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

Waves: Greater wave activity (see 3.3.2 Waves) suggests that intertidal and subtidal organisms may experience greater physical forces. A number of studies indicate that the strength of organisms does not always scale with their size (Denny et al. 1985; Carrington 1990; Gaylord et al. 1994; Denny and Kitzes 2005; Gaylord et al. 2008), which can lead to selective removal of larger organisms, influencing size structure and species interactions that depend on size. However, the relationship between offshore significant wave height and hydrodynamic force is not simple. Although local wave height inside the surf zone is a good predictor of wave velocity and force (Gaylord 1999, 2000), the relationship between offshore H_s and intertidal force cannot be expressed via a simple linear relationship (Helmuth and Denny 2003). In many cases (89% of sites examined), elevated offshore wave activity increased force up to a point (H_s > 2-2.5 m), after which force did not increase with wave height. Since many northern sites on the west coast of North America already experience wave heights of this magnitude, forces may not increase with increasing H_s. On the other hand, the remaining 11% of sites examined exhibited a positive relationship with H_s that did not level off (Helmuth and Denny 2003). At sites such as these, larger wave forces may accrue, as well as greater wave splash and ensuring modulated temperatures by means of chronic wetting. Also note that the above percentages reflect at least in part the spectrum of bathymetries represented in the sites examined, suggesting that a greater or lesser fraction of shores could be influenced by changes in wave height than implied in the analysis of Helmuth and Denny (2003).

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

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

6.6 Nearshore Subtidal Habitat

The nearshore subtidal environment within the study region includes sandy continental shelf habitat as well as rocky reefs, which support kelp forest communities (Fig. 6.9). Primary climate change drivers of interest for nearshore subtidal habitats include changes in upwelling, stratification, ocean acidification, storm activity, and sea level rise.

Figure 6.9. *Kelp forest community. Claire Fackler, NOAA/ ONMS.*

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

Stratification and Mixing: Thermoclines have become stronger and deeper in offshore waters in the study region (Palacios et al. 2004; see 3.3.3 Coastal Upwelling) and a similar increase in stratification could be expected in sheltered bays (e.g., Monterey Bay; see 6.1 Pelagic Habitat). In offshore waters, stratification as a consequence of climate change has already been reported to change zooplankton communities in the California Current (Roemmich and McGowan 1995). In nearshore regions sheltered from the direct effects of upwelling, an increase in stratification would reduce nutrient delivery to surface waters and thus to subtidal habitats, as well as decrease offshore transport of larvae and spores. In Southern California, where stratification is observed during summer, nitrate availability limits kelp forest productivity (Zimmerman and Kremer 1984; 1986; Zimmerman and Robertson 1985), and if conditions in sheltered northern waters approached those found further south, it is conceivable that these important ecosystems could be significantly altered. Further, changes in horizontal mixing and transport is expected to occur with changes in upwelling and the associated mesoscale (10s-100s km) circulation, such as recirculation cells in the lee of headlands. Mesoscale features are important corridors between offshore and nearshore habitats. Climate moderates mesoscale circulation in the California Current System, thereby affecting nearshore-offshore connections (Keister and Strub 2008).

Ocean Acidification: The northern and central California coast is especially vulnerable to acidification because of upwelling, which transports acidified waters (under-saturated with respect to aragonite) from offshore onto the continental shelf, potentially reaching the coastal shallow subtidal (Feely et al. 2008). The acidified upwelled water may affect calcifying organisms utilizing the nearshore subtidal habitat (see 3.6.2 Ocean Acidification), although, unlike the rocky intertdal, few nearshore subtidal habitats in this region are dominated by calcifying organisms.

