CLIMATE CHANGE IMPACTS

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GULF OF THE FARALLONES AND CORDELL BANK

NATIONAL MARINE SANCTUARIES

Report of a Joint Working Group of the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries Advisory Councils

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Executive Summary

On global and regional scales, the ocean is changing due to increasing atmospheric carbon dioxide (CO_2) and associated global climate change. Regional physical changes include sea level rise, coastal erosion and flooding, and changes in precipitation and land runoff, ocean-atmosphere circulation, and ocean water properties. These changes in turn lead to biotic responses within ocean ecosystems, including changes in physiology, phenology, and population connectivity, as well as species range shifts. Regional habitats and ecosystems are thus affected by a combination of physical processes and biological responses. While climate change will also significantly impact human populations along the coast, this is discussed only briefly.

Climate Change Impacts, developed by a joint working group of the Gulf of the Farallones (GFNMS) and Cordell Bank (CBNMS) National Marine Sanctuary Advisory Councils, identifies and synthesizes potential climate change impacts to habitats and biological communities along the north-central California coast. This report does not assess current conditions, or predict future changes. It presents scientific observations and expectations to identify potential issues related to changing climate – with an emphasis on the most likely ecological impacts and the impacts that would be most severe if they occur. *Climate Change Impacts* provides a foundation of information and scientific insight for each sanctuary to develop strategies for addressing climate change. These strategies will outline priority management actions for the next 10 years to address the impacts of climate change specific to the site, its communities, and the region.

Key Issues

⇒ Observed increase in sea level (100 year record at mouth of San Francisco Bay)

⇒ Expected increase in coastal erosion associated with changes in sea level and storm waves

⇒ Observed decrease in spring runoff of freshwater through San Francisco Bay (decreased Sierra snowpack)

⇒ Observed increase in precipitation variability (drier dry years, wetter wet years)

⇒ Observed increase in surface ocean temperature offshore of the continental shelf (50 year record)

⇒ Observed increase in winds driving coastal upwelling of nutrient-rich waters and associated observed decrease in surface ocean temperature over the continental shelf (30 year record)

⇒ Observed increase in extreme weather events (winds, waves, storms)

⇒ Expected decrease in seawater pH, due to uptake of CO_2 by the ocean

⇒ Observed northward shift of key species (including Humboldt squid, volcano barnacle, gray whales, bottlenose dolphins)

⇒ Possible shift in dominant phytoplankton (from diatom to dinoflagellate blooms)

⇒ Potential for effects of climate change to be compounded by parallel environmental changes associated with local human activities

Physical Effects of Climate Change

The observed rise in *sea level* at the mouth of San Francisco Bay over the last century is 20 cm, and this rise is expected to continue. The State of California is using a projection of 40 cm rise in sea level by 2050 and 140 cm by 2100 for planning purposes. However, the most recent sea level rise analysis projects 75 to 190 cm respectively. The rise in sea level exacerbates 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).

As a result of rising sea level, together with more intense precipitation/runoff events and an increase in extreme wave and storm conditions, an increase in *coastal erosion* is expected. If sea level rises 1.4 m by 2100, scientists project that the total erosion area for the five counties along the study region will reach nearly 50 km^2. Coastal habitats may be directly affected by erosion through habitat loss, or indirectly via human responses such as coastal armoring, beach nourishment, or planned retreat (see 3.5 Coastal Erosion).

Climate-related changes in *precipitation and runoff* are primarily related to reduced snowpack due to warmer winter storms. Reduced Sierra snowpack will result in stronger winter runoff events and reduced spring runoff through San Francisco Bay. In smaller coastal watersheds, as well, more extreme winter precipitation events are expected. Further, it is projected that there will be a greater variability in annual precipitation during the 21st century (i.e., drier dry years and wetter wet years). In turn, these changes in runoff can be expected to lead to increased flooding of coastal lowlands, erosion of estuarine habitats, increased delivery of watershed material to the ocean, expanded plume areas, and increased nearshore stratification (see 3.2 Precipitation and Land Runoff).

Surface *ocean temperatures* have increased in the North Pacific, offshore of the north-central California continental shelf. This increase in temperature has significant effects on water column structure (i.e., stratification), sea level rise, and ocean circulation patterns. While sea temperature also appears to have increased in shallow bays, estuaries and sheltered nearshore locations, waters over the north-central California continental shelf have cooled over the last 30 years (by as much as 1°C in some locations) due to stronger and/or more persistent *upwelling winds* during spring, summer and fall (see 3.6.1 Temperature; 3.5 Coastal Upwelling).

Stronger *alongshore winds* are expected as a result of an increasing difference in land-ocean atmospheric pressure associated with an increasing difference in land-ocean temperature as climate warms. These stronger winds push surface waters away from the coast more rapidly and force a stronger upwelling of deep, cold, nutrient-rich waters along the coast. This upwelled supply of nutrients is the foundation of the high biological productivity of the ocean in the study region. Both the strength of upwelling winds and the variability in winds affect the amount of primary production available, and the amount delivered to coastal ecosystems rather than offshore ecosystems. Enhanced upwelling results in less phytoplankton availability in coastal waters and a greater but more diffuse supply of phytoplankton to offshore waters. Further, there is preliminary evidence that upwelling will also be more persistent, extending into the fall – but results from analyses of changes in the start of the upwelling season ("spring transition") are mixed (see 3.5 Coastal Upwelling).

In addition to the increase in average coastal winds during spring, summer, and fall, data from the San Francisco tide gauge (from 1858 to 2000) show an increase in intense *winter storms* since 1950, consistent with an observed increase in the largest waves (see 3.3.2 Waves). Coastal flooding events that were previously 1-in-100 events are now projected to occur with a probability of 1-in-10 years (see 3.1 Atmosphere).

Coastal waters are expected to become more acidic as *pH is lowered* in response to increased concentration of carbon dioxide in ocean waters. While data and model studies are insufficient to be certain how pH will change in the study region, this phenomenon is critical, as it will decrease the availability of chemical building blocks for marine life with shells and skeletons made out of calcium carbonate. Ocean acidification leads to decreased shell growth in key species such as sea urchins, mussels, oysters, abalone, and crabs, thus making the animal more susceptible to predation, as well as decreased skeleton production of deep sea corals and hydrocorals. As deeper water tends to be more acidic already, deepwater corals such as the hydrocorals located at Cordell Bank may be one of the first to experience deleterious effects of acidification. Also, of particular concern are the larval and juvenile stages of these organisms, which may be more susceptible to ocean acidification due to their small size. In addition, there is concern for negative effects on shell-building plankton at the base of the food web (see 3.6.2 Ocean Acidification; 4.1 Physiology; 5.3 Invertebrates).

In addition to trends in the physical climate, natural climate fluctuations occur in association with El Niño and other phenomena, e.g., Pacific Decadal Oscillation (PDO). The combination of climate change trends with this natural variability may create new extreme conditions. For example, high waves that occur during El Niño events are likely to be more extreme when combined with higher sea level and increased wave heights due to climate change. Similarly, during the positive phase of the PDO, the trend for warmer weather with increased rain, runoff and waves will be enhanced; whereas climate-change trends will be temporarily alleviated during the negative phase of the PDO, yielding periods in which climate change appears to have stalled only to be followed by years of apparently rapid climate change (see 3.0 Physical Effects of Climate Change).

Marine Species Respond

Physical changes in sea level, winds, waves, temperature, pH, and runoff may influence a variety of critical biotic processes, such as metabolic rates, planktonic transport, prey availability, and/or predation rates (see 5.0 Responses in Marine Organisms). The response of a single species to climate change depends not only on environmental changes, but also upon how other interacting species will respond to this change. Marine organisms may respond in a variety of ways to the changing ocean conditions, e.g., (i) remain in the same area but adapt to changing conditions, (ii) persist in sub-optimal conditions but with potentially significant physiological costs, (iii) move to environmental conditions that suit their physiological tolerances by expanding or contracting their range in space (along latitudinal, depth, or intertidal gradients), or (iv) adjust the timing of their life history (e.g., breeding events) – see 4.0 Regional Biotic Responses. In *Climate Change Impacts* available data and detailed studies are discussed to provide a sense of the nature of species-specific changes that may result from climate change in this region.

A general northward *range expansion* of organisms is anticipated owing to warming of ocean waters. Consistent with this projection, there have been observed northward expansions of volcano barnacles, gray whale calving, bottlenose dolphins, and Humboldt squid. However, not all organisms exhibit this shift, suggesting that species responses will likely differ, and that non-uniform changes in ocean temperature from the nearshore, to the continental shelf, to offshore of the shelf will complicate expectations (see 4.2 Range Shifts; 3.6.1Temperature).

Changes in the timing of the spring transition or the seasonal peak in upwelling 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. In turn, 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).

Recent increases in *dinoflagellate blooms* in Monterey Bay are consistent with warmer surface temperatures and an associated increase in water stratification in the Bay over the last decade. In contrast, a decrease in phytoplankton concentration is expected along open coasts due to a 30-year increase in upwelling winds and associated offshore movement of phytoplankton – with an increased supply of phytoplankton to offshore waters. Longer data records are needed to determine if these are long-term trends or decadal variability (see 5.1 Plankton).

Macroalgae can be impacted as well through a variety of changes including: (i) increasing nearshore sea surface temperatures; (ii) sea level rise – which can reduce light availability and the availability of suitable attachment surfaces; (iii) changes in upwelling – which can affect the availability of nutrients for photosynthesis; and (iv) increased waves and turbulence – which can detach algae and compromise growth (see 5.2 Macroalgae and Plants).

The availability of prey species for *fish, seabirds, and marine mammals* may be negatively affected by changes in upwelling, as well as ocean acidification. Changing temperatures will directly influence fish physiology, as most fishes are cold-blooded. Fish could respond to these changes by shifting their distributional range to preferred temperatures (see 4.2 Range Shifts). Seabirds and marine mammals may also be impacted by expected increases in sea and air temperature, sea level rise, and extreme storm events – leading to altered migration patterns as well as changes in abundance, timing of breeding, reproductive success, and behavior (see 5.5 Seabirds; 5.6 Marine Mammals).

And Marine Habitats Respond

Productivity in open-ocean *pelagic habitats* is controlled through a delicate balance between wind-driven upwelling and stratification of the water column due to surface warming. Increasing surface temperatures offshore and in bays appear to be reducing vertical mixing and causing a shift in the phytoplankton community, while increased upwelling over the continental shelf may be having the opposite effect. Further, changes in large-scale ocean circulation may be altering

the zooplankton community and increasing gelatinous zooplankton (which are undesirable prey for higher trophic levels; see 6.1 Pelagic Habitat).

During weak-upwelling years such as 2005 and 2006, a reduction in phytoplankton and zooplankton abundances was seen in the region. 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. Further, the decreased survival of Chinook salmon entering the ocean that year and low salmon returns in California in 2008 appear to be related. Also, sightings of blue whales (another krill predator) decreased significantly from 2004.

Because of their limited ability to move, communities associated with *benthic habitats* are particularly susceptible to changes in water properties (e.g., temperature, dissolved oxygen, and ocean pH). While short-lived species with dispersive life stages may shift their spatial distribution, other members of benthic communities will have to adapt in order to survive (see 6.2 Offshore Benthic Habitat).

Of particular concern to *island habitats* is rising sea level and increased wave/storm intensity. Models show that a sea level rise of 0.5 m would result in permanent flooding of approximately 5% of the surface area of the Farallon Islands, including many of the intertidal areas where seals and sea lions haul out. In turn this will shrink the area available for seabirds to nest and breed, reducing the capacity of the largest seabird-breeding colony in the contiguous United States. In addition, the average annual air temperature at the Farallones has exhibited an increasing trend over 36 years (1971- 2007), which will impact many island species that are adapted to cold and windy conditions and quickly become stressed when conditions change. During unusually warm weather, seabirds have abandoned their nests, neglected dependent offspring, and died of heat stress. Marine mammals spend less time hauled out (resting) and would be expected to abandon young in the rookeries if temperatures become too warm (see 6.3 Island Habitat).

In *nearshore subtidal habitats* organisms are susceptible to a variety of changes affecting the habitat, including ocean acidification, changes in upwelling and water stratification that affect nutrient delivery, increases in wave heights that affect sediment redistribution, and sea level rise that decreases light availability to macroalgae (see 6.6 Nearshore Subtidal).

Of primary concern for *rocky intertidal habitat* are possible increases in average water and air temperature, specifically the occurrence of extreme conditions that can result in mass mortality of intertidal organisms. Further, ocean acidification is likely to severely affect the ability of intertidal organisms to produce shells. Sea level rise will also affect habitat distribution for intertidal organisms (i.e., increased sea level rise and increased air temperatures may compress the range of high intertidal species into lower zones; see 6.5 Rocky Intertidal Habitat).

