

**Draft Climate Change Site Scenario**  
**January 19, 2009**

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**Gulf of the Farallones and Cordell Bank National Marine Sanctuaries**

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The document that follows is a copy of the DRAFT Climate Change Site Scenario for the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries that was disseminated to four individuals who served as peer reviewers. In December 2004, the White House Office of Management and Budget (OMB) issued a Final Information Quality Bulletin for Peer Review (OMB Bulletin) establishing peer review standards that would enhance the quality and credibility of the federal government's scientific information. Among other information, these standards apply to Influential Scientific Information (ISI), which is information that can reasonably be determined to have a "clear and substantial impact on important public policies or private sector decisions." The Climate Change Site Scenario is considered Influential Scientific Information. For this reason, this report is subject to the review requirements of both the Information Quality Act and the OMB Bulletin guidelines. Therefore, following the completion of the report was reviewed by four individuals who were considered to be experts in the field, were not involved in the development of the report, and are not Office of National Marine Sanctuaries employees. Following the External Peer Review the comments and recommendations of the reviewers were considered by sanctuary staff and incorporated, as appropriate, into a final draft document.

The comments and suggested edits that were received from the reviewers are embedded in the below draft. The final Climate Change Site Scenario will be available at:  
<http://sanctuaries.noaa.gov/>.

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## Executive Summary

It is apparent today that our ocean faces significant challenges. Findings of the Intergovernmental Panel on Climate Change state that, "...the resilience of many ecosystems (their ability to adapt naturally) is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances... and other global change drivers...". On both global and regional scales, the ocean faces a variety of physical impacts due to increasing carbon dioxide (CO<sub>2</sub>) and subsequent climate change, such as sea level rise, coastal erosion and flooding, and changes in precipitation and land runoff, ocean-atmosphere circulation, and ocean water properties. These physical changes have cascading effects leading to biotic responses within ocean ecosystems, including changes in physiology, phenology, and population connectivity, as well as species range shifts, and species-specific responses.

The Climate Change Site Scenario developed by the joint working group of the Gulf of the Farallones (GFNMS) and Cordell Bank (CBNMS) National Marine Sanctuary Advisory Councils, identifies and synthesizes an extensive suite of potential climate change impacts to habitats and biological communities along the north-central California coast. It outlines observed climate change effects in this region as well as changes that are considered to be highly likely and changes of notable concern (even if their likelihood is uncertain). It should not be considered an assessment of current conditions, or a prediction of future changes. It is a scoping document that discusses potential issues as they relate to a changing climate through both observation and science-based expectations. The GFNMS and CBNMS Climate Change Site Scenario document is the precursor and companion to the climate change action plans that will be developed for each sanctuary. These plans will identify priority management actions that will be taken over the next 10 years to address the impacts of climate change specific to the site, its communities, and the region.

### Regional Effects of Climate Change

Global changes in carbon dioxide levels, ocean warming, precipitation, sea level, and ocean circulation will lead to changes in winds, currents, land runoff, sea level, coastal erosion and ocean water properties along the California coast and within the study region. The study region contains a variety of habitats including: offshore pelagic; offshore benthic; island; nearshore subtidal; sandy beach; rocky intertidal; and estuarine. The response of a single species to climate change depends not only on environmental changes within the system, but also upon how other species will respond to each other. A variety of physical changes may occur within each of these given habitats, and communities of organisms will interact in response to these changes.

Marine organisms may respond in a variety of ways to the changing ocean conditions. Species can (1) remain in the same area but adapt to changing conditions, (2) persist in sub-optimal conditions but with potentially significant physiological costs, (3) move to environmental conditions that suit their physiological tolerances by expanding or contracting their range in space (along latitudinal, depth, or intertidal gradients), or (4) they may adjust the timing of their life history (e.g. breeding events) (see 4.0 Regional Biotic Responses).

The synergy of human influences and natural climate cycles is likely to create new extremes in climate conditions. The 21<sup>st</sup> Century will likely see slightly greater annual precipitation and more extreme winter storms in northern California and an earlier, more rapid spring snow melt. Rising

**Comment:** Although well-written and organized, the Executive Summary section contains too much information and is way too long (10 pages) to serve its purpose. To be effective, I think it needs to be cut back to about 3-4 pages. All of the ecosystem-specific sections (e.g., "offshore habitat") should be cut to a few paragraphs.

**Comment:** Although sea level rise is mentioned many times in the Executive Summary, nowhere (that I could find) is the projected scale of sea level rise (100-140 cm by 2100) specifically mentioned. This information is important and needs to be inserted near the beginning of the Summary.

temperatures will likely result in a retreat of snow cover and a corresponding increase in the ratio of rainfall to snowfall in northern and central California (see 3.2 Precipitation and Land Runoff). This predicted increase in high runoff could be analogous to a climatic shift towards more frequent El Niño like conditions. In addition, North Pacific winter cyclones increase precipitation, generating large waves and raising coastal sea levels (through wind-driven storm surge). From 1858-2000, the San Francisco tide gauge showed a significant increase in intense winter storms since 1950. An increase in the largest waves (see 3.3.2 Waves) has also been reported and attributed to increases in storm frequency. Reports indicate that 1-in-100 year coastal flooding events are likely to occur every 10 years in the future (see 3.1 Atmosphere). Both the El Niño-Southern Oscillation (ENSO) phenomenon and the observed long-term increase in wave heights (particularly extreme wave heights) pose significant risks. In addition to more extreme storms, increased global temperatures cause thermal expansion of water and increased ice melt raising sea level. Increases in sea level exacerbate coastal flooding, shoreline erosion, saltwater intrusion into groundwater aquifers, inundation of wetlands and estuaries, and threatens cultural and historic resources as well as infrastructure (see 3.4 Sea Level Rise).

### ***Offshore Habitat***

In the offshore pelagic environment, the availability of nutrients and light are the main factors that determine the distribution of life in this habitat. Physical processes control the biological activity through a delicate balance between wind driven upwelling and stratification of the water column. The global increase in ocean temperatures and the freshening of the Pacific Ocean contribute to reduce mixing between the upper layer of the ocean and nutrient rich water just below the pycnocline. Increased water column stratification may lead to a major shift in phytoplankton communities in the region. Future changes in circulation currents due to climate change could change the distribution of gelatinous zooplankton. These organisms are likely to become the dominant predators in ecosystems where pollution, over-fishing, and climate change impact the marine ecosystem (see 5.1 Offshore Pelagic Habitat).

Regional numerical models predict an increase in global temperatures will lead to stronger wind stress along the California Coast, in particular during the summer-fall seasons in central California. Although the southward wind stress that causes coastal upwelling is likely to increase in magnitude off California, for a number of reasons these winds may be less effective in driving vertical transport of nutrient-rich water. The life cycles of many marine species are tightly aligned to the changing seasons and delayed transitions can cause mismatches in normally stable food webs (see 3.3.3 Coastal Upwelling). Poleward shifts in distribution and earlier timing of important life cycle events have led to changes in species abundance and plankton community structure, with associated generally deleterious changes in dependent upper trophic level predators (see 4.5 Plankton).

Production at all levels of the marine food web could decline if average dates for the spring transition (the onset of seasonal upwelling) and peak upwelling change. Many fishes and invertebrate early life histories are timed to coincide with upwelling. Changes in the timing of the spring transition or the peak upwelling season could have significant population level impacts for many species. Marine fish likely time their spawning efforts to ensure maximum food availability for larval fish later in the season. Similarly, seabirds likely time their breeding to maximize prey abundance during the critical chick-rearing period. Peak upwelling (and peak food production) may occur too late in the season for successful reproduction if marine fish and

seabirds begin breeding in response to an early spring transition. Late upwelling is generally associated with poor ocean productivity, low krill abundance, and late seabird breeding. Late breeding is generally associated with poor seabird reproductive success and could ultimately lead to breeding population declines in the region (see 4.3 Phenology).

During years when upwelling occurred later in the spring, such as 2005 and 2006, a reduction in phytoplankton and zooplankton abundances was seen in the region. The zooplankton community changed as well; not only did abundances of krill (adult krill, in particular) and copepods decline, but abundances of gelatinous zooplankton appeared to increase. Due to the lack of available prey, (e.g., adult krill), Cassin's auklets abandoned nests and failed to breed in these years. The decline in adult krill in 2005 may be related to decreased survival of Chinook salmon entering the ocean that year and low salmon returns in California in 2008. Sightings of blue whales (another krill predator) dropped significantly from 2004 numbers. Drastic bottom-up effects in the ecosystem were observed and documented in a relatively short time period (July 2004 to August 2005), including low primary production, low krill abundance, a decline in at-sea seabird abundance, and late and reduced reproductive success in seabirds on the Farallon Islands (see 5.3 Island Habitat).

Changing temperatures will directly influence fish physiology, as most fishes are poikilothermic ("cold-blooded"). Fish may respond to these changes by shifting their distributional range to accommodate preferred temperature regimes (along latitudinal or depth gradients; see 4.2 Range Shifts). In general, scientists predict that fishes tolerant of a wide temperature range (i.e. eurythermal) will have an advantage over species tolerant of a narrow temperature range (i.e. stenothermal). Climate change may also lead to a decrease in fish prey (i.e., through ocean acidification or changes in phytoplankton primary productivity) that in turn may decrease fish populations (see 4.8 Fish).

A changing climate can also alter seabird distributions. Long-term studies of seabird distribution and abundance have revealed the importance of mesoscale oceanographic features (fronts and eddies) to these top predators. Changes in ocean circulation patterns could lead to changes in the locations of these mesoscale features and to subsequent changes in seabird distributions. The persistence of seabird populations in this case is dependent on their ability to forage further from the colony during the breeding season or to find alternative nesting areas closer to abundant food supplies (see 4.9 Seabirds).

Within the California Current there are over 40 species of marine mammals, whether resident or long-range migrants to polar regions, that will likely be affected by changes in climate. The predicted climate conditions that likely will affect marine mammals include increased sea temperature, ocean acidification, sea level rise and alternations of oceanic processes. The potential consequences of climate change may be: alterations in movements and migrations, changes in abundance and population structure, timing of breeding, breeding areas, reproductive success, changes in behavior, changes in community structure, stress on body health and susceptibility to disease, and extinction (see 4.10 Mammals).

Climate change can also affect population connectivity (the exchange of individuals between geographically isolated sub-populations through mechanisms such as larval dispersal) by altering

larval transport or by modifying the timing of recruitment favorable conditions through changes in ocean circulation processes, such as upwelling, or changes in ocean temperature. Since many marine organisms exhibit an open water larval stage, the disruption of connectivity can have significant implications for the distribution and abundance of adult populations (see 4.4 Population Connectivity).

The physical drivers that will most directly affect offshore benthic communities are changes in water properties (temperature, dissolved oxygen, ocean acidity) and regional winds (upwelling, transport). Because of their limited ability to move, communities associated with offshore benthic habitats would be particularly susceptible to significant impacts from climate change. Benthic organisms that are unable to extend their geographic range as conditions change will have to adapt in order to survive (see 5.2 Offshore Benthic Habitat).

Increased concentrations of CO<sub>2</sub> in the ocean have impacted the chemistry (pH) and biology of the ocean. Ocean acidification is a recent but major concern and has been described by scientists as the “other CO<sub>2</sub> problem”. Increased atmospheric CO<sub>2</sub> leads to a reduction in ocean pH (i.e., ocean acidification) and a decline in the carbonate ion concentration. The carbonate ion is essential to the formation of calcium carbonate minerals (e.g., calcite and aragonite) that make up the shells and skeletons of many marine animals (see 3.6.2 Ocean Acidification).

Ocean acidification has the potential for significant negative physiological effects on the life stages of many marine organisms such as coccolithophores, foraminifera, pteropods, copepods, euphausiids (krill), benthic bivalves, gastropods, echinoderms, crustaceans, and deep water corals. The larval stages of marine invertebrates are likely to be particularly sensitive to acidification effects due to their small size and because some produce aragonitic structures which are more susceptible to acidification. Likewise, because deeper water tends to be more acidic, deepwater corals such as the hydrocorals located at Cordell Bank may be one of the first to experience acidification (see 4.1 Physiology).

#### ***Island Habitat***

Anticipated changes in climate will significantly impact the physical habitat of offshore islands. Of particular concern are potential alterations to seabird and marine mammal breeding and resting habitat at the Farallon Islands, the largest seabird-breeding colony in the contiguous United States and an important breeding and haul-out area for marine mammals. Digital elevation models have demonstrated that a rise of 0.5 m would result in permanent flooding of approximately 5% of the island surface area including many of the intertidal areas where pinnipeds (seals and sea lions) haul out. As these areas become inaccessible, animals would move higher up onto the marine terrace or abandon the colony. This redistribution of pinnipeds would, in turn, impact seabird habitat by reducing the available nesting areas and causing the destruction of nest sites, particularly for burrow nesting species such as the Cassin’s auklet. Furthermore, during extreme high tides and storm events, waves would be expected to extend higher still, leading to increased erosion, flooding, and loss of habitat (see 5.3 Island Habitat).

During the El Niño events of 1983 and 1992, higher water and increased storm activity resulted in significant erosion of elephant seal breeding areas and the destruction of important beach access routes at the Farallones. This in turn made it more difficult for them to access their

primary breeding areas and led to local population declines and reduced breeding success (see 5.3 Island Habitat).

In addition to risks from flooding and erosion, average annual air temperature at the Farallones exhibited an increasing trend from 1971 to 2007. Many species on the island are adapted to cold and windy conditions and quickly become stressed when conditions change. During unusually warm weather, seabirds may abandon their nests, neglect dependent offspring, and die of heat stress. Marine mammals will spend less time hauled out (resting) and would be expected to abandon young in the rookeries if temperatures become too warm (see 5.3 Island Habitat).

#### ***Subtidal Communities: Kelp and Seagrasses***

The nearshore subtidal environment within the study region includes sandy continental shelf habitat as well as rocky reefs, which support kelp forest communities. Primary climate change drivers for nearshore subtidal habitats include changes in upwelling, offshore stratification, ocean acidification, storm activity, *increasing waves*, and sea level rise. Changes in upwelling will affect nutrient delivery to the nearshore subtidal. In addition, coastal thermoclines have become stronger and deeper in offshore waters in the study region. Further increases in offshore stratification would prevent nutrient delivery to the nearshore subtidal habitat as well as decrease offshore transport of larvae and spores, further increasing retention. Stratification as a consequence of climate change has already been reported to change zooplankton communities in the California Current (see 5.6 Nearshore Subtidal Habitat).

Climate change will have complex effects on the abundance and distribution of bottom and canopy forming macroalgae within the study region, although scientists expect most changes will result in range shifts rather than the loss of key groups (e.g. kelps) from the system. Macroalgae will be impacted by increasing sea surface temperatures and sea level rise, which will affect the availability of light and available substrate suitable for attachment. Changes in upwelling will also affect the availability of nutrients for photosynthesis (see 3.4.4 Coastal Upwelling). Increased turbulence from larger waves may remove macroalgae from exposed subtidal and intertidal locations, and influence the timing and distribution of drift kelp, which can serve as habitat and food in pelagic and benthic systems (see 4.6 Macroalgae and Plants).

Increasing wave heights will affect sediment redistribution and may change the coastal topography of the area. Increased storm activity may increase precipitation, leading to greater freshwater input to the nearshore subtidal. An increase in terrestrial runoff as well as storm activity will lead to higher resuspension of sediment resulting in increased turbidity and light attenuation. Increased turbidity will compromise kelp growth. Turbulence from increased storm activity may also remove kelp growing in shallower water so that nearshore kelp forests are mostly found in deeper water and create greater intra-annual variability in kelp productivity and abundance. Greater turbidity may compromise the growth and recruitment of some kelp species (e.g. *Macrocystis*) while promoting others (e.g. *Nereocystis*). For kelp forest communities on rocky reefs (which form a physical habitat for reef-associated species), increased storm activity may also increase dislodgement of kelp holdfasts resulting in a loss of physical habitat for kelp forest associated species (see 4.6 Macroalgae and Plants).

Seagrasses may benefit from increased light levels due to reduced growth of coralline algae that commonly attach to seagrasses. However, seagrasses are highly susceptible to existing human-induced stressors such as sedimentation (resulting in reduced light levels) and habitat

Deleted: significant

fragmentation from the construction of docks, piers and marinas, and damage from moorings and anchors. Altered runoff schedules (i.e. concentrated runoff during winter months) could also reduce eelgrass populations within Tomales Bay by modifying patterns of sedimentation. As with other species living in the shallow sub-tidal or intertidal, sea level rise could also negatively affect seagrass if no additional upland habitat is available. Surfgrass (*Phyllospadix torreyi*) that is commonly found in exposed rocky intertidal sites may be at risk of dislodgement by extreme wave events (see 4.6 Macroalgae and Plants).

### ***Sandy Beach Habitat***

Sandy beach and dune habitats are increasingly squeezed between the impacts of human land development and manifestations of climate change. Beach armoring and development severely limit the ability of beach ecosystems to adjust to changes in shoreline stability as well as sea level rise and erosion caused by climate change. The majority of the sandy coast in this region is already classified as eroding, partly as a result of human-induced changes in sediment supply and transport (see 5.4 Sandy Beach Habitat).

Scientists predict that an increase in El Niño storms, which typically bring the largest recorded waves and occur in late winter when most beaches are at their narrowest width, will cause the majority of coastal erosion, flooding, and property loss. Most of the coastline in the study area is backed by seacliffs, with Mendocino County projected to lose the largest area of land to coastal erosion. Dune erosion is likely to have the largest impact in Marin County (an estimated 2.6 km<sup>2</sup>), with erosion of almost 9 km<sup>2</sup> for the dunes across the entire study area (see 3.5 Coastal Erosion).

Habitat loss, fragmentation, and alteration from sea level rise will have profound ecological implications, as beaches become narrower and steeper and as previously continuous habitat in front of coastal bluffs and cliffs is converted to isolated pocket beaches. This would have significant impacts for species that depend on this habitat at some point during their life history. Sea level rise will affect threatened birds, such as the western snowy plover and California least tern that nest in dry sand, open beach and dune habitats throughout the study region. Fish, such as the California grunion and smelt, also depend on these vulnerable uppermost intertidal zones of open sandy beaches for spawning, burying their eggs at the driftline for incubation in the region (see 5.4 Sandy Beach Habitat). Finally, pinnipeds, including elephant seals, sea lions, and harbor seals, pup and raise their young on sandy beaches, again using the threatened upper beach zones within the study region. Increased temperature and sea level rise will reduce pinniped haul out areas by submerging low lying coastal areas that are unable to retreat inland. Consequently, the places where pinnipeds can give birth will be altered and/or reduced. Mortality of elephant seal pups along the Point Reyes National Seashore has already been documented to be higher during storm events such as El Niño years (see 4.10 Marine Mammals).

### ***Rocky Intertidal Habitat***

Farallon Islands, Duxbury Reef, and Fitzgerald Marine Reserve are three significant rocky intertidal areas within the study region. Of primary concern for this habitat are possible increases in average water and air temperature as well as the prevalence of extreme conditions (e.g., heat waves) that can result in mass mortality of intertidal organisms. In addition, the combined effects of ocean acidification and upwelling could have tremendous implications for the ability

of intertidal organisms to produce shells as well as capture food. Upwelling will also affect the availability of nutrients for primary producers (plants and algae). Sea level rise and increased wave activity may also affect intertidal organisms, in some cases through interactions with other factors like elevated air temperature, although the outcomes of these processes are less certain. Though range shifts are typically considered on large scales (100-1,000s of km); shifts in elevation (i.e., up the intertidal zone) will occur in response to sea level rise on the scale of meters (see 3.4 Sea Level Rise). Intertidal species will be most affected by increased sea level rise and increased air temperatures may compress the range of high intertidal species into lower zones (see 5.5 Rocky Intertidal Habitat).

Many intertidal invertebrates are already living at the edge of their thermal tolerances. For example, the thermal limits of the common black turban snail have been shown to be within 1 to 3 degrees of temperatures that are already experienced at low tide. In addition to temperature, ocean acidification will affect the ability of many calcifying invertebrates to produce calcium carbonate shells. The combination of increased temperature and ocean acidification can also directly affect the physiological development of larvae by influencing larval metabolic rate (via temperature) or by inhibiting calcification and/or larval development (via ocean acidification). One example of this is the Pacific oyster, whose larvae displays reduced shell growth or a complete lack of shell development when exposed to higher CO<sub>2</sub> levels. Economically and ecologically important species such as sea urchins, mussels, oysters, abalone, crabs, and other invertebrate taxa will also likely be negatively impacted (see 5.5 Rocky Intertidal Habitat).

### ***Estuarine Habitat***

Climate change will effect estuarine circulation, with primary concerns including: (1) changes in mouth closure timing and persistence; (2) changes in degree and frequency of flooding; (3) upstream salinity intrusion; and (4) fate of estuary outflows. The extent of changes will depend on the interaction of river flow rate *and timing*, sea level rise, wave energy and wind-driven currents. Significant estuarine habitats within the study region include the Russian River, Salmon Creek, Estero Americano, Estero de San Antonio, Tomales Bay, Bolinas Lagoon, and Pescadero Marsh (see 3.3.4 Estuarine Circulation).

**Comment:** i.e., changes in snow melt...

Sea level rise is among the most important climate change factors forcing changes in the physical structure of estuarine systems in the coming decades. Other factors such as increasing air and sea surface temperatures and CO<sub>2</sub> may interact with sea level rise to influence the physical environment of these habitats. Climate change is also predicted to result in changes in oceanographic and atmospheric linkages resulting in changes in ocean currents and storm cycles that will likely influence estuarine geomorphology. The hydrological cycle, including rainfall and outflow from rivers into estuaries will also influence the transport and deposition of sediments with long-term consequences for the physical structure of California estuaries. In addition, freshwater inundation could lower the pH of estuaries by reducing the buffering capacity of estuaries with lower salinities, higher organic inflows and more acidic freshwater (such as Tomales Bay; see 5.7 Estuarine Habitat).

**Comment:** Awkward sentence.

Sea level rise will increase salinity within tidal marshes and either result in marsh “drowning” or an inland shift in the distribution of tidal marshes if they are able to expand sediments quickly enough. The extent to which these communities can migrate will depend on the type and amount

**Comment:** “expand sediments” is confusing. Are some words missing?

of available upland habitat. Estuaries bordered by roads or other infrastructure may see an estuarine squeeze effect where available habitat is compacted into a narrow range, whereas marshes *bounded by an undeveloped, low relief* corridor may be able to migrate. In response to sea level rise, platform-like marshes will likely lose little area initially, until a critical point when the marsh will rapidly become inundated, and ramped marshes will exhibit a slow but gradual loss. Areas where estuarine upland borders are entirely surrounded by infrastructure, such as Bolinas Lagoon, are significantly at risk of habitat loss (see 5.7 Estuarine Habitat).

Deleted: that have a

Increasing sea surface and air temperatures are magnified in estuaries relative to the outer coast and are important drivers of community and ecosystem responses in estuaries. Increasing sea surface temperatures can result in the range expansion of both native and non-native species into new areas. Increased temperatures may generally put greater stress on plants and animals and magnify problems with parasites, pathogens, and invasive species (see 5.7 Estuarine Habitat).

Deleted: i

Shorebirds are among the most sensitive species to sea level rise in estuarine habitats, because of their dependence on exposed intertidal mudflat habitats for foraging. Studies of restoration planning efforts have shown the importance of tidal elevation for maintaining populations of foraging shorebirds. Other studies have indicated that sea level rise may have negative effects on the amount and type of prey available to individual shorebirds and therefore influence choice of foraging habitats, such as movement from bays to outer coast (see 5.7 Estuarine Habitat).

Anadromous fish found in the study region (such as steelhead trout, chinook, and coho salmon) will be sensitive to changes in river/stream habitat, as will estuarine fish (such as juvenile California halibut, bat rays, and leopard sharks) that utilize estuaries as nursery or feeding grounds (see 4.8 Fish). Additionally, climate change is predicted to exacerbate impacts on fish populations that are commercially and recreationally fished (see 6.1 Fishing).

### **Multiple Ecosystem Stressors**

Through both land and marine-based activities, there is no area of the ocean that is not affected by humans, and in actuality, 41% is affected by multiple human influences or “stressors”. Often time these stressors do not function independently, but instead interact to produce combined impacts on biodiversity and ecosystem health. Some examples of interacting ecosystem stressors within the study region include fishing activities, invasive species, pollutants and contaminants, harmful algal blooms, disease, habitat modification, wildlife disturbance, and potentially, emerging alternative energy projects such as offshore wind, wave and tidal energy. When combined with or exacerbated by the effects of climate change, the resiliency of marine ecosystems can become compromised (see 6.0 Multiple Ecosystem Stressors).

### **Direct Impacts on Humans**

In addition to a multitude of impacts on marine ecosystems, there are many effects climate change will have on human populations living and working along the coast. Human impacts will lead to adaptive management and planning responses that in turn affect coastal ecosystems. Issues of particular concern in coastal communities within the study region include: water quality; health consequences of toxic algal blooms; shoreline safety; and economic impacts to natural assets (such as beaches) physical infrastructure (such as electrical utility facilities),

residential and business infrastructure, and businesses that rely on ocean commodities such as fisheries (see 7.0 Direct Impacts on Humans).

### Conclusion

An extensive suite of potential climate change impacts to habitats and biological communities along the north-central California coast have been identified and synthesized in the Site Scenario. Changes are anticipated in atmospheric conditions (e.g., wind, cloud, fog), ocean circulation and water properties (e.g., temperature, pH), ocean waves, *sea level*, and land runoff. In turn, changes in these forcing factors will lead to changes in coastal upwelling, stratification, and plankton dispersal patterns. Biological systems will be impacted through changes to the quality of ocean habitat (e.g., changes in temperature, pH, dissolved oxygen, nutrient availability and wave exposure), the timing of seasonal cycles (e.g., upwelling, runoff, fog and waves), and the connectivity within and between populations. However, a variety of community response scenarios exist within the study region for offshore pelagic, offshore benthic, offshore island, sandy beach, rocky intertidal, nearshore subtidal, and estuarine habitats.

The conclusions of this report are that the most severe ecological changes will be associated with changes in the following parameters – for each the likelihood of change is high and the impact of change is equally high (i.e., these are high-risk phenomena):

- Upwelling
- Ocean temperature
- Sea level
- Ocean pH

### Working Group Recommendations

The question that now arises is, “what should we do?” Based on the immensity of ocean systems, even small coastal ones, and aware of the uncertainty in anticipating how global changes will downscale to regional and local change, the working group recommends that the Gulf of Farallones and Cordell Bank National Marine Sanctuary Advisory Councils recommend GFNMS and CBNMS pursue five lines of action:

- **Educate** – *inform people to allow optimum decisions to be made.*

Use the opportunities inherent in the National Marine Sanctuary System to educate both local residents and federal/state/local decisions makers. Education is not intended to prescribe options, but to provide people with the insight that will optimize difficult decisions, including use of public funds and regulation of activities in developing a strategy for minimizing disruptions to ecosystems and socio-economic systems due to climate change.

**Comment:** What about businesses/private sector?

- **Advocate** – *link greenhouse gas emissions with marine ecosystem health.*

The IPCC has made it clear that observed changes in global climate are due to a buildup in greenhouse gases (GHG). Further, there is a long-term commitment to climate change due to the delay between increases in GHG concentration and responses in atmosphere and ocean conditions. Our actions now will have huge benefits in mitigating climate change impacts on human society and ecosystems decades from now.

**Comment:** To whom?

➤ **Anticipate** – obtain best available information on changing and future conditions. The primary antidote to uncertainty in predictions is to maximize certainty in real-time assessments. The most critical action is to know how the environment and ecosystems are changing, and to know how these changes relate to global climate change (as opposed to other local drivers of environmental change). Our information may not be perfect, but it can be much improved with strategic investment in monitoring and assessment. Given that sanctuaries are seen as sentinel sites, this is where GFNMS and CBNMS can play a leadership role in collaboration with regional groups.

**Comment:** I recommend adding something about the NMS role in science/management community building.

➤ **Mitigate** – reduce manageable stressors that compromise system resiliency. While climate change cannot be managed in the short-term, nor *prevented*, we can enhance the resiliency of coastal ecosystems to handle this environmental change. Resiliency suggests a complex system that can adapt to change – typical attributes of such a system include being modular and heterogeneous, and having tight feedback loops and redundancy. This system understanding is developing rapidly through the promotion of ecosystem-based management (EBM). The sanctuaries are important players in developing EBM for this region and can play an increased leadership role if supported in this.

**Deleted:** diverted

➤ **Adapt** – create policies and management strategies that are flexible to future changes. As we identify future problems, we need to adapt our way of thinking as well as the way we engineer human infrastructure to minimize future impacts. For example, within sanctuary jurisdiction, policies such as a preference for realigning the coast or removal of shoreline armoring should be developed to help nearshore and estuarine habitats adapt to sea level rise.

**Comment:** Doesn't ecosystem-based science supported through the previous bullet, Anticipate, lead to the understanding of system resiliency and EBM puts that understanding into action?

**Comment:** And what about MSP? Considering this is a priority of the administration and (1) the sanctuaries will be involved in MSP discussions and (2) climate change will certainly affect MSP-related decisions, acknowledging MSP in the recommendations may be warranted.

Action amongst government agencies, non-profit organizations, academia, businesses, and individuals is necessary now to ensure viable ocean ecosystems in the future. As this document serves as a baseline for understanding relevant climate change impacts to habitats and biological communities within the study region, the working group recommends that this document is sent by the Advisory Councils to GFNMS and CBNMS with a recommendation that both sanctuaries begin identifying priority management actions that will be taken over the next 10 years to address the impacts of climate change along the north-central California coast.

## 1. Introduction

This document is the result of a year long collaborative effort that brought together local scientists to downscale current global climate change information into a regional climate change document for Gulf of the Farallones and Cordell Bank National Marine Sanctuaries (GFNMS and CBNMS) Advisory Councils with a recommendation to forward the document to GFNMS and CBNMS (two of fourteen sites within the National Oceanic and Atmospheric Administration's (NOAA) National Marine Sanctuary System) management. This document is referred to as a Climate Change Site Scenario, with the goal of identifying relevant climate change impacts to habitats and biological communities along the north-central California coast. As a joint working group established under the GFNMS and CBNMS Advisory Councils, members developed the structure and outline of the Site Scenario, authored and/or edited sections based on areas of expertise, and requested the assistance of expert contributors and staff to develop a comprehensive scoping document, offering a synopsis of the best available knowledge on observed and predicted physical and biological impacts from climate change in north-central California coastal waters. The working group also made recommendations for five lines of future action for GFNMS and CBNMS management that can be found in the conclusion of this document.

**Comment:** Need to globally search document to replace this word with projected

The GFNMS and CBNMS Climate Change Site Scenario will serve as the precursor and companion to the climate change action plans that will be developed for each sanctuary. These plans will identify priority management actions that will be taken over the next 10 years to address the impacts of climate change specific to the site, its communities, and the region. Action plan strategies will be developed in the areas of research and monitoring, policy and planning, education and outreach, and facilities and operations. The site scenario document will provide a foundation to guide development and prioritization of research and monitoring activities that will ultimately inform future policy actions.

The climate change site scenarios and action plans are being prepared in response to recommendations from an U.S. Government and Accountability Office (GAO) report on climate change and land and water areas under federal jurisdiction (GAO 2007). The report recommended that the Secretary of Commerce (along with the Secretaries for Interior and Agriculture) “develop guidance incorporating agencies’ best practices, which advise managers on how to address climate change effects on the resources they manage and gather the information needed to do so.”

The GFNMS and CBNMS Climate Change Site Scenario synthesizes an extensive suite of potential climate change impacts relevant to north-central Californian ocean waters. This document outlines observed climate change effects in this region as well as changes that are considered to be highly likely and changes that are considered to be of notable concern (even if their likelihood is uncertain). It should not be considered an assessment of current conditions, or a prediction of future changes; instead it is a scoping document that discusses potential issues as they relate to a changing climate through both observation and science-based expectations.

The report addresses the following key topics:

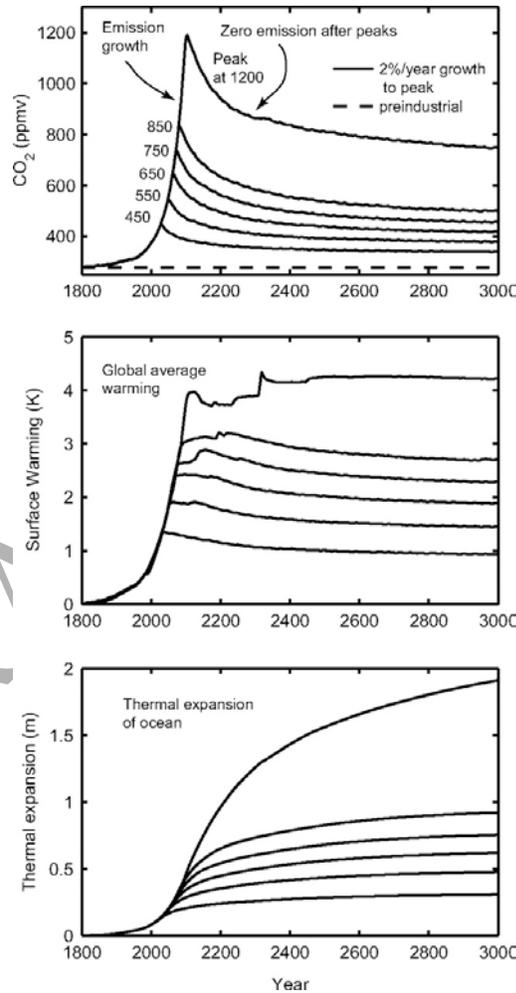
- Physical effects of climate change such as sea level rise, coastal erosion and flooding, and changes in precipitation and land runoff, ocean-atmosphere circulation, and ocean water properties. This section provides the physical basis for regional biotic responses to climate change. For each physical effect, large-scale, global observations and predictions are first discussed, followed by small-scale, regional observations and predictions.
- Regional biotic responses including changes in physiology, range shifts, changes in phenology, changes in population connectivity, and species-specific responses. This section focuses on the biological implications of climate change specific to the study region.
- Ecosystem and community response with examples from offshore pelagic, benthic and island habitats and sandy beach, rocky intertidal, nearshore subtidal, and estuarine habitats. These examples provide ecosystem-wide snapshots specific to each habitat on observed and predicted regional responses to changing climatic conditions.
- Additional ecosystem stressors such as fishing activities, invasive species, pollution, harmful algal blooms, and wildlife disturbance. This section discusses the implications of multiple stressors acting on an ecosystem and the cumulative impacts that can result.
- Direct impacts on humans, including public health issues and economic consequences to fisheries, ecotourism and infrastructure. This section provides a brief look at the observed and predicted impacts human populations may face with a changing ocean climate.

**Comment:** I don't see the global observations and projections. Not a clear distinction between global, regional, and small-scale, which I would differentiate from regional

Our ocean faces significant challenges. Findings of the Intergovernmental Panel on Climate Change (IPCC, 2007b) state that, "...the resilience of many ecosystems (their ability to adapt naturally) is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances... and other global change drivers...". The need for well-communicated science to inform policy and management actions is of the utmost importance, and the following document is the first step to meeting this urgent need.

## 2. Background

**Global Climate Change:** The global carbon cycle is in a state of unbalance due to anthropogenic additions of carbon dioxide (CO<sub>2</sub>). A 31% increase of CO<sub>2</sub> in the atmosphere has been observed since 1750 (IPCC 2007), increasing from 280 ppm in the pre-industrial 18<sup>th</sup> century to 380 ppm in 2005 (Raupach et al. 2007), and 385 ppm in 2008 (NOAA, ESRL 2009). In contrast, atmospheric CO<sub>2</sub> concentrations varied by less than 10 ppm over the millennium prior to the industrial revolution (King et al. 2007). Due to feedback loops inherent within the carbon cycle, stabilizing atmospheric CO<sub>2</sub> concentrations at 450 ppm would require cumulative emissions over the 21st century to be reduced from an average of approximately 670 gigatons of carbon (GtC) to approximately 490 GtC. Regardless of stabilization, both past and future CO<sub>2</sub> emissions will continue to contribute to effects of climate change, such as warming and sea level rise, for over a millennium due to the timescales required to remove this gas from the atmosphere (IPCC, 2007c). Solomon et al. (2009) concludes that irreversible impacts, such as “inexorable” sea level rise and reductions in rainfall in some regions of the world similar to those of the “dust bowl” era will ensue if atmospheric CO<sub>2</sub> concentrations increase from current levels to a peak of 450–600 ppm over the next century.



