

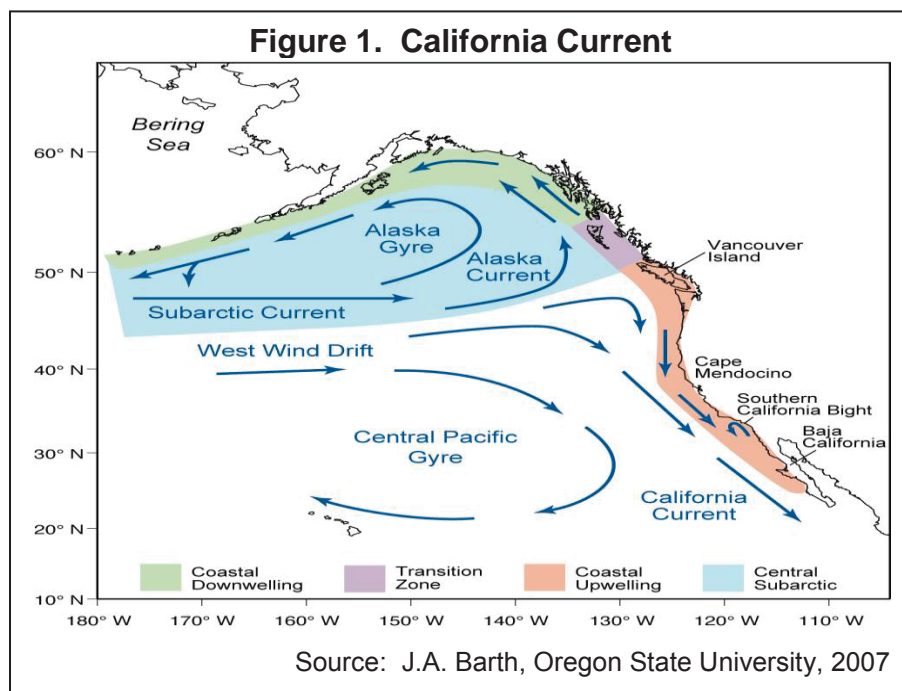
APPENDIX A. NORTH PACIFIC OCEAN CONDITIONS AND PROJECTIONS FOR CLIMATE CHANGE

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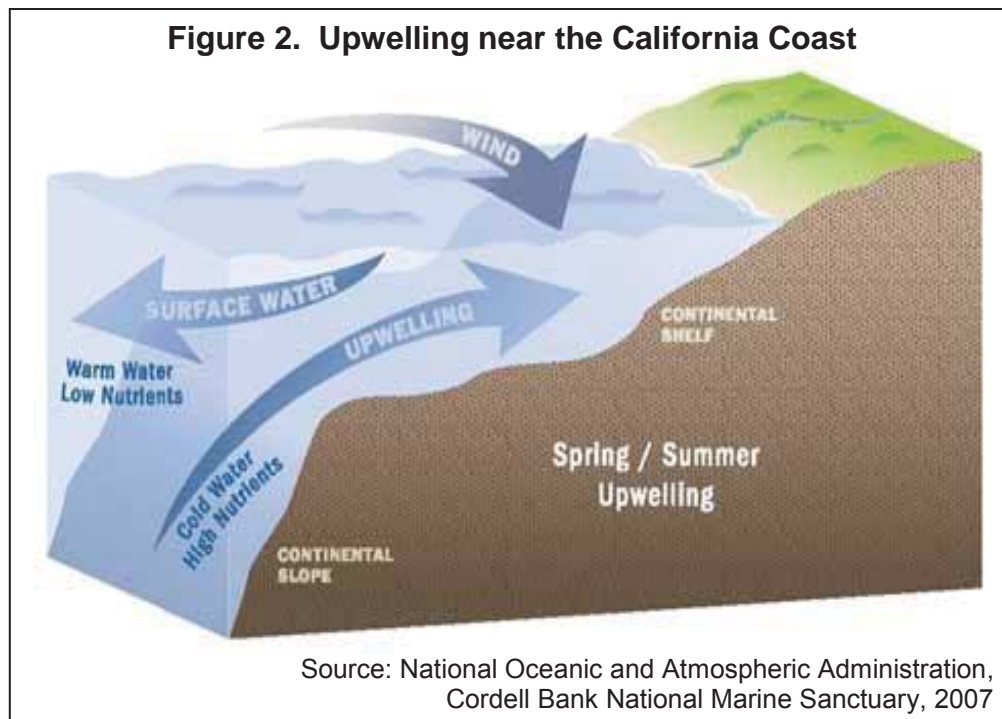
The Pacific Ocean influences California's mild, Mediterranean climate. Temperature and precipitation patterns for much of the state, including the cool wet winters and warm dry summers flavored with coastal fog, are determined largely by ocean conditions. Even the weather in the Sierras and over much of the nation is influenced by conditions in the North Pacific Ocean.