Sea level rise and increased storminess are expected to have significant impact on *beach habitats* within the study region, by increasing rates of shoreline erosion and retreat, and degrading habitat quality. Aggravating this habitat change is the loss of habitat due to the expected increase in shoreline armoring to protect properties from rising sea levels. Threatened species include birds such as the western snowy plover and California least tern that nest in dry sand, fish such as the California grunion and smelt that depend on open sandy beaches for spawning,

and pinnipeds such as elephant seals, sea lions, and harbor seals that pup and raise their young on sandy beaches (see 6.4 Sandy Beach Habitat).

Estuary habitats in the study region may be most affected by changes in the timing and persistence of seasonal mouth closure and the intensity and timing of seasonal runoff, as well as the continued rise in sea level. Sediment delivery and availability will strongly influence the ability of estuary morphology to adjust to rising sea level and maintain intertidal estuarine habitat. Also, water properties such as temperature, salinity, dissolved oxygen, and pH can be expected to change significantly, as well as patterns of primary production (see 6.7 Estuarine Habitat).

Climate Change is Not Alone

In parallel with global climate change impacts to the regional ocean environment, land- and marine-based human activities impose additional stress to these habitats, species and ecological communities in the study region. *Multiple stressors* may interact to produce unexpectedly severe impacts on biodiversity and ecosystem health. Additional stressors within the study region include pollution, invasive species, fishing, disease, habitat modification, wildlife disturbance, and development of infrastructure along the coast and at sea. Given that reducing the threats of climate change is a large and global challenge, local and regional natural resource managers should focus on reducing local stressors in order to maintain the resiliency of the ecosystem (so that it can adapt to changes caused by changing climates; see 7.0 Parallel Ecosystem Stressors).

Coastal Communities Feel the Heat

People living and working along the coast will be directly impacted by climate change. While this is not the focus of this report, human responses to these direct impacts on society and the economy are expected to significantly impact marine ecosystems. Issues of particular concern for human populations living along the coast include: water pollution and public health; shoreline safety; and the economic impact from the loss of beaches, loss or damage to coastal infrastructure, damage or loss of homes and commercial structures, and losses incurred by ocean-related businesses. These losses will have significant effects on a variety of economic sectors, including transportation (such as roads and highways, airports, ports and shipping), tourism, fishing, and coastal businesses; see 8.0 Direct Impacts on Humans).

So Now What?

It is certain that marine wildlife, coastal ocean ecosystems, and human populations along the coast will be subject to significant changes. The changes discussed in this report present daunting challenges for long-term management of the Gulf of Farallones and Cordell Bank national marine sanctuaries. While 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, we can improve our understanding through monitoring and study and we can define a range of potential impacts. Sanctuary staff needs to develop an action plan, which includes monitoring and adaptive management approaches that can be implemented as the environment continues to change, seeking to maximize benefits of change while mitigating the negative impacts (see 9.0 Conclusion).

Recommendations

⟹ *Educate society* – *inform people to allow for optimum decisions*

⟹ *Put ecosystems in context* – *link greenhouse gas emissions with marine ecosystem health*

⟹ *Anticipate change* – *obtain best available information on changing and future conditions*

⟹ *Mitigate impacts on the system* – *reduce manageable stressors that compromise system resiliency*

⟹ *Adapt to change* – *create policies and management strategies that are flexible to future changes*

1. Introduction

This document is the result of a one-and-a-half-year 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 *Climate Change Impacts*, 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 report, 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 projected physical and biological impacts from climate change in north-central California coastal waters. In addition, the working group made recommendations for five lines of future action for GFNMS and CBNMS management that can be found in the conclusion of this document.

Climate Change Impacts: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries will serve as the precursor and companion to 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 climate change impacts report and action plans are being prepared in response to recommendations from a 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."

Climate Change Impacts synthesizes an extensive suite of potential climate change impacts relevant to north-central Californian coastal ocean waters. It outlines observed climate change effects in this region as well as changes that are expected but not yet observed and changes that could have major ecological impact (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 in which potential issues are identified and discussed as they relate to a changing climate – drawing from both observation and science-based expectations.

The report addresses the following key topics:

- *Physical effects of climate change,* providing the physical basis for regional biotic responses to climate change. Physical effects include sea level rise, coastal erosion and flooding, and changes in precipitation and land runoff, ocean-atmosphere circulation, and ocean water properties.
- *Regional biotic responses,* addressing the biological implications of climate change in this study region. Biotic responses include changes in physiology, range shifts, changes in phenology, changes in population connectivity, and species-specific responses.
- *Habitat response*, providing ecosystem-wide snapshots of observed and projected responses to changing climatic conditions specific to each habitat. Habitats include pelagic, benthic, island, sandy beach, rocky intertidal, nearshore subtidal, and estuarine.
- *Parrallel ecosystem stressors,* addressing the implications of multiple stressors acting on an ecosystem and cumulative impacts. Parallel stressors include pollution, invasive species, fishing, harmful algal blooms, and wildlife disturbance.
- *Direct impacts on humans* are briefly reviewed so as to anticipate responses that may aggravate or mitigate climate change effects on coastal ecosystems in the study region. Direct impacts on humans include public health issues and economic consequences to fisheries, ecotourism and infrastructure.

Ocean ecosystems are changing, which poses challenges for sanctuary management as organisms and habitats within the study region respond to changes in their environment. 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. This document is a response to that urgent need.

2. Background

Global Climate Change: A 31% increase of CO_2 in the atmosphere has been observed since 1750 (IPCC 2007), increasing from 280 ppm in the pre-industrial 18th century to 380 ppm in 2005 (Raupach et al. 2007), and 387 ppm in 2009 (NOAA, ESRL 2010). In contrast, atmospheric CO_2 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_2 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_2 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_2 concentrations increase from current levels to a peak of 450–600 ppm over the next century.

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_2 produced since the industrial revolution (Sabine and Feely 2007). The ocean is considered to be the only significant long-term sink for anthropogenic CO_2 over the past 200 years (Sabine et al. 2004; Kleypas et al. 2006). Atmospheric CO_2 would be about 55 ppm higher without the ocean's continuous uptake of carbon (Sabine et al. 2004). Temperature, alkalinity and
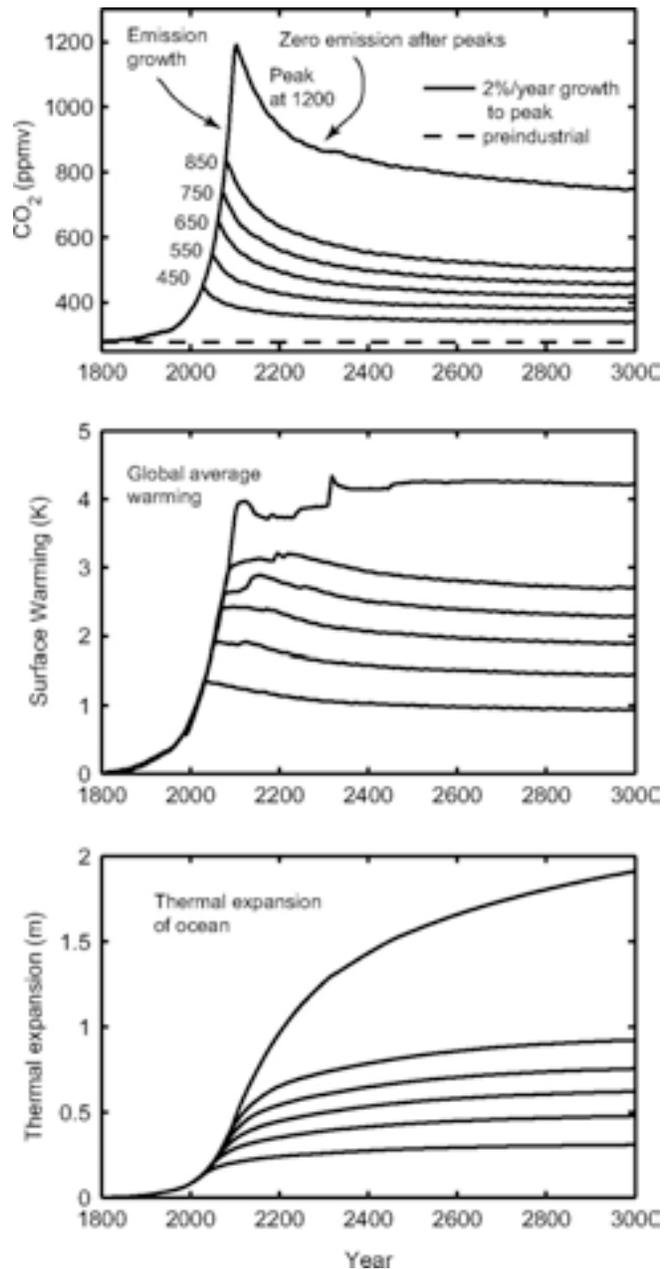
Figure 2.1. *(Top) Carbon dioxide projections based on the Bern 2.5CC model. CO_2 emissions ramp at a rate of 2%/year to peak CO_2 values listed in the figure. After the peak, emissions are reduced to zero. (Middle) Globally averaged surface warming for the different peak values. (Bottom) Sea level rise due to thermal expansion only. Source. Solomon et al. 2009. Copyright (2009) National Academy of Sciences, U.S.A.*

salinity of surface water dictate the equilibrium distribution of CO_2 between the ocean and the atmosphere (Raven and Falkowski 1999). Lower CO_2 solubility will occur as a result of higher temperatures and salinity. Warm water holds less dissolved gas than cold water; therefore CO_2 storage capacity decreases as the oceans warm (Gille 2002). It is estimated that in the future, the amount of anthropogenic CO_2 emissions produced will far exceed the amount of CO_2 the oceans can take up due to the inherent slow mixing time of the ocean. Over the coming decades, the oceans may become a less efficient sink for CO_2 (Sabine et al. 2004).

The IPCC has developed a series of green house gas emissions scenarios that describe alternate pathways of emissions based on a variety of demographic, economic, and technological driving forces. There are four families of scenarios (A1, A2, B1, B2) that form the basis of global climate models (GCMs) that many studies discussed within this document utilize. For further information, the Special Report on Emissions Scenarios (SRES 2000) provides detailed information on the development of each projection. It is also important to recognize that no likelihood is attached to any of these scenarios.

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 32º F and at least three months out of the year above 50º 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).
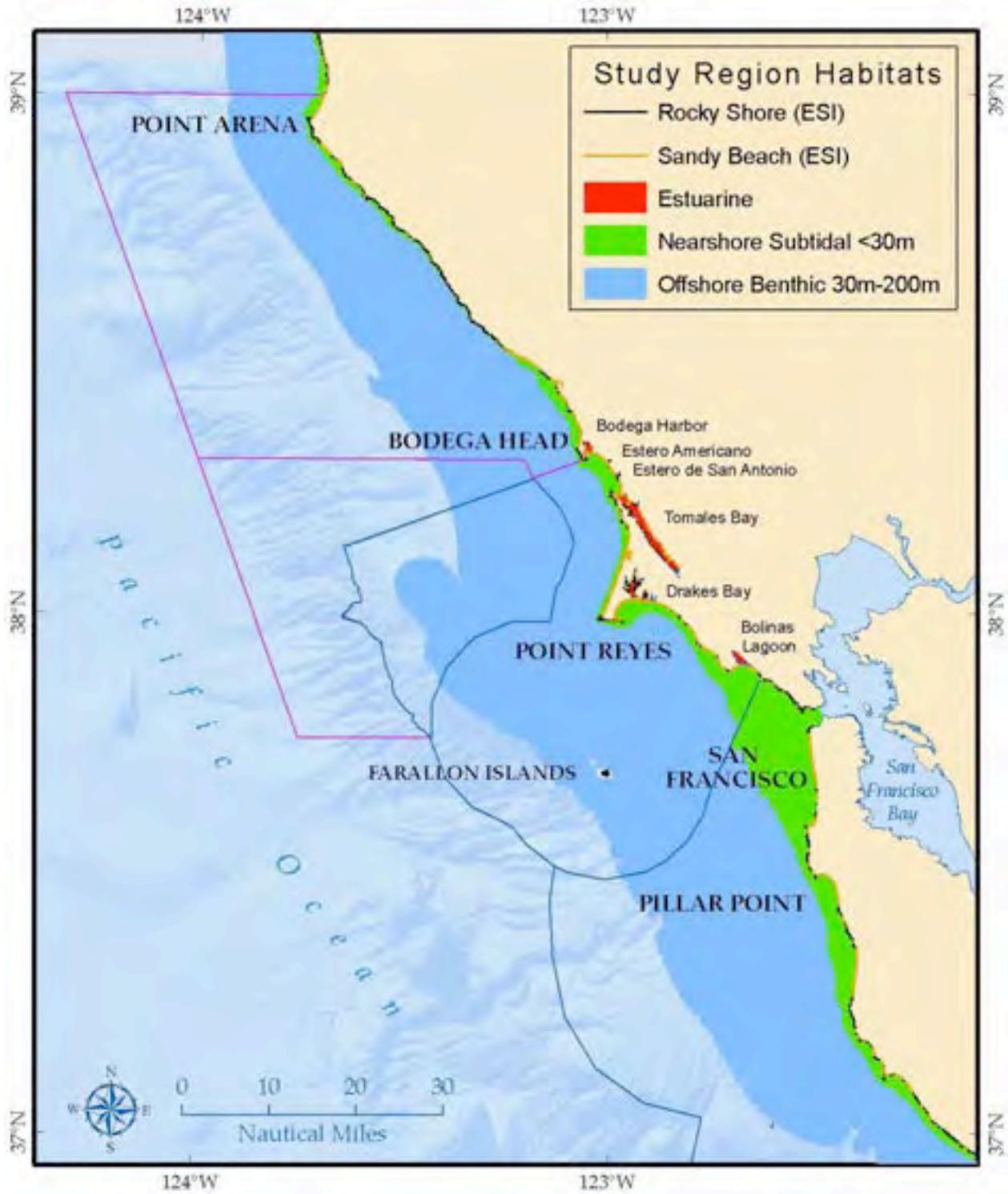
Figure 2.2. *The study region extends from Point Arena in the north to Point Año Nuevo in the south. T. Reed (2009).*

3. Physical Effects of Climate Change

Increases in atmospheric carbon dioxide levels have resulted in warmer air and water temperatures with cascading effects on winds, precipitation, sea level, and ocean circulation. In turn, these changes can interact to produce consequences such as increased flooding and erosion due to increased precipitation and sea level rise. In addition, increased atmospheric CO_2 has altered ocean chemistry. 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. As an additional resource, the United States Global Climate Change Research Program published "Global Climate Change Impacts in the United States" (2009), which contains scientific assessments of global climate change impacts specific to coastal regions.