Storm Activity: Increasing significant wave heights will affect sediment redistribution and may change the coastal topography of the area. Increased storm activity may increase precipitation in this area, leading to greater freshwater input to the nearshore subtidal, including inputs from the San Francisco Bay outflow. An increase in terrestrial inputs as well as storm activity will lead to higher resuspension of sediment resulting in increased turbidity and light attenuation. Increased turbidity will compromise kelp growth. Increased storm activity may also move nearshore kelp forests into deeper water (Graham 1997) and create greater intra-annual variability in kelp productivity and abundance (Graham et al. 1997). Greater turbidity may compromise the growth and recruitment of some kelp species (e.g., *Macrocystis*) while promoting others (e.g., *Nereocystis*). For kelp forest communities on rocky reefs (which form a physical habitat for reef-associated species), increased storm activity may also increase dislodgement of kelp holdfasts resulting in a loss of physical habitat for kelp forest associated species (Seymour et al. 1989; Graham et al. 1997). Some of these effects may also be modulated by alterations in mean transport, perhaps tied to alterations in upwelling phenomena, through subtle interactions between waves and currents (Gaylord et al. 2003). The loss of kelp forests can have further effects due to their immense importance as subsidizing agents to other communities. Dislodged kelp biomass serves as a critical food resource both to deep-water ecosystems as well as for intertidal and (in particular) beach fauna (ZoBell 1971; Harrold et al. 1998; Vetter and Dayton 1999; Colombini and Chelazzi 2003).

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

6.7 Estuarine Habitat

The physical structure of estuarine habitat is likely to undergo significant changes in the face of changing climates. Sea level rise is among the most important climate change factors forcing changes in the physical structure of estuarine systems in the coming decades. Other factors such as increasing air and sea surface temperatures and CO_2 may interact with sea level rise to influence the physical environment of these habitats. Climate change is also projected to result in changes in oceanographic and atmospheric linkages resulting in changes in ocean currents and storm cycles that will likely influence estuarine geomorphology. Finally, the hydrological cycle, including rainfall and outflow from rivers into estuaries will also influence the transport and deposition of sediments with long-term consequences for the physical structure of California estuaries.

Figure 6.10 *Left: Bolinas Lagoon, CA. GFNMS Photo Library. Right: Tomales Bay, CA. Brad Damitz NOAA/GFNMS.*

Sea Level Rise: Despite the certainty of rising sea levels, much uncertainty surrounds the long-term effects of sea level rise on the physical habitats of estuaries. Many other factors can potentially interact with climate change to influence the rates at which tidal elevation is altered and consequently the extent to which estuarine habitat is lost. For instance, increasing inundation may be offset by increased rates of inorganic sediment deposition (Friedrichs and Perry 2001). Also, increasing CO_2 levels may also result in greater production of C_3 plants thereby increasing rates of organic deposition (Morris et al. 2002; Körner 2006). However, this increased deposition could, in turn, be offset by increased freshwater intrusion, which can increase rates of decomposition (Weston et al. 2006). In particular, estuarine habitats more dependent on organic rather than inorganic deposition may be more subject to the influences of changes in sea level (Stevenson et al. 1986). Sediment supply remains an important if not completely understood indicator of wetland and estuary resiliency.

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

Coastal lagoon habitat types, such as those occurring in Bolinas Lagoon (Fig. 6.10), have been modeled in detail (PWA 2006). Each estuarine habitat type will respond differently based on the overall response of the individual systems. Brackish and salt marsh estuarine habitats are likely to be exposed to salt water more frequently and at higher elevations. This expansion of subtidal wetlands will increase the area for wind wave formation potentially accelerating erosion along the marsh edges. Along estuaries with unarmored barrier spits (e.g., Drakes Estero) overwash events will be more frequent, depositing sediment on the inland side of the spit. These overwash deposits generally form small deltas, which over time can result in a “rollover” of the spit, or landward migration of the entire spit toward the mainland. This “rollover” may reduce the tidal prism and flushing characteristics of the lagoon and potentially lead to changes in frequency and duration of breaching events. In estuaries unconstrained by development, infrastructure, and landscapes, the wetland habitats will likely migrate inland and upward to remain in balance. However, in locations where development, infrastructure, and landscapes constrain or border wetlands, intertidal wetlands habitats may be lost as indicated above.

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

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

Changing patterns of precipitation and consequently outflow may have significant affects on the biota of estuaries as well (Kimmerer 2002). Predictions for much of California suggest increasingly interannual variability in rainfall and outflow patterns (Cayan et al. 2008). Current predictions suggest that these increasingly variable flows may favor the invasion of coastal estuaries by invasive species. These changing patterns of outflow will mean that there will also be increasing changes in the salinity gradient with substantial consequences for estuarine biota. Increasing storm activity will also potentially alter estuarine geomorphology due to greater transport of sediments into estuaries from both ocean and watershed sources (Hoyos et al. 2006; Day et al. 2008). Storm activity will interact with other cyclic phenomena, such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, to influence estuaries in complex ways (Day et al. 2008).