The broad southward-flowing ocean current that is part of the clockwise circulation vortex pattern of the North Pacific (gyre) is known as the California Current (Figure 1). This coastal current transports relatively cool, fresh (low salinity), and nutrient-rich water, as well as many organisms, from sub-Arctic regions to the California coast. This sub-Arctic water also contains a different composition of plant and animal species than the more sub-tropical, oceanic water over which it flows. A regional process known as "upwelling" carries the deep, cooler waters transported by the current upward, closer to the surface where photosynthesis by phytoplankton occurs (Smith, 1968; Huyer, 1983). The biologically productive coastal region, dominated by valuable fisheries such as sardine, market squid and salmon, and a variety of marine mammals, turtles, and birds, is one consequence of this nutrient-rich current (Parrish et al., 1981).



Prevailing winds over the North Pacific drive both the California Current and upwelling, on different space and time scales. Ocean circulation for the North Pacific basin is caused by large-scale winds, combined with the Earth's rotation. The North Pacific gyre adjusts to changes in global climate by transfers in heat and momentum of wind forces, on scales of months to years. Since the principal characteristics of the California Current ecosystem are linked so strongly to a small set of atmospheric processes, it is no surprise that variations in the intensity and timing of winds are often connected to global-scale shifts, which can cause significant changes in ecosystem production and organization.

Coastal upwelling is due to the onset of local coastal winds from the northwest. These winds are associated with the atmospheric high-pressure system that strengthens in spring and summer, the upwelling "season" [Figure 2]. The strong northwest winds (roughly parallel to the coastline) drive surface waters away from the coast, replacing these with the upwelling of deeper cooler waters. As air flows offshore from land over the cooler upwelled waters, its moisture condenses into fog. Unlike the relatively slow adjustment of the North Pacific gyre, upwelling responds within a day to fluctuations in coastal winds (Rosenfeld et al., 1994) and can intensify and relax as the alongshore wind strengthens and weakens. Similar upwelling-dominated ecosystems are found off the west coast of South America, Africa, and Iberia.



Changes in the flow of the California Current affect local water quality, including the biological effectiveness of upwelling. Greater transport of nutrient-rich water from the north means that upwelled water will support more biological productivity in surface waters. As California Current transport decreases due to

changing climate conditions, coastal water will include relatively more subtropical water, and the upwelling of this water will lead to less primary production.

Another consequence of lower transport by the California Current is lower oxygen in coastal areas (Bograd et al. 2008), since subtropical water carries less dissolved oxygen (Stramma et al., 2008). During reduced southward flow, a shallow oxygen-deficient zone can develop, which reduces the depth of favorable habitat for many marine organisms.