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 may 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 (termed El Niño) and typically occurs every three to seven years (Rasmussen and Wallace 1983; Fig. 3.1). 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. El Niño has a marked negative effect on ecosystem productivity (Barber and Chavez 1983). During strong El Niño events, storm tracks have a more westerly approach (Seymour et al 1984) and are associated with greater wave height and precipitation (Storlazzi and Griggs 2000). The opposing phase of El Niño is termed La Niña and is mostly characterized by the opposite effects of El Niño.

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 Hurell 1994; Fig. 3.1). During the "warm" phase of PDO, warmer ocean temperatures are 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 such as temperature and sea level, the NPGO correlates well with decadal scale fluctuations in salinity, nutrient concentrations and chlorophyll. This suggests that the NPGO may best describe the relationship between nutrient fluxes and ecosystem productivity (Di Lorenzo et al. 2008; 2009).
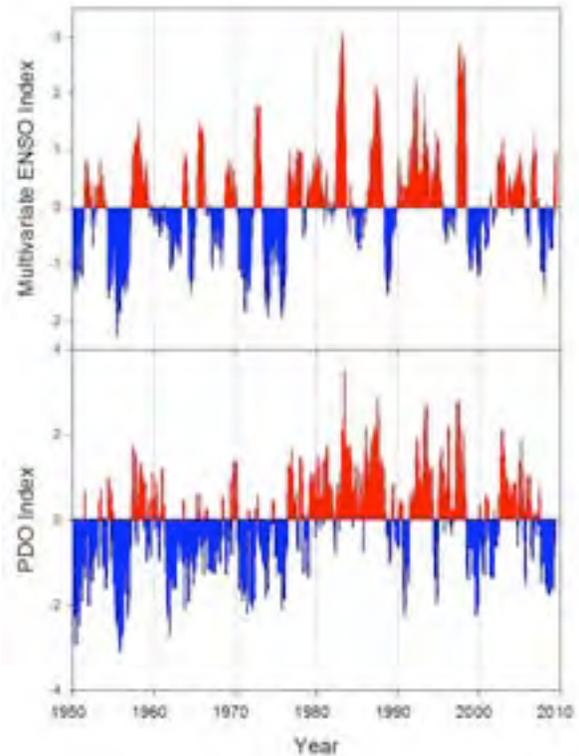
Figure 3.1. *Time series of the Multivariate ENSO Index (top) and the PDO (bottom). Positive values are shaded red and negative values are shaded blue. Derived from N.Mantua time series: http://jisao.washington.edu/pdo/PDO.latest.*

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. The North Pacific High also promotes the formation of the marine layer near coastal California. Descending air "caps" cold air that is formed near the cool ocean water resulting in a temperature "inversion" that subsequently forms the marine layer. In turn, the marine layer promotes the formation of fog and stratus clouds, with important effects on coastal temperature and solar radiation.

3.1.1 Wind

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 2010). 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 2010), as projected by the numerical models (Snyder et al. 2003, Auad et al. 2006). 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 marine air is stronger (but see contrary evidence later in this section). 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 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.

Scale Dependency of Climate Change: Air Temperature

Observed responses to climate change will show differences due to their 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". Warming refers to a specific process and direction of change at the global scale, whereas climate change refers to a broader suite of more complex changes in climate.

For example, 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°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°C decade^{-1}) and inland stations warmed (0.16° C decade^{-1}). Potential mechanisms for this may be the increase in upwelling (see above and 3.3.3 Coastal Upwelling) 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

3.1.2 Storms

Graham and Diaz (2001) observed 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[1] 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).

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).

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[1] Generally, 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).

3.1.3 Clouds

During late spring and into early fall, the California coastline is quite often shrouded in marine stratus (low lying clouds that do not contact the ground) and/or fog (clouds that come in contact with the ground and reduce visibility). This is a very important part of the long-term climate of coastal California because the formation of stratus and fog can significantly reduce solar insolation and temperature on the coast. Recently, Johnstone and Dawson (2010) analyzed hourly records of cloud ceiling height from airports at Arcata and Monterey, California, going back to 1951. Since this time, there was evidence of a decreasing trend in fog frequency (-2.2% per decade in relative terms). Furthermore, when this data was analyzed with a larger and older temperature dataset they infer a decline in fog frequency since the beginning of the 20th century (Fig. 3.2). The authors speculate that a gradual retraction of the North Pacific High could contribute to decreased formation of the marine layer with subsequent declines in fog and increases in coastal temperature
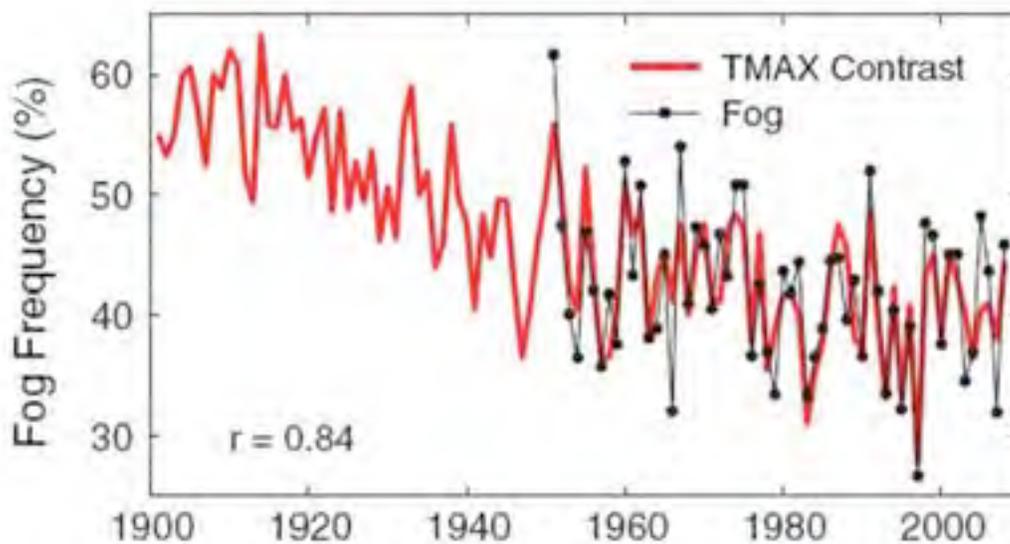
Figure 3.2. Fog frequency (black line) and T_{MAX} contrast (red line). The T_{MAX} contrast is a statistical proxy for 114 summer temperature records. Because T_{MAX} is correlated with the existing fog frequency dataset, the authors infer a decline in overall fog frequency over the 20th century. *Adapted from Johnstone and Dawson (2010). Copyright (2010) National Academy of Sciences, U.S.A.*

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, Mote et al. 2005) and monthly mean streamflow (Lettenmaier et al. 1994) in California have increased since the early 20th 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. However, using low and medium-high IPCC emissions scenarios and two global climate models, Cayan et al. (2008) see small to no effects of warming on precipitation. The authors also note that the GCMs do not offer fine enough spatial resolution to adequately describe the heterogenous character of California climate. Furthermore, analyses by California state climatologist James Goodridge suggest no trend in precipitation from 1890-2002 for the entire state (DWR 2006). When California is divided into three regions (northern, central, southern), a slight increase in precipitation is seen in northern California, as opposed to slight decreases for central and southern California. The marked differences in results among these studies may be due to differences in the period of analysis, the number and location of stations, and the region selected for analysis.

A warming-induced change in the timing of peak streamflow events is a consistent result among both historical observations and modeling efforts (Dettinger and Cayan 1995, Stewart et al. 2004, 2005). 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 (Knowles et al. 2004). 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 suggest that heavy precipitation events will become more prevalent (Kundzewicz et al. 2007). This is supported by an increasing variability in precipitation (DWR 2006; Fig. 3.3).
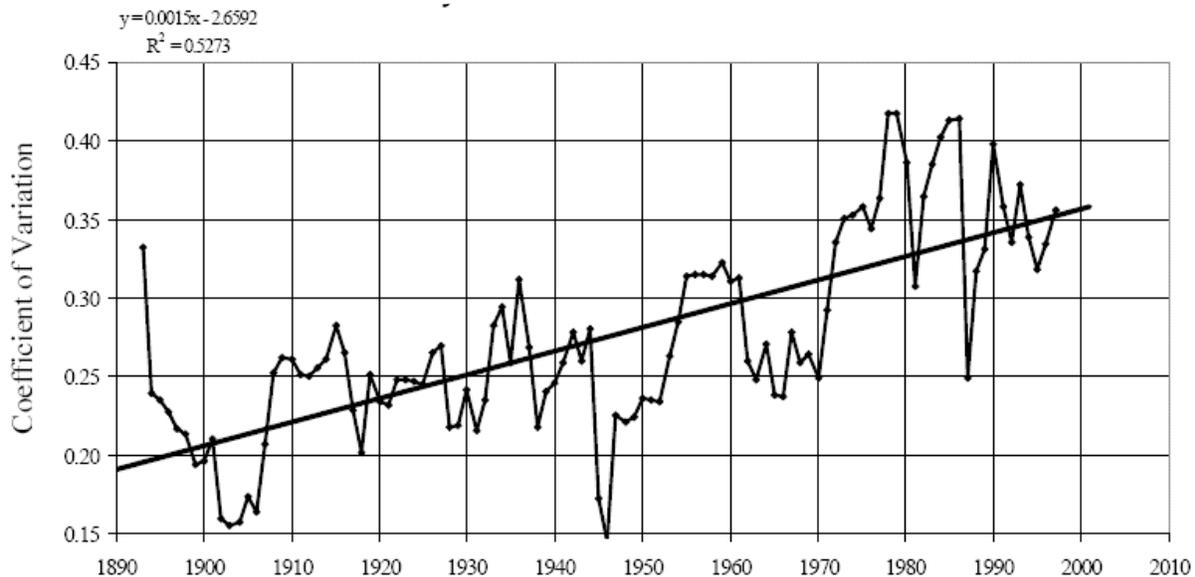
Figure 3.3. *Variation in precipitation over time in California. The solid line is the best-fit regression line. DWR (2006).*

The anticipated change in the occurrence of wildland fires associated with climate change (Westerling et al. 2006) may lead to enhanced 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, it is difficult to interpret trends in the historical record of precipitation as the results are highly dependent on the methodology used. Available evidence does suggest an increased frequency of 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 estuarine 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.