Temperature: Increasing water and air temperatures are magnified in estuaries relative to the outer coast and are important drivers of community and ecosystem responses in estuaries. Increasing water temperatures can result in the range expansion of both native and non-native species into new areas (Williams and Grosholz 2008), and can have significant demographic effects as well. For instance, temperature increases have been responsible for the disappearance of the marine bivalve, *Macoma balthica*, in Northern Spain. Common in study region mud flats from San Francisco Bay north, the Baltic clam experienced elevated temperatures in Northern Spain, (> 30^0C) increasing metabolic rates and resulting in eventual starvation. M. *bathica* disappeared from the northern Spanish coast because of increasing summer maxima during past decades (Jansen et al. 2007). The impacts of increasing water temperature on intertidal plants can affect desiccation stress and may interact with nutrient dynamics, tolerance to soil conditions and recruitment from seed vs. vegetative growth (Levine et al. 1998). Increasing temperatures may also alter interactions between marine plants and their herbivores (O'Connor 2009). In addition, increased temperatures may generally put greater stress on plants and animals and magnify problems with parasites and pathogens. For instance, Poulin and Mouritsen (2006) found increasing evidence that parasites such as trematodes are extremely sensitive to temperature increases of less than four degrees Celsius, causing amphipod population crashes. Relatively small perturbations may translate into large alterations of mud flat communities.

Ocean Acidification: Ocean acidification may adversely affect estuaries because they are subject to freshwater input that lowers buffering capacity as well as intrusion of upwelled waters from the adjacent coastal ocean. Increasing atmospheric CO_2 will also disproportionately influence C_3 plants (Mayor and Hicks 2009). Current studies from experimental CO_2 enrichment arrays show that increasing levels of CO_2 can influence the relative above and below ground growth of plants and favor C_3 plants relative to C_4 plants. Long-term studies have not found that these effects continue without the expected effects of nitrogen limitation. In addition, the additional production may increase the role of estuarine plants as a carbon sink with implications for the future carbon budgets (Mayor and Hicks 2009).

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

<u>Transport</u>: Finally, climate change is likely to alter linkages between atmospheric and oceanographic forces resulting in changes in upwelling, coastal advection and variety of processes influencing the transport of organisms within and between estuaries (Gawarkiewicz et al. 2007). These changes in coastal ocean transport processes are likely to result in changes in the frequency or magnitude of delivery of plankton and various larval and adult dispersal stages among estuaries (Harley et al. 2006). Therefore, the degree of connectivity among populations and communities, both from a population genetic and a population dynamic perspective, are likely to be altered with unknown consequences.

Figure 6.11 *Mudflats in Tomales Bay, CA. Dan Howard.*

<u>Mudflats</u>: Estuarine mud flats, in contrast to other intertidal soft sediment habitats such as sandy beaches, cannot develop in the presence of wave action and need a source of fine grain sediments (Lenihan and Micheli 2001). Mud flats are located in partially protected bays, lagoons and harbors. Examples within the study region include: Pillar Point Harbor, Bolinas Lagoon, Esteros Americano and de San Antonio, Tomales Bay (Fig. 6.11) and Bodega Bay. Mud flats will be threatened by sea level rise, ocean acidification, organic loading and sea surface temperature change. Low lying muddy shores are most vulnerable to sea level rise with accompanying stronger tidal currents, wave action and changes in salinity. This will result in sediment starvation, erosion and the eventual loss of this coastal ecosystem (de la Vega-Leinert and Nicholls 2008; Lebbe et al. 2008; Callaway et al. 1997). Mud flats with hypsometric characteristics (an extensive intertidal area and a restricted inlet) will be particularly sensitive to sea level rise (French 2008). Deteriorating sediment conditions are thought to be responsible for declining recruitment success in Wadden Sea cockles (Beukema and Dekker 2005). Salt water inundation will cause vegetation changes as more saline water replaces brackish and fresh water (Callaway et al. 2007). For example, at Pillar Point, this would impact the upstream brackish water cattail (*Typha* spp.) and freshwater willow (*Salix* spp.) marshes.