**Figure 2.1.** (Top) Carbon dioxide projections based on the Bern 2.5CC model. CO<sub>2</sub> emissions ramp at a rate of 2%/year to peak CO<sub>2</sub> values listed in the figure. After the peak, emissions are reduced to zero. (Middle) Globally averaged surface warming for the different peak values. (Bottom) Sea level rise due to thermal expansion only. Source: Solomon et al. 2009. Copyright (2009) National Academy of Sciences, U.S.A.

With a current uptake rate of 22 million metric tons per day (Feely et al. 2008), the world ocean has served as a sink (or storage reservoir) for about one third of all anthropogenic CO<sub>2</sub> produced since the industrial revolution (Sabine and Feely 2007). The ocean is considered to be the only significant long-term sink for anthropogenic CO<sub>2</sub> over the past 200 years (Sabine et al. 2004; Kleypas et al. 2006). Atmospheric CO<sub>2</sub> would be about 55 ppm higher without the ocean’s

continuous uptake of carbon (Sabine et al. 2004). Temperature, alkalinity and salinity of surface water dictate the equilibrium distribution of CO<sub>2</sub> between the ocean and the atmosphere (Raven and Falkowski 1999). Lower CO<sub>2</sub> solubility will occur as a result of higher temperatures and salinity. Warm water holds less dissolved gas than cold water, therefore CO<sub>2</sub> storage capacity decreases as the oceans warm (Gille 2002). It is estimated that in the future, the amount of anthropogenic CO<sub>2</sub> emissions produced will far exceed the amount of CO<sub>2</sub> the oceans can take up due to the inherent slow mixing time of the ocean. On a decadal time scale, the oceans may become a less efficient sink for CO<sub>2</sub> (Sabine et al. 2004).

**Comment:** Do you mean in a decade or two?  
Using the word 'decadal' here is a little confusing.

**Study Region:** The study region for this document is the waters off north-central California, from Point Arena to Año Nuevo (Fig. 2.2), within which Gulf of the Farallones and Cordell Bank National Marine Sanctuaries are located (see Appendix 1 for additional sanctuary details). The boundaries of these sanctuaries are also located within the California Current Ecosystem (CCE), one of four major eastern boundary currents in the world, that stretches along the western coast of North America from southern Canada to northern Mexico. Due to a high degree of wind-driven upwelling, there is a ready supply of nutrients to surface waters and the CCE is one of the most biologically productive regions in the world (see 3.3.3 Coastal Upwelling).

The region is characterized by a Mediterranean climate, also referred to as a “dry summer subtropical climate.” The defining characteristics of this climate are moist winters and dry summers. A Mediterranean climate is only found in the middle latitudes on the west side of subtropical continents (parts of western North America, the southwestern tip of Africa, central Chile, and southwestern Australia) and the coast of the Mediterranean Sea. These regions experience moderate temperatures throughout the year, with no monthly temperature falling below 32° F and at least three months out of the year above 50° F. There is a seasonal precipitation regime along the North-central California coast with the majority of rain falling between November and April. Many coastal subtropical regions experience intense fog in the summer due to rapid cooling of warm, moist air as it travels over colder ocean water (as seen locally; Ritter 2006).

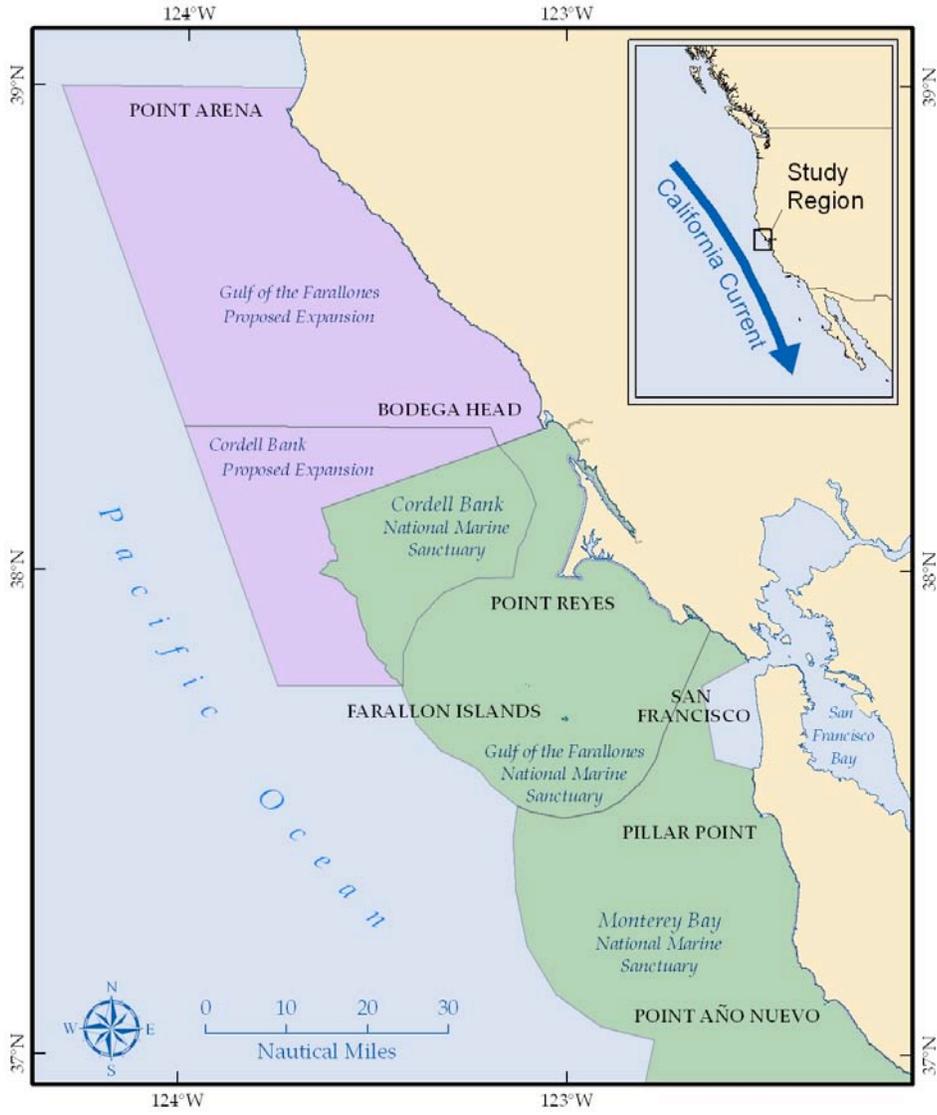


Figure 2.2. The study region extends from Point Arena in the north to Point Año Nuevo in the south. T. Reed (2009).

### 3. Physical Effects of Climate Change

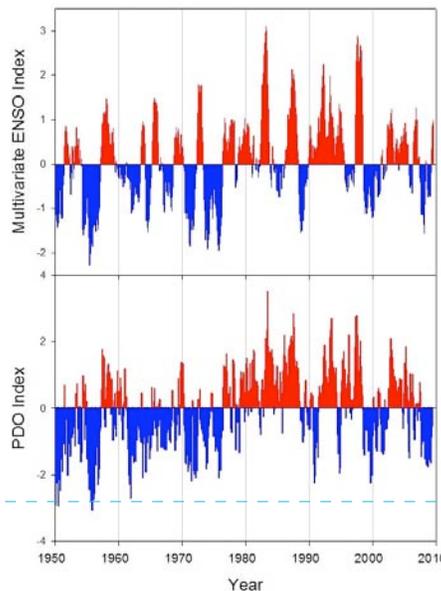
Global changes in carbon dioxide levels, warming, winds, precipitation, sea level, and ocean circulation will in turn lead to changes in winds, currents, land runoff, sea level, coastal erosion and ocean water properties along the California coast and within the study region. This chapter outlines the changes in the physical ocean-atmosphere environment off north-central California that are anticipated to occur as a result of global climate change.

In addition to anthropogenic trends in the climate of the northeast Pacific Ocean, significant *natural* climate fluctuations occur on interannual, interdecadal, and *multi decadal* time scales. It is important to recognize this *natural* variability in identifying long-term trends in ocean and atmospheric properties. It is anticipated that anthropogenic climate change is likely to alter this *natural* variability as well as annual average conditions. The combination of climate change trends with this *natural* variability is likely to create new extreme conditions. For example, the high waves during El Niño events will be more extreme when combined with the climate-change trend of increased wave height (see 3.3.2 Waves and 3.4 Sea Level Rise). Likewise, in the positive phase of the Pacific Decadal Oscillation (PDO), climate-change warming may be accelerated along with enhanced rainfall, runoff, wave activity, and erosion but with overall reduced upwelling. During the negative phase, in contrast, climate-change warming effects will be slowed. Thus expected impacts of climate change could be delayed many years during the negative phase of the PDO and accelerated during the positive phase.

The following modes of variability (natural climate fluctuations) are well documented for the ocean and atmosphere off California:

**El Niño Southern Oscillation (ENSO)** – Easterly trade winds and the piling up of warmer waters in the western Pacific Ocean relax during the positive phase of ENSO (typically about every three to seven years; Rasmusen and Wallace 1983). This results in greater sea surface temperatures in the eastern Pacific and a deeper surface mixed layer, which results in upwelling of warm low-nutrient waters and a reduction in productivity that is confined to a narrow band along the U.S. west coast. ENSO has a marked negative effect on the ecosystem productivity (Barber and Chavez 1983).

**Pacific Decadal Oscillation (PDO)** – The PDO describes a longer-term fluctuation in ocean climate that changes state approximately every 20–40 years (Trenberth 1990, Trenberth and Hurrell 1994). During the “warm” phase of PDO, warmer ocean temperatures are



**Figure 3.1.** Time series of the Multivariate ENSO Index (top) and the PDO (bottom). Positive values are shaded red and negative values are shaded blue. Derived from N. Mantua time series <http://jisao.washington.edu/pdo/PDO.latest>.

**Comment:** There should be some reference to the west coast regional assessments in the USGCRP report *Global Climate Change Impacts in the U.S.* in this chapter and also chapter 7.

**Comment:** Confusing? Need a better description of conceptual feedbacks with graphic. CO<sub>2</sub> leads to warming. Warming leads to sea level rise and altered currents and winds. SLR lead to increased flooding along with greater precipitation or flashier runoff from short duration, high magnitude storms. Flooding, particularly flashier floods, leads to erosion.

More importantly, I think it would be worthwhile to include a statement about why the physical changes are important (i.e. because they lead to changes in biological productivity).

**Comment:** Anthropogenic changes also have variability, so it's important here to differentiate between anthropogenic and 'natural' climate change.

**Deleted:** and

**Comment:** What are the effects on storminess (air temp/press)?

observed in the California Current, while lower sea surface temperatures are found in the northwest Pacific. The “cool” phase of PDO exhibits the opposite pattern. In contrast to ENSO, where a coupled ocean-atmosphere response has been well documented as the mechanism, the dynamics underlying the PDO are not well understood (Mantua and Hare 2002).

**North Pacific Gyre Oscillation (NPGO)** – Fluctuations in sea surface height and temperature data across the northeastern Pacific are well described by the NPGO in combination with the PDO (Di Lorenzo et al. 2008). While the PDO is the dominant signal in physical parameters like temperature and sea level, the NPGO correlates well with salinity, nutrient concentrations and phytoplankton chlorophyll, suggesting a closer relationship to nutrient fluxes and ecosystem productivity (Di Lorenzo et al. 2008; 2009).

**Comment:** What is time scale of this cycle?

### 3.1 Atmosphere

During spring and summer, winds blow strongly and persistently along the California coast towards the equator. The wind speed diminishes during fall and in the winter the average alongshore winds are near zero, in spite of strong southerly (northward directed) winds during winter storms (Dorman and Winant 1995). These winds are due to a large-scale land-ocean pressure gradient and their strength is governed by the position of the North Pacific High Pressure system and the strength of the continental thermal low-pressure system. Winds tend to be weaker closer to the coast, owing to the effects of friction and topography. This pattern of wind shear (known as wind stress curl) extends upwelling effects further offshore. Topographic features like Point Arena lead to stronger local winds (Winant and Dorman 1997), partly explaining the upwelling maximum observed at this headland in the northern portion of the study region.

It has been proposed that the build-up of greenhouse gases will result in the enhancement of daytime heating and inhibition of nighttime cooling, leading to intensification of the continental thermal low-pressure system (Bakun 1990). This intensification will enhance the cross-shore pressure gradient and thus also enhance equatorward winds along the coast. Regional numerical models (Snyder et al. 2003, Auad et al. 2006) have found that increased global temperatures indeed lead to stronger wind stress along the California Coast, in particular during the summer-fall seasons in central California.

Alongshore wind time series in the region, from the 1940's to the 1990's, show that equatorward alongshore winds have increased in central California (Bakun 1990; Schwing and Mendelssohn 1997, Mendelssohn and Schwing 2002). Analysis of wind data from National Data Buoy Center (NDBC) buoys in the study region corroborate an enhancement in the alongshore winds between April and October from 1982 to 2007 (Garcia-Reyes and Largier, *in preparation*). Other upwelling regions similar to central California also appear to have experienced increased upwelling-favorable winds in the last decades (see 3.3.3, Coastal Upwelling; Bakun 1990; Mendelsson and Schwing 2002; McGregor et al. 2007). A similar pattern of coastal upwelling intensification has been observed along other eastern ocean margins that support ecosystems comparable to the California Current (Bakun 1990).

The time of year when the strong equatorward winds start, known as spring transition, has not changed consistently. However, the strong equatorward winds appear to be enhanced

consistently during the summer and early fall, extending the normal wind season into the fall off central and northern California (Garcia-Reyes and Largier, *in preparation*), as predicted by the numerical models (Snyder et al. 2003, Auad et al. 2006). Further north (north of 44° N), a trend towards a later spring transition and shorter upwelling season has been reported by Bograd et al. (2009).

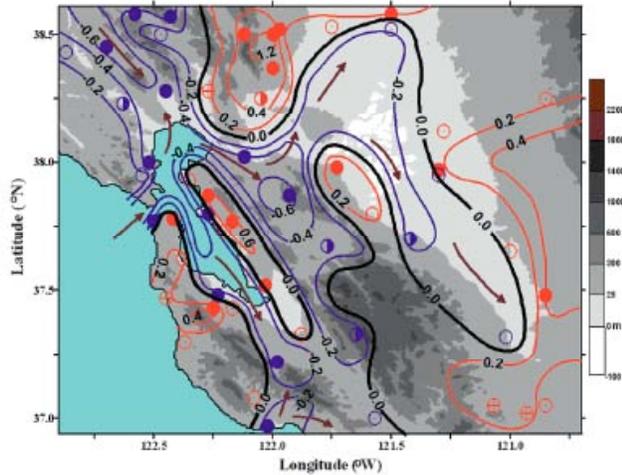
A recent study by Lebassi et al. (2009) indicates that summer air temperatures at inland sites of California are warming while coastal valleys have actually cooled since the late 1940s. Results also show an increase in local onshore pressure gradients during the warm season, leading to the hypothesis that onshore movement of the marine layer is stronger. This would imply a stronger sea breeze and most likely more extensive coastal cloudiness. The authors note that the higher elevations of the coastal mountains are warming while the coastal valleys are cooling, implying a stronger marine layer effect in coastal areas. A stronger marine layer would induce a stronger coastal wind jet moving from north to south and thus an increase in coastal upwelling. This in turn would lead to more frequent development of coastal stratus formation leading to positive feedback on the strength and persistence of the marine layer.

**Comment:** The terms “marine layer” and “marine layer effect” should be defined.

### Scale Dependency of Climate Change: Air Temperature

Observed responses to climate change will show differences due to the spatial or temporal scale. For example, patterns of change at one spatial scale (e.g. the Pacific Ocean) may be very different than patterns at another spatial scale (e.g. the Farallon Islands). In other words, patterns *depend* on the spatial or temporal scale that is being examined. This “scale dependency” results in a cautionary approach by many scientists who thus do not generalize their results to larger or smaller scales without careful further study. In part, this is the rationale in referring to the anthropogenic forcing of world climate as “climate change” as opposed to “global warming”, because warming refers to a specific process and direction of change at the global scale, whereas climate change refers to a broader suite of changes in climate associated with this global warming but which may appear differently in different places and at different scales. Air temperature is highlighted as a scale-dependent ?? processes to illustrate the inherent variability and complexity of climate change. *Is something missing from the preceding sentence?*

A recent analysis of air temperature data at 253 California National Weather Stations further highlights the complexities of a changing climate. Lebassi et al. (2009) documented increased average air temperatures ( $0.23^{\circ}\text{C decade}^{-1}$ ) when analyzing all stations from 1950 – 2005. However, further analysis of the data by region indicated that low-elevation coastal areas actually cooled ( $-0.30^{\circ}\text{C decade}^{-1}$ ) and inland stations warmed ( $0.16^{\circ}\text{C decade}^{-1}$ ). Potential mechanisms for this may be the increase in upwelling (see above and section 3.3.3) and/or a “reverse reaction” to warming in which increased temperature differentials between the land and ocean result in stronger sea breezes that lead to cooler air temperatures in coastal areas (Fig. 3.2). In summary, it should be clear that generalized statements for broad regions and long periods may not sufficiently characterize the complex response of a changing environment at all scales.



**Figure 3.2.** Spatial distribution of San Francisco Bay Area 2-m summer maximum-temperature trends ( $^{\circ}\text{C decade}^{-1}$ ) for 1970–2005; arrows indicate predominant summer daytime flow-patterns; blue, red, and black colors indicate cooling, warming, and no-change isopleths and station locations; dashed isopleths are extrapolated; and statistical  $p$  values of  $\leq 0.01$ , between 0.01 and  $\leq 0.05$ , between 0.05 and  $\leq 0.1$ , and  $> 0.1$  are represented, respectively, by full-colored, half-colored, plus signs, and open circles. Adapted from Lebassi et al. (2009).

**Comment:** Need label for elevation gradient and units. Also, it would be useful to add hillshade

Graham and Diaz (2001) describe an increase in extreme winds associated with North Pacific winter cyclones (i.e. extra-tropical cyclones) since 1948, due to an increase in deep cyclone<sup>1</sup> frequency and intensity. The authors report a 50% increase in the frequency of deep cyclones and 10-15% increase in winds. McCabe et al. (2001) corroborate the finding of increased intensity at both high (60-90°N) and mid-latitudes (30-60°N), but find a decrease in the frequency of cyclones at mid-latitudes while frequency does increase at high latitudes. This relative increase of cyclone frequency at high latitudes suggests a poleward shift of storm tracks (Trenberth et al. 2007).

**Comment:** Are these observations or predictions?

North Pacific winter cyclones play an important role in increasing precipitation, generating large waves and raising coastal sea levels (wind-driven storm surge). Bromirski et al. (2003) studied non-tidal sea level residuals from the San Francisco tide gauge between 1858 and 2000. Their results show a significant increase in intense winter storms since 1950. Further, Wang and Swail (2001) report an increase in the largest waves (see 3.3.2 Waves), which they also attribute to an increase in the occurrence of storms. These results are consistent with reports indicating that 1-in-100 year coastal flooding events are likely to occur more frequently, with a probability of 1-in-10 years in the future (DWR 2006).

<sup>1</sup> Generally speaking, stronger cyclones have lower pressure. In this context, the authors defined a “deep cyclone” as one that has a minimum central pressure less than 975 hectopascals (Graham and Diaz 2001).

During late spring and into early fall, the California coastline is quite often shrouded in what is called marine stratus and (or) sea fog. This is a very important part of the long-term climate of coastal California. Unfortunately there are no long-term climate records of the extent, or frequency of occurrence of the stratus that would allow identification of trends over the past 50 years. One can only speculate on the impact of warming on the stratus frequency and inland penetration during the spring, summer and fall period. LeBassi et al. (2009) state that the seabreeze circulation has intensified increasing onshore flow and cooling the coastal valleys during at least the summer months. There are several impacts from this, including potential modification of the extent and persistence of marine stratus. With increased onshore flow the stratus should be more persistent, that is burn off later and return earlier at the coast and in coastal valleys. As the differential heating between the inland valleys and coast intensifies over the next several decades, this should increase both the frequency and persistence of marine stratus for most coastal and coastal valley locations during the late spring, summer, and fall. It can thus be speculated that the marine stratus season would increase in length, that is, begin earlier as spring will arrive earlier, and extend longer into the fall. Under a warmer climate, with the ocean warming much slower than the land, coastal stratus and sea fog could be more frequent, persist longer each day, return earlier each evening, and persist for a longer duration throughout the year.

**Comment:** Presumably this is the same as the “marine layer” used but not defined above? If so, use one term to avoid confusion. If not, then “marine layer” still needs definition.

### 3.2 Precipitation and Land Runoff

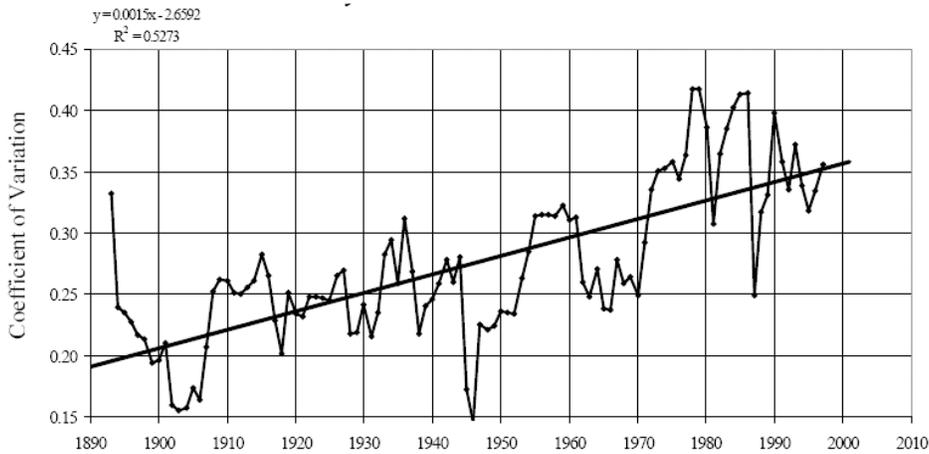
During the dry months in California, the flow from the Sacramento and San Joaquin Rivers to San Francisco Bay and the ocean is primarily due to snowmelt from the snowpack covering the Sierra Nevada range. This snowpack acts as a natural reservoir, delaying runoff from winter precipitation (Kiparsky and Gleick 2005). Although precipitation and runoff records from 1900 are the primary source for planning purposes, the past 200 years have consistently been wet when compared with longer-term records (Meko et al. 2001). Statistically significant trends indicate that both precipitation (Groisman et al. 2001) and monthly mean streamflow (Lettenmaier et al. 1994) in California have increased since the early 20<sup>th</sup> century. This is consistent with a 10% increase in precipitation for all of North America since 1910. Multiple studies report that the majority of the increase in runoff is accounted for by increases in extreme precipitation during single-day events (Groisman et al. 2001; Kundzewicz et al. 2007). Kim et al. (2002) and Snyder et al. (2002) used global climate models to show that precipitation in California is likely to continue to increase, with the greatest change centered in northern California.

A warming-induced change in the timing of peak streamflow events is a consistent result among both historical observations and modeling efforts. Rising temperatures will likely result in a retreat of snow cover and a decrease in the precipitation ratio of snowfall to rainfall in northern and central California. In both modeling and observations this is seen as an increase in runoff during winter months, a decrease in runoff during spring and summer, and a higher annual peak runoff (Kiparsky and Gleick 2005). Additionally, recent studies argue that heavy precipitation events will become more prevalent (Kundzewicz et al. 2007). This change is due to an increase in the moisture-holding capacity of the atmosphere as temperatures rise.

**Comment:** Re-word

Changes in climate variability will also likely have a significant effect on annual precipitation (DWR 2006). Timmerman et al. (1999) argue that the predicted increase in high runoff events is analogous to a climatic shift towards more frequent El Niño conditions. El Niño events have

been associated in the past with both drought and flood periods, many of which have been severe. An increase in drought and flood severity, as often seen with El Niño conditions, corresponds to a trend of increasing annual precipitation variability as evident from at least the end of the 19th century (Fig. 3.3). The variability of California's precipitation is strongly tied to annual and decadal shifts in oceanic parameters such as sea surface temperature (e.g. McCabe et al. 2004).



**Figure 3.3.** Variation in precipitation over time in California. The solid line is the best-fit regression line. DWR (2006).

The anticipated change in the occurrence of wildland fires associated with climate change (Westerling et al. 2006) is also likely to lead to enhance runoff events. While relatively few studies have analyzed the effect of fires on runoff in California, those that have been conducted in similar regions have arrived at common results. The consensus is that fires increase runoff, sometimes by several orders of magnitude. Inbar et al. (1998) have shown that this is a result of lost vegetation coverage and changes to the soil properties resulting from the fire, while Johansen et al. (2001) show that total runoff volume after a fire is positively correlated with the percent of the landscape covered by bare soil created during the event. Johansen et al. (2001) also show that the intensity of the fire strongly influences the eventual runoff rates, with low-intensity fires producing the least subsequent runoff volumes. In all studies, post-fire sediment yields also increased dramatically, in many cases by a higher proportion than that of runoff.

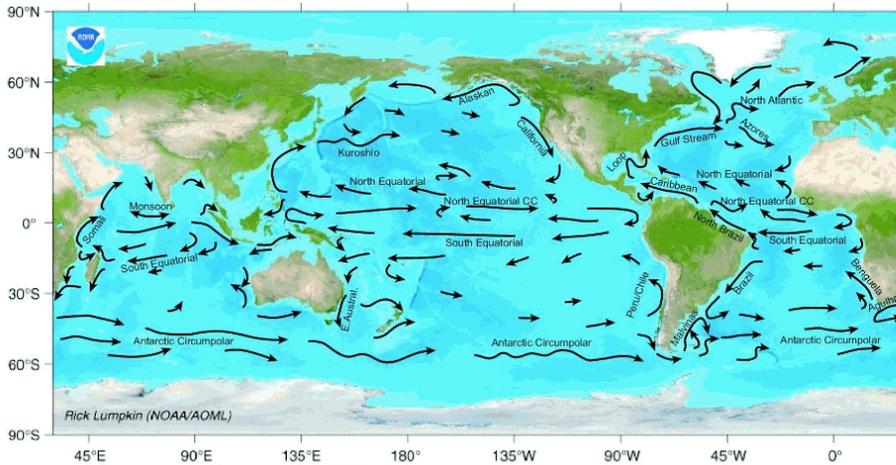
In summary, the 21<sup>st</sup> century will likely see slightly greater annual precipitation and more extreme winter precipitation events in northern California and a more rapid spring melting of snowpack (DWR 2006). This will lead to a shorter, more intense period of river flow and freshwater discharge in winter and spring (Dettinger and Cayan 1995, Cayan et al. 2001). In turn, this will greatly alter circulation patterns, riverine plume formation and coastal stratification and mixing (see 3.3.4 Estuarine Circulation and 3.6.3 Salinity), as well as the seasonal timing of the transport of materials and organisms to the ocean.

**Comment:** “likely” here seems to be based on Meko et al. I wonder if one reference, based on historical conditions, warrants the tag likely. It’s reasonable to say that runoff will likely increase in part because we can confidently project how earlier snowmelt (from increasing air temp – a highly likely change as defined by IPCC and regional GCM efforts) would affect reservoir management. But, I thought that there is still debate about how precipitation is projected to change in the future.

In both this section and previous section, it might be good to explain how terms such as “likely” and “highly likely” were derived

### 3.3 Ocean Currents and Waves

The movement of water in the ocean is driven by winds and differences in water density due to temperature and salinity. All of these factors are expected to change with the changing global and regional climate. In turn, changes in water movement will alter the transport of sediment, nutrients, plankton, contaminants and other water-borne material. The California Current is the eastern arm of the North Pacific Gyre (Fig 3.4), which is largely driven by the winds that blow clockwise around the large high-pressure cell known as the Pacific High. The Pacific High strengthens and expands north in the northern summer and dominates west-coast winds from March through September. These northerly winds drive offshore transport of surface waters and upwelling of cold, deep, nutrient-rich waters along the coast. In addition to this larger scale wind-driven circulation are smaller density-driven flow features within or associated with estuaries (see 3.3.4 Estuarine Circulation) and the incessant action of waves on the shoreline (see 3.3.2 Waves).



**Figure 3.4.** World map showing the major ocean currents. The California current is the cold return current of the North Pacific Gyre moving south along the West Coast. Courtesy Rick Lumpkin, NOAA/AOML.

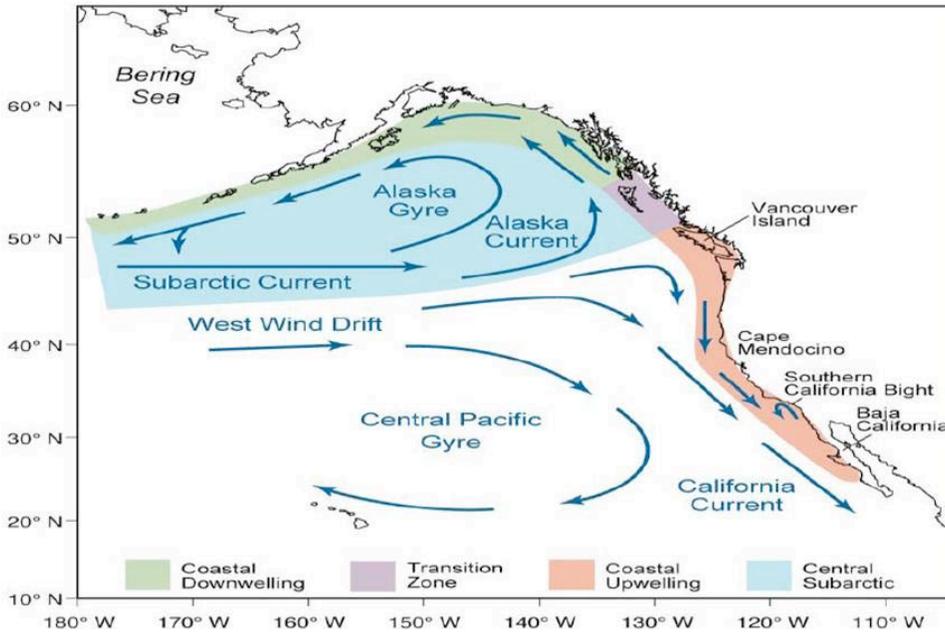
#### 3.3.1 Ocean Circulation

The circulation of the California Current, and the general upper ocean circulation for the north Pacific, is controlled by the North Pacific High pressure center off California and the Aleutian Low pressure cell near Alaska. A strong North Pacific High and weak Aleutian Low lead to enhanced southward transport in the California Current, cool surface waters and reduced stratification in addition to strong upwelling along the coast. These changes in ocean transport are known to affect the entire California Current Ecosystem (CCE), particularly the northern portion. However, the circulation of the North Pacific subtropical gyre combines with regional and local upwelling and advection to create a complex coastal circulation pattern for which future climate related changes have not been addressed adequately. Global-scale IPCC climate assessments do not address the effects of global climate change on ocean circulation satisfactorily and no attempt is made to assess changes in ocean circulation at the regional scale. One of the complexities of these *projections* is that natural interannual/interdecadal variations in

Deleted: predictions

ocean circulation can exceed the magnitudes expected due to long-term anthropogenic climate change (McPhaden and Zhang 2004). Long-term records of ocean circulation are needed to discern climate-change trends from fluctuations.

Decadal variations in regional transport patterns and water mass characteristics such as salinity, nutrients, and chlorophyll are linked to shifts in regional and large-scale circulation characterized by patterns such as the PDO and NPGO (DiLorenzo et al. 2008). Basin-scale adjustments in the subtropical gyre (e.g., NPGO) due to changing global wind stress patterns are thought to be a principal factor in these decadal fluctuations within the CCE, and can explain variations in regional water mass characteristics and related biological variables that are not correlated with surface indicators such as the PDO. A regime shift in the 1970s to a positive PDO state (warm CCE) accelerated eastward transport in the North Pacific Current (area annotated as West Wind Drift in Figure 3.5) and produced more subtropical source water for the CCE (Parrish et al. 2000).



**Figure 3.5.** Map showing the locations of the major currents in proximity to the study region. J.A. Barth (OSU, 2007).

Some climate models suggest that global warming will weaken atmospheric circulation (Meehl and Teng 2007; Vecchi and Soden 2007), which could lead to a state in the north Pacific more like that during El Niños, along with a generally weaker southward flow of the California Current. The complexity of near-coastal circulation contributes to fronts and eddies that are important habitat features for many organisms, and corresponds to the speed of the subtropical gyre (Logerwell et al. 2003). It is thought that a stronger gyre will increase the southward

transport of the California Current, creating more wind shear and a more complex circulation field.

### 3.3.2 Waves

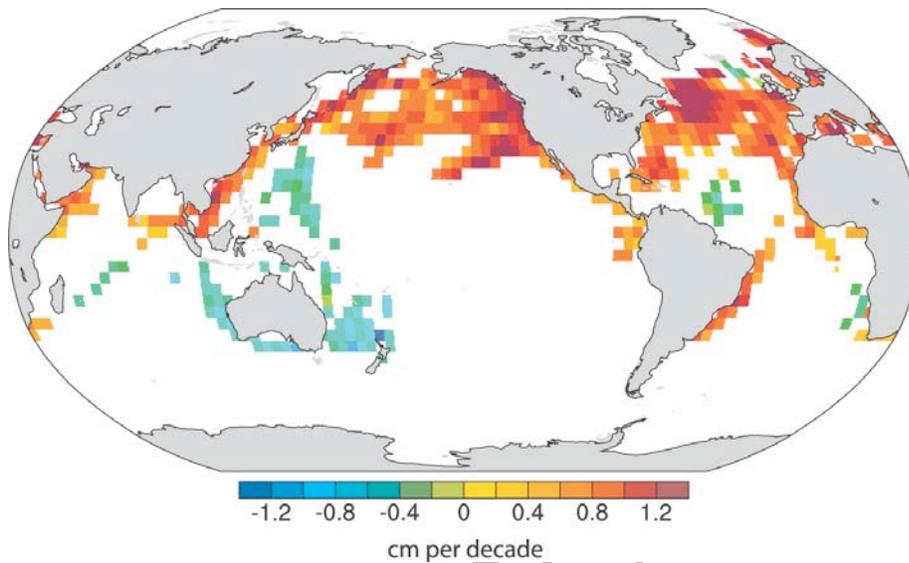
Waves are a product of both local and distant processes. Large extra-tropical cyclones in the North Pacific send long-period swell towards the California coast between November and March, generating significant wave heights that occasionally exceed 8 m (Allan and Komar 2000). Significant wave height ( $H_s$ , defined as the average height of the highest third of measured waves) may reflect either these seasonal changes in swell wave generation or the intensity of the locally generated wave field. Short period ( $T_s < 10$  s) waves are generated by



**Figure 3.6.** Wave breaking at Maverick's, Half Moon Bay, CA. Josh Pederson / SIMoN NOAA.

local winds, and vary in height throughout the year. In summer, the development of the North Pacific High leads to strong northerly winds along the California coast that generates waves with smaller heights and shorter periods (Wingfield and Storlazzi 2007). Interannual differences in the wave field off California, especially north of the Golden Gate Bridge, are extremely responsive to climate variations such as ENSO (e.g., Seymour 1998, Allan and Komar 2000).

Installation of a buoy network along the US Pacific Coast in the 1980s, as well as a wealth of voluntary observer ship data, have allowed for comparative analyses of multiple phenomena that affect the California wave climate. Available data suggests that wave heights are increasing with latitude along the Pacific coast, with the greatest increases ( $>2$  cm year<sup>-1</sup>) occurring off the coasts of Washington and Oregon (Allan and Komar 2006; Fig 3.7). Northern California's waves have increased less so, by an average rate of about 1.5-2 cm yr<sup>-1</sup>, based on measurements from the NDBC Point Arena Buoy (# 46014). Increases for central California (Half Moon Bay #46012) are not statistically significant (Wingfield and Storlazzi 2007). These trends are verified by an extensive dataset from 1950-2002 (Gulev and Grigorieva 2004; 2006). This change in mean wave height is largely attributable to a disproportionate increase in peak storm waves relative to average waves (Wang and Swail 2001, Menendez et al. 2008).