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).
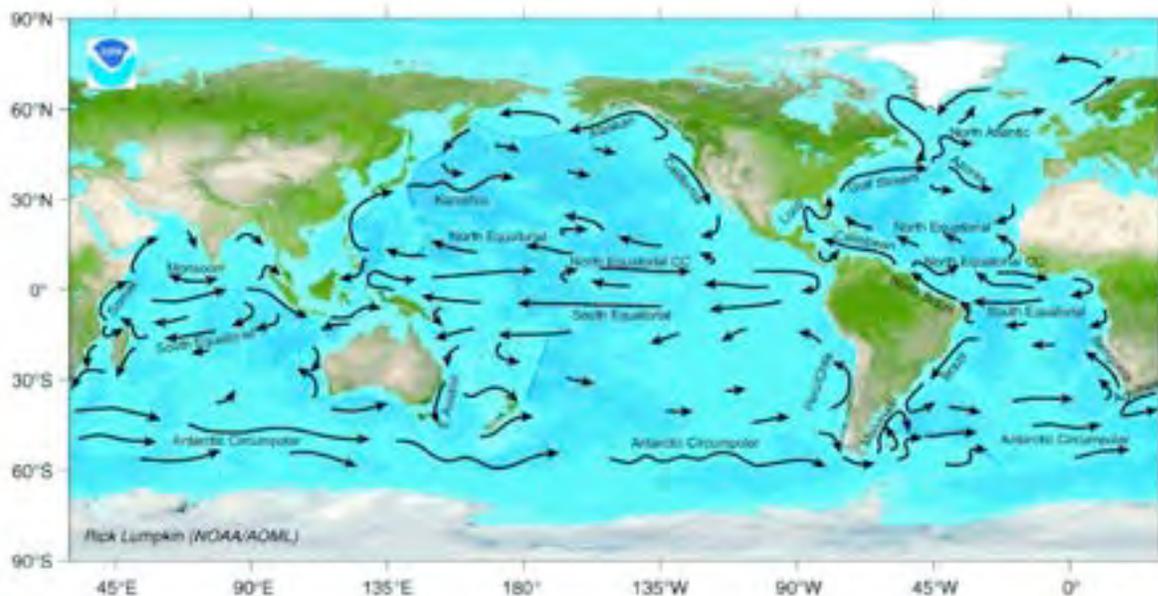

Figure 3.4. *World map showing the major ocean currents. The California current is the cold return current of the North Pacific Gyre moving south along the West Coast. Courtesy Rick Lumpkin, NOAA/AOML.*

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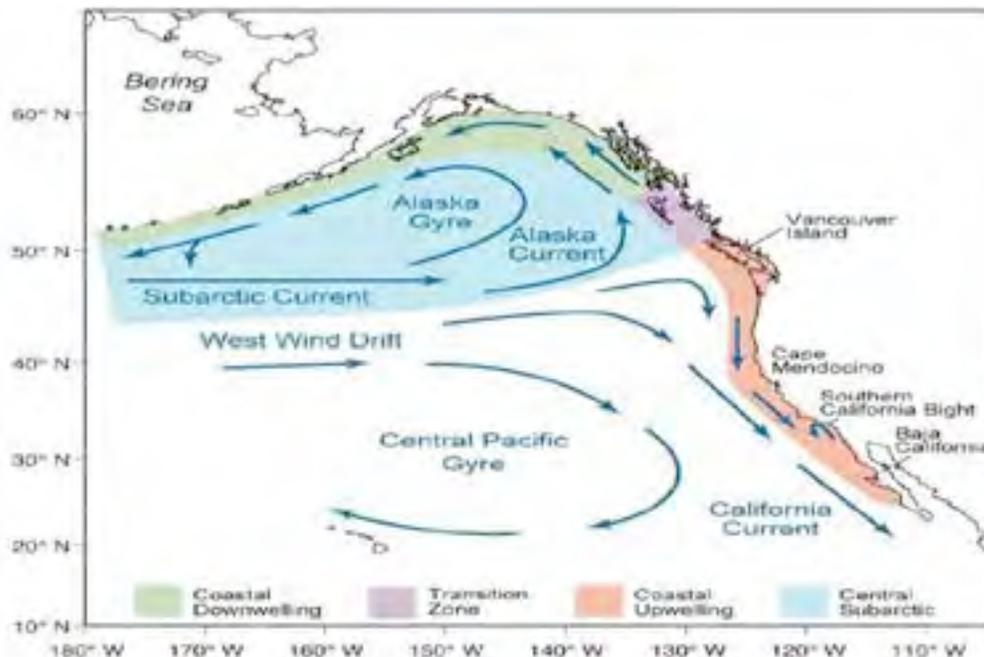
Figure 3.5. *Map showing the locations of the major currents in proximity to the study region. J.A. Barth (OSU, 2007).*

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^{-1}) 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^{-1}, 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).
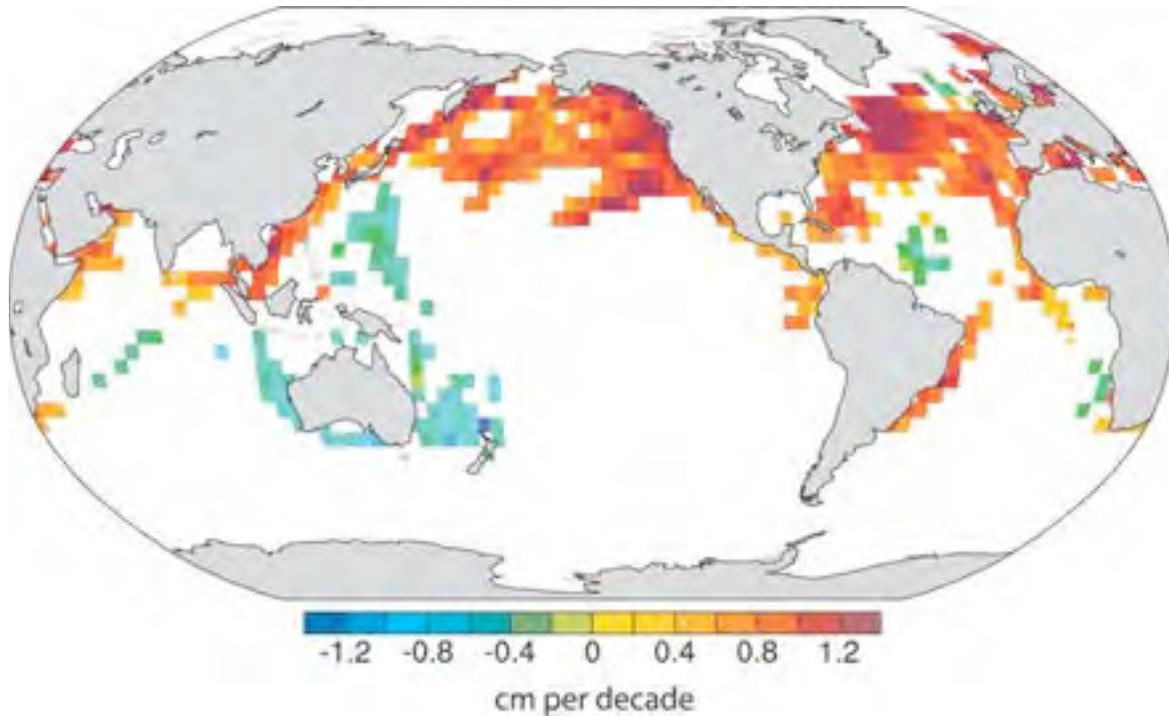
Figure 3.7. *Estimates of linear trends in significant wave height (cm per decade) for regions along the major ship routes of the global ocean for 1950 to 2002. Trends are shown only for locations where they are significant at the 5% level. Adapted from Gulev and Grigorieva (2004). IPCC.*

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 Teleconnectic 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; Wingfield and Storlazzi 2007). 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; Storlazzi and Griggs 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, CA (Sallenger et al. 2002).

Available evidence suggests that significant wave height is increasing, particularly for northern California. These waves may also have greater impacts on coastal erosion, as El Niño conditions tend to modify the approach (more southerly) resulting in greater wave impact. If waves coincide with high tides they will also have a greater impact on erosional processes. Monitoring the intensity and direction of waves is important for biological communities because waves play a large role in structuring nearshore subtidal and intertidal marine communities (see 6.4 Sandy Beach Habitat, 6.5 Rocky Intertidal Habitat, and 6.6 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 5.2 Macroalgae and Plants). Sub-tidal and intertidal ecological communities can also be affected by wave-driven abrasion of sediment (Storlazzi et al 2007). 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).

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 2010) describe enhanced alongshore winds in this region. Along with the increase in wind forcing, a cooling trend in sea surface temperature has been observed for the upwelling season (Bakun 1990; Mendelssohn and Schwing 2002; Garcia-Reyes and Largier 2010; Fig. 3.9). The implications of this for primary production, plankton dispersal, habitat changes, frontogenesis, and the occurrence of fog and low-level clouds are poorly known. Much depends on an understanding of how changes in the upwelling process will affect the larger California Current Ecosystem.
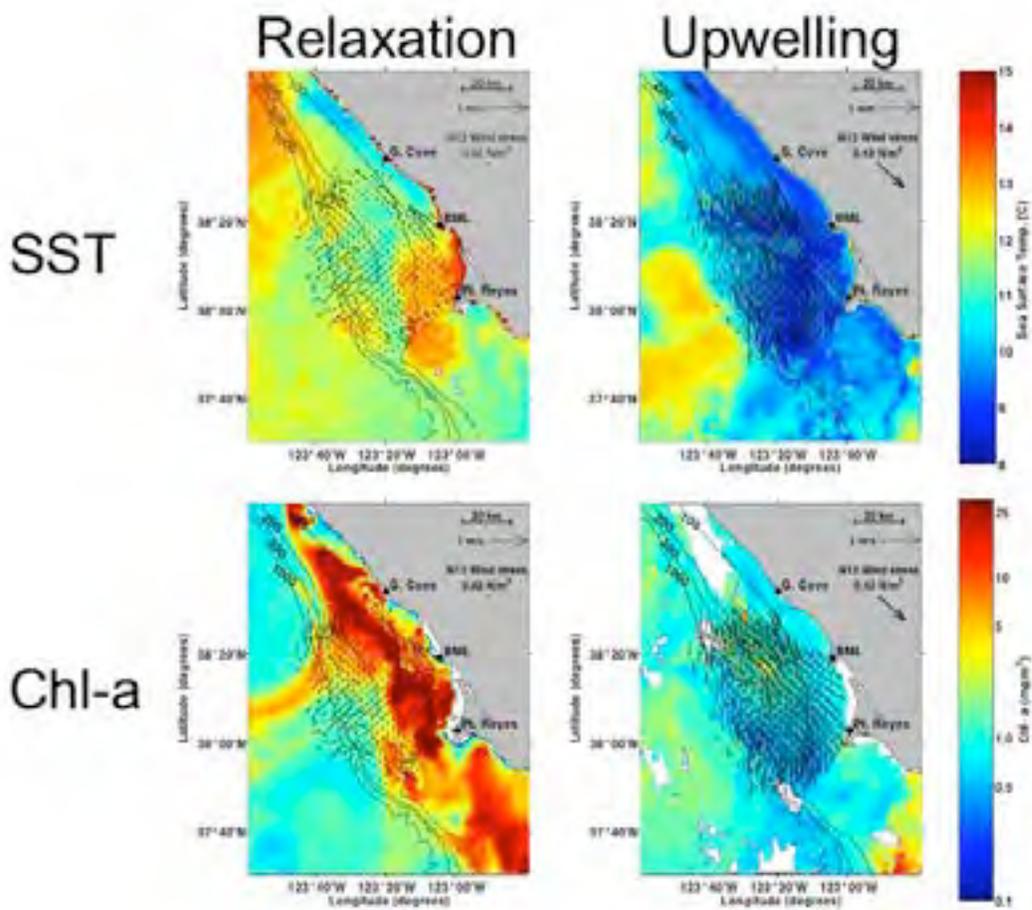
Figure 3.9. *Sea surface temperature (SST) and chlorophyll-a during upwelling and relaxation events. Largier et al. (2006).*

Cross-shore differences in ocean conditions are expected to arise with a warming of nearshore and enclosed bay waters, while enhanced upwelling can be expected to cool waters over the shelf. Further offshore, however, beyond the active upwelling due to a divergence in Ekman transport, an increase in surface heating is expected to exceed the cooling effects of increased upwelling. Offshore surface temperatures are expected to increase, along with an increase in

near-surface stratification and a decrease in the vertical mixing that replenishes near-surface nutrient levels and fuels primary production (Roemmich and McGowan 1995; Palacios et al. 2004.

The temporal variability in coastal upwelling is also very important to primary production and other critical ecological processes. Both the strength of upwelling winds and the nature of the 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.

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 2010).

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 Niño events.

3.3.4 Estuarine Circulation
In addition to sea level rise, estuaries are expected to respond significantly to altered land runoff due to changes in precipitation and to changes in wave energy at the mouth. Secondary influences include changes in local winds as well as temperature (i.e., changes in heating). A significant increase in sea level is expected (see 3.4 Sea Level Rise), resulting in flooding of littoral marshes and low-lying lands, unless there is a concomitant elevation of the land surface due to flood-induced sedimentation. While tides are forced by gravitational effects of the sun and moon, and not expected to be altered by global climate change, rising sea level may alter how tides propagate into estuaries, altering the timing and extent of the tidal rise and fall of water levels. 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.

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 is influenced by and/or includes three types of estuaries: (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 (Abe 2008). 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).