7. Parallel Ecosystem Stressors

Through both land and marine-based activities, there is no area of the ocean that is not affected by humans. Halpern et al. (2008) estimate that two-fifths of the ocean is affected by multiple human influences, or “stressors.” Stressors are defined as variables that adversely affect an organism’s physiology or population performance in a statistically significant way (Vinebrooke et al. 2004; Barrett et al. 1976; Auerbach 1981). Often time these stressors do not function independently, but instead interact to produce combined impacts on biodiversity and ecosystem health (Vinebrooke et al. 2004; Breitburg et al. 1998; Frost et al. 1999; Schindler 2001). Some examples of interacting ecosystem stressors within the study region include pollutants and contaminants, invasive species, fishing activities, harmful algal blooms, disease, habitat modification, wildlife disturbance, and potentially the future development of offshore energy projects (both conventional sources such as oil and gas, and alternative energy sources such as wave and tidal energy). Both locally induced stress and climate change stress reduce the resiliency of ecosystems – the ability of the ecosystem to respond to further change (see box: Ecosystem Resilience). Thus, in order to assess the possible impacts of climate change on ecosystems in the study region, the existence (or anticipated development) of parallel stressors due to local human influences must also be recognized.

7.1 Pollutants and Contaminants

To highlight the influence of pollutants on the study region, the San Francisco Bay Estuary alone carries a pollution load generated by approximately eight million people living in the San Francisco Bay Area as well as effluent from the agricultural Central Valley, via the Sacramento and San Joaquin rivers. Contaminants – including agricultural and livestock waste, wastewater, sewage outfalls, historic mining and industrial wastes – can be carried into the study region via the freshwater outflow from San Francisco Bay (i.e., the San Francisco Bay plume; Fig. 7.1). The plume extends as far as the Farallon Islands and Cordell Bank after heavy rainfall (*unpublished data*); and carries nutrients during spring and summer that stimulate phytoplankton growth within the study region.

Figure 7.1: *San Francisco Bay plume from space. NASA. http://www.nasa.gov/mission_pages/station/main/iss004e10288_feature_prt.htm.*

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

A major but often overlooked consequence of climate change is the effect on ocean chemistry beyond the calcium carbonate system (Doney et al. 2009). For example, the release of methylmercury[3] from sediments is favored in conditions of lower salinity, lower pH, anoxia, and greater temperature (Ullrich et al. 2001). Climate change may therefore increase the bioavailability of contaminants to marine organisms, which when combined with other climate change stressors (e.g. temperature extremes), may push organisms past their ecological tipping point. Changing freshwater runoff schedules combined with increased fire frequency may also affect the delivery and availability of contaminants to coastal watersheds.

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

7.2 Invasive Species

Changing climates can influence both the process and the consequences of invasion (Dukes and Mooney 1999) however, there are few studies of the intersection between climate change and invasions in marine systems (Occhipinti-Ambrogi 2007). Among the most important aspects of climate change for marine invasions are increasing sea surface temperatures and changes in wind driven surface currents. These can potentially alter both the frequency of transport of dispersal stages of invaders among locations (e.g., invaded and not) influencing the likelihood of spread and establishment in new locations. Stachowicz et al. (2002) examined long-term data in recruitment of native and invasive tunicates relative to winter minima and summer maxima in sea surface temperatures. They found that increasing sea surface temperatures resulted in both earlier and greater recruitment of invasive species as well as increased growth rates of invasives relative to natives. They predicted that increasing temperatures will lead to greater success of invasive species. Changing temperature regimes could also influence human-mediated pathways including shipping vectors by changing commercial activity or shipping routes due to potentially extended shipping seasons or new ice-free shipping routes (Hellman et al. 2008). Increasing sea surface temperatures and changing ocean current systems could increase the degree of habitat matching between invaded and uninvaded sites, facilitating the spread or establishment of new invaders (Herborg et al. 2007). Other climate factors such as increasing atmospheric CO_2 would favor C_3 over C_4 plants, thus potentially affecting competition among marine plants (Craft et. 2009).