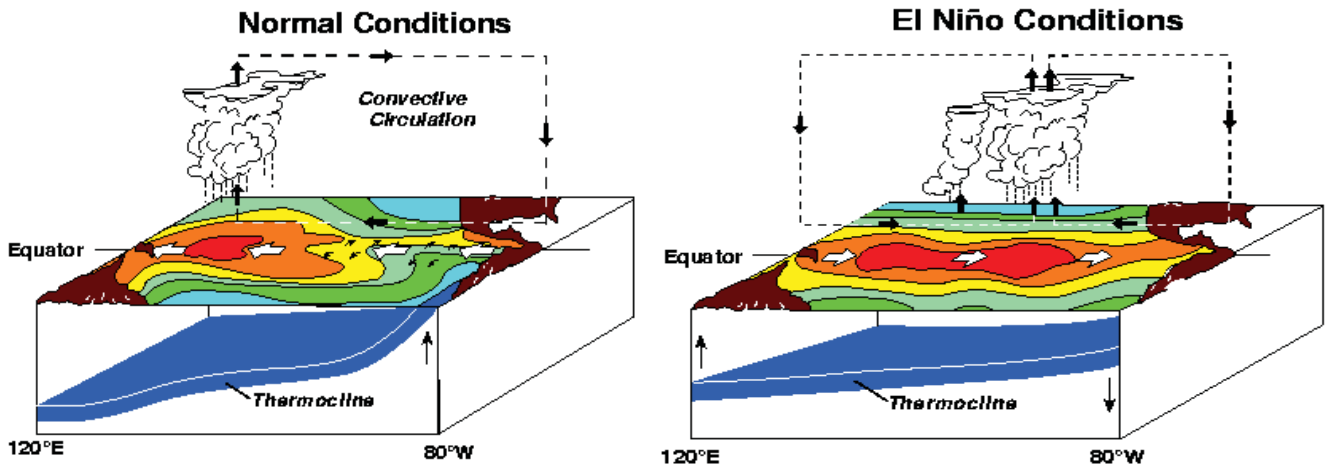
Another factor that influences upwelling is vertical stratification, which is a measure of the increase in water density with depth. Higher stratification represents a greater contrast between the less dense (warmer, fresher) surface water layer and denser (cooler, more saline) deep water; greater wind energy is required to mix these layers or to upwell nutrients to the surface. Thus, a consequence of global warming will be a more strongly stratified coastal ocean and less biological productivity (Roemmich and McGowan, 1995).

Variability in climate, with characteristic patterns in space and cycles or oscillations in time, is increasingly recognized to be part of a global interconnected system. The timing, evolution and signals of these patterns influence our weather (e.g., heatwaves, fog, snowpack, floods, droughts), one of the more obvious aspects of our environment. Likewise, global climate change will drive this ecosystem into a new, possibly previously unknown state. The California Current ecosystem is also impacted heavily by climate change. The dominant climate variability affecting California is identified by a few important climate phenomena and indices, including the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).

El Niño-Southern Oscillation

El Niño (Philander, 1990) is the ocean part of a climate disruption of global oceanic and atmospheric conditions that originates from the tropical Pacific [Figure 3]. It often produces heavy rains and floods in California, droughts and wildfires in Australia, and fewer Atlantic hurricanes. One of the factors that cause El Niño events is the Southern Oscillation (SO), a fluctuation in atmospheric air pressure at sea level between the western and central tropical Pacific. During the positive phase of ENSO (El Niño), abnormally high atmospheric pressures develop in the western tropical Pacific and Indian Ocean regions, and unusually low pressure develops in the southeastern tropical Pacific. This is associated with a large-scale weakening of the Pacific trade winds, leading to warming of the surface waters in the eastern and central equatorial Pacific Ocean.

Figure 3. Schematic of the tropical Pacific, showing atmospheric circulation, sea surface temperature anomalies, and position of thermocline