Sea level rise and reduced freshwater inflow are expected to 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 snowmelt flows in spring. In estuaries fed by coastal watersheds, concern is more related to 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 the combination of rising sea level and decreased summer runoff is expected to result in significant intrusion of saline waters, affecting local water resources.

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 working with tidal flow is also important in maintaining an open mouth in bar-built estuaries, removing sediment deposited in the mouth by wave action. The seasonal cycle of estuary mouth closure will change in response to changes in river flow, tidal prism changes due to sea level rise, and changes in wave energy. If river flow is enhanced (stronger and more persistent) or wave forcing becomes weaker, then the mouth will remain open longer – or, alternatively the mouth will tend to close for weaker river flow and/or stronger waves. In addition to changes in intensity, changes in the relative seasonal timing of river flow and wave

energy are important. 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 may prevent estuary-ocean migrations that typically occur in spring, e.g., smolts emigrating to the ocean). 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 (e.g., Russian River) and/or very high water temperatures (e.g., 34°C in Salmon Creek, Largier et al. 2007). Longer closures may aggravate these conditions. When estuaries are open, there is a continual exchange of ocean and estuary waters – and a surface plume of estuarine water forms during ebb tides (or continuously during periods of strong river flow). This plume delivers biogenic material, sediment and contaminants to nearshore waters. The fate of these plume waters and their loading will change with climate-related changes in river flow, mouth condition, nearshore wave-forced currents, and offshore wind-forced currents.

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). Vulnerability studies have utilized a medium-high emissions 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) and Cayan et al. (2008). 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. However, it should be noted that a new analysis projects sea level rise of 75 to 190 cm by the year 2100 (Vermeer and Rahmstorf 2009).

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. Uplift rates have been documented for marine terraces just south of the study region through Point Arena and show rather small rates of uplift ranging from 0.4 - 1.1 mm/yr (Prentice et al. 1999, Perg et al. 2001). When comparing these rates of uplift with a 100 year projected sea level rise of 1.4 m (~14 mm), the relative influence of this uplift is minor.

Local rates of sea level rise also vary in response to interanual/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 19th century to the early 21st 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 19th 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.
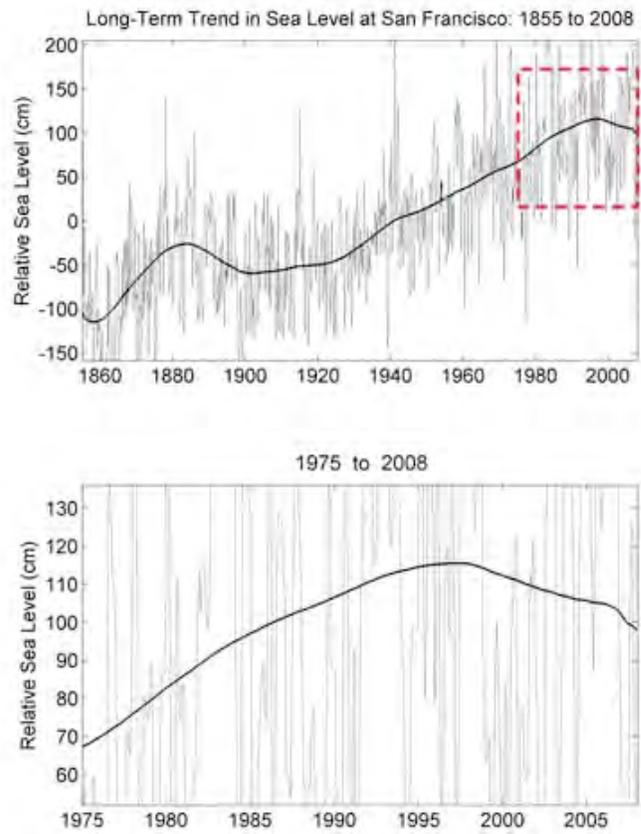
Figure 3.11. *Long-term trends in sea level at San Francisco, 1855 to 2008. The lower panel is an expansion from the upper panel. Adapted from Ramp et al. (2009).*

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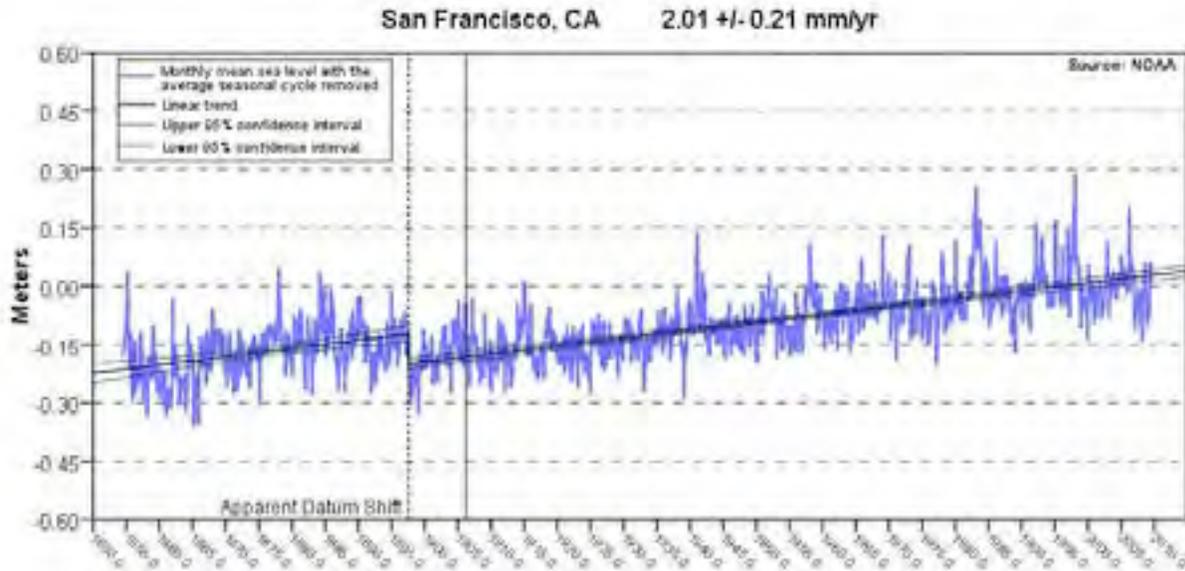
Figure 3.12. *The mean sea level trend for Gauge No. 9414290 San Francisco, CA is 2.01 millimeters/year with a 95% confidence interval of +/- 0.21 mm/yr based on monthly mean sea level data from 1897 to 2006, which is equivalent to a change of 0.66 feet (~20.1 cm) in 100 years. NOAA (2009).*

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, 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).

Extreme Conditions

Recent climate change studies have pointed out that the average frequency or average intensity of weather events may not change, as opposed to the occurrence of extreme conditions, 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 70th 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 (Fig. 3.13, and see http://www.pacinst.org/reports/sea_level_rise/hazlist.html for additional 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. Pendlelton 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 practical salinity units (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*

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 may increase in the study region as a result of rising sea level, changing wave conditions, and storm frequency and intensity (PWA 2009a). Coastal habitats may be directly affected by these changes, or indirectly via human responses such as armoring, beach nourishment, or retreat. The extent of inland shoreline migration and loss of upland depends on geology and sediment supply, all of which affect wave exposure, shoreline elevation and resiliency. 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.

Erosion: Erosion results from the interaction of coastal processes with coastal geological formations, although 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 U.S. Geological Survey (USGS) for sandy shorelines (Hapke et al. 2006) and seacliffs (Hapke and Reid 2007). The magnitude of coastal erosion is related to the coastal geomorpology. 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.

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 thought to have the largest impact in Marin County (an estimated 2.6 km^2), with erosion of almost 9 km^2 for the dunes across the entire study area. Total erosion by 2100 is estimated to reach nearly 50 km^2 (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 projected. Overall, an enhanced potential for coastal erosion in this region is expected, however these projections 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^2 (km^2)	Cliff erosion miles^2 (km^2)	Total erosion miles^2 (km^2)
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)
Total (study area)	**3.3 (8.8)**	**15.4 (40.1)**	**18.7 (48.9)**

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
Average m (ft)	**172 (564)**	**338 (1,109)**	**61 (200)**	**206 (676)**

Sediment Supply: To understand the impact of changes in sediment supply it is important to understand the sediment budget (for a variety of grain sizes) at a "sediment-shed" scale that includes the watershed, coastal wetlands and the littoral cell (e.g., Revell et al. 2007). A littoral cell is a defined nearshore region, constrained by headlands and submarine canyons, in which a beach-sand budget can be constructed, including a variety of sources and sinks. If there is a surplus in this sediment budget then beaches tend to be wide and shoreline erosion is weak or non-existent. Alternatively, if there is a deficit in the sediment budget then beaches are usually narrow and erosion rates are significant. The following are the littoral cells within the study region that have been identified: Navarro, Russian River, Bodega Bay, Point Reyes, Drakes Bay, Bolinas Bay, San Francisco, and Santa Cruz (Habel and Armstrong 1978; Patsch and Griggs 2007).

Human alterations in the watersheds, such as dams and debris basins, trap sediments and also affect peak flow rates – reducing the sediment transport to the coast (Willis and Griggs 2003; Slagel and Griggs 2008). This reduced supply of sand and cobbles to the individual littoral cells, pushes them towards a deficit and greater potential for erosion, 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).

The traditional human response to coastal erosion for protection of houses and infrastructure has been to armor the coast with physical structures such as 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.

Changes in precipitation and sediment discharge (see 3.2 Precipitation and Land Runoff) may play an important role in altering coastal erosion. If most precipitation events occur in short heavy events as projected (Dettinger and Cayan; 1995; Cayan et al. 2001; Kundzewicz et al. 2007), then sediment discharge is thought to increase which may widen beaches and reduce coastal erosion in places. However, given the numerous sediment and water retention structures in the watersheds, the sediment and water discharge effect of these events may be reduced and thus have negligible effect on the shoreline. In addition to greatly affect the resiliency of wetlands and beaches, changes in the magnitude of river and sediment discharge will as also interact with sea level rise and affect coastal hazards such as flooding and storm erosion events.

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.