[3] Methylmercury is a potent neurotoxin that is readily accumulated by aquatic organisms and can be passed onto humans via consumption of contaminated fish and invertebrates.

Increasing ocean acidification associated with increasing CO_2 (Feely et al. 2008) could influence species interactions and success of invading species in numerous ways, such as predator-prey interactions among invasive whelks and native prey. Projected rise in sea levels along the California coast may shift species interactions, particularly in urbanized estuaries or other ‘armored’ habitats where migration to higher tidal elevations is restricted (Heberger et al. 2009). Estuaries with reduced tidal exchange (microtidal) experience slower rates of vertical accretion resulting from the accumulation of organic matter. Therefore, species in these estuaries may be at greater risk of inundation due to sea level rise than species in estuaries with greater tidal exchange (mesotidal), where more rapid accumulation of inorganic sediments may be more likely to compensate for rising sea levels (Stevenson and Kearney 2009). This could favor introduced species more tolerant of increased tidal inundation relative to natives. Lastly projected increases in storm intensity and frequency and changes and resulting changes in coastal geomorphology (Day et al. 2008) could provide more opportunity for spread of opportunistic coastal invaders. In summary, climate change is likely to interact with coastal invaders in ways that are likely to increase their impacts, facilitate their spread and necessitate additional management actions.

7.3 Fishing

The study region currently supports active commercial and recreational fisheries that are managed by the State of California and the National Marine Fisheries Service, but fishing, when combined with habitat destruction, poor recruitment, and anomalous oceanographic conditions can contribute to declines of some marine species (Barnes and Thomas 2005; Ralston 2002). Impacts on marine ecosystems from fisheries exist in three main areas: 1) overfishing of a population; 2) physical impacts on habitat due to gear type; and 3) incidental take of non-target species or “bycatch” (Keller et al. 2008). Although local fisheries are managed for sustainable yield, if a fishery population is overstressed or overfished, it becomes more susceptible to the effects of climate change as well as other human induced stressors and the average life span, reproductive success, and larval quality of a fish population can be reduced. Thus, making it more vulnerable to both short- and long-term changes in the physical ocean environment. If exploitation occurs of a single keystone species, an ecosystem can become destabilized, making it more vulnerable to the effects of climate change (Keller et al. 2008). In addition, lost fishing gear can become entangled on the seafloor and could lead to damage of sensitive habitats that provide food and shelter for invertebrates and fishes (Barnes and Thomas 2005). Significant amounts of derelict fishing gear have been documented in rocky areas of Cordell Bank (ONMS 2009). Also, selected open ocean fisheries have contributed to bycatch of seabirds (Forney et al. 2001), pinnipeds, cetaceans (Read et al. 2006) and sea turtles (Spotila et al. 2000).

7.4 Harmful Algal Blooms

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

An example of the response of harmful algae to climate change in the study region may be seen in the observed increase in dinoflagellates in Monterey Bay over the last decade. Using data from the Santa Cruz Wharf in Monterey Bay, California, Jester et al. (2009) documented a dramatic shift in phytoplankton community structure starting in 2004, resulting in an increasing dominance of dinoflagellates and a corresponding decrease in diatoms. With this shift, Jester et al. (2009) reported a concomitant increase in HAB problems associated with dinoflagellates (paralytic shellfish poisoning, diarrhetic shellfish poisoning, red tides, including fish and shellfish killing red tides). Jessup et al. (2009) also documented, for the first time, a harmful event linked to what was previously assumed to be a harmless red tide organism. While it is only suggested that these events may be linked to climate change (as opposed to other oscillations in the oceanic environment), they provide a glimpse at what a warmer California Current may look like in terms of harmful algae.

Climate predictions also indicate that the timing and intensity of terrestrial runoff will be modified, both as a function of precipitation patterns and indirectly by changing the snowpack in California (Barnett et al. 2008; see 3.2 Precipitation and Land Runoff). These changes will almost certainly have secondary effects on harmful algae, particularly in estuarine systems. Recent evidence points to the importance of anthropogenic nutrients on the development and proliferation of harmful algae in California (Anderson et al. 2008; Kudela et al. 2008). Changes in the hydrological cycle, as well as long-term trends in coastal (human) populations and nutrient discharge, could result in dramatic shifts in the timing, intensity, and duration of HAB events, resulting in both positive and negative changes. For example, a recent study in the western English Channel linked climate-driven changes in rainfall to a large increase in diatom blooms and a simultaneous increase in phosphorous limitation by *Prorocentrum minimum* (a HAB organism) due to changes in nutrient availability and stratification (Rees et al. 2009).