**Figure 3.7.** Estimates of linear trends in significant wave height (cm per decade) for regions along the major ship routes of the global ocean for 1950 to 2002. Trends are shown only for locations where they are significant at the 5% level. Adapted from Gulev and Grigorieva (2004). IPCC.

Observed changes in the regional wave climate are typically attributed to large-scale climatic changes in the central Pacific Ocean. Observed increases in sea surface temperatures in the Pacific could be responsible for the simultaneous increase in average wave heights (Graham and Diaz 2001), while the roles of the Eastern Pacific Teleconnective Pattern (Allan and Komar 2000) and the difference between the Hawaiian high and the Aleutian low pressure zones have also been discussed (Wang and Swail 2001). Large-scale phenomena such as ENSO have also been shown to have dramatic effects on the California wave climate (e.g. Gulev and Grigorieva 2006). El Niño events shift the subtropical jet responsible for bringing storm systems to the California coast to a more southerly approach angle, which increases storm magnitude (Allan and Komar 2000). Both El Niño and La Niña events tend to bring large waves to California, although El Niños are associated with the highest wave heights (Seymour 1998, Allan and Komar 2000; 2006). Both the ENSO phenomenon and the observed long-term increase in wave heights (particularly extreme wave heights) pose significant risks. Since El Niño events typically bring the largest recorded waves (Seymour 1998) and occur in late winter when most beaches are at their narrowest width, they are often the cause for the majority of coastal erosion, flooding, and property loss (Storlazzi and Griggs 2000; Wingfield and Storlazzi 2007).

The PDO also plays an important role in wave climate by moderating or increasing the intensity of El Niños and by further shifting the subtropical jet stream and affecting wave directionality (Bromirski et al. 2005, Adams et al. 2008). Changes in wave forcing during both PDO and ENSO events cause dramatic changes in wave direction which can expose normally sheltered beaches to dramatic erosion (Adams et al. 2008), or serve to rotate segments of sandy shoreline

from the south to the north, exposing the southerly ends of littoral cells to increased erosion such as in Pacifica (Sallenger et al. 2002).

Waves play a large role in structuring nearshore subtidal and intertidal marine communities (see 5.4 Sandy Beach Habitat, 5.5 Rocky Intertidal Habitat, and 5.6 Nearshore Subtidal Habitat). In intertidal habitat, wave forces affect organisms that are attached to or interacting with the substrate. In addition, the distribution of subtidal algal populations (e.g., kelps) is in large part determined by wave exposure (see 4.6 Macroalgae and Plants). Waves can also influence sediment transport, the morphology of estuary mouths (see 3.3.4 Estuarine Circulation), and patterns of inundation (see 3.4 Sea Level Rise and 3.5 Coastal Erosion).

**Comment:** In summary... this section needs a short wrap up on the anticipated impact of climate change on waves and wave impacts.

### 3.3.3 Coastal Upwelling

Wind-driven coastal upwelling delivers cold nutrient-rich waters to the near-surface light-filled zone, providing the foundation of the high biological productivity off California and within the study region (Fig 3.8). Coastal upwelling results from the offshore transport of near-surface water due to alongshore winds from the north and the influence of the earth's rotation (known as Ekman transport). This water is replaced with cold, salty, nutrient-rich water from depths below.



**Figure 3.8.** Spring/Summer upwelling diagram. GFNMS.

In addition to this vertical circulation and the upward bending of isotherms towards the coast, there is a set-down or lowering of sea level of about 0.1-0.2 m during upwelling events. Further, this cross-shore sea level slope drives a strong southward upwelling jet over the shelf, with current speeds ten times more than that due to offshore Ekman transport – such that plankton and other water-borne material may move alongshore more so than offshore. When distant from active upwelling centers like Point Arena and along the coast north of Point Reyes, the newly upwelled waters warm while nutrients are consumed by developing phytoplankton blooms. In the lee of headlands like Point Reyes and Point Año Nuevo, the southward jet separates from the coast such that recirculation occurs and aging upwelled waters may be retained near the coast as they support phytoplankton blooms. The resultant surface lenses of warm water in northern Monterey Bay and the northern Gulf of Farallones region are observed to propagate northward along the coast during relaxation periods between upwelling events.

Earlier suggestions that global warming will lead to stronger alongshore winds and enhanced coastal upwelling (Bakun 1990) have been supported by recent model and observational studies. As the earth warms, the land is expected to heat up faster resulting in an increase in the land-sea temperature difference and in the associated land-sea pressure gradient that drives the northerly upwelling winds. Numerical simulations (Snyder et al. 2003, Auad et al. 2006) and measured wind time series (Mendelssohn and Schwing 2002, Garcia-Reyes and Largier *in preparation*)



synoptic variability in winds affect the amount of primary production available, and the amount delivered to coastal ecosystems rather than offshore ecosystems (Botsford et al. 2003, 2006). It is possible that enhanced upwelling will also be more persistent, resulting in less phytoplankton availability in coastal waters and a greater but more diffuse supply of phytoplankton to waters over the outer shelf and slope, while enhanced surface heating reduces phytoplankton availability due to increased stratification further offshore.

**Deleted:** even

The seasonal timing of upwelling is expected to vary due to climate change and this will have numerous ecological impacts due to mismatches between the timing of upwelling-induced primary production and the less-variable seasonal phenology of higher trophic levels. While an anomalous late onset of upwelling winds in spring 2005 and 2006 had negative impacts on the coastal ecosystem (Kosro et al. 2006, Sydeman et al. 2006), there is no evidence of a trend towards a delay in the start of the upwelling season associated with climate change. However, an enhancement of upwelling in the late summer and fall and delayed end to the season has been noted in studies based on models and data analysis (Snyder et al. 2003, Garcia-Reyes and Largier, *in preparation*).

**Comment:** The lack of a persistent trend versus the possibility of an extreme event underscore the importance of modeling climate change scenarios to perform a sensitivity analysis. It is also why the discussion, throughout the document, should distinguish where the “likely” changes in the study area are concluded solely from historic, empirical data or from modeling projected impacts or both.

Finally, the consequences of upwelling will also vary from year-to-year due to interannual to interdecadal variability in the offshore thermocline depth – a phenomenon associated with climate fluctuations such as ENSO and NPGO, and may also exhibit a trend associated with climate change. When the thermocline is deeper, wind-driven coastal upwelling will bring an increased amount of lower nutrient waters from above the thermocline to the surface, as happens during El Nino events.

### 3.3.4 Estuarine Circulation

The primary drivers of change in estuaries are expected to be altered land runoff due to changes in precipitation and changes in wave energy at the mouth. Secondary influences include changes in local winds as well as temperature (i.e., changes in heating). Climate change is not expected to alter tides, which are an important factor in estuarine physics. Significant climate-related changes in land runoff strength and timing are expected (see 3.2 Precipitation and Land Runoff), in addition to changes due to water management in each watershed. Changes in local waves (see 3.3.2 Waves) and winds are also expected as a result of global climate change, in turn giving rise to changes in coastal currents that determine the fate of estuary outflow plumes.

**Comment:** Please provide a reference. Initial modeling results from the CaSCADE project suggest that the phase is unaltered but the amplitude is. Small shifts in the amplitude of the tides could alter the elevation at which vegetation thrives, thereby changing estuarine habitats significantly

Estuaries are characterized by the intrusion of salty seawater into basins or channels that carry freshwater runoff from land to sea. Within the estuary, waters are typically stratified with a low-salinity layer overlying a high-salinity layer. By averaging tidal motion into and out of an estuary, “estuarine circulation” is observed, comprised of a seaward flow of the upper, low-salinity layer and a landward flow of the lower, high-salinity layer. The outflowing upper layer entrains high-salinity water from below, completing a conveyor-belt-like circulation for seawater into and back out of the estuary. This mixture of freshwater and seawater then exits the estuary as a stratified plume that spreads offshore and alongshore, with the fate of these plume waters determined by wave, wind, tide, buoyancy, and coastal currents.

The study region includes many estuaries, which fall into three types: (i) San Francisco Bay and the tributary estuary system known as the Delta; (ii) semi-enclosed bays, e.g., Tomales Bay, Drakes Bay, Bolinas Lagoon, Bodega Harbor, with tributary estuaries; and (iii) drowned river

valley and bar-built estuaries on the Gualala River, Russian Gulch, Russian River, Salmon Creek, Cheney Gulch, Estero Americano, Estero de San Antonio, Walker Creek, Lagunitas Creek, Pine Gulch Creek, Geronimo Creek, Waddell Creek, Scott Creek, Pescadero Creek, and smaller creeks/gulches. All of these have a role in providing coupled habitat or in affecting study region environments through runoff plumes.

The semi-enclosed bays exhibit estuarine circulation during the wet Mediterranean-climate winters, but behave as “low-inflow estuaries” in summer (Largier et al. 1997), with warm, salty waters and weak or no stratification due to thermal effects. Cold, upwelled waters may intrude at depth in the outer estuary, but salinity stratification is only observed in the small tributary estuaries, e.g., in the Lagunitas Creek estuary channel at the landward end of Tomales Bay (Parsons et al. 2007). The residence time of waters in these basins is long during the long dry summers (e.g., 2-3 months in Tomales Bay) and controlled by tidal action (Largier et al. 1997).

Where freshwater inflow is important, the strength of flow determines the landward extent of salinity intrusion and climate-related decreases in minimum river flow will result in landward movement of saline waters (unless the estuary mouth closes before the seasonal decrease in river flow). Specifically, increased salinity intrusion is expected in San Francisco Bay in response to decreased snow melt flows in spring. In estuaries fed by coastal watersheds, concern is perhaps more related to dry winter periods as many estuary mouths close in summer. However, the mouths of the tributary estuaries in the semi-enclosed bays do not close (e.g., Lagunitas Creek) and primary concern is with longer, drier summers. Any change in precipitation is likely to affect local water resource management.

Strong runoff is key in flushing estuary basins, but also may scour bottom sediments and erode estuary banks. Where banks are compromised (due to human activities), extreme flow events will lead to major changes in morphology and disruption of socio-economic activities. Increases in storm intensity and rain intensity would lead to more frequent and more severe flooding of low-lying lands, requiring decisions on the merits of flood control versus natural functioning and system adaptation. Flooding risk will also increase due to both past and future rise in sea level.

River flow is also important in maintaining an open mouth in bar-built estuaries. Fast flow through the mouth is capable of removing sediment deposited in the mouth by wave action. Climate change that leads to increased river flow (stronger and more persistent) or weaker wave forcing will result in increased mouth closure. Tides will not change with climate. The most pertinent changes are relative seasonal timing of river flow and wave energy, both of which decrease during spring and increase again in fall. If river flow continues later in spring, this may keep the mouth open beyond the time when waves are big enough to close an estuary – in which case that estuary could remain open much longer than previously (e.g., Behrens et al. 2008). Alternatively, if river flow decreases early, while waves are still large, the estuary will close much earlier than previously (and prevent estuary-ocean migrations). In the fall, if waves increase early while river and runoff is delayed, this would lead to fall closures or keep the mouth closed longer than previously (again preventing estuary-ocean migrations).

When estuaries are closed in summer, they function as a salt-stratified lake. The lower, high-salinity layer is trapped and may develop hypoxic or anoxic conditions (if deep enough for

**Comment:** It might be easier on readers to more clearly organize some of the text below based on the three types of estuaries outlined above. Seems like a logical approach – one I expected.

**Comment:** Is this explained in more detail in section 3.2?

**Comment:** This is just in summer, correct? If so, should clarify as climate predictions call for increased wave heights for most of the year.

**Comment:** See previous comment. Please provide a reference.

**Comment:** Of what species?

**Comment:** How does this relate to changes in snow melt as discussed in section 3.2?

photosynthesis to produce negligible amounts of dissolved oxygen), or very high water temperatures (e.g., 34°C in Salmon Creek, Largier and Ho 2007). Some portion of this saline layer will be exported to the ocean through the sand barrier if the estuary surface is elevated above sea level, leading to a low-salinity lake-like environment by late summer (while others retain this layer and strong stratification throughout the dry season). Changes in local weather will affect heating and light availability, but ocean effects are isolated from the estuary by the sand barrier.

When estuaries are open, there is a continual exchange of ocean and estuary waters – out on the ebb tide and in on the flood tide. During strong river flows, there may be continuous outflow. Whether these estuarine outflows are primarily aged ocean water or land runoff water, the outflow forms a distinct jet near the mouth that evolves into a stratified plume at greater distances from the source. This plume delivers biogenic material, sediment and contaminants to nearshore waters (and offshore waters in the case of larger outflows, such as San Francisco Bay and Russian River estuary). The fate of these plume waters and their loading will change with climate-related changes in outflow water density (due to salinity), wave-forced currents, winds and offshore currents (typically related to wind forcing).

The climate-related changes in estuary conditions that are of primary concern are: (i) changes in mouth closure timing and persistence, (ii) changes in degree and frequency of flooding, (iii) upstream salinity intrusion, and (iv) fate of estuary outflows. The extent of changes depends on the interacting drivers, specifically river flow rate, sea level rise, wave energy and wind-forced currents.

### 3.4 Sea Level Rise

Global sea level rise is a well-recognized result of global warming. Sea level is affected through two primary mechanisms – thermal expansion of ocean water and ice melt (IPCC 2007).

However, large uncertainty exists in predicting sea level rise *due to future melting of polar ice sheets*. (Bell 2008). Global tide gauge data from 1870 to 2004 show a 19.5 centimeter (cm) rise in global sea level during this period (Church and White 2006). Between 1961 and 2003, global sea level rose at an average rate of 0.018 cm per year, with this rate increasing between 1993 and 2003 to about 0.31 cm per year (IPCC 2007). Recent vulnerability studies have utilized a medium-high projection scenario for the California coast of 40 cm of sea level rise by 2050 and 140 cm by 2100, which was developed using the methodology of Rahmstorf (2007), Cayan et al. (2008), Heberger et al. (2009), and PWA (2009a). Currently the state of California has adopted these projections for adaptation planning purposes under the directive issued for sea level rise in Executive Order S-13-08. Therefore, these projections will be used for this document.

The rate of sea level rise at a specific location is determined by tectonic movements as well as the local wind and wave fields that are superimposed on top of global sea level rise. These factors are additive, and when combined, determine the relative sea level rise at that location. Since the study region is along an active margin, the role of tectonic uplift and subsidence are important in determining the relative rates of sea level rise. Along the study area, the San Gregorio, Hayward, and San Andreas Faults play important roles in determining the movement of the land. Because these faults generally slide next to each other (right lateral transform faults), the uplift and subsidence rates are lower than along the Pacific Northwest subduction zone north of Cape Mendocino.

**Comment:** Nice paragraph. Succinctly summarizes the main issues. Similar paragraphs could be written for the previous sections that state the major issues and why they are important. In the case of waves, the closing paragraph emphasizes the importance of waves in shaping habitat, but doesn't summarize the issues.

What about changes in water quality resulting from exchange with altered ocean waters? (i.e. acidified waters)

**Deleted:** is the

**Comment:** ??? Emissions scenario that leads to a medium high SLR estimate?

**Comment:** I think this estimate is from Rahmstorf, Cayan, and Knowles. Heberger and PWA used the results to map and quantify inundation impacts, not the projected rates of SLR.

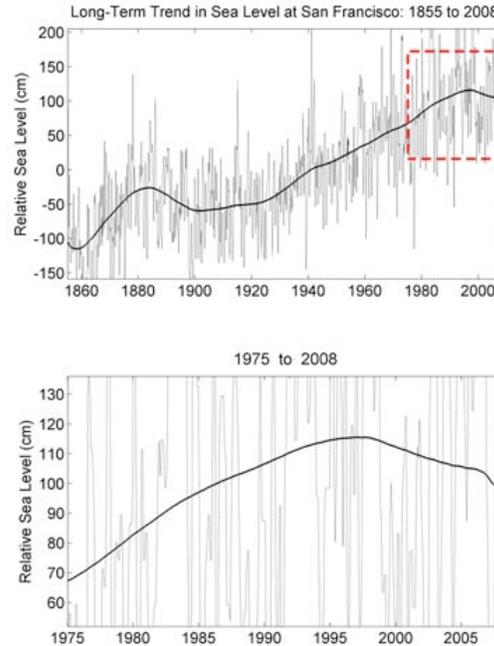
**Comment:** To be completely current, this document might want to cite the most recent Rahmstorf pub (see: <http://www.sciencedaily.com/releases/2009/12/091207165252.htm>) which states sea level will rise 75 to 190 cm by 2100.

**Comment:** More information/context is needed here as it is not clear how the different phenomena will balance. Numerous geology field studies (e.g., Perg et al., 2001) have shown that uplift rates of marine terraces in the Santa Cruz to Sonoma County area range from about 0.4 to 1.1 mm/yr. That means that by the year 2100 (90 years from now), parts of this coastline will have been uplifted somewhere between 3 and 10 cm. This will make just a small dent in the 140 cm of projected sea level rise adopted for planning in California.

Local rates of sea level rise also vary in response to interannual/interdecadal fluctuations in wave and atmospheric circulations. El Niño events, storm surges, and strong onshore directed winds can raise sea levels up to 30 cm above predicted tides (Flick 1998, Bromirski et al. 2003). In addition, larger scale climate fluctuations, such as PDO, moderate or enhance El Niño conditions. Recent research shows that the sea surface elevations off of the central California coast have been suppressed in comparison to global averages (Ramp et al. 2009). The PDO has been implicated in this finding, but researchers also point out that this is a temporary cycle, that when it reverses, is likely to lead to local sea level rise rates higher than global averages (see box: Scale Dependency of Climate Change, Sea Level Rise).

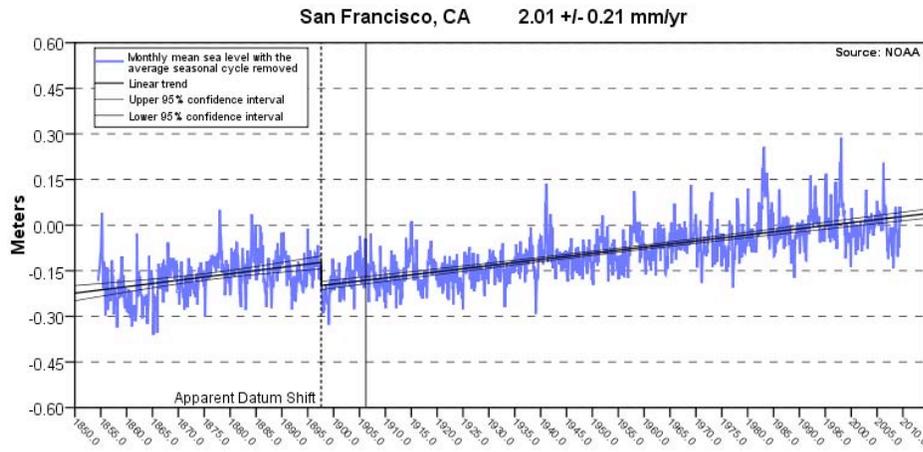
### Scale Dependency of Climate Change: Sea Level Rise

Global average sea level has been rising as indicated by reconstructed and direct data from the late 19<sup>th</sup> century to the early 21<sup>st</sup> century (Bindoff et al. 2007). However, it has become increasingly clear that the rate of sea level change is not consistent in space or time. Recent reanalysis of sea level data from the San Francisco tide gauge station (dating to the mid 19<sup>th</sup> century) corroborates rising sea level trends observed by other studies (Ramp et al. 2009). However, since 1997, sea level has actually been falling due to a phase shift of the Pacific Decadal Oscillation (PDO) to the “cool” state (Fig. 3.11). While the mechanism by which the PDO affects sea level requires further study, it is expected that a transition back to the warm state of the PDO will result in an accelerated rate of sea level rise (Ramp et al. 2009). Therefore, a different answer for sea level rise will be obtained depending on whether data is analyzed for 100 years or 10 years.



**Figure 3.11.** Long-term trends in sea level at San Francisco, 1855 to 2008. The lower panel is an expansion from the upper panel. Adapted from Ramp et al. (2009).

Sea level along the California coast has increased by about 15 cm over the past century (CEC, 2006). Locally, the San Francisco Bay Area has one of the longest recorded time series of sea level data in the United States. The San Francisco tidal gauge was installed in 1854, making it the oldest continually operating tidal observation station in the nation (NOAA/NOS 2008). The trend in sea level rise for the San Francisco Bay Area over the last century is approximately 2.01 millimeters per year which is equivalent to a change in ~0.66 feet (20.1 cm) over the last 100 years. (NOAA 2009; Fig. 3.12).



**Figure 3.12.** The mean sea level trend for Gauge No. 9414290 San Francisco, CA is 2.01 millimeters/year with a 95% confidence interval of  $\pm 0.21$  mm/yr based on monthly mean sea level data from 1897 to 2006, which is equivalent to a change of 0.66 feet (~20.1 cm) in 100 years. Source: NOAA (2009).

A primary impact of sea level rise on coastal habitats and communities is the increased likelihood and depth of coastal flooding. Coastal flood elevations can be determined by the sum of the constituent components including sea level rise, tides, storm surge, barometric pressure, El Niño effect on temperature, and wave run-up. The sum of these components determines a total water level elevation, and as this increases, then the risk to coastal habitats and communities increases (see box: Extreme Conditions).

**Comment:** Is it duplicative to have these in the same list? Low air pressure causes storm surge, which increases flood elevations.

## Extreme Conditions

Recent climate change studies have pointed out that the average frequency or intensity of observations may not change, (*of observations??, is something missing?*) as opposed to the occurrence of extreme events, which may increase. For example, median values of maximum wind speed in Atlantic tropical cyclones exhibit no trend from 1981-2006. In contrast, winds speeds in the 70<sup>th</sup> percentile and above have a positive linear trend, indicating an intensification of extreme cyclone wind speeds (Elsner et al. 2008). The importance of extreme events is highlighted when considering the effects of sea level rise on coastal infrastructure and development. When combined with high tides and storm surge, sea level rise can result in extreme flood events with significant economic consequences. Biological systems are not immune from extreme weather events as well. Indeed, often times average climate variables may not be as important as extreme events, which can have the largest effects on patterns of disturbance and mortality (Gaines and Denny 1993). Examples include large waves in the intertidal zone that dislodge organisms or extreme high temperatures that can result in mass mortality.

As the sea level rises, low-lying areas along the coast are more susceptible to flooding, including communities in Point Arena Cove, Bodega Bay, Bolinas, Tomales Bay and Stinson Beach (see

[http://www.pacinst.org/reports/sea\\_level\\_rise/hazlist.html](http://www.pacinst.org/reports/sea_level_rise/hazlist.html) for coastal flood and erosion hazard maps prepared by the Pacific Institute).

Increased flooding will also affect the quality and functioning of a variety of coastal habitats such as wetlands, beaches, and dunes.

Pendleton et al. (2005) state, "Potential effects of sea level rise include shoreline erosion, saltwater intrusion into groundwater aquifers, inundation of wetlands and estuaries, and threats to cultural and historic resources as well as infrastructure". Sea level rise may also increase salinity in the San Francisco delta and other estuaries by as much as 9 psu (*define "psu"*) (Knowles and Cayan, 2002), particularly if the period of seasonal low flow expands (Gleick 2000).



**Figure 3.13.** Sea level rise flood risk in Tomales Bay. Additional maps are available for the California coast:

[http://www.pacinst.org/reports/sea\\_level\\_rise/hazlist.html](http://www.pacinst.org/reports/sea_level_rise/hazlist.html)

**Comment:** Figure 3.13 text is too small.

### 3.5 Coastal Erosion

The majority of the sandy coast in this region is already classified as eroding (Bird 2000, Hapke et al. 2006, Hapke and Reid 2007, Patsch and Griggs 2007), partly as a result of human-induced changes in sediment supply and transport (Komar 1998). Coastal erosion is likely to increase in the study region as a result of rising sea level, changing wave conditions, and storm frequency and intensity. As the total water level elevations increase, and the coastline is exposed to longer durations of higher water levels, erosion will likely be accelerated (PWA 2009a). *Preceding two sentences basically say the same thing – combine?* Coastal habitats may be directly affected by these changes, or indirectly via human responses such as armoring, beach nourishment, or retreat. The extent of impacts associated with erosion depends on geology, *(geology includes tectonics)* and sediment supply, all of which affect elevation and resiliency. *I'm not sure what the preceding sentence ("extent of impacts") means – clarify.* These are integral factors controlling habitat type and quality. While many of these factors vary on local scales, they are evaluated here on the broader regional scale.

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Erosion: Erosion results from the interaction of coastal processes with coastal geological formations, although *it is also influenced by* terrestrial processes such as elevated groundwater also influence it. Sea cliffs are more or less susceptible to erosion depending on the hardness of the geologic rock type. Other important factors that control erosion include the shoreline orientation, width of the protective beach, and wave exposure (Griggs et al. 2005). Shoreline change rates have been calculated for most of the study area by the USGS for sandy shorelines (Hapke et al. 2006) and seacliffs (Hapke and Reid 2007). The magnitude of coastal erosion is related to the coastal geomorphology. PWA (2009a) characterized the California coast into seacliffs and dunes, and developed a methodology intersecting the USGS shoreline change rates with the variability in geology and erosion rates alongshore to then predict future erosion hazards. Maps of these erosion hazard areas can be found at [http://www.pacinst.org/reports/sea\\_level\\_rise/hazlist.html](http://www.pacinst.org/reports/sea_level_rise/hazlist.html).

Most of the coastline in the study area is backed by seacliffs, with Mendocino County projected to lose the largest area of land to coastal erosion (Table 1). Dune erosion is likely to have the largest impact in Marin County (an estimated 2.6 km<sup>2</sup>), with erosion of almost 9 km<sup>2</sup> for the dunes across the entire study area. Total erosion by 2100 is estimated to reach nearly 50 km<sup>2</sup> (PWA 2009a; Table 1). These areas of erosion are not uniform across each county within the study area and show a range of inland erosion distances (Table 2; PWA 2009a). Maximum erosion distances, occur along the dune backed stretches of coastline and can reach over 400 m in some areas (Table 2). These maps and values are an approximation and not intended to form the basis for site-specific actions, but rather to provide an overall estimate of the potential scale of vulnerability. For example, the estimated erosion may take longer than 100 years as a result of the delay between rapid sea level rise and erosion; it may take less if sea level rises faster than predicted. Overall, an enhanced potential for coastal erosion in this region is expected.

**Comment:** Should be made clear in the above paragraph and in the tables that these are projections that assume no human intervention.

**Table 1.** Total erosion area (alongshore + acrossshore) with a 1.4 m sea-level rise, for counties intersecting the study region.

County	Dune erosion miles <sup>2</sup> (km <sup>2</sup> )	Cliff erosion miles <sup>2</sup> (km <sup>2</sup> )	Total erosion miles <sup>2</sup> (km <sup>2</sup> )
Marin	1.0 (2.6)	3.7 (9.6)	4.7 (12.2)
Mendocino	0.7 (1.9)	7.5 (19.4)	8.3 (21.5)
San Francisco	0.2 (0.6)	0.3 (0.8)	0.5 (1.4)
San Mateo	0.8 (2.1)	2.4 (6.2)	3.2 (8.3)
Sonoma	0.6 (1.6)	1.6 (4.1)	2.2 (5.7)
<b>Total (study area)</b>	<b>3.3 (8.8)</b>	<b>15.4 (40.1)</b>	<b>18.7 (48.9)</b>

**Table 2.** Average and maximum inland erosion distance in 2100, for counties in the study region.

County	Dune erosion		Cliff erosion	
	Average distance (m)	Maximum distance (m)	Average distance (m)	Maximum distance (m)
Marin	140	270	110	240
Mendocino	190	440	33	160
San Francisco	150	230	90	220
San Mateo	230	430	31	220
Sonoma	150	320	41	190
<b>Average m (ft)</b>	<b>172 (564)</b>	<b>338 (1,109)</b>	<b>61 (200)</b>	<b>206 (676)</b>

**Sediment Supply:** To understand the impact of changes in sediment supply it is important to understand the sediment budget and ecosystem connections at a sand-shed scale that includes both the watershed and littoral cell (Revell et al. 2007). A littoral cell can be defined as a natural system of beach sand, constrained by headlands and submarine canyons with a variety of sediment sources and sinks that affect the overall sediment budget. If there is a surplus in the sediment budget then beaches tend to be wide and erosion rates small. *are* If there is a deficit in the sediment budget then beaches are usually narrow and erosion rates are higher. Littoral cells within the study region include: Navarro, Russian River, Bodega Bay, Point Reyes, Drakes Bay, Bolinas Bay, San Francisco, and Santa Cruz (Habel and Armstrong 1978; Patsch and Griggs 2007; Fig. 3.14).

**Comment:** Please consider using "sediment-shed" as opposed to "sand-shed." Wetland resiliency is dependent on fine-grained material as well as coarse. Use of the term sand-shed is biased to a particular condition and habitat, although it does place necessary importance on considering the role of sediment in forming the physical conditions conducive for biological diversity.

**Comment:** Seems like a surplus should mean that beaches are growing and accretion is occurring, not that erosion rates are "small." Conversely, a deficit in the sediment budget suggests beaches are narrowing and erosion is occurring.



**Figure 3.14.** Littoral cells of California. *California Master Plan for Coastal Sediment Management, Project Workplan (2002).*

Human alterations in the watersheds, such as dams and debris basins, have affected the peak flow rates reducing the sediment transport to the coast (Willis and Griggs 2003, Slagel and Griggs 2008). *Yes* This reduction has diminished the supply of sand and cobbles to the individual littoral cells, reducing the resiliency of the beaches and wetlands. For example, construction of the Coyote Valley and Warm Springs Dams on the Russian River has reduced the annual supply of coarse grained material by more than 30% (Slagel and Griggs 2008).

**Comment:** This figure has no useful information. It should be replaced with something specific to the study area, labeling each of its watersheds and littoral cells. County boundaries are not important.

**Comment:** Yes, dams affect peak flow rates. But isn't the trapping of sediments behind dams their larger impact on sediment supply?

*The traditional human/engineering response to coastal erosion for protection of houses and infrastructure has been to armor the coast. (Add sentence that describes "armoring," – seawalls and rip-rap. Shoreline armoring fixes the backshore in position and as sea level rises; the beach becomes trapped between the ocean and the armoring. Known as passive erosion, this impact effectively drowns beaches reducing the recreational and habitat value of this ecosystem.*

**Deleted:** In addition, a host of shoreline armoring has been constructed to protect houses and infrastructure along the coast. The traditional engineering response to erosion has been to armor the coast.

Changes in precipitation and sediment discharge (see 3.2 Precipitation and Land Runoff) will play an important role in moderating or exacerbating coastal erosion. If most precipitation events occur in short heavy events as predicted (Dettinger and Cayan, 1995; Cayan et al. 2001, Kundzewicz et al. 2007), then sediment discharge is likely to increase which may widen beaches

and reduce coastal erosion. However, given the numerous sediment and water retention structures in the watersheds, these events may remain reduced in magnitude of sediment and water discharge and thus not lead to a widening of beaches. The magnitude of river and sediment discharge will greatly affect the resiliency of wetlands and beaches as well as coastal hazards (erosion and flooding) from rising sea levels.

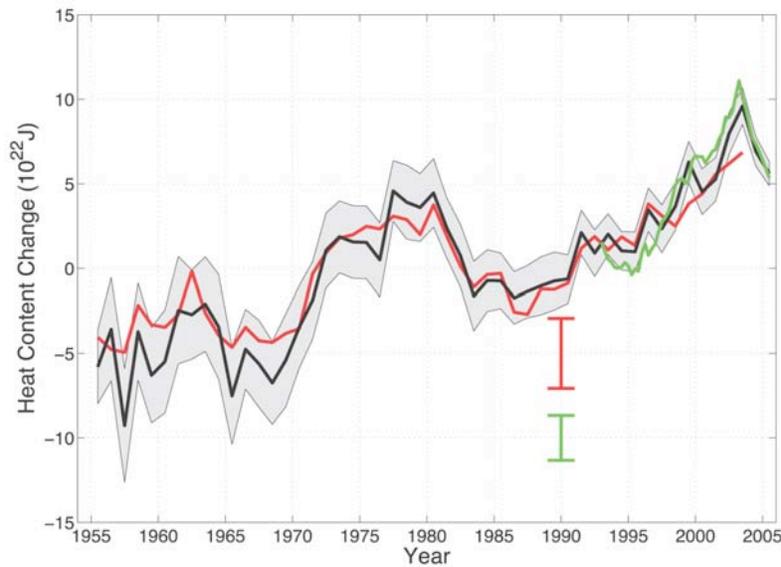
### 3.6 Ocean Water Properties

Both changes in the wind-driven coastal upwelling process and changes in the flow of the California Current will affect local water properties, including nutrient delivery to the euphotic zone and the biological effectiveness of upwelling. Decreasing upwelling winds and/or increasing stratification would lead to upwelling of waters from shallower depths – in turn resulting in higher temperatures, lower salinity and lower nutrient concentrations. At the same time, decreases in California Current transport would lead to the upwelling of coastal waters containing relatively more nutrient-poor subtropical water, leading to lower primary production. Another consequence of weaker transport by the California Current would be lower levels of dissolved oxygen in coastal waters (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 (Chan et al. 2008). In addition, the source waters that feed the California Current affect the composition of the plankton community, which in part determine the condition of higher trophic organisms.

Climate change may also affect non-obvious properties of seawater. For example, Hester et al. (2008) found that ocean acidification will result in decreased ocean sound absorption for frequencies less than 10 kHz. Their study suggests that a decrease of 0.3 pH units will result in a decrease in sound absorption by almost 40%. Therefore, the auditory range of human activities (e.g. commercial and military activities) could expand greatly.

#### 3.6.1 Temperature

Global oceans have increased in temperature by 0.10° C from 1961-2003 (IPCC 2007). Levitus et al. (2005) and Ishi et al. (2006) documented long-term increasing trends in temperature coupled with decadal variability using temperature profiles from surface waters to 700 m. A third analysis over a more recent time period is also in general agreement with these findings (Willis et al. 2004). Increases in ocean heat content account for more than 90% of the change in global heat content from 1961-2003 (IPCC 2007; Fig 3.15). This is due to the greater heat capacity of water relative to other components of the global energy budget (e.g. glaciers, ice sheets, continents, and the atmosphere). This increase in temperature may have significant effects on water column structure (e.g., stratification), ocean circulation patterns, sea level rise, and other climate phenomena (e.g., cyclone formation).

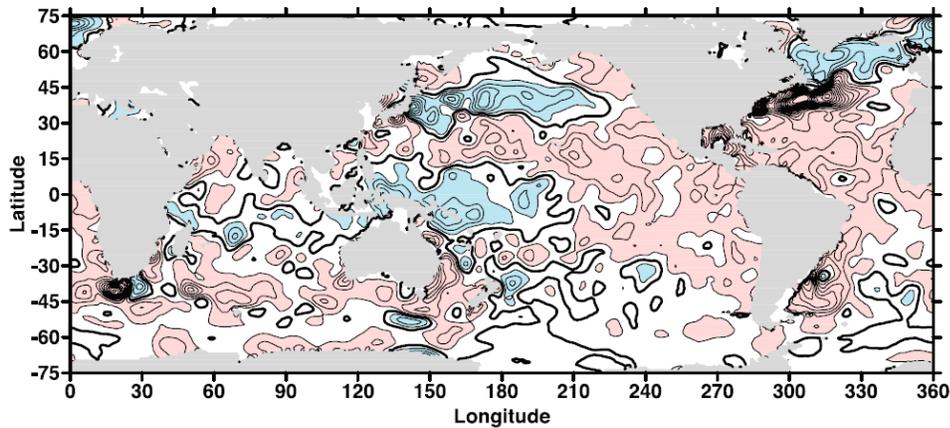


**Figure 3.15.** Time series of global annual ocean heat content ( $10^{22}$  J) for the 0 to 700 m layer. The black curve is updated from Levitus et al. (2005a), with the shading representing the 90% confidence interval. The red and green curves are updates of the analyses by Ishii et al. (2006) and Willis et al. (2004, over 0 to 750 m) respectively, with the error bars denoting the 90% confidence interval. The black and red curves denote the deviation from the 1961 to 1990 average and the shorter green curve denotes the deviation from the average of the black curve for the period 1993 to 2003 (Bindoff et al. 2007). IPCC.