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. 3.14). 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).
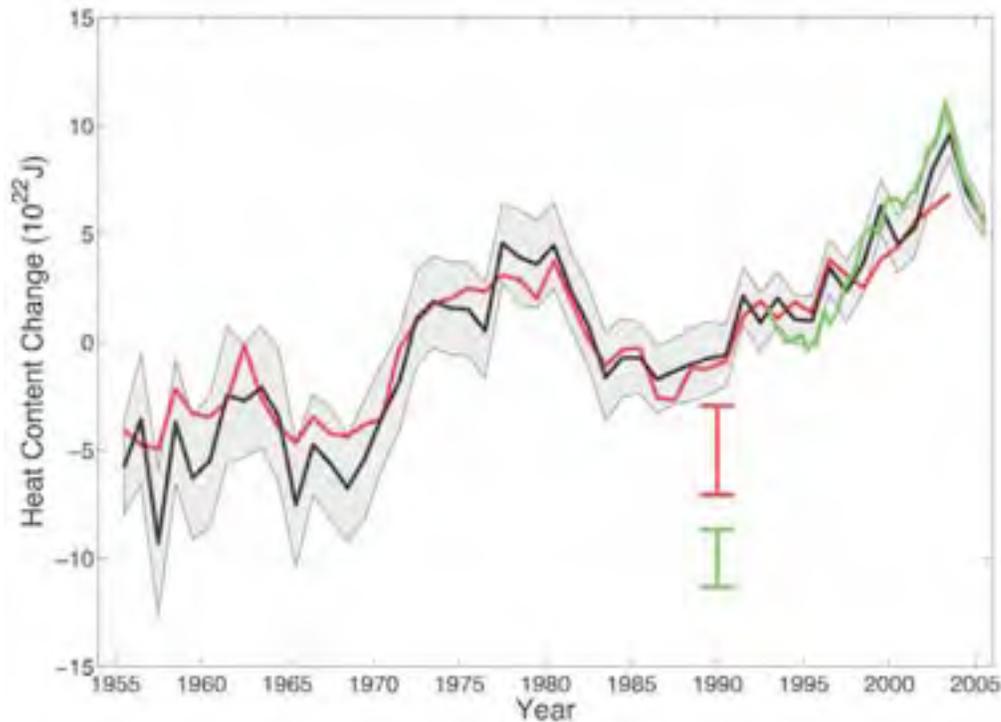
Figure 3.14. *Time series of global annual ocean heat content for the upper ocean (0 to 700 m depths). The black curve is updated from Levitus et al. (2005a), with the shading representing the 90% confidence interval. The red and green curves are updates of the analyses by Ishii et al. (2006) and Willis et al. (2004, depths of 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° N (0-350 m depth) and at the equator (~ 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°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°N (heat content is proportional to temperature; Bindoff et al. 2007; Fig. 3.15). The regions depicted by blue in Figure 3.15 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).
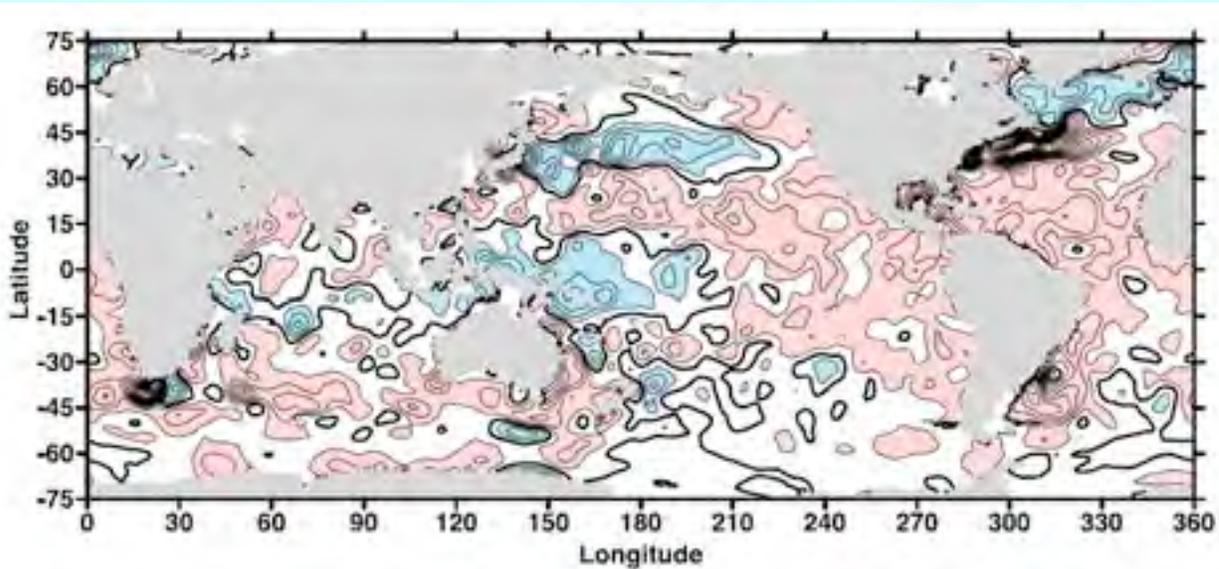
Figure 3.15. *Linear trends (1955–2003) of change in ocean heat content per unit surface area (W m^{-2}) for the 0 to 700 m layer, based on the work of Levitus et al. (2005). The linear trend is computed at each grid point using a least squares fit to the time series at each grid point. The contour interval is 0.25 W m^{-2}. Red shading indicates values equal to or greater than 0.25 W m^{-2} and blue shading indicates values equal to or less than –0.25 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 3.15), other results show a slow warming rate or decrease in SST in coastal waters (Bakun 1990; Mendelssohn and Schwing 2002; Garcia-Reyes and Largier 2010) 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. At sites in Southern California, seawater temperature has increased by as much as 1.5°C since 1951 (Roemmich and McGowan 1995; McGowan et al. 1998). However, ocean temperatures over the continental shelf off central California have exhibited cooling over the last 30 years (Mendelssohn and Schwing 2002; Garcia-Reyes and Largier 2010), consistent with an increase in coastal upwelling (see 3.3.3 Coastal Upwelling).

3.6.2 Ocean Acidification

The increased concentration of CO_2 in the ocean (due to rising atmospheric CO_2 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_2 problem" (Doney et al. 2009).

Increased CO_2 in the atmosphere (CO_{2atm}) leads to a reduction in ocean pH and a decline in the carbonate ion concentration (CO_3^{2-}) 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^+), as follows:

$$CO_{2atm} \rightleftharpoons CO_{2aq} + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-}$$

The exchange of atmospheric carbon dioxide (CO_{2atm}) across the air-sea interface equilibrates surface seawater CO_2 with the atmosphere. This dissolved (aqueous) CO_2 reacts with seawater to form carbonic acid (H_2CO_3). Carbonic acid readily dissociates to hydrogen (H^+), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) ions (see equation above). The relative proportions of these forms of dissolved inorganic carbon (DIC) in an ocean of pH 8.1 are 86.5% bicarbonate, 13% carbonate, and 0.5% dissolved CO_2 (Zeebe and Wolf-Gladrow 2001). Rising CO_{2atm} concentrations force a corresponding increase in H_2CO_3, a weak acid, resulting in increased hydrogen ion concentrations ($[H^+]$), which leads to a decrease in pH, and decreased carbonate ion concentrations. Figure 3.16 illustrates the increase in oceanic pCO_2 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).
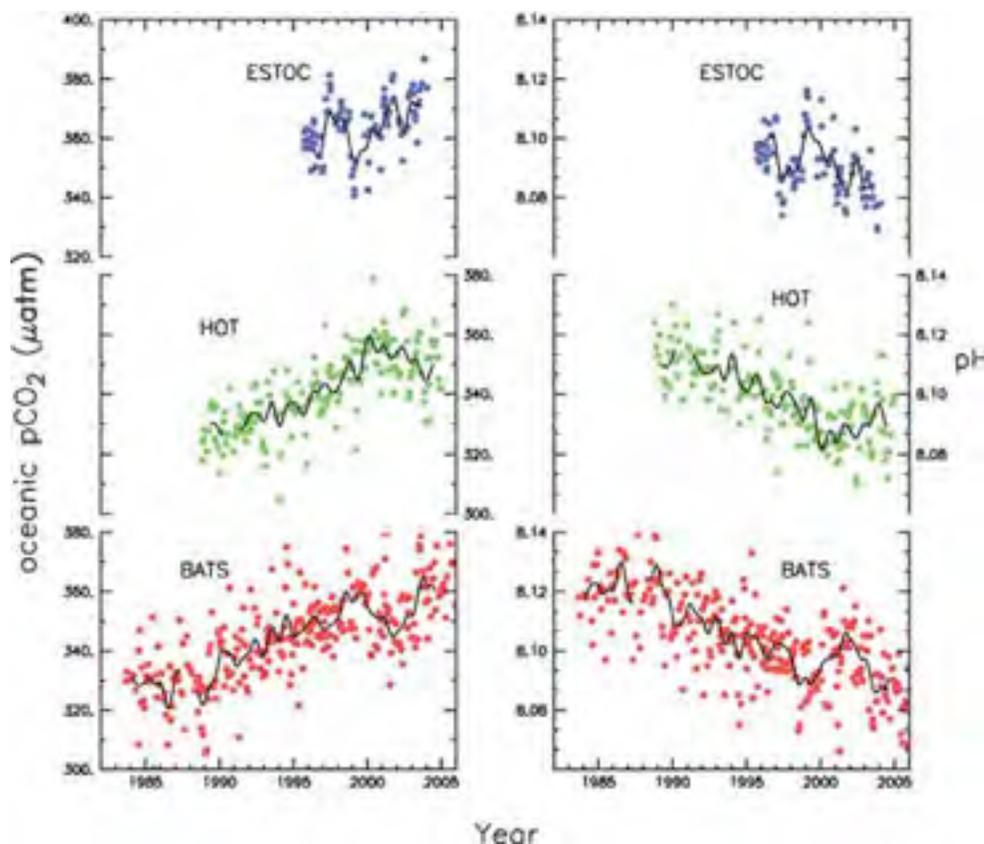
Figure 3.16. *Changes in surface oceanic pCO2 (left; in ìatm) and pH (right) from three time series stations: Blue: European Station for Time-series in the Ocean (ESTOC, 29°N, 15°W; Gonzalez-Dávila et al. 2003); green: Hawaii Ocean Time-Series (HOT, 23°N, 158°W; Dore etal., 2003); red: Bermuda Atlantic Time-series Study (BATS, 31/32°N, 64°W; Bates et al. 2002;Gruber et al. 2002). Values of pCO2 and pH were calculated from DIC and alkalinity at HOT and BATS; pH was directly measured at ESTOC and pCO2 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 at periods less than half a year (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 (), 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 CO_2 levels are elevating the saturation horizon closer to the surface (Feely et al. 2004). Therefore increases in surface ocean 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 very low in upwelled waters in the study region and along the coast of western North America. In spring 2007, in a strong upwelling area off the northern California coast, the entire shelf up to the 50 m bottom contour became under-saturated with respect to aragonite ($\Omega_{arag} < 1.0$) and had a pH < 7.75 concomitant with intense upwelling (Fig. 3.17). 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, 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 and thus difficult to precisely quantify, 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 5.3 Invertebrates).
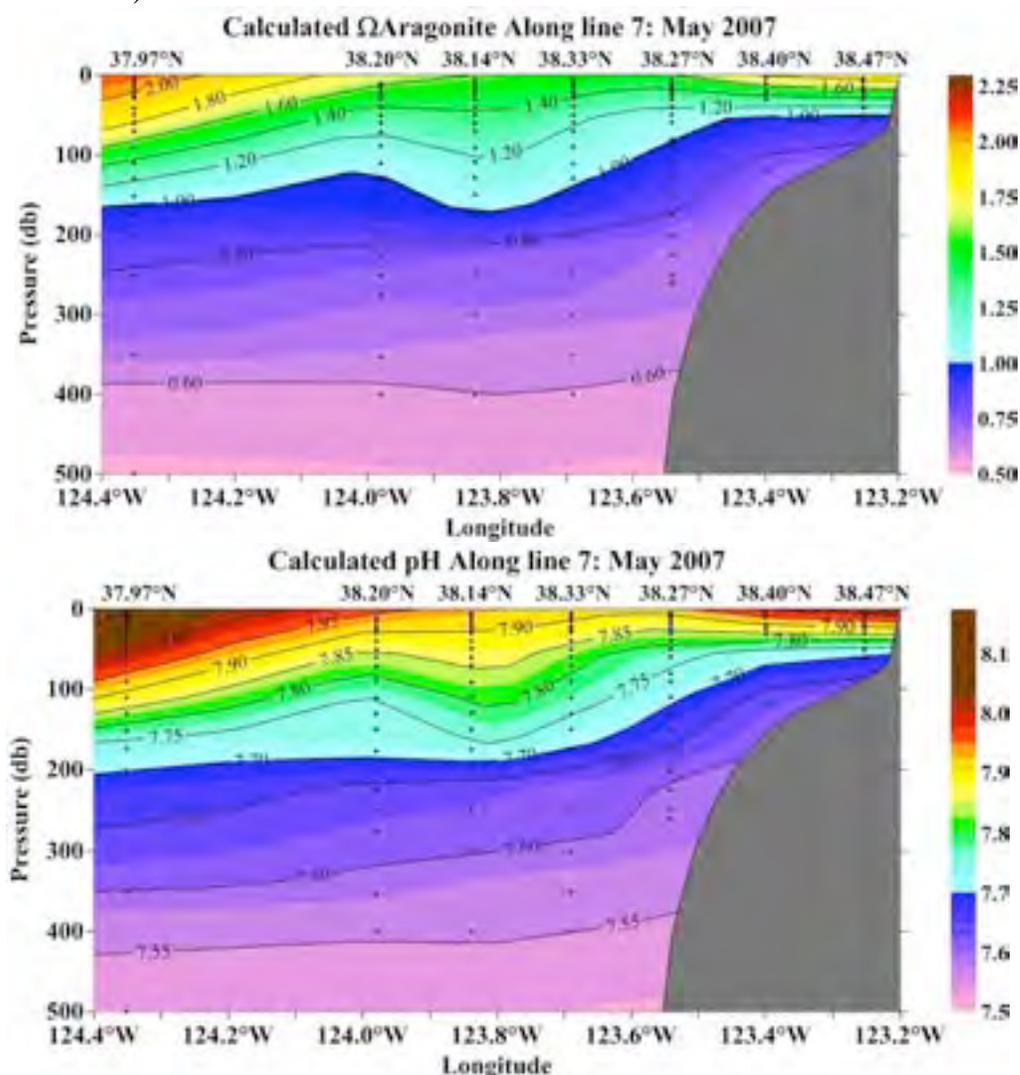
Figure 3.17. *(Top) Aragonite saturation state along transect line 7 (beginning just north of San Francisco Bay). (Bottom) pH values along transect line 7. Results calculated from May 2007 North American Carbon Program (NACP) West Coast Cruise along the continental shelf of western North America. Courtesy 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 projected 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_2 concentrations. In a reanalysis of data from Smith and Hollibaugh (1997) it has been shown that aragonite saturation state () 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 Atmosphere and 3.3.3 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 (~60 μmol 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.

4. Responses in Biological Processes

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 effects of climate change on the physiology of organisms, species' distributions, the timing of life history events, population connectivity, and evolutionary reponse.

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[2], 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).

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

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

(*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 viviparous*) 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*) (Fig. 4.1). 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

Figure 4.1. *Ochre seastars (Pisaster ochraceus) feeding on California mussels (Mytilus californianus). National Park Service.*

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 3.6.2 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 might be above *or* below the chemical saturation state (= 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). 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).