7.5 Disease

The prevalence of disease in marine ecosystems has been projected to increase in response to a warming climate (Harvell et al. 2002). These increases have been documented in corals, seagrasses, oysters, and sea urchins and may act in concert with climate change to reduce the abundance of marine organisms (Harvell et al. 1999). This is because warming can result in increased pathogen development and survival rates, as well as favoring transmission and host susceptibility. One such link has been suggested for black abalone (*Haliotis cracherodii*) that can be afflicted with “withering foot syndrome[4]”. Greater temperatures appear to increase mortality of abalone infected in lab experiments (Friedman et al. 1997) and in the field (Tissot 1995). Furthermore, observations suggest that the disease is spreading from parts of southern California to the north (Raimondi et al. 2002).

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

[4] Withering foot syndrome is caused by a bacterium that infects the gastrointestinal tract of abalone, inhibiting the production of digestive enzymes (Friedman et al. 2000).

7.6 Wildlife Disturbance

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

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

7.7 Wave and Wind Energy

An emerging issue within the study region is the anticipated development of Wave Energy Conversion (WEC) devices, as the wave regime north of Point Conception provides an ideal amount of wave energy for a viable industry (PIER 2007). As the first experimental WEC devices were deployed only recently (in Europe), the impact of wave energy development on the study region is uncertain, and it may impose negligible stress on the ecosystem with careful planning. An outline of possible environmental issues was prepared by Nelson et al. (2008) for the California Energy Commission. First, there is concern about possible direct impacts due to construction and maintenance of the devices offshore and associated cables to the shore. Further, there is concern that intensive use of these devices may change nearshore waves and nearshore wave-driven processes, resulting in possible changes in beach morphology, estuary mouth conditions, and the alongshore transport of sediment and other water-borne materials (including contaminants). Also, for both rocky intertidal and subtidal communities, a reduction in wave energy could influence species zonation, as well as species distribution and abundance. Additional effects could be caused by changes in disturbance regimes, sediment deposition, and flow characteristics of a site (Nelson et al. 2008). It may be possible to address all of these concerns, but studies of specific WEC plans remain to be done.

The four types of WEC devices that could potentially be used within the study region (point absorbers, attenuators, overtopping devices, and oscillating water columns), will cause initial disruptions to the seabed due to drilling and/or anchoring, and the running of transmission cables to the shoreline. Some of these, such as overtopping devices, also have the potential to result in entrainment (organisms are drawn in with seawater) or impingement (organisms are collected, typically on screens) of fish and invertebrates. Construction activities could also decrease photosynthesis due to increased turbidity, as well as cause vibration and noise impacts.

Additionally, release of contaminants, changes in electromagnetic fields, and the introduction of hard substrate to soft bottom habitats can all have negative impacts on the nearshore marine environment (Nelson et al. 2008). However, there may also be positive/synergistic consequences, for example, the introduction of hard substrate is similar to the creation of an artificial reef which may provide valuable habitat (although there is the risk that this new habitat will be colonized by invasive species).

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

Offshore wind generated electricity poses similar potential threats to marine ecosystems as WECs during construction, operation, and decommissioning of turbines. For seabirds, the risk of collision with wind turbine blades is of added concern, and birds may possibly need to exert more energy to avoid collisions and maintain their navigation while migrating (Minerals Management Service 2006). At present, there are no plans for developing wind energy in this region, and it is unlikely given the depth of the continental shelf.

Ecosystem Resilience

Ecosystem resilience is the extent to which ecosystems can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or unexpectedly flipping into alternate states (Hughes et al. 2005). Resilience and alternate states are often conceptualized with a ball model where the "valleys" represent different states and the adjacent "peaks" represent the activation energy needed to shift the system into an alternate state (Fig. 7.2). Resilient systems would sit deep within a valley, requiring large forcing to flip to an alternate state.