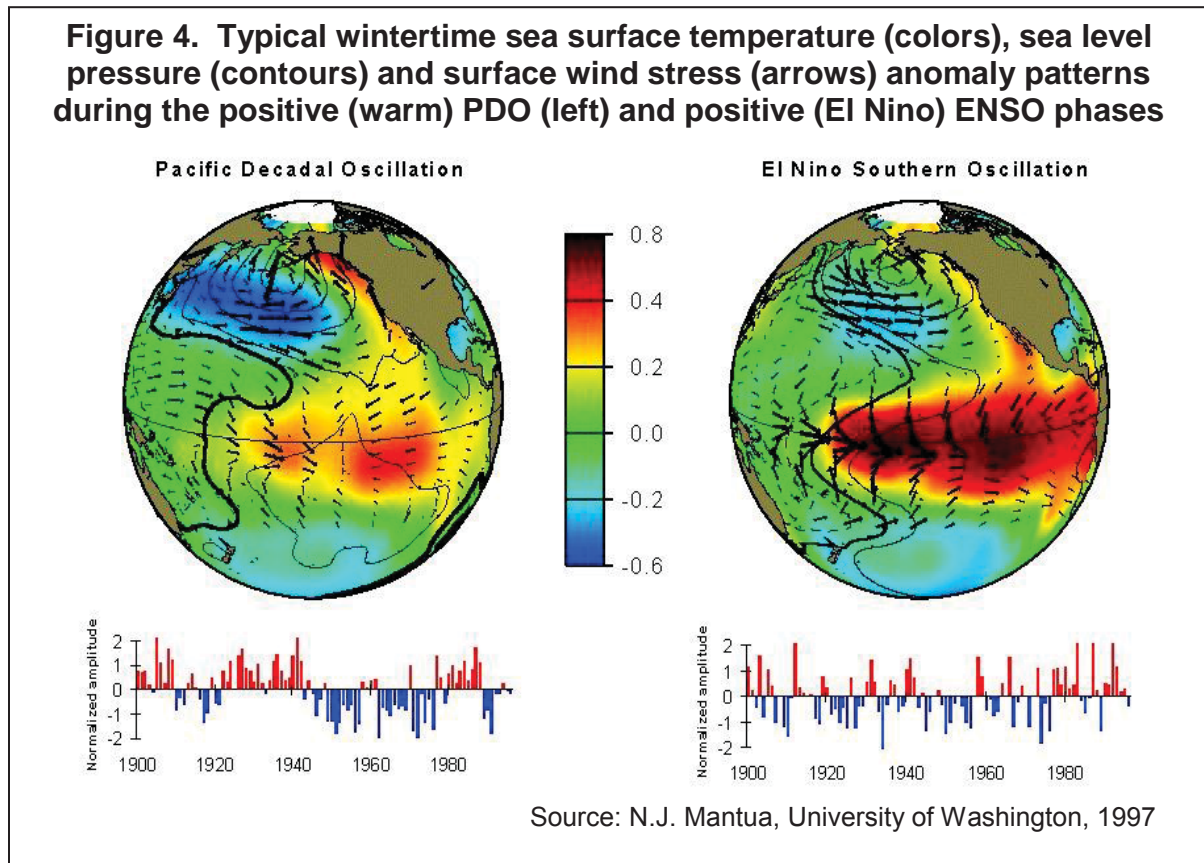
El Niño events occur irregularly at intervals of two to seven years, with the strongest events occurring about once per decade (1941-42, 1957-58, 1965-66, 1972-73, 1982-83, 1986-87, 1997-98). They typically last 12 to 18 months, peaking along the coasts of North and South America around December (hence the name El Niño, Spanish for The Child, in reference to Christmas). The negative phase of ENSO, called La Niña, occurs when the trade winds blow unusually hard and the ocean temperatures become colder than normal.

Along the west coast of the U.S., as well as South America, El Niño events often reduce upwelling, which means warmer waters and fewer nutrients in surface waters. This temporarily lowers ecosystem growth and can be responsible for the temporary collapse of important commercial fisheries in addition to marine mammal and sea bird populations. Because this is a long-established natural cycle, the ecosystem eventually recovers. The signal of El Niño can be seen in the four ocean climate indicators: warmer temperature, lower oxygen, higher copepod species richness, and poorer sea bird breeding success. However, not every El Niño event is identical; the timing, strength, and regions of greatest impact vary with event (Mendelssohn et al., 2003).

Pacific Decadal Oscillation

The Pacific Decadal Oscillation represents a much longer-scale (multi-decadal) phenomenon [Figure 4]. The PDO is based on a statistical analysis of ocean observations, and is the first principle component of monthly ocean surface temperature patterns for the North Pacific (Mantua et al., 1997). Typically, the phases of the PDO, referred to as regimes, represent relatively stable ocean states, separated by sharp and rapid transitions, called regime shifts. Warm (so-called because ocean temperatures along the coast of North America are unusually warm, but cool in the central North Pacific) PDO regimes dominated in 1925-1946 and from 1977 into the late 1990s. Cool PDO regimes prevailed from 1890-1924 and from 1947-1976, and there is some suggestion that the PDO returned to its cool phase in 1998. It must be noted that the PDO is an indicator

of multi-decadal climate variability in ocean temperature, not a climate process like ENSO that has a clear physical mechanism. Scientists are working to understand the mechanisms responsible for the natural decadal variability represented by the PDO. Understanding these variations will improve our ability to detect and quantify anthropogenic changes.