Lowered pH levels may also affect the internal pH of other organisms that do not produce calcareous shells, such as anemones and jellyfish, as their internal pH varies with surrounding water and they are unable to regulate it on their own (Petkewich 2009). In addition, one study on orange clownfish larvae found that larvae rearded in control seawater (pH 8.15) could distinguish between a range of olfactory cues that helped them find reef habitat and suitable settlement sites. Those reared in seawater kept at pH 7.8 were instead attracted to olfactory cues that they normally avoided, and the larvae no longer responded to any ofactory cues at pH 7.6 (Munday et al. 2009). As many fish rely on olfactory stimuli, similar disorientations may occur within the study region, although this has not been documented.

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 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).

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. Therefore, 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 below). 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. However, range shifts by these species have been confirmed by other studies. For example, Connolly and Roughgarden (1998) documented a shift by volcano barnacles (*Tetraclita rubescens*) (Fig. 4.2), a common intertidal species, historically found from Cabo San Lucas, Baja California, Mexico to San Francisco. Some time after 1980, a northward range expansion of 300 km (to Cape Medocino) occurred with the regular

Figure 4.2. *Volcano barnacles (Tetraclita rubescens) have expanded their range northward to Cape Mendocino. KQEDQuest.*

recruitment of individuals north of San Francisco Bay (Connolly and Roughgarden 1998; Sanford and Swezey 2008). Although the exact cause for this expansion is unknown, it is thought that warmer waters along the California coast may have influenced this change in distribution (Enfield and Mestas-Nuñez 1999; Sagarin et al. 1999; Sanford and Swezey 2008). In subtidal kelp forest habitats, the range expansion of the snail Kellet's whelk (*Kelletia kelletii*) from Point Conception to Monterey, CA 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 4.3.
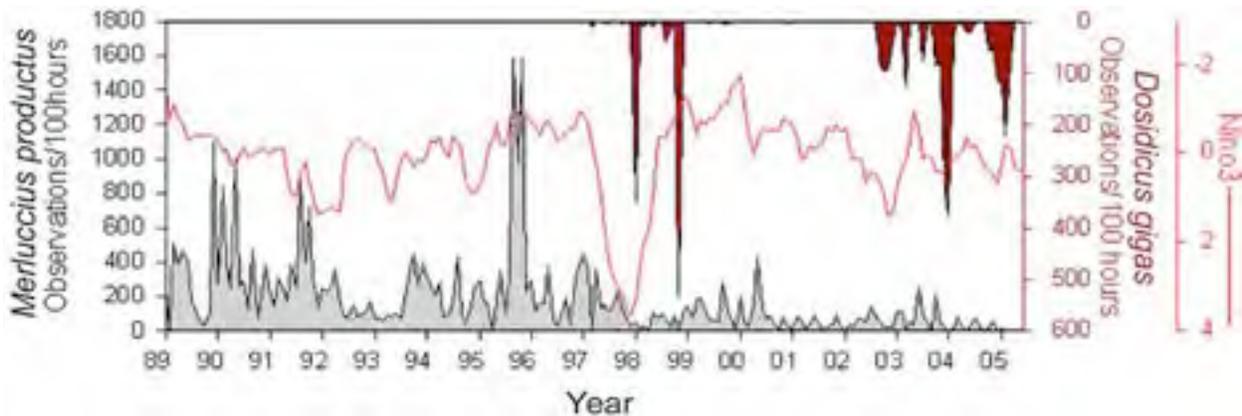
Figure 4.3. *Time series of Pacific Hake abundance and Humboldt Squid abundance in Monterey Bay, CA. Zeidberg and Robison (2009). The increasing incidence of D. gigas is evident by the dark red line in 1998-1999 and from 2002-2005 (right axis).Copyright (2009) National Academy of Sciences, U.S.A.*

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).

Caveats to poleward range expansion theory: One criticism of the theory of projected 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 5.2 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 projected 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_2 levels. Also, Pacific oyster (*Crassostrea gigas*) larvae exposed to enriched CO_2 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 Evolutionary Response

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).

5. Responses in Marine Organisms

Marine biota are subject to multiple local environmental changes due to global climate change, with the potential for different effects to counter-balance or enhance each other. Physical changes in sea level, winds, waves, temperature, pH, and runoff may influence a variety of critical biotic phenomena, such as metabolic rates, planktonic transport, prey availability, and/or predation mortality. Projecting the impact of climate change on specific species is fraught with uncertainty and there are few long-term biotic records from which past climate-related changes can be identified. In the following chapter, available data and detailed studies are discussed to provide a sense of the nature of species-specific changes that may result from climate change in this region.

5.1 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. 5.1). 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,

Figure 5.1: *CalCOFI stations. CENCOOS (2009). http://www.cencoos.org/index.html*

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 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. Bertram et al. (2001) considered the effect of ocean warming and changes in the peak abundance of *N. plumchus* 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.

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 led 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.

5.2 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) (Fig.5.2) 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 3.3.3 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 could have significant consequences in habitats such as the rocky

Figure 5.2. *Giant kelp (Macrocystis pyrifera) is an example of kelp found in the study region. Josh Pederson/ SIMoN NOAA.*

intertidal where they are dominant. In addition, studies at the University of Washington on the kelp *Alaria marginata* have shown that gamephyte growth for this kelp is significantly reduced when subjected to seawater at pH 7.8 and even further reduced at pH 7.6 (Klinger and Kershner 2008*).*

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* (Fig. 5.2) and subcanopy kelps decreased while the foliose red algae *Cryptopleura violacea* increased in abundance. Within the study region, 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_2 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_2 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 runoff from melting snowpack will have negative effects on vegetation in San Francisco Bay (Callaway and Sabraw 1994, Noe and Zedler 2001a; 2001b).

Increasing concentrations of atmospheric CO_2 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_3 vs. C_4 photosynthesis).

5.3 Invertebrates

This section considers the response of benthic invertebrates to climate change. These species regulate their body temperature through external means (i.e., ecothermy) and therefore may be particularly sensitive to changes in the thermal environment. In addition, ocean acidification may have large implications for species that produce calcareous shells, particularly if they reside near prominent upwelling centers. Changes in the nature of upwelling may not only have effects via the transport of this "corrosive" seawater but may also modify the flux of nutrients, with cascading effects on primary producers and their consumers.

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; see section 4.2 for examples of range shifts). 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 funebralis* 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. A variety of calcareous marine invertebrates that could be impacted by ocean acidification include: benthic bivalves, gastropods, echinoderms, and crustaceans. Many of these species are economically important such as sea urchins

Figure 5.3. *Both larval and adult purple sea urchins (Strongylocentrotus purpuratus) are affected by ocean acidifcation. GFNMS Photo Library.*

(Fig.5.3), mussels, oysters, abalone, and crabs. Of particular concern are the larval stages of these organisms, which may be more susceptible to ocean acidification. 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 (Shirayama and Thorton 2005). 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.

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 to gradual long-term changes in ocean chemistry (see 4.4 Population Connectivity). 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*.

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.

5.4 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

Figure 5.4. *Rosy rockfish (Sebastes rosaceus) in the Gulf of the Farallones. Tony Chess.*

estuarine fish that utilize eelgrass and associated areas for shelter. Additionally, climate change is projected to exacerbate impacts on fish populations that are commercially and recreationally fished (see 7.3 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.

Steelhead trout, chinook, and coho salmon (Fig.5.5) (*Oncorhynchus mykiss, O. tshawytscha* and *O. kisutch* respectively) are the primary anadromous fish that are found within the study region and 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

Figure 5.5. *West coast coho salmon (Oncorhynchus kisutch). NOAA 200th Anniversary Image.*

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).

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.

Estuaries act as critical habitat for fishes that utilize these areas for all or a part of their life history. Climate change may affect commercially and recreationally fished species such as juvenile California halibut (*Paralichthys californicus*), bat rays (*Myliobatis californicus*), and leopard sharks (*Triakis semifasciata*) that utilize estuaries as nursery or feeding grounds by modifying estuarine habitat.

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 within the region, but one study outside of the region found that larval clownfish experienced disorientation to normal olfactory cues when subjected to lower levels of pH (Munday et al. 2009; see 4.1 Physiology).

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.

5.5 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

Figure 5.6. Brandt's cormorant *(Phalacrocorax penicillatus) feeding it's young. Roy Lowe/ USFWS.*

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).

Upwelling: 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 adverted 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.

Population Distributions: 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.

5.6 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 species or long-range migrants to polar regions, these mammal species are likely to be affected by changes in climate (Ragen et al. 2008; Learmonth et al. 2006; Simmonds and Isaac 2007). Many predictions are based on the evolutionary record from previous periods of climate change, but other projections are from recent observed changes in species' condition that appear to be manifestations of global warming. The projected 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).

Temperature: 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 projected 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.

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. Giving birth outside the sheltered Baja calving lagoons presents greater risk of storm stress to newborn calves, as well as increased risk of predation by killer whales and large sharks.

El Niño effects on marine mammals provide a window into the likely results of warmer sea temperatures and a subsequent northward movement of warmer water prey. During the 1982-83 and 1997-98 El Niños, in northern California pinniped productivity and survival declined, with the exception of California sea lions, whose numbers increased (Trillmich and Ono 1991; Sydeman and Allen 1999). In addition, the southern California population of bottlenose dolphins (*Tursiops truncatus)* expanded northward into central California after the 1982-83 El Niño (Hansen and Defran 1990; Wells et al. 1990). Since this time, bottlenose dolphins have been consistently sighted as far north as San Francisco (Carretta et al. 2009; Fig. 5.7). A sustained sea temperature increase of 3°C is projected 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.

Figure 5.7. *Approximate range (in bold) of California coastal bottlenose dolphins based on aerial surveys along the coast of California from 1990-2000. These bottlenose dolphins are found within about 1 km of shore. Carretta et al. (2009).*

Observed increases in harmful algal blooms (HABs) may be another indirect effect of changes in ocean temperature, as HABs often result in mortality in marine mammals (Van Dolah 2005). Over the past couple of decades, HABs that produce domoic acid have increased (see 7.4 Harmful Algal Blooms), resulting in episodes of sick and dead California sea lions in central California, and of other species in southern California (Gulland et al. 2002). With a possible rise in ocean temperature, the emergence and spread of other diseases associated with warmer sea temperatures may increase, affecting productivity and marine mammal health (Gulland and Hall 2005).

Prey Availability: 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.

Sea Level Rise: 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 (Fig.5.8).

Figure 5.8. *Northern elephant seals (Mirounga angustirostris) resting at Pt. Reyes National Seashore. Josh Pederson/ SIMoN NOAA.*

Changes in Phenology: 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.

<u>Ocean Acidification</u>: 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_2 concentrations. Marine mammals may also be subject to an unanticipated effect of ocean acidification. 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, and the effects of this on marine mammal health and navigation remain unknown.

