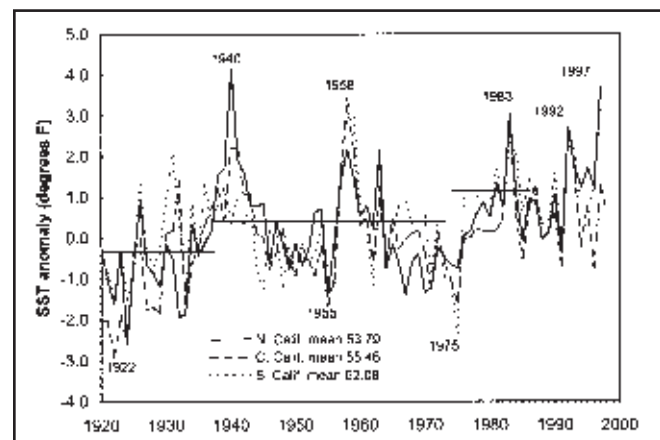
Aerial surveys illustrate huge variability in *Macrocystis* surface canopies in the Southern California Bight. The effects of the 1983 and 1998 El Niño winter storms are apparent in all areas, but the speed of kelp recovery varies with location. Cooler areas such as San Miguel Island recovered from the storms very quickly and had minimal impacts from the warm, nutrient-depleted waters that followed. In contrast, many of the *Macrocystis* populations on the coastline between Santa Barbara and Point Conception, which were largely set in sand, were devastated by the storms of the early 1980s and have not recovered. The 1988-1989 La Niña provided excellent growth conditions after a severe storm largely removed existing giant kelp populations in many areas; this combination led to peaks in kelp canopy biomass in the southeastern part of the bight in 1990.

While effects of El Niño and regime shifts on the kelps are relatively well known, the implications for higher trophic levels and community structure are only beginning to be understood. The effects of storms, warm, nutrient-depleted waters, and anomalous current patterns all

appear to be important. Drift kelp is the primary food for sea urchins and abalones. With up to 60 percent of the biomass of a healthy *Macrocystis* forest in its canopy, the loss of the canopy and varying degrees of mortality of adult plants have huge effects on drift availability. With reduced food supplies, urchin gonad production is very low, often to the point of making processing uneconomical; because the product is the gonads. Many processors closed during the 1982-1984 El Niño, for example. Abalone reproduction and recruitment are also affected, leading to large gaps in size-frequency distributions. The loss of drift food may trigger destructive grazing by sea urchins, transforming kelp forests to barren grounds with cascading implications for other organisms in this community. Anomalously warm waters are also associated with disease outbreaks, especially for sea urchins, sea stars, and abalones.

Reductions in *Macrocystis* populations have critical implications for fishes dependent on giant kelp for foraging habitat and refuge from predators. Recruitment of young-of-the-year kelp bass is dependent on *Macrocystis* density. The presence of giant kelp has a positive effect on the recruitment of other rocky inshore fishes such as kelp rockfish, giant kelpfish, kelp surfperch, pile surfperch, and black surfperch. On the other hand, the striped surfperch, which feeds in foliose red algae, is adversely affected by the presence of *Macrocystis* because of the strong negative relationship between giant kelp and foliose algae. Thus, the structure of a kelp forest has significant effects on the species composition and local density of the fish assemblage, and that structure is strongly affected by ocean climate.

With greatly increased transport from the south, northern range extensions of subtropical, migratory species and larvae are very characteristic of El Niño events. Most



**California Sea Surface Temperature Anomalies**

Annual sea surface temperature anomalies (°F) off northern, central, and southern California, with means of three time periods (1920-1937, 1938-1976, and 1977-1997). Data extract from COADS as monthly means.

migratory species are pelagic, but pelagic red crabs are conspicuous nearshore visitors. Spiny lobsters and sheephead, two important predators of sea urchins in the Southern California Bight, both have their centers of distribution off Baja California and recruit heavily to southern California (and sheephead as far north as Monterey) during strong El Niño events. Conversely, La Niña events with enhanced transport from the north result in increased recruitment of cool water fishes such as blue rockfish in southern California.