Increases in Pacific Ocean temperature are spatially variable. At  $40^{\circ}$  N (0-350 m depth) and at the equator ( $\sim 250$  m depth), temperatures have cooled whereas over the remaining North Pacific, trends indicate warming (IPCC 2007; see box Scale Dependency of Climate Change: Seawater Temperature). Warming at equatorial surface waters and cooling of waters at depth indicate a relaxation of the tropical thermocline (McPhaden and Zhang 2002). Notably, warming in North Pacific waters is not restricted to the surface (0-300 m), but can be observed to 3000 m water depth (Levitus et al. 2000).

### Scale Dependency of Climate Change: Seawater Temperature

From 1961 to 2003 the global oceans have warmed by  $0.10^{\circ}\text{C}$  from the surface to a depth of 700 m (Bindoff et al. 2007). However, as seen with sea level rise, ocean warming is not consistent in space. In the Pacific Ocean, a large swath of cooling exists from the surface to 400 m depth along  $40^{\circ}\text{N}$  (heat content is proportional to temperature; Fig. 3.16; Bindoff et al. 2007). The regions depicted by blue in Figure 3.16 indicate cooling that is consistent with the positive phase of the PDO (via a strengthening of the Aleutian low). Again, different warming trends are obtained for data from different regions (or different time periods).



**Figure 3.16.** Linear trends (1955–2003) of change in ocean heat content per unit surface area ( $\text{W m}^{-2}$ ) for the 0 to 700 m layer, based on the work of Levitus et al. (2005). The linear trend is computed at each grid point using a least squares fit to the time series at each grid point. The contour interval is  $0.25 \text{ W m}^{-2}$ . Red shading indicates values equal to or greater than  $0.25 \text{ W m}^{-2}$  and blue shading indicates values equal to or less than  $-0.25 \text{ W m}^{-2}$ . Adapted from Bindoff et al. (2007).

Similarly, while large-scale studies show an increase in sea-surface temperature (SST) over the eastern Pacific Ocean (Fig. 3.16), other results show a slow warming rate or decrease in SST in coastal waters (Bakun 1990; Mendelsohn and Schwing 2002; Garcia-Reyes and Largier 2009) due to an increase in wind-driven upwelling (see 3.3.3 Coastal Upwelling). Further, unpublished data suggest SST is increasing in sheltered nearshore waters and enclosed bays. So different SST trends will be obtained depending on the spatial scale of analyses.

Coastal measurements of sea surface temperature from Southern California to Oregon document an increasing trend in temperature offshore and at shore stations since these data were first collected in 1955 (McGowan et al. 1998; Enfield and Mestas-Nunez 1999; Sagarin et al. 1999; Mendelssohn et al. 2003; Palacios et al. 2004). Also, anomalies detected at one site were generally correlated with other sites, suggesting that temperature increases in one area captured the thermal signal for a much greater region. Sites in Southern California have increased in seawater temperature by as much as 1.5° C since 1951 (Roemmich and McGowan 1995; McGowan et al. 1998). Ocean temperatures over the continental shelf have also seen a net increase but at a slower rate (Mendelssohn and Schwing 2002, Garcia-Reyes and Largier 2009), which is consistent with an increase in coastal upwelling (see 3.3.3 Coastal Upwelling).

### 3.6.2 Ocean Acidification

The increased concentration of CO<sub>2</sub> in the ocean (due to rising atmospheric CO<sub>2</sub> concentrations) has impacted the chemistry (pH) and biology of the oceans (Feely et al. 2008). The impact of ocean acidification is a recent but major concern and has been described as the “other CO<sub>2</sub> problem” (Doney et al. 2009).

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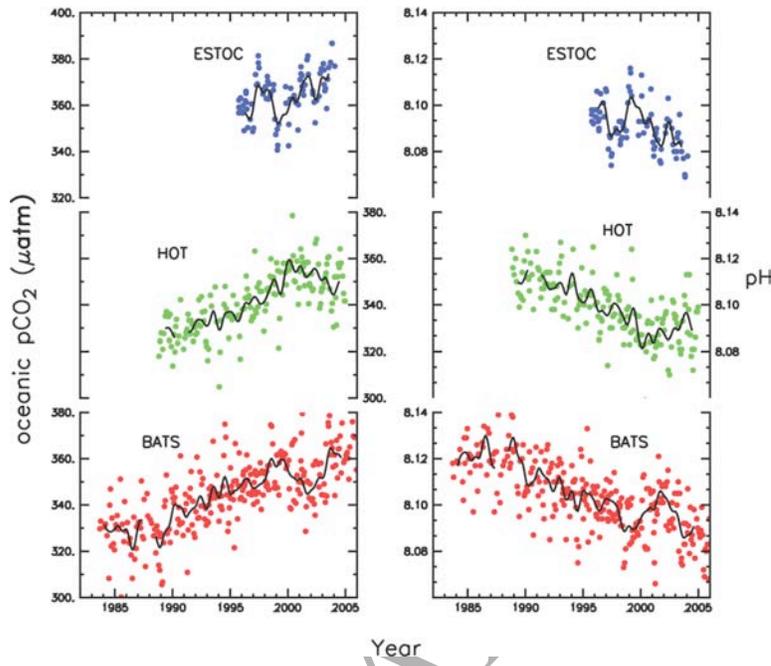
Increased CO<sub>2</sub> in the atmosphere (CO<sub>2atm</sub>) leads to a reduction in ocean pH and a decline in the carbonate ion concentration (CO<sub>3<sup>2-</sup></sub>) resulting in what has been termed “ocean acidification” (Caldeira and Wickett 2003). In the ocean, this carbonate system is controlled by chemical reactions in equilibrium, and the relative proportions of the three forms of dissolved inorganic carbon (DIC) affect seawater pH (a measure of the concentration of the hydrogen ion H<sup>+</sup>), as follows:

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The exchange of atmospheric carbon dioxide (CO<sub>2atm</sub>) across the air-sea interface equilibrates surface seawater CO<sub>2</sub> with the atmosphere. This dissolved (aqueous) CO<sub>2</sub> reacts with seawater to form carbonic acid (H<sub>2</sub>CO<sub>3</sub>). Carbonic acid readily dissociates to hydrogen (H<sup>+</sup>), bicarbonate (HCO<sub>3</sub><sup>-</sup>), and carbonate (CO<sub>3</sub><sup>2-</sup>) ions (see equation above). The relative proportions of these forms of DIC in an ocean of pH 8.1 are 86.5% bicarbonate, 13% carbonate, and 0.5% dissolved CO<sub>2</sub> (Zeebe and Wolf-Gladrow 2001). Rising CO<sub>2atm</sub> concentrations force a corresponding increase in H<sub>2</sub>CO<sub>3</sub>, a weak acid, resulting in increased hydrogen ion concentrations ([H<sup>+</sup>]), which leads to a decrease in pH, and decreased carbonate ion concentrations. Figure 3.17 illustrates the increase in oceanic pCO<sub>2</sub> and the resulting decrease in pH since the mid-1980s at three time series stations. The pH levels at these stations have decreased 0.02 unites per decade, and globally, the average surface ocean pH has decreased by 0.1 units since pre-industrial times (Doney et al. 2009).

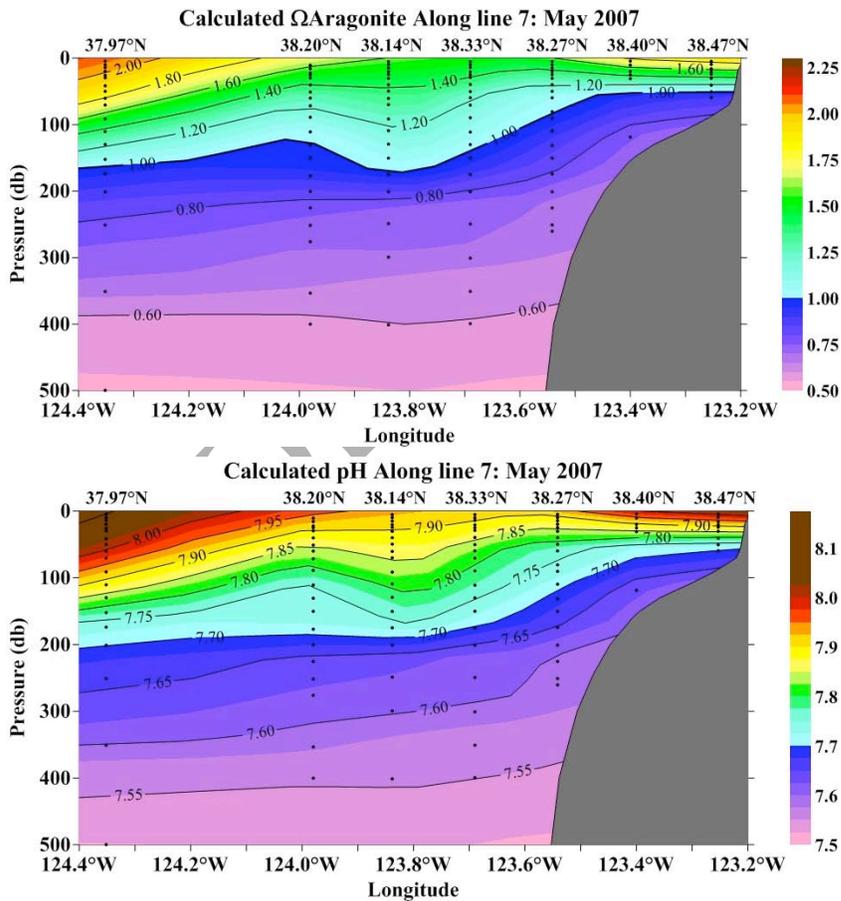


**Figure 3.17.** Changes in surface oceanic  $p\text{CO}_2$  (left; in  $\mu\text{atm}$ ) and pH (right) from three time series stations: Blue: European Station for Time-series in the Ocean (ESTOC,  $29^\circ\text{N}$ ,  $15^\circ\text{W}$ ; Gonzalez-Dávila et al. 2003); green: Hawaii Ocean Time-Series (HOT,  $23^\circ\text{N}$ ,  $158^\circ\text{W}$ ; Dore et al., 2003); red: Bermuda Atlantic Time-series Study (BATS,  $31/32^\circ\text{N}$ ,  $64^\circ\text{W}$ ; Bates et al. 2002; Gruber et al. 2002). Values of  $p\text{CO}_2$  and pH were calculated from DIC and alkalinity at HOT and BATS; pH was directly measured at ESTOC and  $p\text{CO}_2$  was calculated from pH and alkalinity. The mean seasonal cycle was removed from all data. The thick black line is smoothed and does not contain variability less than 0.5 years period. IPCC (2007).

Carbonate ion is essential to the formation of calcium carbonate minerals (e.g., calcite and aragonite) that make up the shells and skeletons of many marine taxa (Orr et al. 2005, Fabry et al. 2008, Doney et al. 2009). Calcium carbonate becomes more soluble with decreasing temperature and increasing pressure (i.e. ocean depth). Calcium carbonate formation and dissolution rates also vary with saturation state ( $\Omega$ ), which depends on the concentrations of calcium and carbonate ions in seawater. Saturation states are typically highest in the tropical oceans, and begin to decrease with increasing latitude and decreasing temperature (Feely et al. 2004). A natural boundary, the saturation horizon, develops in seawater as a result of these variables, and this boundary delineates a depth of seawater above which carbonate minerals can form, but below which they dissolve if unprotected (Feely et al. 2004). The majority of marine organisms that produce shells and skeletons live above the saturation horizon, but increasing  $\text{CO}_2$  levels are elevating the saturation horizon closer to the surface (Feely et al. 2004). Therefore increases in surface ocean  $\text{CO}_2$  could have severe consequences for organisms that utilize external shells and skeletons.

A recent study by Feely et al. (2008) shows that pH is already low in upwelled waters along the coast of western North America. In spring 2007, in a strong upwelling area off the northern

California coast, the entire water column shoreward of the 50 m bottom contour became undersaturated with respect to aragonite ( $\Omega_{\text{arag}} < 1.0$ ) and had a  $\text{pH} < 7.75$  concomitant with intense upwelling (Fig 3.18). These conditions at the ocean surface are not expected to occur elsewhere in the oceans until the year 2050 (IPCC 2007), but it is expected that similar conditions elsewhere along the northern and central California coast and in other strong upwelling systems will display this signal (Feely et al. 2008). While aragonite saturation and precision pH measurements are not often obtained,  $\text{CO}_2$  levels over 1000 ppm have been observed during intense upwelling near Point Reyes and values just less than 1000 ppm have been observed near the surface at a number of other locations in the Arena-Reyes upwelling center (Vander Woude et al. *in preparation*). While monitoring changes in pH is still in its infancy, these processes are expected to adversely influence any organism that produces calcium carbonate shell due to the decrease of pH and carbonate ion concentration (see 4.7 Invertebrates).



**Figure 3.18.** (Top) Aragonite saturation state along transect line 7 (beginning just north of San Francisco Bay). (Bottom) pH values along transect line 7. Results calculated from May 2007 North American Carbon Program (NACP) West Coast Cruise along the continental shelf of western North America. Courtesy of D. Feely and D. Greeley / NOAA.

Ocean acidification may also be driven by increases in freshwater input (low pH, low calcium) to estuarine habitats from rivers and streams, which decreases aragonite and calcite saturation state. Increases in freshwater have been predicted by forecast models of global warming scenarios for California (Snyder and Sloan 2005). For example, Tomales Bay receives freshwater input from two creeks. During the upwelling season (approximately April to August), Tomales Bay becomes hypersaline, especially at the head of the bay (Hearn and Largier 1997, Largier et al. 1997), whereas in winter, sporadic heavy rains can induce low salinities. Runoff and tidal processes control ocean-estuary exchange, and therefore also control blooms of phytoplankton that alter seawater alkalinity and influence ocean pH and CO<sub>2</sub> concentrations. In a reanalysis of data from Smith and Hollibaugh (1997) it has been shown that aragonite saturation state ( $\Omega$ ) was critically low at the head of the bay during four winters, when freshwater input from Lagunitas Creek was greatest (Russell et al. *in preparation*). These processes may increase as northern California experiences changes in winter storms and rainfall in the future.

### 3.6.3 Salinity

Salinity is a key variable that is useful for detecting changes in precipitation, evaporation, runoff, ice melt, and ocean circulation (IPCC 2007). Detection of long term trends in ocean salinity is hampered by data deficits in some areas. Nonetheless, existing global salinity data indicate trends of freshening seawater at subpolar latitudes and increased salinity at tropical and subtropical locations. In the Pacific Ocean, increased precipitation as well as greater runoff and ice melt has resulted in decreased salinity at high latitudes. While Pacific subtropical regions have increased in salinity over time as a result of strong evaporation (IPCC 2007), overall, the Pacific Ocean basin has decreased in salinity (Boyer et al. 2005). CalCOFI data from Southern California indicate a long-term freshening of surface waters associated with decreased mixing of deep saline waters caused by persistent heating of surface waters (McGowan et al. 1998). Additionally, time series measurements indicate that freshening events in Southern California are associated with ENSO episodes and increased impact of subarctic water reaching the California coast in recent years (Gomez-Valdez and Jeronimo 2009). Few data are available that address Northern California sites specifically, but it is expected that similar processes would control salinity in this region. Salinities in coastal California will also be impacted by local-scale changes in precipitation and runoff, which is likely to include increases in precipitation during spring months (Snyder and Sloan 2005).

### 3.6.4 Nutrients

Ocean nutrient concentrations are affected by a variety of processes that have potential links to anthropogenic climate change. However, only a few studies (see Bindoff et al. 2007) exist within the Northeast Pacific that examine long term changes in macro-nutrient concentrations (e.g. nitrate, nitrite, phosphate, silicic acid). Perhaps less even is known about micro-nutrients in the CCE (e.g. iron, zinc). Generally, increased temperature and stratification should act to decrease the mixed layer depth, resulting in the upwelling of warmer nutrient poor waters. However, this is complicated by changes in wind structure and the magnitude of wind stress curl, as well as overall changes in upwelling intensity (see 3.1.1 Atmospheric Circulation and 3.1.4 Coastal Upwelling). Recent work on CalCOFI and Alaskan Gyre Line P datasets has documented a relationship between nutrients and upwelling and the North Pacific Gyre Oscillation (NPGO), suggesting a potentially useful index for measuring changes in long-term nutrient dynamics (Di Lorenzo et al. 2008; 2009). In coastal areas near rivers and estuaries, nutrient concentrations will be linked to precipitation patterns and the subsequent sediment and nutrient plumes created from

freshwater input. Because nutrient concentrations can have such a large effect on primary productivity and overall food web function, more studies are needed to determine how climate change will affect nutrients in the CCE.

### 3.6.5 Dissolved Oxygen

Dissolved oxygen (DO) concentrations in the ocean are dependent on a number of physical and biological processes, including circulation, ventilation, air-sea exchange, production and respiration (Keeling and Garcia, 2002; Deutsch et al. 2005, Bograd et al. 2008). Climate-driven changes in any of these processes can result in significant changes in DO. Models driven by increasing greenhouse gases predict a decline in midwater oceanic DO, primarily as a result of enhanced stratification and reduced ventilation (Sarmiento et al. 1998, Keeling and Garcia 2002).

An extensive oxygen minimum zone (OMZ) exists along the continental margin of North America, within the California Current Ecosystem (CCE). Recent observations within the CCE have revealed significant reductions in DO in several locations, suggesting climate-driven variations in the processes controlling DO concentrations and a potential shoaling of the OMZ (Whitney et al. 2007, Bograd et al. 2008, Chan et al. 2008, Stramma et al. 2008). On the Oregon continental shelf, there has been an increase in the frequency and severity of hypoxic events and the novel rise of water-column anoxia, with accompanying high mortality of demersal fish and benthic invertebrate communities (Grantham et al. 2004; Chan et al. 2008). These events are seasonal and have been attributed to fluctuations in the intensity of upwelling, the DO content of upwelled water, and productivity-driven increases in coastal respiration (Wheeler et al. 2003; Grantham et al. 2004; Chan et al. 2008).

In the southern CCE, anoxic events have generally been limited to the deepest part of the submarine basins within the borderlands off southern California (e.g. Santa Barbara Basin, Berelson 1991, Kennett and Ingram 1995, Bograd et al. 2002). Differences in shelf bathymetry may make productivity-driven anoxic events less common off California relative to Oregon. However, hydrographic data collected on CalCOFI cruises have revealed significant declines in water-column DO throughout the southern CCE (Bograd et al. 2008). The largest relative DO declines occurred below the thermocline (mean decrease of 21% between 1984-2006 at 300 m), with significant linear trends at the majority of CalCOFI stations down to 500 m (the deepest depth sampled). The spatial pattern of the DO trends suggests that the advection of low-DO waters into the region (e.g. from the eastern tropical Pacific via the California Undercurrent) may have been a major contributor to the observed DO decline. Similar DO declines have been observed from the long-term Line P dataset extending from the southern tip of Vancouver Island out to the central Gulf of Alaska (Whitney et al. 2007). The CCE observations are also consistent with the observation of an expanding OMZ in the tropical Pacific, which is a source of deep waters to the CCE (Stramma et al. 2008). It should be noted, however, that there is a lack of historical DO observations from the central CCE (e.g., between Monterey Bay, CA and Cape Blanco, OR), revealing a significant data gap.

A decline in mid-ocean DO concentrations can be viewed as a vertical expansion of the OMZ, which may then impact a larger portion of the California Current shelf and slope regions. In the southern CCE, the hypoxic boundary ( $\sim 60 \mu\text{mol kg}^{-1}$ ) shoaled between 1984-2006 by an average of 40 m, and up to 90 m over the continental slope/shelf (Bograd et al. 2008). This expansion of the oxygen minimum layer could lead to cascading effects on benthic and pelagic ecosystems,

including habitat compression and community reorganization (Diaz and Rosenberg 1995; Childress and Seibel 1998; Levin 2003, Prince and Goodyear 2006, Bograd et al. 2008), range expansion of some organisms such as Humboldt squid (Gilly et al. 2006), as well as increased ocean acidification as low-DO waters are upwelled (Feely et al. 2008). Continued monitoring within the CCE, and particularly in the study region, is essential to understand the mechanisms and mitigate the ecological consequences of climate-driven changes in oceanic oxygen content.

DRAFT

## 4. Regional Biotic Responses

Under changing climatic conditions, marine organisms may exhibit a myriad of responses with a variety of outcomes for individuals and populations. Species can (1) remain in the same area but adapt to changing conditions, (2) persist in sub-optimal conditions but with potentially significant physiological costs, (3) move to environmental conditions that suit their physiological tolerances by expanding or contracting their range in space (along latitudinal, depth, or intertidal gradients), or (4) adjust the timing of aspects of their life history (e.g. breeding events; Fields et al. 1993). This chapter considers the physiological response of organisms to climate change and transitions to observations of range shifts and changing phenology. It then considers the effect of climate change on the degree by which populations are connected by recruitment of new individuals, and the response of specific taxonomic groups to global climate change.

### 4.1 Physiology

Temperature, ocean acidification, and potential synergistic interactions could significantly affect the physiology of marine fauna and flora within the study region. Responses to these factors are likely to be species specific, leading to difficulty in forming generalizations that can be applied to large taxonomic groups for a given climate stressor. Rather, this section demonstrates the large potential for climate to influence many facets of the physiology of marine organisms.

Temperature: Temperature affects virtually all biological structures and processes. In marine organisms, the effects of temperature can be seen on heart function, neural function, mitochondrial respiration, protein synthesis, metabolism<sup>2</sup>, and countless other physiological processes (Somero 2002). Basic theory suggests that climate change could differentially favor species with large thermal windows, short generation times, and a range of genotypes among its populations (Harley et al. 2006, Portner and Farrell 2008). Organisms with a wide thermal window should be able to cope with a wider range of thermal conditions than species with a narrow range (Fields et al. 1993). However, this may not be true if thermally tolerant species are more likely to experience their physiological maximal temperature. For example, intertidal porcelain crabs (genus *Petrolisthes*) in the upper intertidal can cope with a wider range of temperatures than crabs in the lower intertidal. However, those crabs in the upper intertidal are more likely to experience extreme temperatures than those in lower zones due to greater emersion times (Stillman and Somero 2000). Therefore, even though the higher intertidal species is generally more thermally tolerant, they live with greater stress.

Given that many species that reside in the upper intertidal have a greater thermal range (but may be more likely to experience lethal conditions), upper intertidal habitats could be a focal area for monitoring the effects of temperature stress. Other populations that may be useful focal areas for monitoring are those that are closer to their range limits. The intertidal snail (*Nucella canaliculata*) ranges from Alaska to central California. Populations near their southern range edge express a greater heat shock protein response, suggesting a greater degree of thermal stress (Sorte and Hofmann 2004).

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<sup>2</sup> Temperature effects on larval metabolic rates appear to be generally consistent across taxonomic groups. See 4.4 Population Connectivity (O'Connor et al. 2007).

Species with short generation times and high genetic diversity may have a greater ability to rapidly adapt to changing environmental conditions. Indeed, high genetic diversity in eelgrass (*Zostera marina*) has been demonstrated to result in greater resilience to heat waves and disturbance (Reusch et al. 2005, Hughes and Stachowicz 2007; see box “Evolutionary Response”). However, studies of the effects of genetic diversity have generally been biased towards plants and little is known about how genetic diversity could influence the adaptive response of other taxonomic groups to climate change (Hughes et al. 2008).

Temperature can also influence the distribution of fishes by affecting growth rates and aerobic capacity. For example, in the Wadden Sea, the common eelpout (*Zoarces viviparus*) is thermally restricted and has shown decreases in abundance in response to a 1.13° C increase in seawater temperature (Portner and Knust 2007). Even though this fish experienced increased growth rates at higher temperatures, the increased metabolic costs outweighed the growth benefit and resulted in population declines.

Temperature can also modify the metabolic rate of ecologically important species, an example of how small changes in the environment can have large consequences for community structure. The ochre seastar (*Pisaster ochraceus*) is a keystone predator that preys upon one of the dominant species within the intertidal community, the California mussel (*Mytilus californianus*). Small decreases in temperature (3° C) caused by upwelled waters reduced seastar consumption of mussels by 29% (Sanford 1999). If intensified upwelling occurs in coastal waters, mussels may dominate the community due to a lack of seastar predation. Conversely, if temperatures increase due to a stratified water column and solar heating of surface waters, seastars may increase their foraging rates. Further studies using these species have demonstrated that the response of seastars may be more complex; acute high temperature exposure in seastars results in greater foraging, whereas chronic high temperature exposure decreases foraging (Pincebourde et al. 2008).

**Ocean Acidification:** Ocean acidification has the potential for significant negative physiological effects on the life stages of many marine organisms (Doney et al. 2009; see 3.5.2 for a description of the physical process). The most well known consequence of ocean acidification is a depression of calcium carbonate saturation states to levels that can inhibit an organisms' ability to produce calcareous structures. However, it should be noted that the minimum calcification thresholds for any organism may be above *or* below the chemical saturation state ( $\Omega = 1$ ; Doney et al. 2009). In addition, some organisms may counteract lowered internal body fluid pH by dissolving their shell structures (Michaelidis et al. 2005, Miles et al. 2007).

**Comment:** There have been some studies on the effect of reduced pH on physiology of organisms – i.e., some organisms that adjust internal pH to new lowered pH in the environment show negative physiological effects. May want to mention that here if related to important CCE organisms.

A variety of calcareous marine organisms could be negatively affected by ocean acidification. Potentially affected species include: planktonic coccolithophores, foraminifera, pteropods, copepods, euphausiids, benthic bivalves, gastropods, echinoderms, crustaceans, coralline algae, and deep water corals. A literature review of experimental studies on the effects of ocean acidification revealed that 27 of 40 (67.5%) studies detected a negative response in the study organism (Doney et al. 2009). For example, in acidification treatments, adult mussels and oysters experienced reduced calcification rates of their shells by 25 and 10%, respectively (Gazeau et al. 2007). Reduced shell growth has also been observed in gastropods and echinoderms as well (Shirayama and Thorton 2005). The larval stages of marine invertebrates are likely to be particularly sensitive to acidification effects due to their small size and because

some produce aragonitic structures which are more susceptible to acidification. Likewise, because saturation state is a function of seawater depth, deepwater corals such as the hydrocorals located at Cordell Bank may be one of the first to experience acidification (Doney et al. 2009).

One caveat that should be considered when interpreting the results of these studies is whether they actually reflect the gradual long-term biological response of species to ocean acidification. Most studies subject organisms to experimental trials under future atmospheric carbon dioxide scenarios for short periods of time (Doney et al. 2009). However, it is poorly understood how organisms will adaptively respond over gradual longer term changes in ocean chemistry. Furthermore, a recent study examining the effect of ocean acidification on two east coast oysters (*Crassostrea virginica* and *C. ariakensis*) found that both species were able to achieve net shell growth even when aragonite was undersaturated (Miller et al. 2009). This highlights the fact that responses to ocean acidification are likely to be *species specific*.

Synergistic Interactions: Multiple changing environmental stressors can combine to produce novel physiological responses that would be difficult to predict by studying the stressors alone. One such potential interaction exists between ocean acidification and temperature. Using the red sea urchin (*Strongylocentrotus franciscanus*), O'Donnell et al. (2008) demonstrate that the production of heat shock proteins<sup>3</sup> was decreased in acidification treatments. Suggesting that the sea urchins' ability to respond to thermal stress would be impaired in acidified waters. Rosa and Seibel (2008) demonstrated that ocean acidification and changes in temperature and the depth of the oxygen minimum zone may combine to restrict the habitat of the pelagic Humboldt squid (*Dosidicus gigas*). In experimental treatments, acidification treatments reduced squid metabolic rates by 31% and activity levels by 45%. Warmer temperatures also exacerbate reductions in activity and metabolism and when combined with a shoaling of the oxygen minimum zone (in tropical waters; Stramma et al. 2008) could significantly restrict depths within which Humboldt squid can occupy (Rosa and Seibel 2008).

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<sup>3</sup> Molecular chaperones that aid in cellular response to thermal stress.

## Evolutionary Response

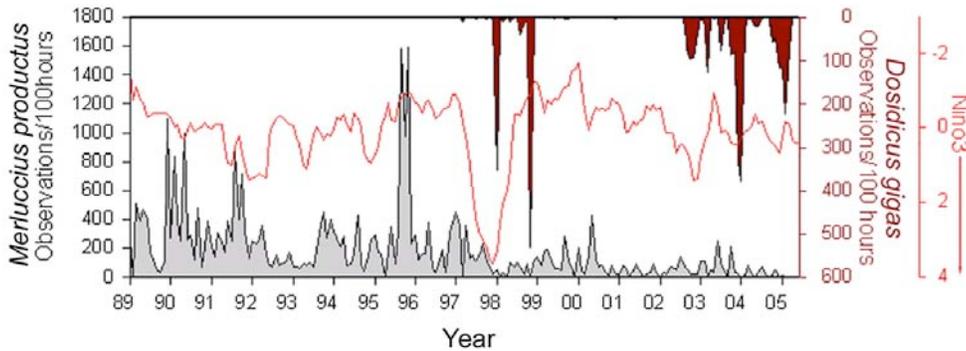
In a changing environment, populations can respond by either: 1) moving to a more suitable environment (i.e. shifting their range); 2) failing to move and subsequently succumbing to mortality; or 3) they can adapt to the new environment through natural selection. In this regard, perhaps one of the most pressing questions is to determine the capacity of populations to adapt to changes in the environment. Several studies (although few overall) have documented the ability of populations to develop genetic responses to climate warming that can be passed on to future generations (Bradshaw 2006). These responses are realized in an adaptation to the timing of seasonal events or to season length. The extent of these populations to adapt to temperature alone is not well understood. Furthermore, it is not only necessary to determine if populations are capable of adapting, rather information is needed about how quickly organisms can adapt and if this rate *is* sufficient to keep pace with climate change.

Greater genetic diversity has been suggested to increase the resilience of marine organisms in the face of climate change. Reusch et al. (2005) evaluated the effect of genotypic diversity in eelgrass (*Zostera marina*) response to an extreme temperature event of 25° C. Field experiments revealed that greater genetic diversity resulted in increased growth of eelgrass in plots relative to low genetic diversity plots after a heat wave. Genetic diversity may therefore be an underappreciated but important factor that underlies species response to climate change. This may be particularly relevant for populations that undergo artificial genetic selection, such as mitigated eelgrass populations that have reduced genetic diversity because only a few source populations were drawn from (Williams 2001).

### 4.2 Range Shifts

A fundamental prediction that can be made regarding biotic responses to climate change is that species will shift their range to maintain optimal environmental conditions. In response to warming temperatures, both northern and southern species may shift their range towards the poles (Parmesan 1996). However, poleward range expansion may not always be the case (see "Caveats to poleward range expansion theory"). Nonetheless, the paleontological record indicates that during past warming events, species have generally responded this way (van Devender and Spaulding 1979, Fields et al. 1993, Roy et al. 1996). Contemporary studies have documented this phenomenon in a variety of marine habitats. This has been described in a rocky intertidal marine community in Monterey, California (Barry et al. 1995, Sagarin et al. 1999). By comparing 46 rocky intertidal species over a 60-year period, Barry et al. (1995) detected an increase in abundance of 10 of 11 southern species with a decrease of 5 of 7 northern species. The nature of the historical data only allowed a comparison at one site, making it difficult to generalize to multiple locations. Nonetheless, the observed range expansions occurred during a time of ocean warming, suggesting that species did in fact shift their range poleward in response to greater temperatures. In subtidal kelp forest habitats, the range expansion of the snail Kellet's whelk (*Kelletia kelletii*) was attributed in part to warming seawater temperatures that resulted in greater recruitment success (Zacherl et al. 2003). Reef fish communities in Southern California have also shifted in dominance from northern to southern species over a 20-year period beginning with a climate regime shift in 1976-1977 (Holbrook et al. 1997). In pelagic

communities, Humboldt squid (*Dosidicus gigas*) is a southern species that has recently expanded its range northward to Monterey Bay, CA (Zeidberg and Robison 2007) as shown in Figure 4.1.



**Figure 4.1.** Time series of Pacific Hake abundance and Humboldt Squid abundance in Monterey Bay, CA. Zeidberg and Robison (2009). Copyright (2009) National Academy of Sciences, U.S.A.

**Comment:** KH: In Monterey Bay?

Though range shifts are typically considered on large scales (100-1,000s of km); the elevational range of species can shift in response to sea level rise on the scale of meters (see 3.4 Sea Level Rise). Intertidal species will be most affected by this process, particularly when it is considered that these species are already under duress because they must deal with variable marine and terrestrial forces (e.g. heavy wave action, desiccation stress, and ultra-violet radiation). These impacts may be the most pervasive when rising sea level reduces the area available for intertidal species to persist. Increased air temperatures and solar radiation may also compress the range of high intertidal species into lower zones (Harley 2003).

**Comment:** And increased waves as well?

**Caveats to poleward range expansion theory:** One criticism of the theory of predicted poleward range shifts is that it does not take into consideration more complicated species interactions. The response of certain key species (e.g. those that form habitat) may exert a greater influence on overall community composition, nullifying the traditional view of range expansions. Schiel et al. (2004) use a before-after control impact study to examine the effect of a 3.5° C temperature increase on marine communities caused by the thermal discharge of the Diablo nuclear power plant in Central California. In reference to adjacent control sites, there was no expected trend of increased southern warm water species and decreased northerly cold water species. Overall responses to warming were unpredictable and linked to the response of a smaller number of key habitat forming species (Schiel et al. 2004; see 4.6 Macroalgae and Plants for details). Furthermore, species ranges are dependent on biotic as well as abiotic factors. Predictions based solely on climate models may lead to erroneous projections because they fail to account for the effect of competitors, predators, and facilitators (and how they themselves may be affected by climate change) that create observed species range (Davis et al. 1998).

Caution is warranted when inferring range distributions from physical data alone. Regional characteristics of the physical environment may result in more complex patterns of biological response as opposed to range shifts. Using modified temperature sensors, Helmuth et al. (2002; 2006) described biologically relevant temperature patterns in the rocky intertidal on the west coast of North America that were locally modified by the timing of low-tides. In the south,

summer low tides occur in the middle of the night and during the day (when temperature is greatest) animals are submerged in water. In the north, the lowest low tides occur in the springtime during the middle of the day, exposing organisms to desiccation and heat stress. This suggests that not all species will be exposed to physical drivers in the same way and may exhibit dynamic shifts in range caused by thermal 'hot spots'. Thus, it cannot be assumed that all species distributions will shift towards the poles.

### 4.3 Phenology

Changes in the timing of physical processes in the marine environment may have substantial impacts on the biological community at all trophic levels. Early spring transitions may disrupt the food supply and survival of larval fish that spawn early in the year. Cury and Roy (1989) evaluated the effects of upwelling and turbulence on fish populations and found parabolic relationships between fish recruitment and upwelling in all four major upwelling regions in the world. They concluded that there is an optimal environmental window for fish production, where ocean productivity is too low to support strong year classes at very low levels of upwelling but turbulence is too high at very high levels of upwelling because fish larvae are desegregated from the food patches that would support them.

Ainley et al. (1993) used Common Murre chick diet data to examine the relationships between juvenile rockfish prevalence in the diet and ocean conditions and found support for Cury and Roy's (1989) hypothesis. Ainley et al. (1993) found a parabolic relationship between rockfish and average upwelling intensity in January and February; rockfish were less abundant in years of prevalent winter downwelling or overly persistent upwelling, though Miller and Sydeman (2004) repeated this analysis and did not find the same pattern when a longer data set was used.

The effect of early spring transitions may extend to top predators in the marine system. Roth et al. (*submitted*) found parabolic relationships between seabird timing of breeding and reproductive success and spring transition date. The results suggest that seabirds are also affected by upwelling that is either too weak or too strong early in the year. In addition, Abraham and Sydeman (2004) found that breeding can be delayed when upwelling is unusually strong at the time of spring transition. Many marine mammals prey heavily on juvenile rockfish and may be negatively impacted by declines in rockfish populations. However, it is important to note that many seabirds and marine mammals have diverse diets and are able to use alternate prey that may not be as affected by the timing of spring upwelling.

Late spring transitions could also have a detrimental effect on the biological community. Late upwelling is generally associated with poor ocean productivity, low krill abundance, and late seabird breeding (Abraham and Sydeman 2004; Jahncke et al. 2008, Roth et al. *submitted*). Late breeding is generally associated with poor seabird reproductive success (Ainley et al. 1995; Sydeman et al. 2001; Sydeman et al. 2006; Jahncke et al. 2008) and could ultimately lead to breeding population declines in the region.