6. Responses in Marine Habitats

The study region is comprised of several habitat types (Fig. 6.1), with each affected in multiple ways by climate change – through influences on physical processes and conditions (see 3.0 Physical Effects of Climate Change), influences on biological processes (see 4.0 Responses in Biological Processes), and influences on biological populations that use a specific habitat (see 5.0 Responses in Marine Species). The following chapter synthesizes the possible changes that can manifest in each of the key marine habitats represented in the study region. While multiple environmental pathways influence each habitat, the response of a given species in this habitat occurs due to a combination of environmental change and changes in the populations with which this species interacts. However, little information is available for community-wide responses to climate change and additional research is needed in this area.
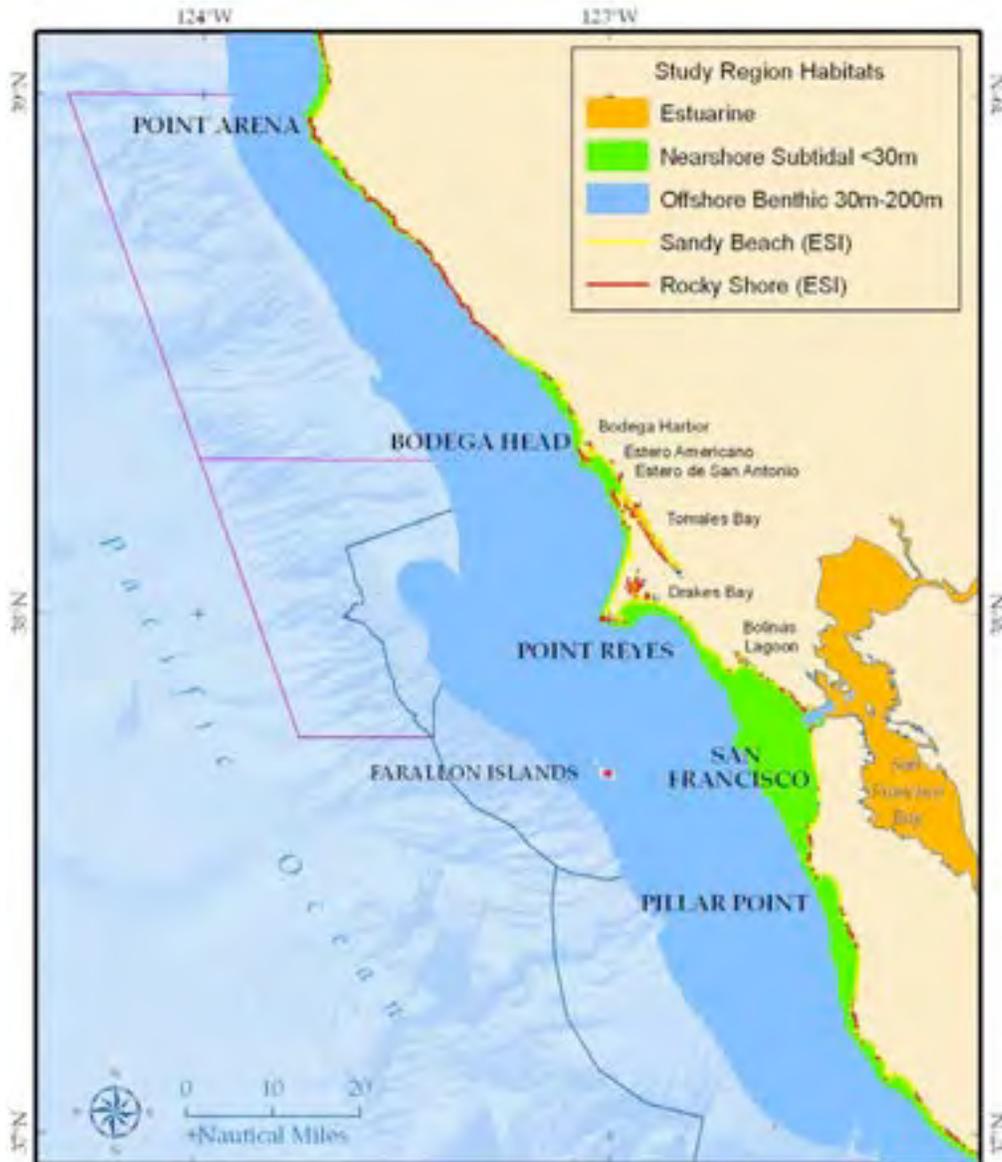
Figure 6.1. *Map of habitat types within the study region. Pelagic habitat is not shown as it overlaps the offshore benthic habitat, with "pelagic" referring to water column habitat and "benthic" referring to habitat associated with the seabed. T. Reed (2009).*

6.1   **Pelagic**

Habitat

Pelagic habitat includes the entire water column from the sea surface to the seabed. This 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.

Temperature and Stratification: 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). Although an increase in upwelling may offset the effect of surface warming over the shelf (see 3.3.3 Coastal Upwelling), an increase in stratification may also be seen in sheltered waters in bays. Increased water column stratification may lead to a major shift in phytoplankton communities in the region, as was observed in Monterey Bay between 2002 and 2004. Diatom abundance declined and dinoflagellate abundance increased concomitant with increased stratification (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 (possible related to the enhanced upwelling observed along the open coast in the same years), led to a massive dinoflagellate bloom in areas with warm sea surface temperatures, highly stratified water column and shallow thermoclines. In the Bering Sea, elevated numbers of gelatinous zooplankton have been linked to warmer and more stratified waters (Brodeur and Terazaki 1999). Increased water temperatures lead to higher reproductive rates and extended growing seasons. These gelatinous organisms may become the dominant predators in altered ecosystems

Diet studies of common seabirds breeding on Southeast Farallon Island have shown major changes in the availability of juvenile rockfish. Diet studies on common murres (*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.

Other Water Properties: Global ocean salinity in subpolar latitudes has decreased whereas in shallower parts of the tropical and subtropical ocean salinity has increased. The total inorganic carbon content of the oceans also continues to rise, resulting in more corrosive waters as shown by trends of decreasing pH over the last 20 years (Fig. 3.16). There is also evidence for decreased oxygen concentrations (see 3.6.5 Dissolved Oxygen), further lowering pH levels in the California Current (Feely et al. 2008) in addition to the reduced availability of oxygen in the water column. How these properties are chaging in the study region remains uncertain and improved observations are needed.

Upwelling: In years where alongshore winds were strong and began earlier in the spring, strong and early upwelling resulted in increased abundance of important zooplankton species (e.g., euphausiids and copepods). The increased abundance of these zooplankton species (specifically krill) during the critical breeding time of the Cassin's auklet resulted in above average breeding success of this species. 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 adult krill, Cassin's auklets abandoned nests and failed to breed in these years. The decline in adult krill in 2005 may also 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) also 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).

6.2 Offshore Benthic Habitat

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 (Fig. 6.2). 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

Figure 6.2 *Benthic community on Cordell Bank. Rick Starr/ CBNMS.*

vulnerable to changes over longer time periods as sedentary animals are unable to move out of an area as conditions 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). Benthic species within a community will respond to climate change in currently unknown and various ways depending on their tolerances of changes in temperature, oxygen and/or pH. Further research is needed to exaime how community structure may change depending on vulnerability levels of individual species.

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 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.

6.3 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: Projected 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^2 of habitat at the South Farallon Islands (PRBO *unpublished data*; Fig. 6.3). 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.
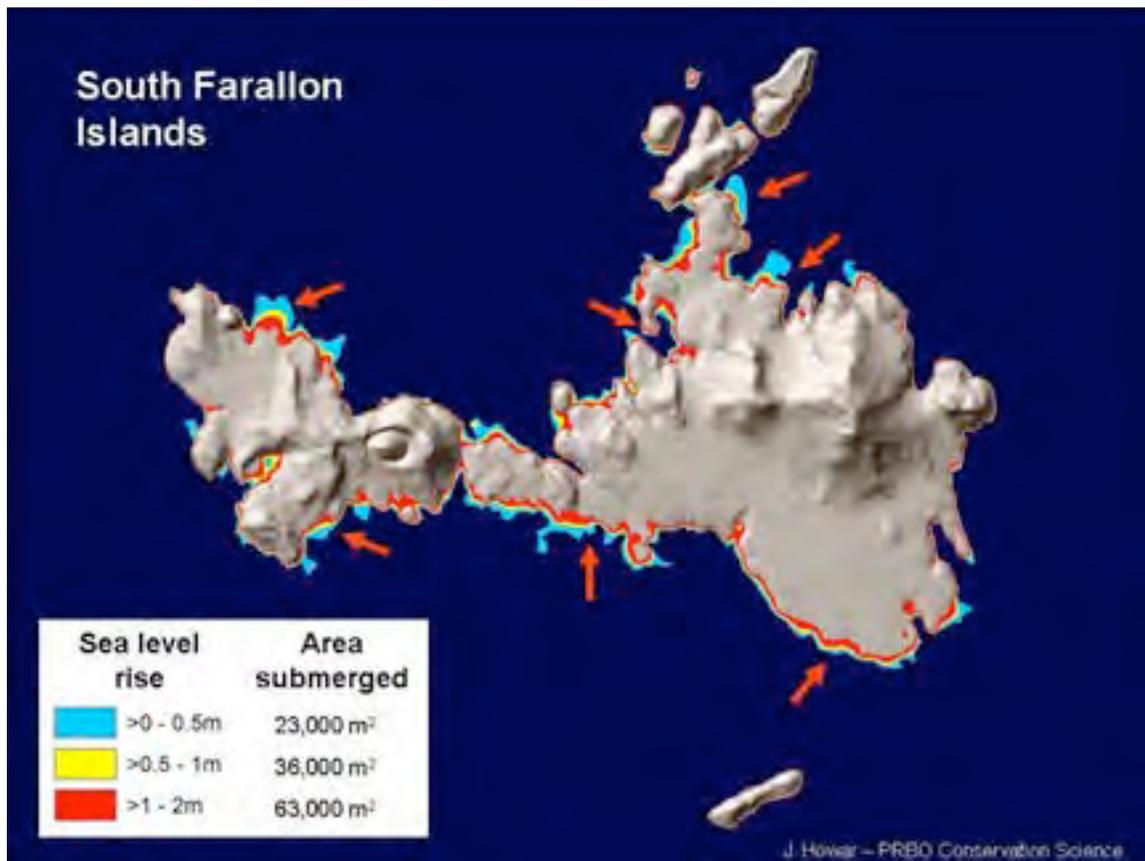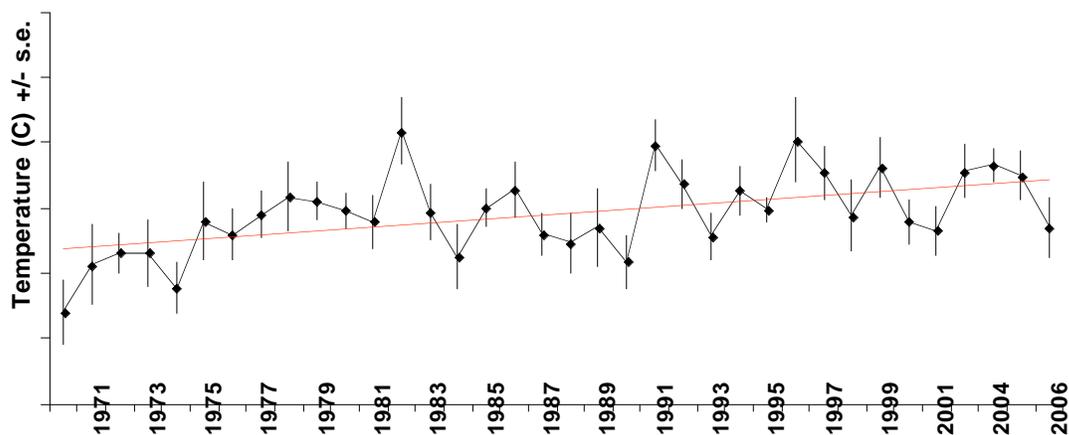

Figure 6.3. *Map of the South Farallon Islands showing the cumulative habitat area (in square meters) submerged by differing degrees of sea level rise relative to the average tide level. The arrows indicate major pinnipeds rookeries and haul out areas. J. Howar, PRBO Conservation Science.*

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 projected 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 over a 36-year period, from 1971- 2007 (PRBO *unpublished data*; Fig. 6.4). Given current predictions, PRBO scientists 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 6.4. *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.*

6.4 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).

Figure 6.5. *Stinson Beach, CA. Golden Gate National Parks Conservancy.*

Sea Level Rise and Erosion: 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 projected effects of climate change, including increased storminess, are expected to intensify pressures on these exposed ecosystems by increasing rates of shoreline 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 projected 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).

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 3.5 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).

Use of Habitat: 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.

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 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.

6.5 Rocky Intertidal Habitat
Rocky intertidal habitat is characterized by complex environmental conditions that are driven by both aquatic and terrestrial forces (Fig 6.6). Of primary concern are possible increases in average water and air temperature as well as the prevalence of extreme conditions 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.

Figure 6.6. *Rocky intertidal habitat in Gulf of the Farallones. Joe Heath.*

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).

Many climate change studies of rocky intertidal communities have focused on the response of the California mussel *Mytilus californianus* (Fig 6.7) 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.

Figure 6.7. *California mussel (Mytilus californianus).* GFNMS Photo Library.
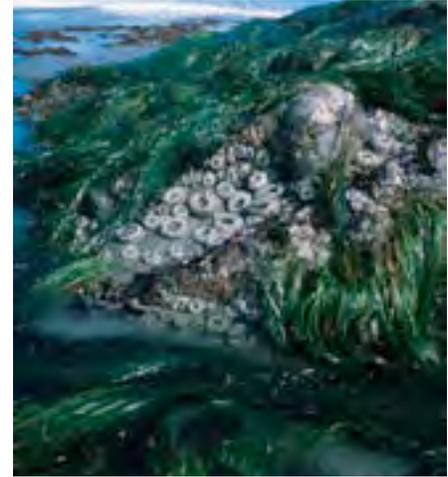
In contrast, intertidal mussels may see population declines depending on the occurrence of extreme environmental conditions. Extreme heat waves have resulted in mass mortality events of California mussels and limpets (*Lottia scabra*) in the Bodega Marine Reserve (Harley 2008). Due to the timing of low 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: The effect of ocean acidification on the saturation state of surface waters is not fully understood (see 3.3.3 Coastal Upwelling and 3.6.2 Ocean Acidification). 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.

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 study region. However, the closely related mussel *Mytilus edulis* exhibits decreased calcification rates with increasing aqueous CO_2 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 (Fig. 6.8). 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).

Figure 6.8. Crustose corraline algae (unidentified sp.). Steve Lonhart / SIMoN NOAA.