Observations of shallow water reef fish assemblages in the Southern California Bight from 1974 to 1993 indicate substantial changes in species composition and productivity that appear to relate to the increased frequency of El Niño events and the regime shift. At two sites off Los Angeles, species diversity fell 15 to 25 percent and the composition shifted from dominance by northern to southern species by 1990. By 1993, 95 percent of all species had declined in abundance by an average of 69 percent. Similar declines of surfperch populations off Santa Cruz Island were linked to declines of their crustacean prey and biomass of understory algae where the fish foraged. Recruitment of young-of-the-year at the three sites fell by over 90 percent, and the decline was highly correlated with the decrease in macrozooplankton abundance in the CalCOFI data. These changes in population abundances and trophic structure were apparently caused by lower productivity associated with the regime shift of 1976-1977.

Statistics from the commercial passenger fishing vessel rockfish fishery of southern California for the period 1980 to 1996 illustrate a substantial decline in catch-per-unit effort. Three species abundant in 1980 were absent by 1996. Catch of others such as bocaccio declined as much as 98 percent. On average, mean length declined due to the removal of larger size classes, and in the case of the vermilion rockfish, the take changed from primarily adults to almost entirely juveniles. On some trips, the catch now mostly consists of dwarf or small species of *Sebastes*. Such population declines probably result from poor long-term juvenile recruitment caused by adverse oceanographic conditions combined with overfishing of adults and sub-adults. This combination results in recruitment overfishing that reduces spawning stocks to levels too low to ensure adequate production of young fish for future fishing.

Dramatic effects on fish assemblages are reported in central California as well, where El Niño events are associated with improved recruitment of southern species, recruitment failures of rockfishes, and poor growth and condition of adult rockfishes. In addition to sheephead, blacksmith and bluebanded goby are southern species that were observed near Monterey. Reproductive success of many species of central California rockfish appears to be

sensitive to El Niño conditions, because it was poor during 1983 and 1992. Poleward advection, downwelling, delayed and reduced phytoplankton blooms, and low zooplankton abundance appear to be important factors in reproductive failure during these periods. Modeling has demonstrated that fishery management practices can exacerbate El Niño effects if harvest is not decreased in response to the environmentally induced decrease in biomass.

In northern California, where the red sea urchin fishery is limited by poor recruitment, there has been strong interest in understanding the role of oceanographic variability on the temporal and spatial patterns of settlement. Recent studies have shown increased settlement in some sites during both the 1992-1993 and 1997 El Niños, but the sampling periods were short and settlement was not consistent among areas. Regional patterns of circulation in northern California and the delivery of larvae to the coast during upwelling relaxation are the best explanation for the observed pattern of recent recruitment for several invertebrate species. Understanding the role of larger scale processes will require longer time series.

## Implications for the Offshore Ecosystem

California's marine fauna and flora are principally components of the subarctic, transition, and central (or subtropical) zones. Subarctic species are more common off northern California and subtropical species more abundant off southern California. With the exception of marine mammals, birds, and a very few fishes (tunas), marine organisms are cold blooded. They are therefore highly affected by temperature, making water temperature one of the most significant physical factors that marine organisms have to cope with. In fact, the most obvious effect of climatic variation in the California offshore ecosystem is the appearance of tropical species such as tunas and pelagic red crabs in association with El Niño events. As mentioned earlier, variations in the major current patterns greatly influence fluctuations in ocean temperatures.

Wind driven upwelling also alters temperature and transport patterns. In the California current, the most obvious consequence is the nearshore core of cold upwelled water that is at a peak in the Cape Mendocino region in the summer. Nearshore species that have pelagic eggs are highly susceptible to the offshore loss of their early life history stages by wind-driven surface transport. Many species are therefore unable to reproduce successfully in the region between Point Conception and Cape Blanco, Oregon (about 35-43°N), where upwelling and offshore transport are at a maximum. Many of the important species that are permanent residents of this region have reproductive adaptations that reduce the offshore dispersion of reproductive products. These include bearing live

young (rockfishes and surfperches), demersal spawning (herring, lingcod and many littoral species), anadromous spawning (salmonids and true smelts), and late winter spawning (Dover sole, sablefish and most rockfishes) to avoid the intense upwelling season (late spring to early summer). The most abundant California Current fishes have pelagic eggs and larvae and these fishes have extensive spawning and feeding migrations (Pacific hake, Pacific sardine, Pacific mackerel, and jack mackerel). The adults of these stocks feed in the more northern portions of the region during the summer and fall, and then return to the area near, or to the south of Point Conception to spawn in the late winter and early spring.