The effects of a shift toward later peak upwelling may depend on the timing of the peak relative to the spring transition. Production at multiple levels of the marine food web could decline if the spring transition becomes earlier and peak upwelling becomes later. Marine fish likely time their spawning efforts to ensure maximum food availability for larval fish later in the season. Similarly, seabirds likely time their breeding to maximize prey abundance during the critical

chick-rearing period. Peak upwelling (and peak food production) may occur too late in the season for successful reproduction if marine fish and seabirds begin breeding in response to an early spring transition. Conversely, if both the spring transition and peak upwelling progressively get later in the season there could simply be a shift in the seasonality of the productive season that does not have a detrimental effect on marine populations.

#### 4.4 Population Connectivity

Population connectivity refers to the exchange of individuals between geographically isolated sub-populations through mechanisms such as larval dispersal (Cowen et al. 2007). Since many marine organisms exhibit a pelagic larval stage, the extent of connectivity can have significant implications for the distribution and abundance of adult populations. Climate change can affect population connectivity by altering spatial patterns of larval transport or by modifying the timing of recruitment favorable conditions. Climate change can also directly affect the physiological development of larvae by influencing larval metabolic rate (via temperature) or by inhibiting calcification and/or larval development (via ocean acidification).

**Spatial Patterns:** Larval transport is mediated by complex ocean circulation processes that vary across many scales. In coastal upwelling systems, much attention has focused on the upwelling and relaxation of ocean currents that transport larvae offshore in surface waters during upwelling and return them onto shore for recruitment during relaxation periods. Regions that experience persistent upwelling are typified by limited recruitment of intertidal organisms. Regions that experience upwelling punctuated by periodic relaxations have been observed to have a greater recruitment of larvae (Broitman et al. 2008). Climate change may affect the intensity of upwelling by altering wind stress (see 3.3.3 Coastal Upwelling) and thus have significant consequences for patterns of recruitment. If upwelling intensity increases and is not interspersed by relaxation events, there could be a net loss of larvae to offshore surface waters. However, recent studies in Bodega Bay and Oregon indicate that larvae are not advected offshore during periods of upwelling (Morgan et al. 2009; Shanks and Shearman 2009). This is further complicated by larvae that may be present in deeper waters that could be brought shoreward during upwelling periods (Shanks et al. 2000). Moreover, larval transport can also be significantly influenced by the formation of internal tidal bores or breaking internal waves.

The topography of the coastlines has been demonstrated to affect the delivery of larvae within the study region. The lee of Bodega Head can act as a larval retention zone where subsurface waters recirculate plankton within the bay (Roughan et al. 2005; Mace and Morgan 2006). Climate change may affect these larval retention zones by modifying the characteristic circulation patterns maintaining this phenomenon. Further monitoring of retention zones in the lee of Pillar Point, Bodega, Drakes, Bolinas, and Monterey Bay could detect shifts in settlement.

**Temporal Patterns:** The timing of upwelling favorable winds has been predicted and observed to shift as a result of differential heating of the land and ocean (Snyder et al. 2003, Bograd et al. 2009). Timing may have significant consequences for the recruitment of intertidal invertebrates. In 2005, off the Oregon coast, Barth et al. (2007) observed delayed upwelling favorable winds resulting in an 83% and 66% reduction in recruitment of mussels (*Mytilus spp.*) and barnacles (*Balanus glandula*) during the delayed upwelling period, respectively. However, later in the season, upwelling favorable winds were initiated and resulted in increased upwelling and primary productivity that was greater than normal. Barth and colleagues suggest that mussels

and barnacles were able to respond to this short term increase in phytoplankton by increasing recruitment during the later period (June –August) with an increased recruitment of 53% and 2.5%, respectively. Summed across the whole period, mussels exhibited normal recruitment levels and barnacles exhibited a 38% reduction. This suggests that biotic responses to the timing of upwelling will affect species differentially.

**Larval Development:** Climate change may result in greater seawater temperatures which will likely affect larval development rate. In turn, the metabolic rate of larvae is closely linked to the time spent by larvae in the plankton (O'Connor et al. 2007), defined as their pelagic larval duration (PLD). Increased temperatures could decrease PLD, resulting in a shorter larval transport distances.

Ocean acidification has been demonstrated to affect the development of larval organisms that produce calcium carbonate structures. Kurihara et al. (2004) report reduced fertilization and development of sea urchins (*Hemicentrotus pulcherrimus* and *Echinometra mathaei*) with increasing CO<sub>2</sub> levels. Also, Pacific oyster (*Crassostrea gigas*) larvae exposed to enriched CO<sub>2</sub> levels displayed reduced shell growth or a complete lack of shell development (Kurihara et al. 2007). This could have potentially drastic effects on the recruitment of marine organisms because larvae are subject to already high mortality rates.

#### 4.5 Plankton

Plankton are highly responsive to ocean climate variability and warming (Keister et al. 2005, Mackas et al. 2007, reviewed by Richardson 2008). Unfortunately, due to the limited length of available time series data sets, there is little compelling information pertaining to climate change and plankton communities in the study region. However, there is a substantial information base on plankton from the southern and northern sectors of the California Current with which to make inferences about the study region. To a large extent, zooplankton data throughout the California Current are inter-correlated with each other (Abraham and Sydeman 2004, Mackas et al. 2004; 2006, Sydeman et al. 2006), and with local and large-scale physical oceanographic attributes of “ocean climate” (Mackas et al. 2001, 2004, Hooff and Peterson 2006). This section is based on what has been learned elsewhere in the California Current, and then relying on patterns of co-variation throughout this ecosystem, it is applied to the study region. The importance of understanding plankton responses to climate change cannot be overstated; plankton are the basis for key food web dynamics and predator-prey relationships which drive fish and many other upper trophic level populations in the California Current (Abraham and Sydeman 2004, Ware and Thompson 2005, Sydeman et al. 2006, Mackas et al. 2007).

**Plankton Data Sets:** According to Miller (2004) there are only two time-series data sets in the world of sufficient duration and quality to investigate changes in plankton quantitatively in relation to climate change and ocean warming. One of these data sets, the California Cooperative Oceanic Fisheries Investigation (CalCOFI) occurs in the California Current (the other is the Northeast Atlantic Continuous Plankton Recorder; Roemmich and McGowan 1995, McGowan et al. 1996, 1998, 2003, Rebstock 2001, 2002; Fig. 4.2). It is not easy to use the CalCOFI data set to parse out the relative effects of “climate change” versus “climate variability”. In the North Pacific, regime shifts, interdecadal environmental variability, and quasi-interdecadal variation characterized by the Pacific Decadal Oscillation and related phenomena (Mantua et al. 1997, Hare and Mantua 2000, Bond et al. 2003) clearly influence

plankton abundance and community dynamics (Hooff and Peterson 2006, Peterson and Keister 2003). Based on roughly 100 years of data on SST, the PDO has a periodicity of ~50-60 years (a half cycle of ~25-30 years), which indicates that all of the data collected to date on CalCOFI or Line P may simply be related to variation of the PDO or regime shifts (e.g., Rebstock 2002, Peterson and Schwing 2003).

#### Changes in Plankton Abundance and Community

**Structure:** Studies with data collected for more than 25-30 years in the Northeast Pacific are limited to the CalCOFI and Line P surveys, and analysis of planktonic sediment cores off southern California. For recent field programs, a key result from the CalCOFI data set is a striking decline in zooplankton biomass, measured as a spatially averaged displacement volume of ~80% since the early 1950s, with associated increases in ocean temperature in the southern California Bight region (Roemmich and McGowan 1995, McGowan et al. 1996, 1998, 2003). However, this analysis included both macro- and meso-zooplankton, and it was unclear whether changes were due to changes in one or the other of these functional size groups. Considering just the mesozooplankton community (e.g., plankton < 2 cm) measured by the CalCOFI program, and copepods more specifically, Rebstock (2001, 2002) demonstrated that while there had been a decline in overall copepod biomass in the mid 1970s; community composition and diversity of copepods had not changed appreciably through time. Brinton and Townsend (2003) examined changes in krill and found no secular changes in the abundance of the two dominant species, *Euphausia pacifica* and *Thysanoessa spinifera*. However, they found that a sub-tropical species, *Nyctiphanes simplex*, with substantially less biomass than either *E. pacifica* or *T. spinifera*, had become more widespread and abundant in the system in the 1980s and 1990s after the 1977 regime shift. These changes in the crustacean community (copepods and euphausiids), though, were not of sufficient magnitude to explain the overall decline in bio-volume originally reported by Roemmich and McGowan (1995). It appears that substantial changes in “macrozooplankton”, characterized by pelagic tunicates are largely responsible for the decline in zooplankton biomass from the 1950s to early 1990s (Lavaniegos and Ohman 2003). Studies of seabirds off southern California, part of the CalCOFI program, also demonstrate declines in the abundance of certain zooplankton feeding species, notably shearwaters, which may be related to the change in zooplankton biomass and community structure described above (Veit et al. 1996, Hyrenbach and Veit 2003, Sydeman et al. 2009).

As the community in central California has become more diverse and “sub-tropical” through time (containing both boreal and sub-tropical species), biomass has not changed, but there are greater numbers of smaller species in the community. Smaller species result in longer and more complicated food webs and less efficient energy transfer to the upper trophic levels. Whether this has occurred within the study region is a matter of speculation as there are limited data with



**Figure 4.2:** CENCOOS (2009).  
<http://www.cencoos.org/index.html>

**Comment:** A time cycle of 20-40 is stated on page 23.

which to test this hypothesis, and conclusions from study areas more or less equidistant from the region, one to the south and one to the north (CalCOFI and Newport, Oregon) are apparently contradictory. While there is little direct evidence for long-term change in copepod or euphausiid communities occurring in the study region, this pattern is reasonably robust for other regions of the California Current, and it can be concluded that there is a strong shift towards a more “southerly” planktonic fauna in the California Current including the study region.

**Mechanisms of Response:** From an oceanographic perspective, ecosystem (and *specifically*, zooplankton) dynamics in the California Current are forced by localized upwelling affecting nutrient input and advection; the WEST program, provides extensive details and models of how upwelling could affect zooplankton in the study region (Largier et al. 2006). Advection of plankton from the north and the south is another important mechanism that has received far less attention than local upwelling, but may be significant; the importance of advection was recognized long ago by Chelton et al. (1982) and has been a favorite hypothesis of some researchers (McGowan et al. 2003).

Little is known on a species by species basis about the physiological or behavioral mechanisms, which may account for the observed changes in abundance, community structure or phenology. While the zooplankton community of the northern California Current appears to be shifting towards one dominated by more southerly “sub-tropical” species, it is unclear how these species will fare in warmer and/or more acidic environments.

Richardson (2008) noted that changes in plankton phenology are one of the most robust findings with respect to climate change, and that changes in plankton phenology have important ecosystem consequences. In the California Current, Mackas et al. (1998, 2007) has shown that the annual timing of peak biomass for the sub-arctic oceanic copepod (*Neocalanus plumchrus*) has shifted earlier as ocean temperatures have increased. In the update of the data set originally published by Mackas et al. (1998), Mackas et al. (2007) showed that the peak biomass of *N. plumchrus* at Ocean Station Papa (OSP) and adjacent waters occurred in early to mid July in the early 1970s whereas it now occurs in mid to late May, an advancement of nearly 6 weeks over 30 years. There are no gaps in this time series, and the trend for earlier peak biomass appears to be a linear one. Along the continental margin of southern Vancouver Island, a similar trend of advancing date of peak biomass has been noted with a series extending from 1979 to 2002; again the trend was linear. Notably, the OSP sampling showed the date of peak biomass getting later from the mid 1950s to early 1970s, suggesting that interdecadal climate variability may be driving some of these changes as well. Recently, Batten and Mackas (*in press*) have shown that in addition to an earlier peak biomass for *N. plumchrus*, the period of peak biomass has narrowed. Changes in the peak biomass date and narrowing of the period of peak biomass would make this species less available to predators, such as fish, seabirds, and marine mammals (*see 5.0 Ecosystem and Community Response*). Bertram et al. (2001) considered the effect of ocean warming and changes in the peak abundance of *N. plumchrus* on the reproductive performance of a planktivorous seabird (auklets) at Triangle Island, B.C., and concluded that this change in dates of availability had caused a mismatch in the availability of the prey to the birds during their chick-rearing period, and resulted in diminished reproductive success. However, auklets on Triangle Island feed primarily on *N. christatus*, not *N. plumchrus*, and it is unlikely that the patterns of phenological change are the same for both copepod species. Sydeman et al. (2006) reached a similar conclusion of predator-prey mismatching in regards to the auklet reproductive

failures at both Triangle Island and Southeast Farallon Island, California in 2005. In California, the mismatch reflected by poor availability of euphausiids instead of *Neocalanus* copepods.

**Comment:** Discuss in Chapter 5?

It has not been determined if patterns observed for plankton relate to a secular trend or variable warming cycles because the underlying mechanisms are poorly known. However, a number of important findings have been established, and a synopsis of the probable impacts of climate change on plankton in the California Current and the study region is as follows: *poleward shifts in distribution and earlier timing of important life cycle events have lead to changes in species abundance and plankton community structure, with associated generally deleterious changes in dependent upper trophic level predators*. This statement would be a fairly accurate one to describe climate and plankton changes worldwide (e.g., Northeast Atlantic based on the CPR study; Beaugrand et al. 2002, Richardson 2008), but it is important to note that this is not the case everywhere. For example, in the Northwest Atlantic just the reverse has been reported, with equatorward shifts in plankton distributions, increasing plankton biomass, and positive effects on dependent predators (see Supplementary Material associated with Beaugrand et al. 2002). Therefore we must be extremely cautious with inferring changes in plankton communities from one region to another, even within the California Current Ecosystem.

#### 4.6 Macroalgae and Plants

This section discusses the potential effects of climate change on marine macroalgae and plants (seagrasses, tidal marsh, and sand dune plants). While these organisms are extremely diverse and are not typically discussed in this taxonomic grouping, they are considered here because they share a common role as primary producers that also form a significant structural component of coastal marine ecosystems.

**Macroalgae:** Climate change will have complex effects on the abundance and distribution of benthic and canopy forming macroalgae within the study region, although most changes will likely result in range shifts rather than the loss of key groups (e.g. kelps) from the system (Schiel et al. 2004). Macroalgae will be impacted by increasing sea surface temperatures as well as sea level rise, which will affect the availability of light and amount of substrate suitable for attachment (Graham et al. 2003, 2008). Upwelling dynamics will also affect the availability of nutrients for photosynthesis (see 3.4.4 Coastal Upwelling). Increased activity of extreme wave heights may also be a significant form of disturbance that removes macroalgae from exposed subtidal and intertidal locations (Graham et al. 1997). These disturbances may also influence the timing and distribution of drift kelp, which can serve as both a habitat and resource in pelagic and benthic systems (Harrold et al. 1998). Of particular concern for calcareous algae (corallines) is ocean acidification (Doney et al. 2009). Increased acidity will likely affect the ability of these species to construct their calcium carbonate skeletons (Kuffner et al. 2008, Martin and Gattuso 2009), which



**Figure 4.3.** Giant kelp (*Macrocystis pyrifera*). Josh Pederson / SIMoN NOAA.

**Comment:** There have also been studies on how OA will affect other macroalgae. See Terrie Klinger's (UW) work on kelp.

could have significant consequences in habitats such as the rocky intertidal where they are dominant.

Complex community interactions may generate future species distributions that do not follow traditionally hypothesized patterns of poleward range shifts. Schiel et al. (2004) document the effect of a 3.5° C increase in seawater temperature at Diablo Cove (San Luis Obispo county) caused by the thermal outfall of a nuclear power plant. No biogeographic patterns in species ranges emerged (i.e. there was no clear pattern of Southern species increasing and Northern species decreasing). Prior to the increase in temperature, sub-tidal habitat in this study was dominated by a canopy of the bull kelp *Nereocystis luetkeana* and an understory mostly comprised of *Pterygophora californica* and *Laminaria setchelli*. After initiation of the thermal outfall, bull kelp was replaced by the giant kelp *Macrocystis pyrifera* and subcanopy kelps decreased while the foliose red algae *Cryptopleura violacea* increased in abundance. Within the Gulf of the Farallones, this highlights the potential for bull kelp to be negatively affected by increased water temperatures and for giant kelp to increase in abundance. Overall, predicting responses to climate change is challenging and may yield unforeseen outcomes based on the response of a few key species (Schiel et al. 2004).

Other macroalgae species may shift their distribution to the north. Of particular concern is the invasive kelp *Undaria pinnatifida*, which has primarily been documented in wave protected habitats in California including the northernmost site, Monterey Bay (Silva et al. 2002) and in 2009, San Francisco Bay. Locations in Northern California may be susceptible to invasion by this species where cooler seawater temperatures may favor its survival (Thornber et al. 2004).

Seagrass: Seagrasses evolved during a time of significantly higher CO<sub>2</sub> concentrations and today it is likely they are limited by carbon availability (Beardall et al. 1998). In experimental trials, the eelgrass *Zostera marina* responded to increased dissolved CO<sub>2</sub> concentrations with increased productivity (Palacios and Zimmerman 2007). Also, eelgrass and surfgrass (*Phyllospadix torreyi*) exhibit increased photosynthetic rates at low pH due to their ability to utilize bicarbonate as a carbon source. In addition, seagrasses may benefit from increased light levels due to reduced growth of coralline algae that commonly attach to seagrasses (caused by ocean acidification; Martin et al. 2008). However, seagrasses are highly susceptible to existing human-induced stressors such as sedimentation (resulting in reduced light levels) and habitat fragmentation from the construction of marinas and other industrial activities (Orth et al. 2006). Altered runoff schedules (i.e. concentrated runoff during winter months) could also reduce eelgrass populations within areas such as Tomales Bay by modifying patterns of sedimentation. As with other species living in the shallow sub-tidal or intertidal, sea level rise could also negatively affect seagrass if no additional upland habitat is available (see further discussion in tidal marshes below). The surfgrass *Phyllospadix torreyi*, commonly found in exposed rocky intertidal sites, may be subject to additional climate driven disturbance. Williams (1995) suggests that heavy wave action can reduce survival of male individuals. This suggests that this species may be at risk of dislodgement by extreme wave events.

Tidal Marshes: Salinity and inundation work together to drive the abundance and distribution of salt marsh communities. Sea level rise will increase salinity within tidal marshes and either result in marsh “drowning” or an inland shift in the distribution of tidal marshes if they are unable to accrete sediments quickly enough (Fitzgerald et al. 2008). The extent to which these

communities can migrate will depend on the amount of available upland habitat. Armored sites may see an estuarine squeeze effect where available habitat is compacted into a narrow range, whereas marshes that have a corridor may be able to migrate.

Even if marshes have an available corridor, community composition shifts may occur. For example, Donnelly and Bertness (2001) tracked the landward migration of *Spartina alterniflora* in New England salt marshes. *Spartina* rapidly moved inland in response to rising sea level and replaced higher marsh communities comprised of marsh hay (*Spartina patens*), spike grass (*Distichlis spicata*), and black rush (*Juncus gerardi*). In this case, *Spartina* was able to dominate the marsh community because its accretion rates were greater than sea level rise and it is adapted to oxygen poor soils. The effect of sea level rise will also depend on the vertical profile of tidal marshes. Initially, platform-like marshes will likely lose little area as a result of sea level rise until a critical point when the marsh will rapidly become inundated. Ramped marshes will exhibit a slow but gradual loss in response to sea level rise (Fitzgerald et al 2008).

Small changes in salinity due to an altered runoff schedule or changing total precipitation can also alter marsh community structure (Callaway et al. 2007). Increased freshwater influx during winter and spring seasons could increase recruitment of salt and brackish vegetation (Callaway et al. 2007). However, greater salinity in the summer and fall due to decreased snowpack will have negative effects on vegetation (Callaway and Sabraw 1994, Noe and Zedler 2001a; 2001b).

Increasing concentrations of atmospheric CO<sub>2</sub> can have positive effects on plant physiology by increasing efficiency of water, nitrogen, and light resource use (Drake et al. 1997). However, it appears that this is determined by individual plant physiology (e.g. C<sub>3</sub> vs. C<sub>4</sub> photosynthesis).

Sand Dunes: As with salt marsh and intertidal ecosystems, the supralittoral coastal sand dune vegetation communities will be affected by several climate change related processes. Sea level rise may force the landward retreat of these communities as inundation floods existing habitat (Feagin et al. 2005). Where coastal dunes are backed by development that blocks retreat, upland habitat for the colonization and persistence of dune vegetation may become increasingly limited, fragmenting this ecosystem further (Feagin et al. 2005). Changes in sediment transport dynamics may also contribute to a reduction of beach width, increased exposure of the dune to wave attack and the subsequent loss of dunes (see section 3.4 Coastal Erosion). Sea level rise and reduced habitat can also disrupt the successional dynamics and coastal evolution that lead to the formation of mature coastal dune vegetation communities and biodiversity (Feagin et al. 2005). Changing climatic variables such as precipitation and salt spray may also affect the composition of these communities by modifying soil salinity, with subsequent effects on plant physiology (Williams et al. 1999, Greaver and Sternberg 2007).

#### 4.7 Invertebrates

Temperature: Physiological adaptations in response to changing temperatures will play an important role in setting intertidal species distributions and biogeographical range limits in California and the study region (Somero 2000). A fundamental challenge for ecologists will be to understand how natural systems respond to environmental conditions that have no analogy to either the present or recent past (Harley et al. 2006). Researchers have addressed several questions in attempting to predict the effects of climate change including: what are the weak physiological links that make organisms vulnerable to temperature change; how close to the edge

of their thermal limits are species now living; and what will be the effects of climate change on marine communities?

Studies have addressed these questions in the California intertidal where temperature gradients are steep. Studies on central California mussels found that three congeners responded to elevated water temperatures with increased heart rates that eventually resulted in heart collapse (Somero 2005, Braby and Somero 2006). Stillman and Somero (1996) had earlier found that two species of porcelain crab, *Petrolisthes cinctipes* and *P. eriomerus*, had heart function collapse at 31°C and 26°C respectively.

Many intertidal invertebrates are already living at the edge of their thermal tolerances. For example, the thermal limits of the common black turban snail, *Tegula funebris* have been shown to be within 1 to 3 degrees of temperatures that are already experienced at low tide (Tomanek and Somero 2000; Tomanek and Helmuth 2002). Because the heat shock response is energetically fixed, animals making large quantities of heat shock proteins to protect cellular function must reduce expenditures elsewhere. Potential tradeoffs could be made by decreasing growth, activity, or reproductive potential (Dahlhoff et al. 2002).

Pincebourde et al. (2008) demonstrated in laboratory trials that temperature variations can alter community structure through altered species interactions. The authors studied the ochre sea star, *Pisaster ochraceus*, a keystone species in the study region rocky intertidal. When the ochre star was exposed to chronic temperatures of 23°C, feeding and growth were negatively affected.

Tomanek (2008) found that the ability to acclimatize to changing temperatures seems to be greatest among animals living in moderately variable environments, such as shallow subtidal areas. Conversely, it is limited in invertebrates from stable or highly variable environments such as the highest intertidal zones. He further wrote that research has suggested that organisms with the narrowest (stenothermal) and the widest (eurythermal) temperature tolerance ranges live closest to their thermal limits and have only a limited ability to acclimate. These will be the organisms most affected by climate change and they would have to adapt, move away or risk death.

**Ocean Acidification:** Ocean acidification will affect the ability of many calcifying invertebrates to produce calcium carbonate shells. In addition, it may affect other physiological processes that are pH dependent. For a review of how ocean acidification will affect marine organisms and a site-specific report on how ocean acidification will influence the Channel Islands National Marine Sanctuary refer to Doney et al. (2009) and Conservation Working Group (2008), respectively. In short, economically and ecologically important species such as sea urchins, mussels, oysters, abalone, crabs, and other invertebrate taxa will likely be negatively impacted by increased dissolution of carbon dioxide in ocean waters. Of particular concern are the larval stages of these organisms, which may be more susceptible to ocean acidification. Also, organisms such as hydrocorals found on Cordell Bank will most likely have increased difficulty producing calcium carbonate structures (see 4.1 Physiology).

**Comment:** KH: does this sound right?

**Upwelling and Productivity:** Within the study region, nutrient-rich upwelled water stimulates the growth of primary producers (e.g. phytoplankton, benthic algae). Many invertebrates act as primary consumers that feed on primary producers, ultimately fueling the production of higher

trophic levels (secondary consumers). Therefore, upwelling can have profound effects on the food available to these consumers at higher trophic levels. Menge et al. (2008) documented increased growth responses of California mussels (*Mytilus californianus*) to warmer temperatures (below extreme high temperatures) and greater phytoplankton concentrations, which were ultimately driven by upwelling dynamics.

#### 4.8 Fish

The study area supports many marine and anadromous fishes that can be affected by climate change through a variety of mechanisms. Changing temperatures will directly influence fish physiology as most fishes are poikilothermic (“cold-blooded”). Fish may respond to these changes by shifting their distributional range to accommodate preferred temperature regimes (along latitudinal or depth gradients; see 4.2 Range Shifts). Climate change may also negatively affect fish prey (i.e., through ocean acidification or changes in phytoplankton primary productivity), resulting in “bottom-up” forces that may decrease fish growth and reproductive success. Some fish habitats may also be of special concern with regards to climate change. Anadromous fish such as salmon will be sensitive to changes in river/stream habitat, as will estuarine fish that utilize eelgrass and associated areas for shelter. Additionally, climate change is predicted to exacerbate impacts on fish populations that are commercially and recreationally fished (see 6.1 Fishing). However, the literature with respect to climate change and fishes is not as well established when compared to other taxonomic groups, making regionally specific projections difficult.

Temperature: Changing temperatures can modify several aspects of fish physiology (e.g. metabolism, growth, respiration; Fields et al. 1993, Roessig et al. 2004). Temperature can affect the performance of proteins involved in energy metabolism and the concentration of heat shock proteins (Fields et al. 1993). Additionally, warming can influence fish physiology by inducing an increased oxygen demand as well as reducing oxygen solubility in seawater (Portner and Knust 2007). The physiological consequences of warming are documented in several datasets; however few of these studies occur in the waters off central California. Therefore, data from other localities is discussed here.

Warming ocean temperatures have been implicated in the shifts of fish distributions along a latitudinal gradient in southern California (Holbrook et al. 1997) and in the North Sea (Perry et al. 2005). Here, “southern” species were observed to be more common than “northern” species. In a warming environment, fish may also seek refuge in cooler deeper waters. Evidence for this lies in the observation that species found towards the warmer reaches of their distribution are frequently found at increased depths (Fields et al. 1993). In general, it has been suggested that species tolerant of a wide temperature range (i.e. eurythermal) will have an advantage over species tolerant of a narrow temperature range (i.e. stenothermal; Fields et al. 1993). There has been no attempt at indexing the broad thermal tolerances of fish or other species and as such this remains a possible area for future research.

Bottom-up Forces: To some extent, all organisms rely on productivity at lower trophic levels to support biomass at higher trophic levels, and fish within this region are no exception. Shell forming fish prey such as krill, copepods, and pteropods may be adversely affected by ocean acidification and changes in phytoplankton primary productivity. The degree to which these

species are affected will also have consequences for organisms at higher trophic levels such as fish.

**Habitat:** Steelhead trout, chinook, and coho salmon (*Oncorhynchus mykiss*, *O. tshawytscha* and *O. kisutch* respectively) are the primary anadromous fish that are found within the study region. These fish are highlighted because they are subject to additional stressors unique to their life history. Climate change can influence their populations by affecting the freshwater tributaries and rivers that these Salmonids utilize for spawning. These fish have been affected in part by habitat loss and reduced stream flows due to modification by humans for a variety of purposes (Myrick and Cech 2004). Climate change may interact with these factors to increase stream temperatures, which can decrease salmon growth rates and increase their vulnerability to predators (Marine and Cech 2004).

Estuaries can act as critical habitat for fishes that utilize these areas for all or a part of their life history. In particular, commercially and recreationally fished species such as juvenile California halibut (*Paralichthys californicus*), bat rays (*Myliobatis californicus*), and leopard sharks (*Triakis semifasciata*) all utilize estuaries as nursery or feeding grounds. Climate change may affect these species by modifying estuarine habitat. Ocean acidification may adversely affect estuaries because they are subject to freshwater input that lowers buffering capacity as well as intrusion of upwelled waters from the adjacent coastal ocean. Additionally, sea level rise may affect the hydrodynamics of estuarine circulation by influencing sediment transport at estuarine mouths.

**Comment:** Does this belong here or in Chapter 3 where I posed this question?

**Ocean Acidification:** The direct effects of ocean acidification on fishes within the study region are not well understood. Most studies of ocean acidification have focused on calcium carbonate forming species (e.g. corals, molluscs, echinoderms, zooplankton). This is likely due to the fact that fish calcium carbonate structures are largely buffered from the ambient environment with soft tissue. More studies are needed to understand the consequences of acidic waters on fish physiology.

**Comment:** Studies on fish from other regions could also inform the sanctuary's planning processes, esp with regards to identifying potential fish-related monitoring needs. May be helpful to briefly describe those studies here. See Checkley et al 09 in Science, Munday et al 09 in PNAS, and Ishimatsu et al 05 in J of Geophys Research.

**Other Processes:** Increased and prolonged upwelling could negatively impact rockfish recruitment and subsequent adult populations. Extended or intense offshore flow of ocean surface waters driven by coastal upwelling could transport these pelagic larvae so far offshore they would be lost to the system (see 4.4 Population Connectivity). The range expansion of Humboldt squid could impact local fish populations through predation. Pacific whiting and other species of mid-water fishes are favored prey of this top predator. As populations of squid shift north, some fish populations could be negatively impacted.

#### 4.9 Seabirds

Expected changes in the marine environment will likely have substantial impacts on seabird reproduction, survival, and distribution. Seabird populations are dependent on an adequate food supply throughout the year. Available information suggests that this food supply may be threatened in the face of long-term changes in ocean conditions. Zooplankton species are important prey for seabirds and for the forage fish that also make up a large portion of the seabird diet. Zooplankton declines have been associated with rising sea surface temperatures (Roemmich and McGowan 1995, Hill 1995). Those declines, in turn, appear to lead to declines in zooplankton predators like rockfish and planktivorous seabirds (Hill 1995). The declines in

top predator populations are likely linked to poor reproductive success and poor survival. One study linked low seabird breeding propensity to high sea surface temperature (Lee et al. 2007). Several others have shown correlations between low seabird reproductive success and warm, non-productive conditions (Ainley et al. 1995, Abraham and Sydeman 2004, Sydeman et al. 2006, Jahncke et al. 2008, Roth et al. *in preparation*). The effect is especially dramatic during El Niño events that are likely to become more frequent in the future. El Niño events have also been linked to low adult survival (Lee et al. 2007). Low productivity that occurs frequently or over many years and low adult survival will ultimately lead to declines in breeding populations (Lee et al. 2007).

Strong upwelling is generally associated with high seabird reproductive success because of its positive effect on ocean productivity (Ainley et al. 1995, Abraham and Sydeman 2004, Sydeman et al. 2006, Jahncke et al. 2008, Roth et al. *in preparation*). However, the effect of a long-term increase in upwelling intensity is difficult to predict. Increased upwelling may mitigate the negative consequences of rising sea surface temperature to some extent by cooling surface temperature and increasing productivity in the system. Conversely, upwelling that occurs too early in the year or is too intense may disrupt the food supply that seabirds rely on. Pringle (2007) found evidence that zooplankton move into deeper waters during intense upwelling to avoid being advected offshore. Increased time at depth could make zooplankton less available to seabirds, because they are restricted to varying degrees in how deeply they can dive for food. Increased turbulence could also lead to decreased production of forage fishes by disrupting the food supply of larval fish (Cury and Roy 1989). Disruptions in the food web ultimately could lead to decreased ocean productivity and decreased seabird reproductive success and survival.

Seabird distributions could also change with a changing climate. Long-term studies of seabird distribution and abundance have revealed the importance of mesoscale oceanographic features (fronts and eddies) to these top predators (Ainley et al. 2005, Yen et al. 2006). These features are often sites of enhanced primary and secondary productivity. For example, researchers found high rates of Pacific sardine (*Sardinops sagax*) production in eddies off of southern California and hypothesized that those rates are due to entrainment of both productive coastal waters and larval fish (Logerwell et al. 2001). These features may also attract and/or concentrate the larger prey that many marine birds and mammals feed on. Changes in ocean circulation patterns could lead to changes in the locations of these mesoscale features and to subsequent changes in seabird distributions. The persistence of seabird populations in this case is dependent on their ability to potentially forage further from the colony during the breeding season or to find alternative nesting areas closer to abundant food supplies.

#### 4.10 Marine Mammals

Within the California Current there are over 40 species of marine mammals (with 36 of these species documented within the study region; GFNMS Management Plan 2008), whether resident or long-range migrants to polar regions, that will likely be affected by changes in climate (Ragen et al. 2008, Learmonth et al. 2006, Simmonds and Isaac 2007). Many predictions are based on what has been gleaned from the evolutionary record from previous periods of climate perturbations, but also from recent observed changes in species' condition that may be manifestations of global warming. The predicted climate conditions that likely will affect marine mammals include increased sea temperature, ocean acidification, sea level rise and alternations of oceanic processes. Each of these hazards has potential direct effects and may cause cascading

indirect effects that will not be readily apparent. The potential consequences of climate change may be: alterations in movements and migrations, changes in abundance and population structure, timing of breeding, reproductive success, changes in behavior, changes in community structure, stress on body health and susceptibility to disease, and extinction (see also Laidre et al. 2008, Learmonth et al. 2006).

Central California has long been recognized as a zone of overlap for many species associated with either cooler temperate or warmer tropical waters. The ranges of many species are directly limited by sea temperature. With increased sea temperature, some species may range farther north whereas others' ranges may contract as has been predicted for the Arctic assemblage of marine mammals (Ragen et al. 2008). The contraction of the Steller sea lion (*Eumetopias jubatus*) range and the commensurate expansion of the California sea lion range over the past two decades may be related in part to warming sea temperatures. Populations have declined in central California waters, including those at Año Nuevo and Farallon Islands, over the past two decades (Sydeman and Allen 1999), while populations in Oregon have seen a gradual increase (Angliss and Outlaw 2008). In contrast, California sea lion (*Zalophus californianus*) numbers are increasing in central and northern California, and they are now breeding at Año Nuevo and Farallon Islands. Bottlenose dolphins (*Tursiops truncatus*) have expanded their range north to San Francisco Bay from Monterey Bay in the past decade, although the link to climate change for this expansion is tenuous.

The migrations of many species, especially baleen whales, closely follow an annual cycle dependent on their need to give birth in warm tropical waters and to feed in temperate and arctic waters. Warming sea temperature likely will result in a shift north of breeding areas. Gray whales (*Eschrichtius robustus*), for example, appear to be giving birth as far north as Monterey Bay expanding north from lagoons of Baja, Mexico.

Changes in prey availability will influence marine mammal distribution, migration and abundance both directly and indirectly. The increased sightings of sperm whales in the region are possibly related to the extension of the range of Humboldt squid in recent years (*unpublished* NMFS Stranding Records 2004-2008). Similarly, recent sightings in the Gulf of the Farallones of pods of killer whales from British Columbia and from an offshore pod may indicate an alteration in their distribution in search of more abundant prey (*unpublished* sighting data from GFNMS and NPS). If animals are unable to find sufficient food to sustain good health, juveniles may experience slower growth rates, reproduction may decline, and mortality may increase (Ragen et al. 2008). Each of these responses is difficult to measure, especially in long-lived mammals such as marine mammals. Nevertheless, a long-term study of elephant seals (*Mirounga angustirostris*) at Año Nuevo demonstrated a link between annual weaning weights and adult female condition with fluctuations in ocean temperature (Le Boeuf and Crocker 2005). While several terrestrial species have responded to climate change with shifts in breeding phenologies, there is no clear evidence to date that marine mammals are similarly responding. Nevertheless, some baleen whales have been documented residing longer in ice free arctic waters in summer while feeding.