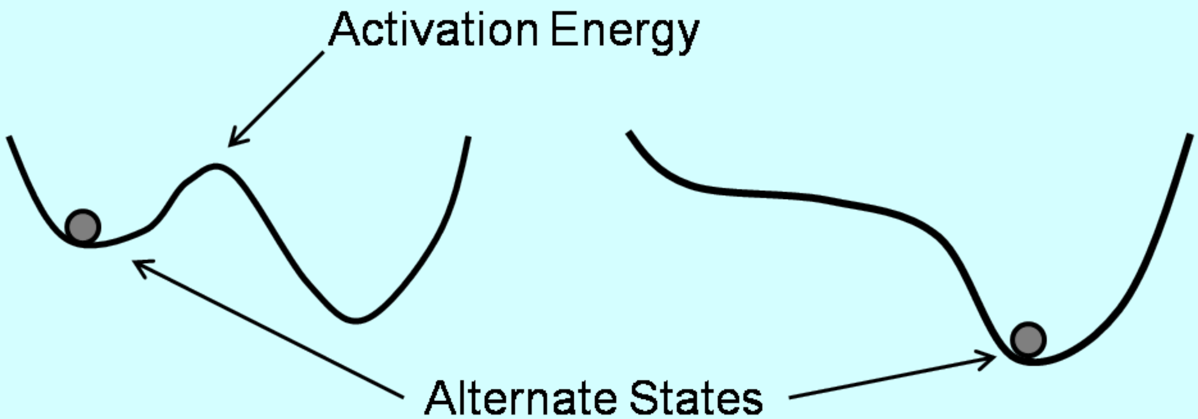

Figure 7.2. *The conceptual "ball and valley" model of alternate stable states. An initial state will remain unless the "activation energy" required to shift states is reached through a change in the system (e.g., natural disturbance, removal of key species, disease, etc.). The end state is resilient to reversion to the initial state. Adapted from Folke et al. (2004).*

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

8. Direct Impacts on Humans

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

8.1 Water Quality

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

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

8.2 Health Consequences of Harmful Algal Blooms

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

While only a small component of the phytoplankton community consists of harmful species, there are a number that produce poisoning syndromes in California. These include the following: diatoms from the genus *Pseudo-nitzschia*, which cause amnesic shellfish poisoning and have resulted in beach closures in California; dinoflagellates from the genus *Alexandrium* that constitute "red tides" and cause paralytic shellfish poisoning, resulting in closures to the shellfish industry in both California and in the Pacific Northwest; and species of cyanobacteria (blue green algae including *Anabaena* and *Microcystis*) found in fresh, brackish and marine waters that cause cyanobacterial poisoning. Blue green algae (BGA) blooms occur regularly in Rodeo Lagoon, and in coastal rivers in northern California where numerous dog deaths have been attributed to toxins associated with cyanobacteria (Humboldt County Department of Health and Human Services, 2006). BGA blooms usually occur in eutrophic waters associated with high nutrient loads (especially phosphorous) from agricultural or urban runoff, or failing sewage disposal systems. Future climate change scenarios all favor harmful BGA blooms in eutrophic waters (Pearl and Huisman, 2009). Humans and other animals are exposed to HAB toxins from eating contaminated fish or shellfish, drinking contaminated water, inhaling aerosolized contaminants (which can lead to respiratory illness[5]) during water-related activities, or by contacting contaminated water.

8.3 Shoreline Safety

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

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

[5] Algal blooms have been documented in Florida to result in respiratory illness from breathing toxins at the seashore (Moore, 2008).

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

8.4 Economic Impacts

The north-central coast of California[6] thrives with abundant and diverse wildlife and natural beauty as well as important and diverse cities, towns, industrial communities and other built environments. As scientists release climate change impact scenarios for this region, it becomes possible to identify where losses might be greatest and to plan mitigation strategies.