## El Niño - La Niña Fluctuations

The most obvious biological effect of El Niño Southern Oscillation events is that environmental factors, especially temperature, affect the behavior and distribution of larger marine organisms. These effects are most marked in the adults of pelagic, migratory, or nomadic species that are able to greatly expand or contract their ranges by actively moving among regions with seasonal cycles or other climatic fluctuations such as El Niño events. Southern species that have the center of their distribution south of California such as bonito, barracuda, white sea bass, and swordfish normally move into southern and central California during the late summer and fall. Both these fishes and tropical fishes such as yellowtail, skipjack, and yellowfin tuna move into southern California in larger numbers during El Niños. Major El Niño events also cause extended migrations of Pacific sardine, jack mackerel, and Pacific mackerel to as far north as Alaska. This migratory response to warmer surface temperatures is primarily behavioral and it may or may not be associated with increased population size of the individual species.

Sub-tropical species with limited swimming ability, such as pelagic red crabs and smaller zooplankton species, often occur in dense concentrations off of California, suggesting that advection also plays a significant role in community structure during El Niño events. El Niños are known to alter the population levels of zooplankton and other animals with short life spans. The market squid, which normally lives for no more than one year, appears to be heavily impacted by El Niños and the California fishery for this species has suffered near total collapse in major El Niño years. Population effects on longer-lived animals are likely, but population time series are lacking for most species. El Niños and other warm water events can result in decreased growth rates and reproductive output in fishes, and decreased size at maturity in market squid.

With the exception of the salmon, the colder water fishes are much less likely to make seasonal migrations. Most of the California groundfish and nearshore fishes make very limited geographical movements, other than the larval drift that occurs during their planktonic early life history stages. Once they settle in good habitat, individuals of these species tend to remain in relatively small areas. La Niña events therefore are not remarkable in the appearance of large numbers of the adults of cold water species moving down from Alaska and Canada. However, they may result in increased recruitment at the southern edges of the range of colder water species.

## Regime Scale Climatic Variations

Longer-term climatic processes appear to be forced by factors outside of the California Current region. Early studies showed that sea surface temperatures are out of phase off of California and Japan. The dominant pelagic fishes of the California, Japan, and Peru/Chile regions have been shown to have strikingly similar population fluctuations, and paleo-sediment studies in both the California Current and the Peru Current suggest that regime scale climatic changes have been occurring for thousands of years. Salmon production in the Pacific Northwest (chinook and coho) has recently been related to interdecadal climatic patterns in the North Pacific and it is out of phase with production of pink and sockeye salmon in Alaska.

In contrast with short term La Niña events, cold water organisms are able to extend their populations into the southern portion of the state during extended cold periods. Many rockfishes that have the center of their distribution in the subarctic zone exhibit this pattern. The reverse pattern occurs in subtropical fishes. Some transition zone pelagic species move as far north as southern Alaska during very warm years but essentially abandon the area north of California during extended cold periods.

The California Current has recently been in its longest recorded period of warm water. During the last two decades, there have been marked population declines in a number of cold water species (salmon, lingcod, and rockfishes) and several stocks are now threatened or endangered. In contrast, several transition zone fishes that spawn off southern California and migrate to feeding grounds between northern California and Canada experienced large population increases following the shift to warm water conditions (Pacific sardine, Pacific mackerel and Pacific hake). It is clear that physical climatic factors may be as important as fishing in regulating the productivity of some exploited species.

## Conclusions

The organisms of the California Current are adapted to an environment that varies on scales from local and short term to very large scale and multidecadal. Growth, reproduction, and larval survival may be depressed for variable periods during short-term adverse environmental conditions, but most adults of larger species survive. The addition of decades of intense fishing pressure onto long term climate disturbances such as those experienced since the 1976-1977 regime shift, however, makes population decline almost inevitable for species adversely affected by the changed environment. The challenge facing fishery managers is how to respond on time scales that will protect spawning stocks during periods of poor reproduction. One approach is to significantly decrease fishing effort on existing, heavily pressured stocks to create a buffer for hard times. El Niño events are being predicted with increasing skill; if fishing effort on sensitive species could be sharply curtailed in favor of species that thrive under warm conditions, the negative effects of these climatic events could be reduced. Another approach is to establish marine protected areas large enough to ensure surviving populations in every region. If some rockfish stocks had been protected in southern California during the present regime shift, for example, recovery during cold water periods would be far faster than the present situation that will largely depend on recruitment from depressed central California populations.

Too much of our fisheries management has been based on the assumption that environmental variability is not important. With 20/20 hindsight and the increasing prospects of human impacts on climate, we know that this cannot continue. It is clear that over the next decade a major research effort will have to be made to better understand the climatic connection and that fishery management will have to consider policies to reduce exploitation rates when species are impacted by adverse climatic factors.

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