El Niño effects on marine mammals provide a window into the likely results of warmer sea temperatures. During the 1982/83 and 1997/98 El Niños, pinniped productivity and survival declined and California sea lion numbers increased in northern California (Trillmich and Ono

1991, Sydeman and Allen 1999). A sustained sea temperature increase of 3° C is predicted to greatly reduce kelp forests, which were temporarily damaged by the very warm 1998 El Niño. Damaged kelp reduces habitat for marine mammals such as sea otters and reduces their prey that are associated with kelp forests. Increases in harmful algal blooms (HAB) are another indirect effect of sea temperature warming, because they often result in blooms of algae that can cause mortality in marine mammals (Van Dolah 2005). Conversely, kelp forests and associated fish species may shift northward, and a shift in fish communities associated with kelp forests have already been noted in Monterey over the past 25 years (Holbrook et al. 1997). Over the past couple of decades, HABs that produce domoic acid have increased (see 6.4 Harmful Algal Blooms), resulting in spikes of sick and dead California sea lions in central California and of other species in southern California (Gulland et al. 2002). As sea temperature rises, the emergence and spread of other diseases associated with warmer sea temperatures may increase, affecting productivity and marine mammal health (Gulland and Hall 2005).

Sea level rise will reduce pinniped haul out areas by submerging low-lying coastal areas that are unable to retreat inland. Pinnipeds give birth to their pups on land and some species also mate on land. The young of most pinnipeds except for harbor seals cannot swim at birth. Consequently, with elevated sea level, the places where pinnipeds can give birth will be altered and/or reduced. This is especially dramatic in harbor seals, because they cannot climb up onto rocky substrates easily. Low slope beaches and intertidal sand bars where harbor seals breed are especially at risk to erosion. Mortality of elephant seal pups has already been documented to be higher during storm events such as El Niño years (Sydeman and Allen 1999, Pettee 1999). Sandy beaches are also important during the elephant seals molting season and for harbor seals year round. Since there is limited area for beaches to retreat, alternative locations for pinnipeds to breed or rest are limited as well.

The life cycles of many marine species are tightly aligned to the changing seasons and delayed transitions can cause mismatches in normally stable food webs (see 3.3.3 Coastal Upwelling). Several marine mammal species, for example, give birth in the spring and summer, and wean young at a time when prey are abundant. Weaned harbor seals, for example, feed extensively on mysid shrimp which swarm in the summer. Several whale species such as gray, humpback (*Megaptera novaeangliae*) and blue (*Balaenoptera musculus*) give birth during winter and spring in sub-tropic waters, and then travel with young in summer to feed in the study region. If upwelling is delayed and food is available later in the season, a mismatch in timing likely will cascade through the food web from fish spawning to whales foraging, and will cause shorter food webs with less energy transfer (Palacios et al. 2004). Those species that cannot follow the distributional changes or cannot find prey in sufficient densities will either switch to other prey or will starve.

Many shell dependent species such as pteropods are fundamental to food webs, and some species of whale (i.e. the Sei whale (*Balaenoptera borealis*)) eat pteropods along with copepods and fish. Squid, a highly significant prey species for many marine mammals, especially beaked whales and female elephant seals, are very sensitive to changes in salinity and CO<sub>2</sub> concentrations.

## 5. Ecosystem and Community Response

Climate change can clearly affect the abundance and distribution of species through a variety of pathways. These effects can manifest themselves via interactions between the environment and the physiology and phenology of individuals and populations. However, natural systems are further complicated due to the interactions among individuals of different species. Therefore, the response of a single species to climate change depends not only on environmental changes within the system, but also upon how other species will respond to each other. This chapter focuses on the physical changes that may occur in a given habitat within the study region (Fig. 5.1), and how communities of organisms and their interactions may respond to these changes.

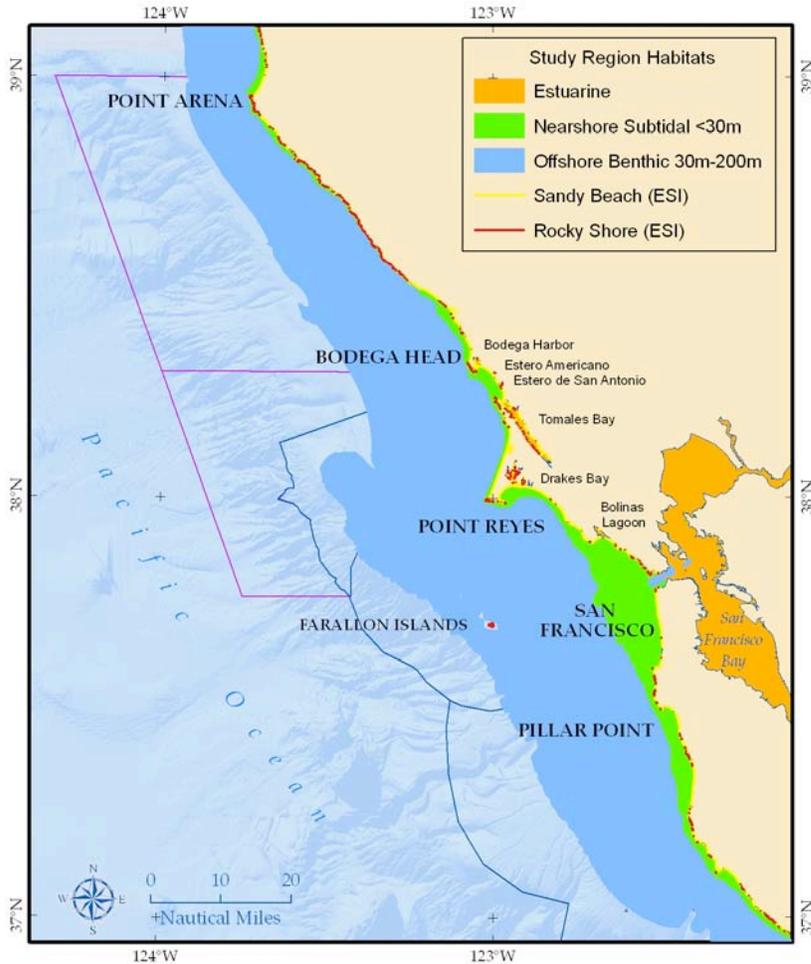


Figure 5.1. Map of habitat types within the study region. T. Reed (2009).

**Comment:** I don't think this chapter adequately addresses community response of climate change. There are a lot of repeated information from Chapters 3 and 4 that could be condensed or deleted. There needs to be more description of multi-species/community level interactions and what the overall effect of climate change will have on the ecosystem. There is not a lot of research at this community/ecosystem level, but researchers have made some guesses as to what those changes would be, especially when they see a clear signal in one or two species (i.e., larger ecological changes can be inferred). You could add a brief description of that caveat in this intro paragraph.

I suggest a rewrite of this section. Organizing by habitat is still okay; however, you may want to remove the physical changes subsections (too similar to Chapter 4) and organize each habitat section as follows (just my suggestion – there may be other ways to do this):

1) Explain what the habitat may look like in a future climate-impacted CCE. This would include some of the information presented here (i.e., how the organismal-level effects on one species may impact another species) but would also discuss some more broad issues (e.g., how organismal-level effects in one species may have an impact on the entire community; what would be impact on top predators or keystone species and how may that reverberate lower in the food chain?; what is the likely overall impact on productivity?; etc...).

2) Explain why you expect these changes. This would involve a brief reiteration of some of the information in Chapters 3 and 4, but in a more comprehensive way, bringing all the info together.

Writing the chapter as described above would integrate all the information provided in Chapters 3 and 4 and introduce new information from other community-level studies. Presented in this way, the information would help to guide the next steps in the sanctuary's planning process and also help to identify where research and monitoring is lacking. I include some comments in the Chapter below that highlights and explains some of these issues.

## 5.1 Offshore Pelagic Habitat

The offshore pelagic habitat includes the entire water column from the sea surface to the seabed. The pelagic habitat is a highly heterogeneous and dynamic environment that results from small differences in water properties, which lead to patchiness in the distribution of primary and secondary production. The availability of nutrients and light are the main factors that determine the distribution of life in this habitat. Physical processes control the biological activity by means of a delicate balance between wind driven upwelling and stratification of the water column.

During upwelling, increased nutrient availability may lead to increased phytoplankton production in the region, but for this to occur, stratification is needed. Heat from the sun, in the absence of wind, warms up the upper layer of the ocean and leads to the stratification of the water column. The stratification is important because it builds a barrier that prevents phytoplankton from sinking below the upper layer of the water, which is exposed to the sun light.

There is convincing evidence that the offshore pelagic oceans have changed since the start of the industrial period (Bindoff et al. 2007). North Pacific and global ocean temperatures have risen by 0.3-0.4°C from the surface to a depth of 300 m from 1948 to 1998 (Levitus et al. 2000). Most of this is attributed to the increase in atmospheric greenhouse gases (Levitus et al. 2001). Global ocean salinity in subpolar latitudes has decreased whereas in shallower parts of the tropical and subtropical ocean salinity has increased. The Pacific Ocean in particular has become fresher while the Atlantic and Indian Oceans have become saltier. There is no clear evidence of changes in ocean circulation even though key oceanic water masses are changing. The biogeochemistry of the world ocean has also changed (Section 3.5.2). The total inorganic carbon content of the oceans continues to rise, resulting in more corrosive waters as shown by trends of decreasing pH over the last 20 years. There is also evidence for decreased oxygen concentrations, likely driven by reduced rates of water renewal, further lowering pH levels in the California Current (Feely et al. 2008).

The global increase in ocean temperatures and the freshening of the Pacific Ocean act in the same direction and contribute to reduce mixing between the upper layer of the ocean and nutrient rich water just below the pycnocline (Bindoff et al. 2007). Along the margins of the continents, wind driven upwelling has been increasing since the mid-1940s (Bakun 1990). This trend of increasing wind driven upwelling is predicted to continue into the future leading to continued production along the coast of California, possibly ameliorating the difficulty in bringing nutrients to the surface due to increased stratification caused by higher sea surface temperature (Snyder et al. 2003; see 3.3.3 Coastal Upwelling).

Increased water column stratification may lead to a major shift in phytoplankton communities in the region. An example of this was documented from 2002 to 2004 where diatom abundance declined and dinoflagellate abundance increased in Monterey Bay (Pennington et al. 2007). Diatoms are generally associated with strong upwelling in the spring and summer, while dinoflagellates become more abundant during the “oceanic period” in the fall and early winter. Reduced atmospheric forcing during 2002-2004 and the presence of elevated nutrient levels in Monterey Bay, led to a massive dinoflagellate bloom in areas with warm sea surface temperatures, highly stratified water column and shallow thermoclines.

Elevated numbers of gelatinous zooplankton in the Bering Sea have been linked to warmer and more stratified waters (Brodeur and Terazaki 1999). Increased water temperatures led to higher reproductive rates and extended growing seasons. Future changes in circulation currents due to climate change could change their distribution. These organisms are likely to become the dominant predators in ecosystems where pollution, over-fishing, and climate change are changing the marine ecosystem.

Copepods represent the most abundant and diverse group of crustacean zooplankton and constitute the largest source of protein in the marine environment, providing the critical first step in the transfer of carbon from phytoplankton to zooplankton. Larger boreal copepod species contain more lipids and are presumably better prey. Copepod community structure off Oregon can change dramatically under different ocean climate conditions. The large boreal species are generally replaced by smaller subtropical species during El Niño events and positive Pacific Decadal Oscillation (PDO) periods (Peterson et al. 2002, Peterson and Schwing 2003).

Diet studies of common seabirds breeding on Southeast Farallon Island have shown major changes in the availability of juvenile rockfish. Diet studies on common murre (*Uria aalge*) have shown a decrease in juvenile rockfish (*Sebastes* spp.) during years with warm sea surface temperatures and/or warm (positive) PDO periods (Miller and Sydeman 2004). Similar findings were found for rhinoceros auklet (*Cerorhinca monocerata*) where the appearance of juvenile rockfish in the diet was higher in years with low sea surface temperatures (Thayer and Sydeman 2007). Trawl data from NOAA National Marine Fisheries Service shows similar results, particularly a sharp decline in juvenile rockfish in response to the warm-water conditions observed in the central California Current region in 2005.

Over the period 2004-2008, PRBO Conservation Science researchers have observed variation in climate within the boundaries of Gulf of the Farallones and Cordell Bank National Marine Sanctuaries, which has led to changes in oceanographic conditions and the marine ecosystem (from zooplankton to top marine predators). In years where alongshore winds (i.e., the driving force for upwelling in the region) were strong and began earlier in the spring, strong, early upwelling conditions have prevailed. Nutrients brought from depth to surface waters during upwelling have increased primary production and increased the abundance of important zooplankton species (e.g., euphausiids and copepods). The increased abundance of these zooplankton species during the critical breeding time of the Cassin's auklet (a seabird that feeds on zooplankton) has resulted in average to above average breeding success of this species.

**Comment:** This concept was introduced earlier. Repeated info. See comment on page 62-63.

The opposite of the above scenario occurs in years when alongshore winds are weak and/or delayed, which was characteristic of conditions in 2005 and 2006. Upwelling occurred later in the spring, causing reduced phytoplankton and zooplankton abundances in the region. The zooplankton community changed as well; not only did abundances of krill (adult krill, in particular) and copepods decline, but abundances of gelatinous zooplankton appeared to have increased. Due to the lack of available prey, (e.g., adult krill), Cassin's auklets abandoned nests and failed to breed in these years. The decline in adult krill in 2005 may be related to decreased survival of Chinook salmon entering the ocean that year and low salmon returns in California in 2008. Sightings of blue whales (another krill predator) dropped significantly from 2004 numbers (PRBO unpublished data). Drastic bottom-up effects in the ecosystem were observed and documented in a relatively short time period (July 2004 to August 2005), including low primary

production, low krill abundance, a decline in at-sea seabird abundance, and late and reduced reproductive success in seabirds on the Farallon Islands (Jahncke et al. 2008).

## 5.2 Offshore Benthic Habitat

The offshore benthic habitat between 30 and 200 meters depth encompasses a large area of the continental shelf between Point Arena and Año Nuevo and makes up the majority of the area protected by the Gulf of the Farallones and Cordell Bank sanctuaries. Benthic habitats can be grossly characterized as soft or hard bottom and each has a characteristic biological community. Benthic communities are characterized by organisms that are attached or slow moving and typically occupy small home ranges. This life history exposes these organisms to acute changes in physical conditions but also makes them vulnerable to changes over longer time periods as sedentary animals are unable to move out of an area as conditions change. Because of their inability to move, communities associated with offshore benthic habitats would be particularly susceptible to significant impacts from climate change. The physical drivers that will most directly affect benthic communities offshore are changes in water properties (temperature, dissolved oxygen, ocean acidification) and regional winds (upwelling, transport).

**Temperature:** Water temperatures in this region may increase due to warming or decrease due to increased upwelling (see 3.6.1 Temperature and 3.3.3 Coastal Upwelling), perhaps increasing temperatures offshore while decreasing temperatures in upwelling centers. Benthic organisms that are unable to extend their geographic range as temperatures change will have to adapt or perish. If temperatures increase, then species with a center of distribution in higher latitudes may have a difficult time adapting as these species are at the southern end of their distribution and likely close to their thermal tolerance limits. In contrast, species that have their center of distribution to the south in warm temperate oceans will likely expand their distribution north as ocean temperatures warm. However, there are complex interactions between temperature and other physical parameters that will have synergistic and unpredictable effects on benthic communities (see 4.1 Physiology).

**Dissolved Oxygen:** When dissolved oxygen (DO) concentrations in coastal oceans fall to hypoxic levels, there are severe consequences for offshore benthic communities. The oxygen depleted water mass suffocates everything that cannot move out of the area resulting in a massive mortality event. Areas adjacent to upwelling centers like Point Arena are particularly susceptible to low DO levels as the upwelling process naturally delivers low oxygen water onto the continental shelf from the deep ocean. Currently the source for upwelled water is shallower than the Oxygen Minimum Zone (OMZ) (Grantham et al. 2004). An extensive OMZ exists along the continental margin of the northeast Pacific Ocean (Kamykowski and Zentara 1990). Recent work indicates that in the vicinity of Point Conception, the OMZ has shoaled by up to 90 meters (Bograd et al. 2008). Shoaling of the OMZ could lead to significant and complex ecological changes in the California Current System including direct hypoxia-related effects on benthic organisms where the OMZ contacts the continental margin (Levin, 2003). If the OMZ were to migrate shallow enough to provide the source water for coastal upwelling, hypoxic events may be observed in this region and there would be severe ecological impacts (Bograd et al. 2008).

**Ocean Acidification:** Ocean acidification will add cumulatively to the stress of benthic organisms. Low-pH waters shoal along the west coast during the upwelling season (e.g., Feely et al. 2008). This seawater is under-saturated with aragonite, a key constituent for animals that rely

**Comment:** Yes, but what species within this community are most vulnerable? – i.e., will all species be equally susceptible or will some species do well and change community structure?

**Comment:** Need a consistent organizational structure in this chapter. I like this breakdown of the community response to a particular physical parameter (e.g. Temp). Why is that missing from the previous subsection?

**Comment:** Same here. See comment above.

on calcium carbonate to build bones and shells. Low-pH water becomes corrosive to a wide variety of marine animals including corals, sea urchins, and mollusks (Guinotte and Fabry 2008), and calcification rates are likely to decline (Gazeau et al. 2007). Decline in the biomass of plankton will also affect the deeper benthic communities but the implications to food webs are poorly understood. Shell-building pteropods and foraminiferans are key species at the base of ocean food webs that will be adversely impacted by increasing acidity (Fabry et al. 2008, Spero et al. 1997). Ocean acidification could also impact larval and juvenile stages of benthic organisms during the developmental phase of their early life history (Kurihara et al. 2007). Many species spend this part of their life in the water column as free-floating plankton.

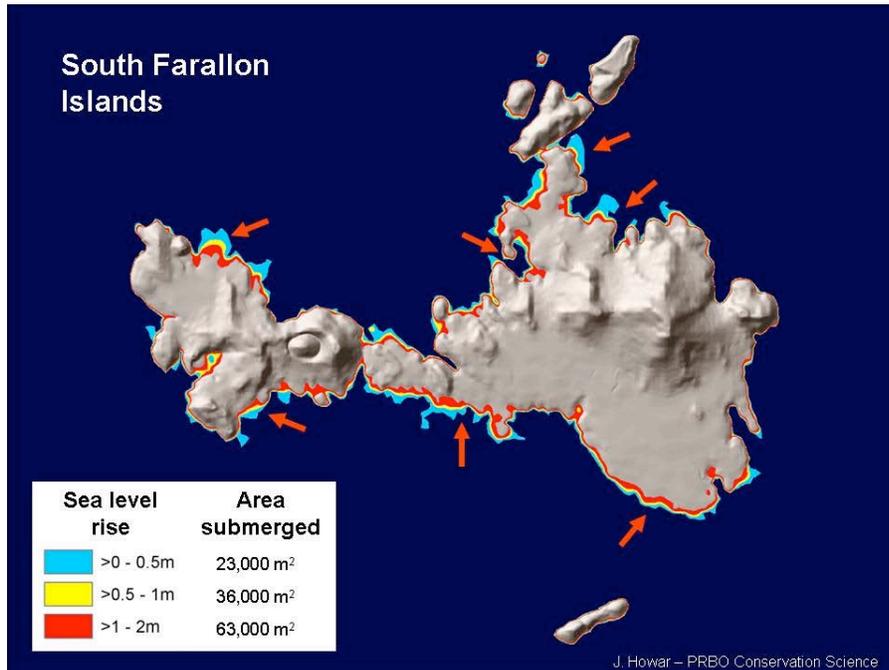
**Upwelling:** Sessile benthic organisms depend on currents to deliver food. Any significant disruption to the timing or intensity of seasonal upwelling winds resulting in reduced productivity over time would have negative impacts on long term survival of benthic animals.

**Transport:** Many offshore benthic organisms that live in the California Current have early life histories linked to an annual production cycle driven by coastal upwelling. Most of these animals spend the first part of their lives as free-floating plankton, which facilitates dispersal, feeding and predator avoidance. If the timing or magnitude of seasonal winds driving coastal upwelling were to change significantly, it could reduce larval survival for many resident species.

### 5.3 Island Habitat

Anticipated changes in climate will significantly impact the physical habitat on offshore islands. Of particular concern are potential alterations to seabird and marine mammal breeding and resting habitat at the Farallon Islands, the largest seabird-breeding colony in the contiguous United States and an important breeding and haul-out area for marine mammals.

**Sea Level Rise:** Predicted sea level rise off northern and central California has the potential to significantly alter island habitats and cause a redistribution of wildlife populations. Digital elevation models have demonstrated that a rise of 0.5 m would result in permanent flooding of 23,000 m<sup>2</sup> of habitat at the South Farallon Islands (PRBO unpublished data, Fig. 5.3). This represents approximately 5% of the island surface area and would include much of the intertidal areas where pinnipeds haul out as well as pocket beaches and gulches around the island. As a result, these areas would become inaccessible, forcing the animals to move higher up onto the marine terrace or to abandon the colony. This redistribution of pinnipeds would, in turn, impact seabird habitat by reducing the available nesting areas and causing the destruction of nest sites, particularly for burrow nesting species such as the Cassin's auklet (*Ptychoramphus aleuticus*). Furthermore, during extreme high tides and storm events, waves would be expected to extend higher still, leading to increased erosion, flooding, and loss of habitat.

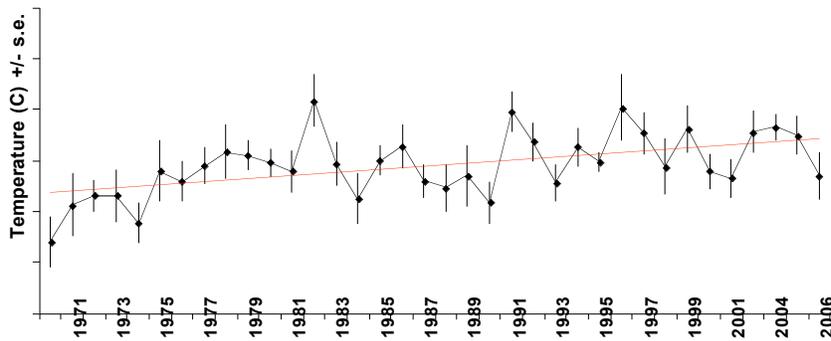


**Figure 5.3.** Map of the South Farallon Islands showing the cumulative habitat area (in square meters) submerged by differing degrees of sea level rise relative to the average tide level. The arrows indicate major pinnipeds rookeries and haul out areas. J. Howar, PRBO Conservation Science.

Examples of these changes can be seen during El Niño events when alongshore winds decrease and warm water floods into the area from the tropical Pacific, leading to higher sea level off the coast of California. During the El Niño events of 1983 and 1992, higher water and increased storm activity resulted in significant erosion of Elephant Seal (*Mirounga angustirostris*) breeding areas and the destruction of important beach access routes at the Farallones (Sydeman and Allen 1999). This in turn made it more difficult for them to access their primary breeding areas and led to local population declines and reduced breeding success (Sydeman and Allen 1999). The distribution of pinnipeds was also significantly altered during El Niño events, resulting in greater numbers of animals hauled out high on the marine terrace, habitat normally occupied by breeding seabirds (PRBO unpublished data). Similar consequences would be expected with rising oceans, particularly if coupled with more extreme weather events, which are also predicted to occur as a result of climate change.

**Precipitation:** Intensified winter precipitation and more significant rainfall later in the season may alter physical habitat in many ways. Increased erosion of the hillsides can alter vegetation structure, increase the frequency of rockslides and degrade nesting habitat, particularly for species that rely on rock crevices such as auklets and storm petrels. Flooding of low lying areas on the marine terrace will also decrease suitable habitat for burrow nesting species and carry away the thin layer of soil in which they dig their burrows.

**Air temperature:** Average annual air temperature at the Farallones has exhibited an increasing trend during the 36 years (1971- 2007) that PRBO has been collecting weather data at the island (PRBO unpublished data; Fig. 5.4). Given current predictions, PRBO scientists would expect this trend to continue, leading to overall changes in the climate of the islands. While warmer temperatures would not necessarily alter the physical structure of the island, it may affect habitat by altering the vegetation structure on the island and facilitating the proliferation of more heat tolerant non-native species, such as grasses. Increasing air temperatures will also have important implications for island wildlife. Many of these species are adapted to cold and windy conditions and quickly become stressed when conditions change. During unusually warm weather, seabirds may abandon their nests, neglect dependent offspring, and die of heat stress (Warzybok and Bradley 2008). Marine mammals will spend less time hauled out and would be expected to abandon young in the rookeries if temperatures become too warm.



**Figure 5.4.** Mean annual air temperature at the South Farallon Islands from 1971 to 2006. The red line illustrates the trend in the data. PRBO Conservation Science.

#### 5.4 Sandy Beach Habitat

Composed of unconsolidated sand from watersheds and coastal bluffs that is constantly shaped by wind, waves and tides, sandy beach ecosystems are strongly influenced by marine and terrestrial processes. The biodiversity and unique ecological functions and resources supported by sandy beach ecosystems are important to include along with their high socio-economic values (Brown and McLachlan 2002, Schlacher et al. 2007). Ecosystem services and ecological values and functions of beaches and dunes in the study region include unique vegetation, rich invertebrate communities that are prey for shorebirds and fish, absorption of wave energy, the filtration of large volumes of seawater, nutrient recycling, and critical habitat for pinnipeds, declining and endangered wildlife, such as shorebirds, and a variety of threatened plants (McLachlan and Brown 2006, PWA 2008).

Sandy beach and dune habitats are increasingly squeezed between the impacts of human land development and manifestations of climate change at sea (Schlacher et al. 2007, Nordstrom 2000). Human alterations severely limit the ability of beach ecosystems to adjust to changes in shoreline stability (Clark 1996) as well as sea level rise and erosion caused by climate change. Sea level rise and other predicted effects of climate change, including increased storminess, are expected to intensify pressures on these exposed ecosystems by increasing rates of shoreline

Deleted: j

erosion and retreat, and degrading habitat (Nordstrom 2000, Slott et al. 2006). In addition, the expected proliferation of shoreline armoring to protect upland properties can significantly degrade sandy beach habitats. Passive erosion associated with this armoring response effectively drowns beaches and shifts the sandy beach habitat zones downward on the beach profile, disproportionately affecting the mid and upper beach zones with resulting effects on biota, biodiversity and food webs (Dugan et al. 2008). Such biotic effects are predicted to expand with sea level rise which will alter the position of existing armoring on the beach profile and act to increase the degree of interaction of these manmade structures with waves and tides (Dugan et al. 2008). Habitat loss, fragmentation, and alteration from sea level rise will have profound ecological implications, as beaches become narrower and steeper and as once continuous habitat in front of coastal bluffs and cliffs is converted to isolated pocket beaches. The type of responses of beach ecosystems to sea level rise and increased storminess associated with climate change are projected to be similar to episodic ENSO storm events (Revell et al. *in press*), although time scales will differ, especially where coastal land uses and development constrain retreat.

Ecological zonation on exposed sandy beaches is extremely dynamic due to the highly mobile nature of the sandy substrate, the intertidal animals and the resources on which these animals depend (McLachlan and Jaramillo 1995, McLachlan and Brown 2006). In general, three different intertidal zones inhabited by distinct groups of mobile animals are present on most exposed sandy beaches (McLachlan and Jaramillo 1995). These zones generally correspond to the: 1) relatively dry sand/substrate of the coastal strand and supra-littoral zone at and above the drift line; 2) damp sand of the middle intertidal; and 3) wet or saturated sand of the lower intertidal zone. Changes in the relative proportions and condition of these zones from the combined effects of sea level rise and coastal development can result in strong ecological responses that propagate up the food web (Dugan et al. 2008). The majority of prey biomass available for birds and fish on beaches within the study region is provided by intertidal invertebrates, such as sand crabs (*Emerita analoga*) whose populations can be strongly affected by storm-generated erosion and coastal evolution, as well as alteration of ocean currents delivering planktonic larvae. Another major prey resource on beaches in the region are the intertidal wrack consumers, such as talitrid amphipods (*Megalorchestia* spp.) and insects, whose populations and presence are strongly affected by erosion, storms and upper beach conditions as well by the availability and production of drift macroalgae from kelp forests and reefs, all of which are vulnerable to climate change effects. These invertebrates are also crucial to wrack processing and subsequent nutrient cycling on beaches (Lastra et al. 2008).

Shorebird use of beaches can be high and has been positively correlated with the availability of invertebrate prey, the amount and type of macroalgae wrack, beach slope and beach width (Dugan 1999, Dugan et al. 2003, Dugan et al. 2004, Neuman et al. 2008; Revell et al. *in press*) in California, including shores in the study region. Birds of all types, including shorebirds, seabirds and gulls, have been shown to respond negatively to beach width and zone losses associated with coastal armoring (Dugan et al. 2008). Threatened birds, such as the western snowy plover (*Charadrius alexandrinus nivosus*) and California least tern (*Sterna antillarum brownii*), nest in open beach and dune habitats on GFNMS shorelines (Lehman 1994, Page et al. 1995) making use of the dry sand zone, a habitat where erosive impacts from climate change will be strongly expressed.

**Comment:** Parts of this paragraph are redundant to Chapter 3 (section on SLR and coastal erosion) and other parts are additive. This happens in other subsections of this chapter. Suggest considering how to combine some of these sections.

Fish, such as the California grunion and smelt, also depend on these vulnerable uppermost intertidal zones of open sandy beaches for spawning, burying their eggs at the driftline for incubation in the region (Thompson 1918). Finally, pinnipeds, including elephant seals, sea lions, and harbor seals, pup and raise their young on sandy beaches, again using the threatened upper beach zones within the study region, such as at Año Nuevo. Along with environmental drivers associated with climate change, evolution in beach and strand geomorphology, sediment dynamics, coastal and watershed perturbations, recreational activity and beach front development all affect these coastal ecosystems, the wildlife that depends on them and the ecosystem function and services they provide.

**Comment:** This description is more 'community level' than others. Includes descriptions of multiple changes in food web.

### 5.5 Rocky Intertidal Habitat

Rocky intertidal habitat is characterized by complex environmental conditions that are driven by both aquatic and terrestrial forces. Of primary concern are possible increases in average water and air temperature as well as the prevalence of extreme conditions (e.g., heat waves) that can result in mass mortality of intertidal organisms. Also, the combined effects of ocean acidification and upwelling could have tremendous implications for the ability of intertidal organisms to produce shell as well as capture food. Upwelling will also affect the availability of nutrients for primary producers (plants and algae). Sea level rise and increased wave activity may also affect intertidal organisms, in some cases through interactions with other factors like elevated air temperature, although the outcomes of these processes are less certain. Three significant rocky intertidal areas within the study region are located at the Farallon Islands, Duxbury Reef, and Fitzgerald Marine Reserve.

**Temperature:** Most rocky intertidal organisms are ectothermic ("cold-blooded") and are therefore sensitive to ambient temperatures. During a low tide, intertidal organisms can experience body temperatures as high as 40° C and as low as 10° C when the tide comes in (Denny and Wethey 2003). The temperature perceived by intertidal organisms is determined by apparent variables such as water and air temperature. However, temperature is also influenced by more subtle factors such as long-term tidal cycles, fog, wind speed, wave splash, and the spatial orientation of the organism in question. As such, studies evaluating the response of intertidal organisms to changes in temperature have generated complex patterns of how species will respond (Helmuth, 2002; Gilman et al. 2006). Moreover, temperature effects in the intertidal are dependent on an 18.6-year lunar cycle. For example, the emergence time for an organism in Monterey, CA can almost double depending on this lunar oscillation because the force exerted by the moon varies (Denny and Paine 1998; Helmuth et al. 2002). Working on intertidal California mussels, Gilman et al. (2006) found that body temperature was most sensitive to climate drivers at northern latitudes (including the study region) and also in those organisms living in the high intertidal zone. Increased temperature may also heighten the susceptibility of intertidal organisms to disease. Raimondi et al. (2002) found that increased warm water conditions associated with ENSO events may accelerate the development of withering foot syndrome in the black abalone, *Haliotis cracherodii*. Similar results have been found in farmed red abalone, *H. rufescens* that were raised in the lab at elevated temperatures of 18° C (Moore et al. 2000).

**Comment:** Many repeats here. Lots of description of physiological impact on single species that is better described in Chapter 4, then integrated here in this Chapter to explain how those impacts affect the food chain and entire structure of the rocky intertidal community.

Many climate change studies of rocky intertidal communities have focused on the response of the California mussel *Mytilus californianus* to climate change stressors. Mussels are a competitively dominant species that can decrease the diversity of other space competitors but also increase the diversity of organisms that live within dense mussel beds. Mussels generally

appear to increase growth rates in response to increased water temperatures and increased food supply (Blanchette et al. 2007, Menge et al. 2008). Increasing temperature trends have been observed across coastal California and mussels may therefore exhibit increased growth. However, the production of phytoplankton for mussel consumption will depend on wind patterns and the transport of nutrients for phytoplankton growth.

In contrast, intertidal mussels may see population declines depending on the occurrence of extreme environmental conditions. Extreme heat waves have resulted in mass mortality events of California mussels and limpets (*Lottia scabra*) in the Bodega Marine Reserve (Harley 2008). Due to the timing of low tides, extreme heat events in the study region are most prevalent in the spring when low tides occur during the daytime when heat stress is greatest (Helmuth et al. 2002, 2006). Mussel mortality patterns are also related to predation rates by their primary predator, the ochre sea star *Pisaster ochraceus*. These sea stars set the lower limit of mussel beds in the intertidal throughout California and Oregon (Menge et al. 2004). Small changes in water temperature have been documented to greatly modify the rate of sea star predation on mussels (Sanford 1999). Cold upwelling waters decreased sea star activity whereas increased seawater temperatures increased sea star consumption. Thus, mussel susceptibility to predation will in large part depend on broad temperature trends (increasing predation) as well as upwelling conditions that can bring cool deep waters onto the rocky intertidal (decreasing predation).

**Ocean Acidification and Upwelling:** While it is generally clear that surface pH has declined, the effect of ocean acidification on the saturation state of surface waters is less understood (see 3.4.4 Coastal Upwelling). The effects of ocean acidification on intertidal habitats will probably be felt most intensely through upwelling events that will bring undersaturated deep waters to the surface (Feely et al. 2008). Undersaturated conditions decrease the ability of calcifying organisms to produce shells and may dissolve already existing shell structure while the organism is still alive. Upwelling will also influence the delivery of food (phytoplankton), nutrients (for algae and plants), and larvae to intertidal habitats.

**Comment:** See Wootton et al 08 in PNAS. May want to include synopsis of results and refer to here.

Many rocky intertidal organisms produce calcium carbonate skeletons. Ocean acidification can make production of calcium carbonate structures more difficult as well as acidify internal body fluids (Doney et al. 2009). As of yet, no ocean acidification studies have been conducted on the mussels found within the sanctuary. However, the closely related mussel *Mytilus edulis* exhibits decreased calcification rates with increasing aqueous CO<sub>2</sub> concentrations (Gazeau et al. 2007). Decreased abundances of mussels on rocky intertidal shores could thus create significant space for other species to attach to. Further, sea star populations may be forced to switch to other prey items in the absence of mussels, although it is not clear what species it could feed upon since other documented prey items are calcifiers as well.

Coralline algae are another dominant species within the sanctuary that will likely be affected by acidic conditions. In one of the few studies examining acidification effects on this taxonomic group, Kuffner et al. (2008) evaluated the response of crustose coralline algae, a widespread non-branching coralline alga. Experiments revealed decreased recruitment and growth of calcifying coralline algae with increased growth of non-calcifying species. Reduced coralline algae abundance within the study region may create space for non-calcifying algal species to establish. Coralline algae dominate shallow marine habitats that have hard substrate and an abundance of herbivores (Steneck 1986).

**Sea Level Rise:** Intertidal organisms will respond to sea level rise by shifting their distributions to keep pace with rising sea level. It has been suggested that all but the slowest growing organisms will be able to keep pace with rising sea level (Harley et al. 2006) but few studies have thoroughly examined this phenomenon. As in soft sediment systems, the ability of intertidal organisms to migrate will depend on available upland habitat. If these communities are adjacent to steep coastal bluffs it is unclear if they will be able to colonize this habitat. Further, increased erosion and sedimentation may impede their ability to move.