The positive phase of the PDO is associated with warmer than normal ocean temperatures off California and generally lower biological productivity, as seen in the ocean indicators. Different dominant assemblages of fish and marine species characterize the phases of the PDO (Peterson and Schwing, 2003). For example, sardine is typically the dominant fishery during the positive (warm) PDO phase, while anchovy and salmon thrive in its cool phase.

The PDO appears to have considerable influence on terrestrial systems as well. Warm phases of the PDO are correlated with North American temperature and precipitation anomalies similar to El Niño, including warm and wet conditions for most of California, and increases in the volume of Sierra snowpack and flood frequency (Cayan, 1996). Over the western U.S., it also corresponds with periods of reduced forest growth (Peterson and Peterson, 2001), more extensive wildfires (Mote et al., 1999), and disease outbreaks. These anomalous conditions are more apparent when the positive PDO phase corresponds with El Niño.

California's Coastal Ocean and Climate Change Projections

Based on model climate projections from the Intergovernmental Panel on Climate Change (IPCC) and other sources, the likely consequences of future climate change to California's coastal ocean can be predicted. IPCC (2007) identifies a number of very likely (90-99% probability) changes in the 21st century of concern to coastal California. Some of the predicted ecological responses are already being noted, and could be a result of recent climate change.

Air and ocean temperatures are projected to become warmer, especially in summer, contributing to greater ocean stratification and weaker upwelling. The biological impact of this may be a lower rate of productivity and less food for many species, a northward shift in the distribution of many populations, and the expansion of invasive and exotic species in number and abundance, possibly outcompeting and displacing native species.

Changes in storm patterns and precipitation are likely to cause warmer and wetter winters; greater freshwater discharge into the coastal ocean, and coastal flooding. Projected shifts in precipitation and Sierra snowmelt will modify the seasonal patterns of streamflow. These changes could reduce coastal water quality, and increase toxic algal blooms and other ocean-borne health hazards. Changes in freshwater flow, as well as stream temperatures, would be particularly critical to salmon and other anadromous stocks. Higher coastal sea level could displace intertidal species and reduce the area of coastal and estuarine wetlands that are crucial nursery grounds for many marine species.

Other likely (66-90% probability) 21st century changes have been identified (IPCC, 2007). More extreme weather and climate events, such as stronger storms and greater coastal erosion, more frequent or intense El Niño events, and perhaps even hurricanes are possible. Important fisheries could be displaced and reduced during such events, but exotic subtropical fisheries may become available. Alterations in the winds may change the North Pacific gyre circulation patterns which will affect the transport of nutrients, dissolved oxygen, and marine organisms. Increased CO₂ concentrations in the upper ocean will lower pH and cause the water to become more acidic to marine life (Feely et al., 2004). The impacts of this are just being explored, but could include a substantial disruption of the food chain in the California Current. Changing seasonal cycles are also likely (Parmesan and Yohe, 2003). One likely scenario is a delay in the start of the upwelling season and, consequently, a delay of the spring plankton bloom (Snyder et al., 2003). This will impact migration and reproductive cycles of fish, birds and marine animals as their source of food is not synchronized with their life cycles (Mackas et al., 2006; Sydeman et al., 2006).

While indicators (e.g., Scripps ocean temperature) with long-term tendencies such as warming throughout the 20th century suggest trends due to increased greenhouse gases and anthropogenic climate change, indicators featuring multi-year climate variability are equally important in characterizing climate change. One of the limitations to quantifying and projecting climate change is

distinguishing between natural and anthropogenic signals in many observational records. Indicators with interannual to interdecadal variability associated with natural phenomena like ENSO and the PDO are necessary to isolate anthropogenic signals.

These natural variations also help us to understand the relationships between climate forcing and their impacts on human systems and ecosystems. They help identify the key physical drivers of natural climate variability and ecosystem response. This insight is vital to improve the ability to predict how future climate change will shape California and our world.

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