**Waves:** Increased wave activity in the form of greater significant wave height ( $H_s$ ) and the occurrence of extreme waves has been observed in the Eastern Pacific (see 3.3.2 Waves). Waves affect intertidal communities because they not only deliver food for filter and suspension feeding organisms; they impose high physical forces upon both mobile and non-mobile organisms (e.g. seastars, snails, barnacles, mussels). Greater wave activity suggests that intertidal organisms may experience greater physical forces. However, the relationship between offshore significant wave height and the intertidal force is not simple. Although local wave height inside the surf zone is a good predictor of wave velocity and force (Gaylord 1999, 2000), the relationship between offshore  $H_s$  and intertidal force cannot be expressed via a simple linear relationship (Helmuth and Denny 2003). In many cases (89%), elevated offshore wave activity increased force up to a point ( $H_s > 2\text{-}2.5$  m), after which force did not increase with wave height. Since many northern sites on the West coast of North America already experience wave heights of this magnitude, forces may not increase with increasing  $H_s$ . On the other hand, the remaining 11% of sites exhibited a positive relationship with  $H_s$  that did not level off (Helmuth and Denny 2003). At sites such as these, larger wave forces may accrue, as well as greater wave splash and ensuring modulated temperatures by means of chronic wetting.

**Comment:** Will some organisms living in this habitat be more susceptible to increased wave activity, and if so, how will changes in that organism affect entire community? If kelp is impacted, how will pelagic organisms that use kelp habitat be impacted?

**Population Range Shifts:** Forecasting changes in marine communities is limited because of the large number of complex interactions that can result from climate change (see 4.2 Range Shifts). Theory predicts that species will shift their ranges towards the poles in response to warming (Peters and Darling 1985). However this prediction is complicated by the fact that species not only respond to climate but they also respond to other species (e.g. predators, habitat-forming flora and fauna). For the purposes of evaluating climate change, it can therefore be useful to focus on the response of key species that have large roles in structuring marine communities. These species can form habitat for other organisms (e.g., foundation species such as mussels that provide structure and refuge for infaunal organisms, or kelp that support populations of many associated invertebrates). Alternatively, key species can be ones that have a large influence on populations of other species (consumers such as sea urchins or sea stars).

The vast majority of marine species have planktonic larval stages that may be subject to entirely different selective pressures than adults on the shore (Strathmann 1987). Correlations between adult habitat “suitability” and the abundance of adults across the range thus become complex. Many species exhibit abrupt shifts in density near range edges, raising questions about the applicability of simplistic climatic envelope models that assume that organisms are most abundant in the centers of their ranges (Sagarin et al. 2006). In this context, understanding that range boundaries can potentially be set by circulation patterns *per se*, rather than by thermal constraints or other conditions local to an intertidal habitat may become critically important (Gaylord and Gaines 2000; see 4.2 Range Shifts).

## 5.6 Nearshore Subtidal Habitat

The nearshore subtidal environment within the study region includes sandy continental shelf habitat as well as rocky reefs, which support kelp forest communities. Primary climate change drivers of interest for nearshore subtidal habitats include changes in upwelling, stratification, ocean acidification, storm activity, and sea level rise.

**Upwelling:** The direction of change in upwelling for the study region is uncertain, but either scenario (increases or decreases in intensity) will affect nutrient delivery to the nearshore subtidal. Increased nutrient availability in the nearshore may therefore benefit benthic macroalgae as well as phytoplankton. However, intensification of upwelling could also alter the strength of offshore transport, increasing the dispersion of larvae and spores released in the nearshore subtidal, as well as enhance turbulent mixing, thus disturbing food particle concentrations critical to larval survival (Bakun 1990, see 4.4 Population Connectivity).

**Stratification and Mixing:** Coastal thermoclines have become stronger and deeper in offshore waters in the study region (Palacios et al. 2004; see 3.3.3 Coastal Upwelling). Further increases in stratification would prevent nutrient delivery to the subtidal habitat as well as decrease offshore transport of larvae and spores, further increasing retention. In Southern California, nitrate availability limits kelp forest productivity (Zimmerman and Kremer 1984, 1986; Zimmerman and Robertson 1985), and if conditions in northern waters approached those found further south, it is conceivable that these important ecosystems could be threatened. Stratification as a consequence of climate change has already been reported to change zooplankton communities in the California Current (Roemmich and McGowan 1995). Changes in mixing and transport will further be moderated by changes in mesoscale (10s-100s km) circulation, such as recirculation cells in the lee of headlands. Mesoscale features are important corridors between offshore and nearshore habitats. Climate moderates mesoscale circulation in the California Current System, thereby affecting nearshore-offshore connections (Keister and Strub 2008).

**Ocean Acidification:** The northern and central California coast is especially vulnerable to acidification because of upwelling, which transports acidified waters (under-saturated with respect to aragonite) from offshore onto the continental shelf, potentially reaching the coastal shallow subtidal (Feely et al. 2008). The acidified upwelled water may affect calcifying organisms utilizing the nearshore subtidal habitat (see 3.5.2, Ocean Acidification), although, unlike the rocky intertidal, few nearshore subtidal habitats in this region are dominated by calcifying organisms.

**Storm Activity:** Increasing significant wave heights will affect sediment redistribution and may change the coastal topography of the area. Increased storm activity may increase precipitation in this area, leading to greater freshwater input to the nearshore subtidal, including inputs from the San Francisco Bay outflow. An increase in terrestrial inputs as well as storm activity will lead to higher resuspension of sediment resulting in increased turbidity and light attenuation. Increased turbidity will compromise kelp growth. Increased storm activity may also move nearshore kelp forests into deeper water (Graham 1997) and create greater intra-annual variability in kelp productivity and abundance (Graham et al. 1997). Greater turbidity may compromise the growth and recruitment of some kelp species (e.g. *Macrocystis*) while promoting others (e.g. *Nereocystis*). For kelp forest communities on rocky reefs (which form a physical habitat for reef-

**Comment:** Already discussed in section 3.3.3. Any way to integrate this information to make a broader inference on how community and higher tropic levels will be impacted by changes in upwelling?

associated species), increased storm activity may also increase dislodgement of kelp holdfasts resulting in a loss of physical habitat for kelp forest associated species (Seymour et al. 1989, Graham et al. 1997). Some of these effects may also be modulated by alterations in mean transport, perhaps tied to alterations in upwelling phenomena, through subtle interactions between waves and currents (Gaylord et al. 2003). The loss of kelp forests can have further effects due to their immense importance as subsidizing agents to other communities. Dislodged kelp biomass serves as a critical food resource both to deep-water ecosystems as well as for intertidal and (in particular) beach fauna (ZoBell 1971, Harrold et al. 1998, Vetter and Dayton 1999, Colombini and Chelazzi 2003).

**Comment:** Good description of community-level impacts.

**Sea Level Rise:** Sea level rise will affect kelp forest communities on rocky reefs in the nearshore subtidal (Graham et al. 2003, 2008). Increased sea level will decrease light availability to sessile macroalgae and cause a shoreward migration, which will depend on available rocky substrate at shallower depths. Sea level rise may also change the shape of the coastline and substrate composition (i.e., rocky vs. sandy shores; Graham 2007), and thus impact the availability and living conditions of macroalgae and their associated species.

### 5.7 Estuarine Habitat

The physical structure of estuarine habitat is likely to undergo significant changes in the face of changing climates. Sea level rise is among the most important climate change factors forcing changes in the physical structure of estuarine systems in the coming decades. Other factors such as increasing air and sea surface temperatures and CO<sub>2</sub> may interact with sea level rise to influence the physical environment of these habitats. Climate change is also predicted to result in changes in oceanographic and atmospheric linkages resulting in changes in ocean currents and storm cycles that will likely influence estuarine geomorphology. Finally, the hydrological cycle, including rainfall and outflow from rivers into estuaries will also influence the transport and deposition of sediments with long-term consequences for the physical structure of California estuaries.

Despite the certainty of rising sea levels, much uncertainty surrounds the long-term effects of sea level rise on the physical habitats of estuaries. Many other factors can potentially interact with climate change to influence the rates at which tidal elevation is altered and consequently the extent to which estuarine habitat is lost. For instance, increasing inundation may be offset by increased rates of inorganic sediment deposition (Friedrichs and Perry 2001). Also, increasing CO<sub>2</sub> levels may also result in greater production of C<sub>3</sub> plants thereby increasing rates of organic deposition (Morris et al. 2002, Körner 2006). However, this increased deposition could, in turn, be offset by increased freshwater intrusion, which can increase rates of decomposition (Weston et al. 2006). In particular, estuarine habitats more dependent on organic rather than inorganic deposition may be more subject to the influences of changes in sea level (Stevenson et al. 1986). Sediment supply remains an important if not completely understood indicator of wetland and estuary resiliency.

An important factor that will influence estuarine response to sea level rise is the ability of estuaries to migrate where the upland border abuts roads, levees or other armored structure *or by natural steep slopes or bluffs*. This upper border may result in an accelerated loss of habitat as has been demonstrated for sandy beaches (Fletcher et al. 1997, Dugan et al. 2008). It also may severely limit the upland migration of estuarine plants and animals as rising sea levels inundate

lower tidal elevations (Dugan et al. 2008). Areas where estuarine upland borders are *partly or* entirely surrounded by armored structures *or by bluffs and slopes* are therefore significantly at risk of habitat loss.

Coastal lagoon habitat types, such as those occurring in Bolinas Lagoon, have been modeled in detail (PWA 2006). Each estuarine habitat type will respond differently based on the overall response of the individual systems. Brackish and salt marsh estuarine habitats are likely to be exposed to salt water more frequently and at higher elevations. This expansion of subtidal wetlands will increase the area for wind wave formation potentially accelerating erosion along the marsh edges. Along estuaries with unarmored barrier spits (e.g., Drakes Estero) overwash events will be more frequent, depositing sediment on the inland side of the spit. These overwash deposits generally form small deltas, which over time can result in a “rollover” of the spit, or landward migration of the entire spit toward the mainland. This “rollover” may reduce the tidal prism and flushing characteristics of the lagoon and potentially lead to changes in frequency and duration of breaching events. In estuaries unconstrained by development, infrastructure, and landscapes, the wetland habitats will likely migrate inland and upward to remain in balance. However, in locations where development, infrastructure, and landscapes constrain or border wetlands, intertidal wetlands habitats may be lost as indicated above.

Among the most sensitive species to sea level rise in estuarine habitats are shorebirds, because of their dependence on exposed intertidal mudflat habitats for foraging. Studies of restoration planning efforts have shown the importance of tidal elevation for maintaining populations of foraging shorebirds (Stralberg et al. 2008, Goss-Custard and Stillman 2008). Other studies have indicated that sea level rise may have negative effects on foraging budgets of individual shorebirds and influence choice of foraging habitats, such as movement from bays to outer coast areas (Durell et al. 2006, Goss-Custard and Stillman 2008). Sea level rise is also likely to strongly influence the plant and animal communities of the nearshore benthos (Scavia et al. 2002).

**Freshwater Input:** Estuaries with regular and substantial inputs of freshwater may be influenced by changes in watershed outflow (Kimmerer 2002). Predictions for much of California suggest that the amount of water entering estuaries will have increased interannual variation (Cayan 2008). However, equally influenced may be estuaries where the outflow and connection to coastal marine waters may be seasonal or intermittent (Largier and Taljaard 1991). These ‘bar-built’ estuaries, which include Estero Americano and Estero de San Antonio in GFNMS, are strongly influenced by the creation of sandbars that are in turn affected by changes in the magnitude and variability of runoff (Kensch 1999).

Changing patterns of precipitation and consequently outflow may have significant effects on the biota of estuaries as well (Kimmerer 2002). Predictions for much of California suggest increasingly interannual variability in rainfall and outflow patterns (Cayan et al. 2008). Current predictions suggest that these increasingly variable flows may favor the invasion of coastal estuaries by invasive species. These changing patterns of outflow will mean that there will also be increasing changes in the salinity gradient with substantial consequences for estuarine biota. Increasing storm activity will also potentially increase geomorphology of estuaries with transport of sediments into estuaries from both ocean and watershed sources (Hoyos et al. 2006, Day et al.

2008). Storm activity will interact with other cyclic phenomena, such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, to influence estuaries in complex ways (Day et al. 2008).

**Comment:** Awkward. Re-word. Geomorphology doesn't increase Shoreline and estuarine morphology change with altered hydrodynamics and sediment transport and supply.

**Temperature:** Increasing sea surface and air temperatures are magnified in estuaries relative to the outer coast and are important drivers of community and ecosystem responses in estuaries. Increasing sea surface temperatures can result in the range expansion of both native and non-native species into new areas (Williams and Grosholz 2008). Increasing sea surface temperatures can have significant demographic effects as well. For instance, temperature increases have been responsible for the disappearance of the marine bivalve, *Macoma balthica*, in Northern Spain. Common in study region mud flats from San Francisco Bay north, the Baltic clam experienced elevated temperatures in Northern Spain, ( $> 30^{\circ}\text{C}$ ) increasing metabolic rates and resulting in eventual starvation. *M. balthica* disappeared from the northern Spanish coast because of increasing summer maxima during past decades (Jansen et al. 2007). The impacts of increasing sea surface temperature on intertidal plants can affect desiccation stress and may interact with nutrient dynamics, tolerance to soil conditions and recruitment from seed vs. vegetative growth (Levine et al. 1998). Increasing temperatures may also alter interactions between marine plants and their herbivores (O'Connor 2009). In addition, increased temperatures may generally put greater stress on plants and animals and magnify problems with parasites and pathogens. For instance, Poulin and Mouritsen (2006) found increasing evidence that parasites such as trematodes are extremely sensitive to temperature increases of less than four degrees Celsius, causing amphipod population crashes. Relatively small perturbations may translate into large alterations of mud flat communities.

**Ocean Acidification:** Increasing levels of atmospheric  $\text{CO}_2$  will have several affects that will likely influence estuarine flora and fauna. Increasing atmospheric  $\text{CO}_2$  will disproportionately influence  $\text{C}_3$  plants (Mayor and Hicks 2009). Current studies from experimental  $\text{CO}_2$  enrichment arrays show that increasing levels of  $\text{CO}_2$  can influence the relative above and below ground growth of plants and favor  $\text{C}_3$  plants relative to  $\text{C}_4$  plants. Long-term studies have not found that these effects continue without the expected effects of nitrogen limitation. In addition, the additional production may increase the role of estuarine plants as a carbon sink with implications for the future carbon budgets (Mayor and Hicks 2009).

Ocean acidification will likely cause serious and unknown effects in mud flat community structure. Alvarado-Alvarez et al. (1996) found at a pH of  $< 8.5$  the Pismo Clam (*Tivela stultorum*) had decreased fertilization and embryo development rates. Similarly, Green et al. (2004) found that the clam *Mercenaria mercenaria* showed juvenile shell dissolution leading to increased mortality at aragonite saturation states of 0.3 ( $\Omega_{\text{arag}}$ ). The authors found that the removal of the surface layer would expose the reduced organic rich deposits to oxidation resulting in reduced pH and carbonate undersaturation. Shell dissolution is a recognized source of mortality for juvenile bivalves and has serious implications as populations can be modified by thermodynamic conditions encountered by juveniles (Gosselin and Qian 1997). Freshwater inundation could also lower the pH of estuaries by reducing the buffering capacity of estuaries with lower salinities, higher organic inflows and more acidic freshwater. These are conditions found in Tomales Bay (Smith and Hollibaugh 1997, Marshall et al. 2008).

**Transport:** Finally, climate change is likely to alter linkages between atmospheric and oceanographic forces resulting in changes in upwelling, coastal advection and variety of

processes influencing the transport of organisms within and between estuaries (Gawarkiewicz et al. 2007). These changes in coastal ocean transport processes are likely to result in changes in the frequency or magnitude of delivery of plankton and various larval and adult dispersal stages among estuaries (Harley et al. 2006). Therefore, the degree of connectivity among populations and communities, both from a population genetic and a population dynamic perspective, are likely to be altered with unknown consequences.

**Mudflats:** Estuarine mud flats, in contrast to other intertidal soft sediment habitats such as sandy beaches, cannot develop in the presence of wave action and need a source of fine grain sediments. Mud flats are located in partially protected bays, lagoons and harbors. Examples within the study region include: Pillar Point Harbor, Bolinas Lagoon, Esteros Americano and de San Antonio, Tomales Bay and Bodega Bay.

Mud flats will be threatened by sea level rise, ocean acidification, organic loading and sea surface temperature change. Low lying muddy shores are most vulnerable to sea level rise with accompanying stronger tidal currents, wave action and changes in salinity. This will result in sediment starvation, erosion and the eventual loss of this coastal ecosystem (de la Vega-Leinert and Nicholls 2008; Lebbe et al. 2008; Callaway et al. 1997). Mud flats with hypsometric characteristics (an extensive intertidal area and a restricted inlet) will be particularly sensitive to sea level rise (French 2008). Deteriorating sediment conditions are thought to be responsible for declining recruitment success in Wadden Sea cockles (Beukema and Dekker 2005). Salt water inundation will cause vegetation changes as more saline water replaces brackish and fresh water (Callaway et al. 2007). For example, at Pillar Point, this would impact the upstream brackish water cattail (*Typha* sp.) and freshwater willow (*Salix* sp.) marshes.

**Comment:** Please include a reference. I would think that mudflats consisting of fine grained sediments are cohesive and, therefore, have greater resistance to shear stress caused by waves than sandy beaches. Mudflats are, however, very sensitive to fine grained sediment supply

## 6. Multiple Ecosystem Stressors

Through both land and marine-based activities, there is no area of the ocean that is not affected by humans, and in actuality, 41% is affected by multiple human influences (Halpern et al. 2008) or “stressors.” Stressors are defined as variables that adversely affect an organism’s physiology or population performance in a statistically significant way (Vinebrooke et al. 2004, Barrett et al. 1976, Auerbach 1981). Often time these stressors do not function independently, but instead interact to produce combined impacts on biodiversity and ecosystem health (Vinebrooke et al. 2004, Breitbart et al. 1998, Frost et al. 1999, Schindler 2001). Some examples of interacting ecosystem stressors within the study region include fishing activities, invasive species, pollutants and contaminants, harmful algal blooms, disease, habitat modification, wildlife disturbance, and potentially, emerging alternative energy projects such as wave and tidal energy. When combined with or exacerbated by the effects of climate change, the resiliency of marine ecosystems can become compromised (see box: Ecosystem Resilience).

### 6.1 Fishing

The study region currently supports active commercial and recreational fisheries, but fishing, combined with habitat destruction, poor recruitment, and anomalous oceanographic conditions has contributed to declines of some marine species in central and northern California waters (CBNMS Condition Report, 2009). Effects on marine ecosystems resulting from fisheries exist in three main areas: 1) overfishing of a population; 2) physical impacts on habitat due to gear type; and 3) incidental take of non-target species or “bycatch” (Keller et al. 2008). If a fishery population is overstressed or overfished, it becomes more susceptible to the effects of climate change as well as other human induced stressors. The average life span, reproductive success, and larval quality of a fish population can be reduced, making it more vulnerable to both short- and long-term changes in the physical ocean environment. If exploitation occurs of a single keystone species, an ecosystem can become destabilized, leading to greater susceptibility to the effects of climate change (Keller et al. 2008). In addition, and as discussed in the Cordell Bank National Marine Sanctuary Condition Report (2009), lost fishing gear has been observed entangled in rocky areas of Cordell Bank. This entanglement leads to damage of sensitive habitats that provide food and shelter for invertebrates and fishes (Barnes and Thomas 2005). Also, selected open ocean fisheries in the study region have contributed to bycatch of seabirds, (Forney et al. 2001), pinnipeds, cetaceans, (Read et al. 2006) and sea turtles (Spotila et al. 2000) resulting in mortality from entanglement in active and derelict fishing gear (CBNMS Condition Report, 2009).

### 6.2 Invasive Species

Changing climates can influence both the process and the consequences of invasion (Dukes and Mooney 1999) however, there are few studies of the intersection between climate change and invasions in marine systems (Occhipinti-Ambrogi 2007). Among the most important aspects of climate change for marine invasions are increasing sea surface temperatures and changes in wind driven surface currents. These can potentially alter both the frequency of transport of dispersal stages of invaders among locations (e.g. invaded and not) influencing the likelihood of spread and establishment in new locations. Stachowicz et al. (2002) examined long-term data in recruitment of native and invasive tunicates relative to winter minima and summer maxima in sea surface temperatures. They found that increasing sea surface temperatures resulted in both

earlier and greater recruitment of invasive species as well as increased growth rates of invasives relative to natives. They predicted that increasing temperatures will lead to greater success of invasive species. Changing temperature regimes could also influence human-mediated pathways including shipping vectors by changing commercial activity or shipping routes due to potentially extended shipping seasons or new ice-free shipping routes (Hellman et al. 2008). Increasing sea surface temperatures and changing ocean current systems could increase the degree of habitat matching between invaded and uninvaded sites, facilitating the spread or establishment of new invaders (Herborg et al. 2007). Other climate factors such as increasing atmospheric CO<sub>2</sub> would favor C<sub>3</sub> over C<sub>4</sub> plants, thus potentially affecting competition among marine plants (Craft et al. 2009).

Increasing ocean acidification associated with increasing CO<sub>2</sub> (Feely et al. 2008) could influence species interactions and success of invading species in numerous ways, such as predator-prey interactions among invasive whelks and native prey. Predicted rise in sea levels along the California coast may shift species interactions, particularly in urbanized estuaries or other 'armored' habitats where migration to higher tidal elevations is restricted (Heberger et al. 2009). Estuaries with reduced tidal exchange (microtidal) experience slower rates of vertical accretion resulting from the accumulation of organic matter. Therefore, species in these estuaries may be at greater risk of inundation due to sea level rise than species in estuaries with greater tidal exchange (mesotidal), where more rapid accumulation of inorganic sediments may be more likely to compensate for rising sea levels (Stevenson and Kearney 2009). This could favor introduced species more tolerant of increased tidal inundation relative to natives. Lastly predicted increases in storm intensity and frequency and changes and resulting changes in coastal geomorphology (Day et al. 2008) could provide more opportunity for spread of opportunistic coastal invaders. In summary, climate change is likely to interact with coastal invaders in ways that are likely to increase their impacts, facilitate their spread and necessitate additional management actions.

### 6.3 Pollutants and Contaminants

To highlight the influence of pollutants on the study region, the San Francisco Bay Estuary alone carries a pollution load generated by approximately eight million people living in the San



Francisco Bay Area as well as effluent from the agricultural Central Valley, via the Sacramento and San Joaquin rivers. Contaminants – including agricultural and livestock waste, wastewater, sewage outfalls, historic mining and industrial wastes – can be carried into the study region via the freshwater outflow from San Francisco Bay (i.e., the San Francisco Bay plume). The plume extends as far as the Farallon Islands after heavy rainfall; and carries nutrients during spring and summer that stimulate phytoplankton growth within the region.

**Figure 6.1:** San Francisco Bay plume from space. NASA.  
[http://www.nasa.gov/mission\\_pages/station/main/iss004e10288\\_feature\\_prt.htm](http://www.nasa.gov/mission_pages/station/main/iss004e10288_feature_prt.htm).

The study region's coastal waters, particularly the estuarine habitats of Bolinas Lagoon, Tomales Bay, Estero Americano and Estero de San Antonio, are vulnerable to non-point pollution from a variety of sources including runoff, agriculture, livestock grazing, marinas and boating activities, dumping, historic mining, and improperly treated effluent from aging and undersized septic systems. Land-use activity and development are increasing in Dillon Beach and the Bolinas Lagoon area. Tomales Bay, Bolinas Beach, Muir Beach, and Esteros Americano and San Antonio are listed as impaired under Section 303(d) of the Clean Water Act because they do not meet water quality standards for specific pollutants, such as mercury (from past mining), pathogens, sediments and nutrients. Precipitation intensity is expected to increase with climate change, making control of non-point source pollution even more challenging.

A major but often overlooked consequence of climate change is the effect on ocean chemistry beyond the calcium carbonate system (Doney et al. 2009). For example, the release of methylmercury<sup>4</sup> from sediments is favored in conditions of lower salinity, lower pH, anoxia, and greater temperature (Ullrich et al. 2001). Climate change may therefore increase the bioavailability of contaminants to marine organisms, which when combined with other climate change stressors (e.g. temperature extremes), may push organisms past their ecological tipping point. Changing freshwater runoff schedules combined with increased fire frequency may also affect the delivery and availability of contaminants to coastal watersheds.

In addition, oil spills can greatly impact marine mammals, seabirds and other natural resources in and around the study region. All transiting vessels carry crude oil, bunker fuel, and/or other hazardous material, and therefore potentially pose a risk. Over 6,000 commercial vessels (excluding domestic fishing craft) enter and exit the San Francisco Bay every year. Just fewer than 25% of the vessels are tankers of intermediate size and about 5% are large vessels. Other vessels that transit through the study region include: container ships, bulk carriers, chemical carriers, military vessels, research vessels, cruise ships, and tugs. Large cargo vessels are of particular concern because they can carry up to one million gallons of bunker fuel, a heavy, viscous fuel similar to crude oil (GFNMS Management Plan 2008).

**Comment:** May want to include results of pre and post 2007 Cosco Busan intertidal monitoring to provide info on an example of biological impact of oil spills (contact Pete Raimondi and MARINE network).

#### 6.4 Harmful Algal Blooms

Harmful Algal Blooms (HABs) are now generally recognized as occurring over a wide range of oligotrophic to hyper-nutriented habitats, and appear to be expanding globally (Anderson et al. 2005; Glibert et al. 2005; Kudela et al. 2005). Unlike many other ecosystems impacted by HABs, upwelling systems worldwide are dominated by a common set of physical parameters and are likely to respond similarly to changes in physical forcing, regardless of locale. This forcing includes drivers on many spatial and temporal scales, particularly El Niño cycles, the Pacific Decadal Oscillation, and the North Pacific Gyre Oscillation, as well as trends related to global climate change.

Since HABs are a subset of all phytoplankton, global trends in phytoplankton biomass and productivity will likely be mirrored to some extent by HAB organisms. There is a global downward trend in oceanic phytoplankton productivity linked to climate change (Behrenfeld et al. 2006). However, the major eastern boundary current systems, including the California Current, are "greening" (Kahru and Mitchell, 2008) and becoming more productive (Kahru et al.

<sup>4</sup> Methylmercury is a potent neurotoxin that is readily accumulated by aquatic organisms and can be passed onto humans via consumption of contaminated fish and invertebrates.

2009). It is not clear what drives this trend in the eastern boundary currents or how it will affect HABs, but it is clear that the mechanisms are complex.

Despite this uncertainty, there are some clear examples of what the response of harmful algae to climate change may look like in California. Climate change will result in a warmer surface ocean and a corresponding increase in surface stratification (Di Lorenzo et al. 2005). These conditions are ideal for dinoflagellates, the algae that are responsible for most harmful algal events. Using data from the Santa Cruz Wharf in Monterey Bay, California, Jester et al. (2009) documented a dramatic shift in phytoplankton community structure starting in 2004, resulting in an increasing dominance of dinoflagellates and a corresponding decrease in diatoms. With this shift, Jester et al. (2009) reported a concomitant increase in HAB problems associated with dinoflagellates (paralytic shellfish poisoning, diarrhetic shellfish poisoning, red tides, including fish and shellfish killing red tides). Jessup et al. (2009) also documented, for the first time, a harmful event linked to what was previously assumed to be a harmless red tide organism. While these events cannot be linked directly to climate change (as opposed to other oscillations in the oceanic environment), they provide a glimpse at what a warmer California Current would look like in terms of harmful algae.

Climate predictions also indicate that the timing and intensity of terrestrial runoff will be modified, both as a function of precipitation patterns and indirectly by changing the snowpack in California (Barnett et al. 2008; see 3.2 Precipitation and Land Runoff). These changes will almost certainly have secondary effects on harmful algae, particularly in estuarine systems. Recent evidence points to the importance of anthropogenic nutrients on the development and proliferation of harmful algae in California (Anderson et al. 2008, Kudela et al. 2008). Changes in the hydrological cycle, as well as long-term trends in coastal (human) populations and nutrient discharge, could result in dramatic shifts in the timing, intensity, and duration of HAB events, resulting in both positive and negative changes. For example, a recent study in the western English Channel linked climate-driven changes in rainfall to a large increase in diatom blooms and a simultaneous increase in phosphorous limitation by *Prorocentrum minimum* (a HAB organism) due to changes in nutrient availability and stratification (Rees et al. 2009). Thus, while we cannot predict at this time what the impacts of climate change will be on harmful algae, it is clear that changes will occur. For further discussion on the direct effects of HABs on humans see 7.2 Health Consequences of Harmful Algal Blooms.

## 6.5 Disease

The prevalence of disease in marine ecosystems has been predicted to increase in response to a warming climate (Harvell et al. 2002). These increases have been documented in corals, seagrasses, oysters, and sea urchins and may act in concert with climate change to reduce the abundance of marine organisms (Harvell et al. 1999). This is because warming can result in increased pathogen development and survival rates, as well as favoring transmission and host susceptibility. One such link has been suggested for black abalone (*Haliotis cracherodii*) that can be afflicted with “withering foot syndrome<sup>5</sup>”. Greater temperatures appear to increase mortality of abalone infected in lab experiments (Friedman et al. 1997) and in the field (Tissot 1995). Furthermore, observations suggest that the disease is spreading from parts of southern California to the north (Raimondi et al. 2002).

<sup>5</sup> Withering foot syndrome is caused by a bacterium that infects the gastrointestinal tract of abalone, inhibiting the production of digestive enzymes (Friedman et al. 2000).

In the North Sea, pinniped (seals, walruses, sea lions) populations experienced mass mortalities caused by a virus linked to increased temperatures and high population densities (Lavigne and Schmitz 1990). In this case, small increases in air temperature caused the mammals to ‘haul out’ and bask in extremely high densities, resulting in increased contact and facilitating the spread of the disease. Rising sea level could additionally interact with disease transmission by decreasing available haul out area and thereby increasing densities for transmission.

### 6.6 Wildlife Disturbance

Halpern et al. (2009) mapped the cumulative impacts of 25 human activities and found that central California is one of the most heavily impacted areas within the California Current. With increasing human populations, and more individuals migrating to coastal areas, pressures on marine resources will intensify (Halpern et al. 2009) and access to nearshore and offshore environments will become easier. Nature tourism activities, such as wildlife viewing from aircrafts, boats, kayaks and land (including wildlife photography and videography) will also continue to increase. These activities have the potential to harm wildlife and disrupt breeding, feeding, nesting, roosting, young-rearing and mating rituals.

High levels of disturbance, including frequent interruptions of natural behaviors or a single severe event, can impact wildlife; examples of marine mammal disturbances include mother and pup separation; stampedes; and disrupted nursing activities (Allen et al. 1984; Becker et al. 2009). Breeding and roosting seabird species, particularly those species that nest or roost on cliffs or offshore rocks, are highly susceptible to human disturbances (Carter et al. 1998; Carney and Sydeman 1999). These disturbances can cause nesting seabirds to flee from and abandon their nests, leaving eggs or chicks exposed to predators, or causing eggs to fall from the nest. In some cases, disturbances can cause complete breeding failure of a seabird colony, and/or colony abandonment. These disturbance events can result in a reduction in the long-term health and survival of affected marine species, and when coupled with changing oceanic conditions and other human induced stressors, cumulative small impacts can impart large-scale harm.

### 6.7 Wave and Wind Energy

An emerging issue within the study region is the use of Wave Energy Conversion (WEC) devices, as the wave regime north of Point Conception provides an ideal amount of wave energy for a viable industry (PIER 2007). As outlined in Nelson et al. (2008), the use of these devices will change nearshore wave energy and nearshore wave-driven processes, resulting in two main sets of environmental impacts: 1) direct impacts due to construction and maintenance of the devices or associated cables at or near the shoreline; and 2) indirect impacts due to a reduction in wave energy reaching the shore and nearshore waters. Decreased wave energy at the shore can result in changes in the profile of a beach and decreases in cross-shore and long-shore sediment transport. For both rocky intertidal and subtidal communities, a reduction in wave energy could influence species zonation, as well as species distribution and abundance. Additional effects could be caused by changes in disturbance regimes, sediment deposition, and flow characteristics of a site (Nelson et al. 2008).

The four types of WEC devices that could potentially be used within the study region (point absorbers, attenuators, overtopping devices, and oscillating water columns), will cause initial disruptions to the seabed due to drilling and/or anchoring, and the running of transmission cables to the shoreline. Some of these, such as overtopping devices, also have the potential to result

in entrainment (organisms are drawn in with seawater) or impingement (organisms are collected, typically on screens) of fish and invertebrates. Construction activities could also decrease photosynthesis by phytoplankton due to increased turbidity, as well as cause vibration and noise impacts. Additionally, release of exotic substances, such as chemicals or effluent, changes in electromagnetic fields, and the introduction of hard substrate to soft bottom habitats (i.e., essentially creating an artificial reef that would lead to the colonization of species associated with hard surfaces, including invasive species) can all have negative impacts on the nearshore marine environment (Nelson et al. 2008).

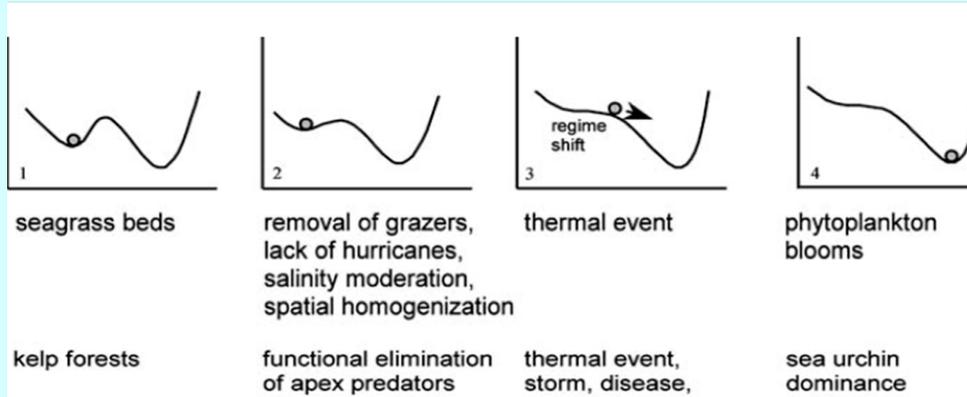
In addition, WEC devices could affect top predators in the marine ecosystem. Seabirds face the risk of collision with the devices both above and below the water's surface, as well as disturbance to breeding colonies, the release of oil or hydraulic fluids, and changes in prey base. Year round residents of the study region such as Common Murres, cormorants, and Marbled Murrelets have the greatest chance for negative impacts. Risks to marine mammals include: collision with the devices, disruption of migratory pathways, release of oil or hydraulic fluids, changes in food availability, disruption of sensory systems, and disturbance to haul-out and rookery sites. Of particular concern would be impacts from numerous large-scale wave parks along the California coast that could block the migratory pathway of the entire population of eastern gray whales (Nelson et al. 2008).

Offshore wind generated electricity poses similar potential threats to marine ecosystems as WECs during construction, operation, and decommissioning of turbines. Direct and indirect impacts can occur as a result of noise, interference with navigation from electromagnetic fields created by the electric cables, pollutants, disturbance to the seafloor, alteration of benthic habitat (i.e., the creation of an artificial reef), and collision. For seabirds, the risk of collision with wind turbine blades is of added concern, and birds may possibly need to exert more energy to avoid collisions and maintain their navigation while migrating (Minerals Management Service 2006).

**Comment:** Wind energy in this area is unlikely. Not sure the above paragraph is needed.

## Ecosystem Resilience

Ecosystem resilience is the extent to which ecosystems can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or unexpectedly flipping into alternate states (Hughes et al. 2005). Resilience and alternate states are often conceptualized with a ball model where the “valleys” represent different states and the adjacent “peaks” represent the activation energy needed to shift the system into an alternate state (Fig. 5.2). Resilient systems would sit deep within a valley, requiring large forcing to flip to an alternate state.



**Figure 5.2.** The conceptual “ball” and “valley” model of alternate stable states. 1) An initial state, 2) causes of a shift in state, 3) triggers of the state shift, 4) the end state. Folke et al. (2004).

Common marine examples of regime shifts include kelp forest transitions to urchin barrens and coral reefs that shift to algae dominated reefs. In these examples, state shifts were likely caused by the loss of resilience of the initial state by a variety of forces. These forces are natural and anthropogenic in nature and include: over-exploitation, pollution, natural disturbance, habitat destruction, and changes in water use (termed “gradual changes”, sensu Folke et al. 2004). It is not these forces that induce a regime shift, rather it is a trigger, often times a climate event such as a heat wave or storm. Therefore, measures to prevent regime shifts should focus on managing these gradual changes in order to maintain ecosystem resiliency in the face of global change (Folke et al. 2004). As a recent example of the importance of these gradual changes, Russell et al. (2009), demonstrate the combined effect of ocean acidification and nutrient pollution on the formation of sub-tidal algal turf in place of understory calcifying algae. The authors point out that while ocean acidification is beyond the control of managers; nutrient pollution is a stressor that can be addressed locally, potentially increasing the resiliency of these ecosystems.

## 7. Direct Impacts on Humans

In addition to a multitude of impacts on marine ecosystems, there are many effects climate change will have on human populations living and working along the coast. The focus of this document is not to provide a socioeconomic analysis of human impacts from climate change, yet they are important to note in this context as part of the larger biophysical system. Human impacts will lead to adaptive management and planning responses that in turn affect coastal ecosystems. Issues of particular concern in coastal communities include: water quality; health consequences of toxic algal blooms; shoreline safety; and economic impacts to natural assets (such as beaches) physical infrastructure (such as electrical utility facilities), residential and business infrastructure, and businesses that rely on ocean commodities such as fisheries.

### 7.1 Water Quality

Water quality within the study region is threatened by a number of factors including oil pollution, non-point source pollution, urbanization and watershed development. In 2005, it was estimated that 27 million gallons per day (mgd) of sewage and 406 million tons of sewage sludge per year was deposited directly into the Pacific Ocean in the San Francisco region (Heal the Ocean 2005). While the City and County of San Francisco discharges 18 mgd of secondary-treated sewage in deeper waters 3.75 miles offshore, Daly City discharges 6.8 mgd of secondary treated sewage only 2,500 ft. from shore in 32 ft. of water and Half Moon Bay discharges 22 mgd of secondary treated sewage only 1,900 ft. from shore in 37 ft. of water. In addition, a number of stormwater outfalls discharge combined effluent treated stormwater and treated sanitary flow directly onto beaches in San Francisco, resulting in periodic beach closures. As ocean temperature rises, the nutrient inputs from wastewater discharge to the ocean, may contribute to increased toxic algal blooms and poorer beach water quality. Flood waters from increasingly intense storms and early snowpack melt will carry a greater load of nutrients and contaminants into the Pacific Ocean.

Wastewater treatment and discharge infrastructure, as well as septic systems along the coastline will also be impacted by rising sea level, with deleterious effects on water quality within the study region. Combined (stormwater and sewage) wastewater transport facilities in Daly City (Vista Grande canal and tunnel) and in San Francisco (Westside transport/storage box under the Great Highway along Ocean Beach) would be impacted as sea level rise interferes with discharge from outfalls along the coast, or if increased storm intensity, storm surge and/or wave run-up inundate these storage and transport facilities beyond capacity. The Westside transport under the Great Highway, while buried 50 feet, is not reinforced to withstand coastal erosion and is only partially protected by existing seawalls (not designed to accommodate 1.4 m of sea level rise) seaward of the transport box. The Daly City outfall at Fort Funston is currently being re-designed where it has been exposed as a result of severe bluff erosion ( $2 \text{ ft yr}^{-1}$  over 50 years in the Merced formation). Twenty-two wastewater treatment facilities inside San Francisco Bay as well as the Mid-Coastside Sewer Authority treatment plant in Half Moon Bay, have been identified as vulnerable to sea level rise and could further degrade local waters if not mitigated (Heberger et al. 2009). Additionally, rising sea level is expected to inundate numerous hazardous waste sites within San Francisco Bay, and compromise levee systems in the Delta and Central Valley.

**Comment:** Although I think this section (Chapter 7) is excellent and comprehensive, authors should consider adding a few paragraphs that describe the controversies and consequences of humans attempting to cope with climate change. For example, issues associated with sea-level rise, coastal erosion and loss of recreational beaches, habitats and infrastructure, proposed coastal engineering and armoring, etc., will be hugely contentious and divisive. Solutions will not be arrived at cheaply and easily and there will be few “win-win” outcomes.

## 7.2 Health Consequences of Harmful Algal Blooms

Numerous septic systems exist directly adjacent to the study region at Stinson Beach, Seadrift Lagoon, and Tomales Bay and along the San Mateo and Sonoma County coastlines. Septic systems in sand substrates adjacent to beaches may add nutrients (particularly nitrogen and phosphorous) that can trigger harmful algal blooms (HABs) via submarine discharge of nutrient-enriched groundwater into the surf zone (de Sieyes et al. 2008). Other septic systems exist adjacent to creeks that drain to Tomales Bay or the ocean, or on bluff tops where seeps discharge onto Sanctuary beaches (for example at Muir Beach). Harmful algal blooms are increasing in frequency, intensity and duration in all aquatic environments on a global scale.

While only a small component of the phytoplankton community consists of harmful species, there are a number that produce poisoning syndromes in California. These include the following: diatoms from the genus *Pseudo-nitzschia*, which cause amnesic shellfish poisoning and have resulted in beach closures in California; dinoflagellates from the genus *Alexandrium* that constitute “red tides” and cause paralytic shellfish poisoning, resulting in closures to the shellfish industry in both California and in the Pacific Northwest; and species of cyanobacteria (blue green algae including *Anabaena* and *Microcystis*) found in fresh, brackish and marine waters that cause cyanobacterial poisoning. Blue green algae (BGA) blooms occur regularly in Rodeo Lagoon, and in coastal rivers in northern California where numerous dog deaths have been attributed to toxins associated with cyanobacteria (Humboldt County Department of Health and Human Services, 2006). BGA blooms usually occur in eutrophic waters associated with high nutrient loads (especially phosphorous) from agricultural or urban runoff, or failing sewage disposal systems. Future climate change scenarios all favor harmful BGA blooms in eutrophic waters (Pearl and Huisman, 2009). Humans and other animals are exposed to HAB toxins from eating contaminated fish or shellfish, drinking contaminated water, inhaling aerosolized contaminants (which can lead to respiratory illness<sup>6</sup>) during water-related activities, or by contacting contaminated water.

## 7.3 Shoreline Safety

Public safety along the outer coast will be impacted both by accelerated coastal cliff and bluff erosion, as well as by increased magnitude and frequency of winter storms with large waves, dangerous currents and increased water levels. The projected trends of increased storm energy are likely to result in more powerful rip currents as higher water levels set up stronger offshore flows. The increased overall wave energy may result in deeper, better defined, more stable and powerful rip currents (P. Barnard, *personal communication*), all of which can lead to increased drownings.

Every year hundreds of rescues occur when visitors, dogs and even horses get too close to the edge of coastal bluffs, or when people attempt to climb up and down steep cliffs. These accidents endanger or result in the death of visitors, but also endanger the rescuers. Helicopter rescues are often the only safe means of evacuating or recovering the victims; and may occur in sensitive resource locations. Bluff and cliff edges are attractive to visitors enjoying the scenery along the coast. Trails, roads and overlooks are often designed to provide these vistas. Coastal erosion is already reclaiming popular trails and roads in areas like Devil’s Slide, Fort Funston

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<sup>6</sup> Algal blooms have been documented in Florida to result in respiratory illness from breathing toxins at the seashore (Moore, 2008).

and the Marin Headlands. Maintenance is challenging or impossible resulting in closure and/or relocation of roads and trails. These trends, and associated exposure of visitors to dangerous conditions, are likely to increase greatly over the next century with projected climate change.

## 7.4 Economic Impacts

The north-central coast of California<sup>7</sup> thrives with abundant and diverse wildlife and natural beauty as well as important and diverse cities, towns, industrial communities and other built environments. As scientists release climate change impact scenarios for this region, it becomes possible to identify where losses might be greatest and to plan mitigation strategies.

With a total population of 2,576,559 in the six coastal counties within the study region, and population densities ranging from 24.6 people/square mile in Mendocino County to more than 17,000 people/sq. mile in San Francisco County (Kildow et al, 2008), this unique area has a high percentage of population and structures at risk from a 100-year flood with a 1.4 meter sea level rise along the Pacific Coast (Heberger, et al, 2009).<sup>8</sup> This section provides an overview for short- and long-term economic impacts that will affect those who live and work along the north central coast. While there are several types of potential costs that will be incurred from climate change impacts to this area, this section focuses on the current values of what could be at risk, and the implicit replacement values for these assets should they be lost.<sup>9</sup>

Three types of economic values can be estimated that relate to projected climate change impacts along California's north central coast: 1) natural assets not traded in the market place, such as beaches, estuaries, watersheds, natural harbors, and designated state parks; 2) large and essential physical infrastructure such as electrical utility facilities, waste disposal and waste treatment plants, water delivery systems, refineries, and transportation infrastructure, such as airports, seaports, railroads, surface highways and streets, and telecommunications facilities; and 3) business, industrial and residential structures, the taxes they generate, and their human dimensions of jobs, wages, and business productivity that generate local, state and federal revenues. In this third category, the fishing industry—commercial and recreational—and the tourism industry are particularly tied to the local economies of the region. For San Francisco County, the transportation sector also is very important.

### 7.4.1 Natural Assets

Beaches are one of California's most valuable assets (Pendleton and Kildow 2006). While it is difficult to put a dollar value on the beaches for the North Central Coast, it is safe to say that inundation and erosion of popular beaches could remove millions of dollars of annual local and visitor revenue. Millions of dollars already have been spent on estuary restoration in San Francisco Bay to enhance biodiversity and fisheries, improve water quality, and provide buffers for storms. The added value of expensive residential and commercial shorefront developments to some of these areas and the benefits derived from estuaries could be significantly lost with rising sea levels as there is no place for an estuary to move other than upland toward developments.

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<sup>7</sup> This report considers the counties of Santa Cruz, San Mateo, San Francisco, Sonoma, Marin and Mendocino. Included is the west shoreline of San Francisco Bay. Reference is also made to the eastern shore of San Francisco Bay, where several large ports are sited. Additional data is available for this area.

<sup>8</sup> Similar population densities are located along the east shore of San Francisco Bay.

<sup>9</sup> Other potential costs include costs of mitigation to prevent damage or harm to assets, and costs of investments that are needed for the future to adapt to new conditions caused by climate change, which are not covered in this paper.

### 7.4.2 Physical Infrastructure

As a result of climate change, large, essential parts of public infrastructure will either need to be relocated over time or armored and protected. These decisions will depend on important cost-benefit assessments of the best way to sustain their functions despite changes in water levels and climate. Costs of relocation need to be weighed against costs of retrofitting to strengthen resiliency and/or armoring of these structures. According to Heberger et al. (2009), the capacities of vulnerable power plants along the entire California coast range from very small plants to plants generating more than 2,000 megawatts. The majority of these plants are located in Southern California and around San Francisco Bay. The authors conclude the power plants and sewage treatment facilities in this region that are subject to high-risk warrant immediate consideration.

In addition, Heberger et al. (2009) estimate that along the Pacific coast, 52 miles of roads and highways in Marin County, 50 miles in San Francisco County, and 105 miles in San Mateo County, are vulnerable to erosion and flood from a 1.4 m rise in sea level (combined with a year 2000 100 year flood elevation). The San Francisco and Oakland airport runways would lie below the projected 1.4 m sea level rise by 2100. Sea level rise could directly affect shipping and port facilities and operations at the Port of Oakland with serious impacts to the Bay Area economy. Bridge clearances may be reduced, limiting the size of ships able to pass or restricting movement to low tides and rail and road corridors to and from the port may be flooded. Ship channel dredging and dredge spoil disposal will likely increase, at increased cost, as more intense storms convey greater volumes of sediment into San Francisco Bay.

Structural coastal protection measures including beach nourishment, jetties and groins, seawalls, bulkheads and revetments, breakwaters, dikes and levees and their effectiveness could also be impacted as sea level rises. Impacts may include: flanked or overtopped groins; fixed shoreline positioning due to coastal armoring, that could result in the drowning of adjacent beaches and loss of recreation opportunities; a reduction in the ability of breakwaters to reduce wave heights and littoral drift; and a reduction in the stability of dikes and levees. Many of these types of structures exist within or adjacent to the study region, such as in Bodega Bay, Bolinas Lagoon, Ocean Beach in San Francisco, and Pacifica. Experimental beach nourishment is currently ongoing at Ocean Beach (Barnard, et al. 2009). An inventory in 1998 determined that 2% of the Marin coastline, 17% of the San Francisco shoreline and 11% of the San Mateo coastline was armored (Griggs, 1998). Heberger, et al (2009) also estimates that approximately 4,000 property parcels in Marin, San Francisco and San Mateo are located within the projected erosion hazard and 1.4 m sea level rise zone. Many of these would be completely lost to accelerated coastal erosion.

### 7.4.3 Business and Residential Infrastructure

In 2007, the six counties within the study region provided 1,330,964 jobs (8.7% of the state), paid \$85.9 billion in wages (11.2% of the state), and generated over \$225.9 billion in direct productivity for California (Kildow et al. 2008). Business and residential structures and their contents that lie in the path of rising seas pose complex economic considerations (Heberger et al. 2009) including: 1) potential costs of repair and replacement of damaged and destroyed buildings must rely on non-uniform data on real estate sales estimates and taxes; 2) the cost of damage to building contents can only be estimated from insurance estimates; 3) loss of inventories can only

be estimated from insurance losses and lost productivity; and 4) potential loss of jobs/employment are mostly uninsured losses and have large ripple effects.

The leisure and hospitality (or tourism) industry in the six counties was worth approximately \$7.8 billion in 2007, producing more than \$4 billion in wages and almost 165,033 jobs. The same year, the transportation and utilities sector was a \$25 billion industry with \$10 billion in wages and 217,000 jobs in these counties (not counting seaport revenues from the three largest ports in the Bay Area, Richmond, Oakland and San Francisco). Financial activities, including real estate, accounted for \$86 billion with \$14 billion in wages and 100,000 jobs (Kildow et al. 2008).

#### 7.4.4 Tourism and Fisheries

Tourism is a large part of the local economy within the study region with activities including beachgoing, coastal hiking, kayaking, boating, fishing, whale watching, birding, and tidepooling. Curtis et al. (2009) compare the tourism industry to that of the agriculture and transportation industries, as it too is a “highly climate-sensitive economic sector,” stating that tourists base their travel decisions on their perception of weather conditions and climate. Changes to the food web, as well as increased coastal fog and storminess can have a large effect on the local tourism industry. One survey performed in North Carolina, found that beachgoers were actually more influenced by factors such as wind and cloud cover as opposed to heat (Curtis et al. 2009). Business such as recreational fishing and whale watching operations could be negatively impacted by both changes to the food web and increased fog and storminess. It is known that climate variability and changing weather patterns over the short term have an effect on tourism. What is not well understood yet is how long term changes in climate will affect the overall sustainability of tourism business operations (Curtis et al, 2009).

The fishing industry is critically important in some coastal communities within the study region. Both recreational and commercial fishing bring important revenues that sustain communities that are less economically diversified than those in urban areas. Changing climatic variables could affect the catch significantly. San Francisco, one of the larger fishing harbors in the state, landed fish valued at \$21,727,957 in 2006 – 18% of the total landed value of fish caught in California that year (Kildow et al. 2008).

Ocean acidification could negatively affect the shellfish industry and result in economic impacts to individuals such as oyster growers and crab fishermen. Cooley and Doney (2009) estimate that potential losses to the U.S. shellfish industry due to ocean acidification could reach \$860 million/year. Depending on the extent of the local economy or fisheries dependent on shellfish, the losses to local regions could be enormous. As stated by Cooley and Doney (2009), “Expanding job losses and indirect economic costs will follow harvest decreases as ocean acidification broadly damages marine habitats and alters marine resource availability. Losses will harm many regions already possessing little economic resilience.” However, according to this report, the Pacific Region will suffer less loss than other U.S. coastal regions, so counties within the study region will experience loss, but possibly to a lesser degree than other areas.

Salmon are especially vulnerable to changes in conditions throughout coastal and ocean ecosystems. Climate-induced effects on watersheds, rivers, estuaries, and ocean ecosystems may already be affecting salmon species, particularly in stream systems with already low populations.

Both commercial and recreational salmon fisheries have suffered as a result of recent fishing closures along the central California coast. Coho salmon have suffered two years in a row as a result of winter drought, and some year classes are particularly threatened in Redwood and Pine Gulch in Olema and Lagunitas Creeks in Marin County.

DRAFT

## 8. Conclusion

It is clear that the marine environment within the study region will evolve as global climate changes. These environmental changes impact marine populations and coastal ocean ecosystems, as well as ocean-human interactions, presenting challenges for managing Gulf of Farallones and Cordell Bank National Marine Sanctuaries. While there are early observations of change (e.g., rising sea level in San Francisco Bay) and models of physical processes, we are far from any true predictive capability – and it is unlikely that we will ever be able to fully predict future states of a system as complex as the coastal ecosystem within the study region. Yet, we have to understand the range of potential impacts and be prepared to take action by adaptively managing how humans interact with this remarkably productive natural system, and optimizing the benefits of change while mitigating the negative impacts. Our present knowledge is briefly reviewed in this report and science-based expectations are outlined. A risk-assessment approach directs emphasis, giving primary attention to changes that are either (i) likely to occur, or (ii) likely to have high impact if they occurred.

**Comment:** Model versus empirical

The outline and logic of the report is to work from global-scale changes in the atmosphere-ocean system to regional and local changes in habitat and ecological communities within the study region (Point Arena to Año Nuevo). Systemic global change is carefully outlined in the 2007 IPCC assessment and serves as a starting point for identifying and understanding large-scale change. In short, the atmosphere is warming due to a dramatic increase in greenhouse gases. While the ocean buffers the atmosphere, there are now clear indications of the ocean warming and being enriched with CO<sub>2</sub> – providing multiple mechanisms by which a specific region can be impacted. The study region is subject to changes in physical and chemical forcing as a result of these global changes and the ultimate impact on regional ecology will be due to an interaction of multiple forcing mechanisms and biological responses of specific populations and communities. Changes are anticipated in atmospheric conditions (e.g., wind, cloud, fog), ocean circulation and water properties (e.g., temperature, pH), *sea level*, ocean waves, and land runoff. In turn, changes in these forcing factors will lead to changes in coastal upwelling, stratification, and plankton dispersal patterns. Biological systems will be impacted through changes to the quality of ocean habitat (e.g., changes in temperature, pH, dissolved oxygen, nutrient availability and wave exposure), the timing of seasonal cycles (e.g., upwelling, runoff, fog and waves), and the connectivity within and between populations. Community response scenarios are described for offshore pelagic, offshore benthic, offshore island, sandy beach, rocky intertidal, nearshore subtidal, and estuarine habitats.

In parallel with climate-related changes, there are a myriad of other causes of environmental change due to human activity at the local scale (e.g., pollution, fishing, invasive species, disease). These are briefly reviewed in this report, as these are stressors that can be managed. It can be argued that change is not necessarily bad for all, but it is true that change will require populations and communities to adapt. To be able to adapt, persist, and remain vital, these marine populations and communities will need enhanced resiliency, which can be provided through a reduction in managed stressors. In the end, it is humans that will benefit significantly from an ocean environment that can continue to provide the goods and services that it has provided for millennia.

The conclusions of this report are that the most severe ecological changes will be associated with changes in the following parameters – for each the likelihood of change is high and the impact of change is equally high (i.e., these are high-risk phenomena):

- Upwelling
- Ocean temperature
- Sea level
- Ocean pH

Upwelling appears to be increasing in this region, due to a more rapid increase in land temperature than ocean and an associated increase in summer atmospheric pressure gradients that drive the strong northerly winds off northern and central California. Both model and data analysis support this assertion. Further, given that this region is characterized by upwelling processes and populations, the impact of any change in upwelling (and thus nutrient delivery) will ripple through the whole ecosystem. However, it also appears that surface waters are warming outside of the active upwelling zones that are found over the continental shelf – which means both offshore waters and waters in bays and estuaries are warming. In addition to direct thermal effects on organism physiology, warmer surface waters result in enhanced stratification offshore being observed offshore and a reduction in the vertical mixing that underpins offshore primary production.

The primary cause of sea level rise is the global increase in ocean temperatures. In addition to being well documented in IPCC assessments, data at the mouth of San Francisco Bay show a 7-inch rise in sea level over the last century. Sea level rise directly affects intertidal communities in estuaries as well as on rocky and sandy shorelines, but it also increases the risk associated with storm wave events, which heavily impact human activities and shoreline ecosystems.

**Comment:** See page 37 of this document. The 2007 IPCC sea level rise estimates were indeed based primarily on projected increases in ocean temperatures. Subsequent significant increases in sea level rise estimates (e.g., Rahmstorf and other refs. cited herein) are derived from adding the important ice-melt component.

Finally, the acidification of ocean waters has recently been called “the other CO<sub>2</sub> problem” in recognition of the immensity of this threat. Alone, acidification may seriously alter coastal ecosystems as we know them. Decreasing pH (increasing acidity) will preclude many organisms from forming calcium carbonate structures, like shells and exoskeletons. Deep upwelled waters are more acidic than most of the surface ocean and this region is thus threatened by the double effect of increased dissolved CO<sub>2</sub> in the ocean plus increased upwelling in this region. It is quite possible that the “saturation horizon” will shoal to depths where it can impact the near-surface ecosystem, making this region uninhabitable for numerous key invertebrate populations. Having highlighted these parameters, it is important to realize that we may yet be surprised and find that changes in other parameters like fog and cloud cover, or dissolved oxygen, or dispersal patterns, or trophic landscape connectivity plays a critical role in the trajectory of ecosystem change. Clearly, in understanding a changing system, one has to reduce the complexity of analysis, but one cannot focus exclusively on the high-risk phenomena.

## 8.1 Working Group Recommendations

The question that now arises is, “what should we do?” Based on the immensity of ocean systems, even small coastal ones, and aware of the uncertainty in anticipating how global changes will downscale to regional and local change, the working group recommends that the Gulf of Farallones and Cordell Bank National Marine Sanctuary Advisory Councils recommend GFNMS and CBNMS pursue five lines of action:

➤ **Educate** – *inform people to allow optimum decisions to be made.*

Use the opportunities inherent in the National Marine Sanctuary System to educate both local residents and federal/state/local decisions makers. Education is not intended to prescribe options, but to provide people with the insight that will optimize difficult decisions, including use of public funds and regulation of activities in developing a strategy for minimizing disruptions to ecosystems and socio-economic systems due to climate change.

- Citizen science
- Outreach through exhibits & lectures
- Web presence

**Comment:** “Collaborative fisheries” seems out of place – why singled out here?

➤ **Advocate** – *link greenhouse gas emissions with marine ecosystem health.*

The IPCC has made it clear that observed changes in global climate are due to a buildup in greenhouse gases (GHG). Further, there is a long-term commitment to climate change due to the delay between increases in GHG concentration and responses in atmosphere and ocean conditions. Our actions now will have huge benefits in mitigating climate change impacts on human society and ecosystems decades from now.

- Interpret global assessments in terms of local ecosystem threats
- Work with partners regionally and globally to abate the increase in greenhouse gas concentrations

**Comment:** I’m struggling with whether this is the responsibility of the sanctuaries. The sanctuaries can help adapt and mitigate impacts by making management decisions that take into consideration climate change. They can also ‘work with partners regionally and globally to explain the linkages between GHG emissions and marine ecosystem health to the public and our decision makers. But ‘abating the increase in GHGs’ is the responsibility of local, state, and national governments, international negotiations, businesses, and individuals.

➤ **Anticipate** – *obtain best available information on changing and future conditions.*

The primary antidote to uncertainty in predictions is to maximize certainty in real-time assessments. The most critical action is to know how the environment and ecosystems are changing, and to know how these changes relate to global climate change (as opposed to other local drivers of environmental change). *Available information and modeling may not be perfect, but it can be much improved with strategic investment in monitoring and assessment. Given that sanctuaries are seen as sentinel sites, this is where GFNMS and CBNMS can play a leadership role in collaboration and community building with other federal, state, and local agencies, academia, and regional groups.*

**Deleted:** Our

- Monitor the environment. Through collaboration with CeNCOOS and PaCOOS, develop a set of strategic monitoring activities that can reasonably track the pulse of the environment. This would include fixed stations, boat-based surveys and remote sensing (e.g., satellites and HF radar) to monitor water properties, currents and plankton.
- Monitor populations. Through collaboration with resource agencies (e.g., CDFG, *CA Monitoring Enterprise*, NMFS, *USFWS*, *USGS*) and research groups (e.g., *CalCOFI*, *PISCO*, etc....) develop annual assessments of changes in fish, bird and mammal population. In addition, develop collaborative assessments of habitat-defining populations such as krill and macrophytes (e.g., kelp & seagrass).
- Annual assessment. Building on updated global and eastern Pacific regional assessments of climate change, develop an annual assessment of changing conditions and anticipated future change for the study region. These assessments will include data on environment and ecosystem conditions in addition to the results of down-scaling models. The initial assessment should include a schematic view of the ecosystem components and processes.

**Comment:** Not sure if this is the right place for this comment, but I think the NMS can have a significant role in building a community of interested entities (e.g., the BAEC) to deal with climate change issues and impacts. This is a good section for identifying many important partners

**Comment:** This bullet is very oddly limited. Things that could be added: (1) monitor local sea level rise; (2) monitor shoreline change – beaches and cliffs (with USGS); (3) monitor benthic habitats – building on recent baseline developed by CA Seafloor Mapping Program (with USGS, NOAA NOS, academia); (4) monitor wave climate (CeNCOOS, CDIP); (5) monitor weather (e.g., T°, fog, storm frequency), precipitation, coastal watershed discharge (local agencies, USGS, others). Etc.

**Comment:** Developing a meaningful annual assessment will be a massive undertaking. Good idea, but don’t underestimate the time and resources this will require.

➤ **Mitigate** – reduce manageable stressors that compromise system resiliency.

While climate change cannot be managed *or diverted* in the short-term, we can enhance the resiliency of coastal ecosystems to handle this environmental change. Resiliency suggests a complex system that can adapt to change – typical attributes of such a system include being modular and heterogeneous, and having tight feedback loops and redundancy. This system understanding is developing rapidly through the promotion of ecosystem-based management (EBM). The sanctuaries are important players in developing EBM for this region and can play an increased leadership role if supported in this.

**Deleted:** nor diverted,

- Develop an assessment of ecological goods and services in this region.
- Develop an assessment of stressors that are constraining the “breathing room” of these coastal ecosystems; identify strategic opportunities to reduce manageable stressors and motivate this action in terms of the reduced risk of losing critical ecological goods and services.
- Work with regional partners to develop EBM for this region.
- Prioritize wetland restoration to sequester greenhouse gases.

**Comment:** Although I like this wetland restoration/sequestration idea a lot, I think it is odd to read about it for the first time in the Conclusions. The issue should probably be discussed in Section 5.7.

➤ **Adapt** – create policies and management strategies that are flexible to future changes.

As we identify future problems, we need to adapt our way of thinking as well as the way we engineer human infrastructure to minimize future impacts. For example, within sanctuary jurisdiction, policies such as a preference for realigning the coast or removal of shoreline armoring should be developed to help nearshore and estuarine habitats adapt to sea level rise.

Action amongst government agencies, non-profit organizations, academia, businesses, and individuals is necessary now to ensure viable ocean ecosystems in the future. As this document serves as a baseline for understanding relevant climate change impacts to habitats and biological communities within the study region, sanctuary management will use this information to begin identifying priority management actions that will be taken over the next 10 years to address the impacts of climate change along the north-central California coast.

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**Comment:** KH: I believe one standard is that you can state "et al" after listing 3 authors in the references. It looks like we have multiple instances of this. Is it ok to keep or do we need all of the authors listed?

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## Appendix 1: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries

The National Marine Sanctuary System consists of 14 marine protected areas that encompass more than 150,000 square miles of marine and Great Lakes waters from Washington State to the Florida Keys, and from Lake Huron to American Samoa. The system includes 13 national marine sanctuaries and the Papahānaumokuākea Marine National Monument (ONMS 2006). The study



**Figure 1A:** Cordell Bank, Gulf of the Farallones and northern jurisdictional area of Monterey Bay National Marine Sanctuaries. T. Reed (2008).

region for this document are the waters off north-central California, from Point Arena to Año Nuevo, within which Gulf of the Farallones and Cordell Bank National Marine Sanctuaries are found. The boundaries of these sanctuaries are also located within the California Current ecosystem, one of four major eastern boundary currents in the world, that stretches along the western coast of North America from southern Canada to northern Mexico. Due to a high degree of wind-driven upwelling, there is a ready supply of nutrients to surface waters and the California Current ecosystem is one of the most biologically productive regions in the world.

Designated in 1981, Gulf of the Farallones National Marine Sanctuary (GFNMS) spans 1,279-square-miles (966 square nautical miles) just north and west of San Francisco Bay, and protects open ocean, nearshore tidal flats, rocky intertidal areas, estuarine wetlands, subtidal

reefs, and coastal beaches within its boundaries. It is a globally significant, extraordinarily diverse and productive marine ecosystem that supports abundant wildlife and valuable fisheries. The sanctuary provides breeding and feeding grounds for at least twenty-five endangered or threatened species; thirty-six marine mammal species, including blue and humpback whales, and seals; over a quarter-million breeding seabirds; and one of the most significant white shark populations on the planet. In addition, GFNMS has administrative jurisdiction over the northern portion of the Monterey Bay National Marine Sanctuary, from the San Mateo/Santa Cruz County line northward to the existing boundary between the two sanctuaries and maintains offices in both San Francisco and Half Moon Bay.

Cordell Bank National Marine Sanctuary (CBNMS) is comprised of the extremely productive offshore waters surrounding the Cordell Bank seamount and extending offshore beyond the shelf edge, to depths of 1000 fathom (1829 m). The southern and eastern boundary of CBNMS is shared with the Gulf of the Farallones National Marine Sanctuary. Cordell Bank is a 4.5 mile (7.2 km) by 9.5 mile (15.2 km) rocky undersea feature located 18 miles (29 km) west of the Point Reyes headlands. It rises abruptly from the soft sediments of the shelf to within 115 feet (35 m) of the ocean surface. The sanctuary protects a total area of 529 square miles (1369 square km). Seasonal upwelling drives an annual productivity cycle at Cordell Bank that supports a rich biological community, including local species as well as migratory sea turtles, fishes, seabirds and marine mammals that travel thousands of miles to feed around the bank. The combination of a healthy benthic community on the bank and its close proximity to offshore, open water species contributes to the unique biological diversity in a relatively confined area around Cordell Bank.

## Glossary

- Accretion:** the accumulation of sediment, deposited by natural fluid flow processes
- Amplitude:** the magnitude of change in a wave; one half the wave height
- Anthropogenic:** effects, processes or materials derived from human activities
- Aragonite:** a carbonate mineral; one of the two common (the other is calcite) naturally occurring polymorphs of calcium carbonate
- Biodiversity:** the variation of life forms within a given ecosystem, biome, or for the entire Earth
- Bottom-up:** nutrient supply and productivity and type of primary producers (plants and phytoplankton) are controlling the ecosystem structure
- C3 plants:** over 95% of earth's plant species; use rubisco to make a three-carbon compound as the first stable product of carbon fixation; flourish in cool, wet, and cloudy climates, where light levels may be low, because the metabolic pathway is more energy efficient, and if water is plentiful, the stomata can stay open and let in more carbon dioxide, however, carbon losses through photorespiration are high
- C4 plants:** less than 1% of earth's plant species; possess biochemical and anatomical mechanisms to raise the intercellular carbon dioxide concentration at the site of fixation, and this reduces, and sometimes eliminates, carbon losses by photorespiration; inhabit hot, dry environments, have very high water-use efficiency, so that there can be up to twice as much photosynthesis per gram of water as in C3 plants, but C4 metabolism is inefficient in shady or cool environments
- Calcite:** the most stable polymorph of calcium carbonate
- Carbon cycle:** The carbon cycle is the biogeochemical cycle by which carbon is continuously exchanged among Earth's five major reservoirs of carbon (biosphere, pedosphere, geosphere, hydrosphere, and atmosphere)
- Carbon sink:** a natural or manmade reservoir that accumulates and stores some carbon-containing chemical compound for an indefinite period
- Climate change:** a change in the statistical distribution of weather over periods of time that range from decades to millions of years; it can be a change in average weather or a change in the distribution of weather events around an average (i.e. greater or fewer extreme weather events)
- Congener:** another organism within the same genus
- Conspecific:** another organism within the same species
- El Niño Southern Oscillation (ENSO):** a condition of decreased westward winds over the equatorial Pacific. This results in warm waters in the eastern Pacific that reduce nutrient availability, having significant consequences for coastal fisheries of western North and South America.
- Elevational range:** the component of a species range in terms of the elevation or altitude it occupies

**Extratropical Cyclones:** a type of storm system formed in middle or high latitudes, in regions of large horizontal temperature variations called frontal zones; they present a contrast to the more violent cyclones or hurricanes of the tropics, which form in regions of relatively uniform temperatures

**Frontogenesis:** the formation or strengthening of an atmospheric front

**Forcing (climate):** altering the global energy balance and “forcing” the climate to change through mechanisms such as variations in ocean circulation and changes in the composition of the Earth’s atmosphere, which can occur naturally or be human induced (i.e. through greenhouse gas emissions)

**Greenhouse gases:** naturally occurring gases in the atmosphere that absorb and emit radiation within the thermal infrared range to cause the “greenhouse effect”; without them the Earth would be about 59° F warmer than at present; the main gases are water vapor, carbon dioxide, methane, nitrous oxide, and ozone; since the start of the Industrial Revolution, human activities have increased the levels of greenhouse gases in the atmosphere

**Groin:** a shore-protection structure (built usually to trap littoral drift or retard erosion of the shore). It is narrow in width (measured parallel to the shore) and its length may vary from tens to hundreds of meters (extending seaward).

**Heat shock protein (HSP):** molecular chaperone that modifies the shape and accumulation of other proteins

**Hyper-nutrient:**

**Interannual (time scale, variability):** Variation that occurs predominantly between years.

**Interdecadal (time scale, variability):** Variation that occurs predominantly between decades.

**Keystone species:** a species that has a disproportionate effect on its environment relative to its biomass; such species affect many other organisms in an ecosystem and help determine the types and numbers of various other species in a community

**Littoral Cell:** a natural system of beach sand, constrained by headlands and submarine canyons with a variety of sediment sources and sinks that affect the overall sediment budget

**Macroalgae -** large aquatic photosynthetic plants that can be seen without the aid of a microscope

**Mesotidal:** two to four metres of tidal range; used to classify coasts based solely on tidal range without regard to any other variable

**Microtidal:** less than two meters of tidal range; constitute the largest percentage of the world’s coasts

**North Pacific Gyre Oscillation (NPGO):** Describes fluctuations in sea surface height and temperature data across the northeastern Pacific in combination with the PDO; while the PDO is the dominant signal in physical parameters like temperature and sea level, the NPGO correlates well with salinity, nutrient concentrations and phytoplankton chlorophyll, suggesting a closer relationship to nutrient fluxes and ecosystem productivity

- North Pacific High (NPH):** a semi-permanent, subtropical area of high pressure in the North Pacific Ocean; strongest in the Northern Hemispheric summer and displaced towards the equator during the winter when the Aleutian Low becomes more dominate
- Oligotrophic:** an ecosystem or environment offering little to sustain life; commonly used to describe bodies of water or soils with very low nutrient levels
- Pacific Decadal Oscillation (PDO):** a longer-term fluctuation in ocean climate that changes state approximately every 20-40 years
- Phenology:** the study of periodic plant and animal life cycle events and how these are influenced by seasonal and interannual variations in climate
- Population Connectivity:** the exchange of individuals between geographically isolated sub-populations through mechanisms such as larval dispersal or migration
- Saturation depth (horizon):**
- Saturation state:**
- Significant wave height ( $H_s$ ):** the average height of the one third highest waves.
- Stratification:** the building up of layers
- Stressor:** an agent, condition, or other stimulus that causes stress to an organism
- Thermocline:** a thin but distinct layer in a large body of fluid (e.g. water, such as an ocean or lake, or air, such as an atmosphere), in which temperature changes more rapidly with depth than it does in the layers above or below; in the ocean, the thermocline may be thought of as an invisible blanket which separates the upper mixed layer from the calm deep water below
- Top-down:** top predators are controlling the structure/population dynamics of the ecosystem
- Turbulence:**
- Uptake:** an act of taking in or absorbing
- Upwelling:** results from the offshore transport of near-surface water due to alongshore winds from the north and the influence of the earth's rotation (known as Ekman transport), this water is replaced with cold, salty, nutrient-rich water from depths below.
- Wind curl (stress):** the drag or tangential force per unit area exerted on the surface of the earth by the adjacent layer of moving air
- Wind shear:** a change in wind direction and speed between slightly different altitudes, especially a sudden downdraft