With a total population of 2,576,559 in the six coastal counties within the study region, and population densities ranging from 24.6 people/square mile in Mendocino County to more than 17,000 people/sq. mile in San Francisco County (Kildow et al. 2008), this unique area has a high percentage of population and structures at risk from a 100-year flood with a 1.4 meter sea level rise along the Pacific Coast (Heberger et al. 2009).[7] This section provides an overview for short- and long-term economic impacts that will affect those who live and work along the north central coast. While there are several types of potential costs that will be incurred from climate change impacts to this area, this section focuses on the current values of what could be at risk, and the implicit replacement values for these assets should they be lost.[8]

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

8.4.1 Natural Assets

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

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[6] This report considers the counties of Santa Cruz, San Mateo, San Francisco, Sonoma, Marin and Mendocino. Included is the west shoreline of San Francisco Bay. Reference is also made to the eastern shore of San Francisco Bay, where several large ports are sited. Additional data is available for this area.
[7] Similar population densities are located along the east shore of San Francisco Bay.
[8] Other potential costs include costs of mitigation to prevent damage or harm to assets, and costs of investments that are needed for the future to adapt to new conditions caused by climate change, which are not covered in this paper.

8.4.2 Physical Infrastructure

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

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

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

8.4.3 Business and Residential Infrastructure

In 2007, the six counties within the study region provided 1,330,964 jobs (8.7% of the state), paid $85.9 billion in wages (11.2% of the state), and generated over $225.9 billion in direct productivity for California (Kildow et al. 2008). Business and residential structures and their contents that lie in the path of rising seas pose complex economic considerations (Heberger et al. 2009) including: 1) potential costs of repair and replacement of damaged and destroyed buildings must rely on non-uniform data on real estate sales estimates and taxes; 2) the cost of damage to building contents can only be estimated from insurance estimates; 3) loss of inventories can only be estimated from insurance losses and lost productivity; and 4) potential loss of jobs/employment are mostly uninsured losses and have large ripple effects.

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

8.4.4 Tourism and Fisheries

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

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

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

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

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

9. Conclusion

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

The outline and logic of the report is to work from global-scale changes in the atmosphere-ocean system to regional and local changes in habitat and ecological communities within the study region (Point Arena to Año Nuevo). Systemic global change is carefully outlined in the 2007 IPCC Assessment Report and serves as a starting point for identifying and understanding large-scale changes that could influence the study region. In short, the atmosphere is warming due to a dramatic increase in greenhouse gases over the last century. While the ocean buffers change in the atmosphere, there are now clear indications of changes in the ocean, including warming and CO_2 enrichment – providing multiple mechanisms by which coastal ocean regions can be impacted. The study region is subject to changes in physical and chemical forcing as a result of these global changes and the ultimate impact on the regional ecosystem will be due to an interaction of multiple forcing mechanisms and the diverse biological responses of specific populations and communities. Changes are anticipated in atmospheric conditions (e.g., wind, cloud, fog), ocean circulation and water properties (e.g., temperature, pH), sea level, ocean waves, and land runoff. In turn, changes in these forcing factors will lead to changes in coastal upwelling, stratification, and plankton dispersal patterns. Biological systems will be impacted through changes to the quality of ocean habitat (e.g., changes in temperature, pH, dissolved oxygen, nutrient availability and wave exposure), the timing of seasonal cycles (e.g., upwelling, runoff, fog and waves), and the connectivity within and between populations. Habitat response scenarios are described for offshore pelagic, offshore benthic, island, sandy beach, rocky intertidal, nearshore subtidal, and estuarine habitats.

In parallel with climate-related changes, there are a myriad of other causes of environmental change due to human activity at the local scale (e.g., pollution, fishing, invasive species, disease). These are briefly reviewed in this report, as these are stressors that can be managed and mitigated to allow for an ecosystem resilient enough to adapt to climate change as it happens. If populations and communities can adapt, then the changing climate is not necessarily entirely bad. To be able to adapt, persist, and remain vital, these marine populations and communities will need resiliency, which can be improved through a reduction in the manageable local stressors. In the end, a societal effort now will be well placed, as it is humans that will benefit significantly from an ocean environment that can continue to provide the goods and services that have underwritten coastal society for millennia.

9.1 Priority Issues

It is expected that the most severe ecological changes will be associated with changes in the following parameters – for each the likelihood of change is high and the impact of change is also high (i.e., these are the highest risk phenomena):

- Upwelling
- Ocean temperature
- Sea level
- Ocean pH

Upwelling appears to be increasing in this region, due to a more rapid increase in land temperature than ocean temperature and an associated increase in the summer atmospheric pressure gradients that drive the strong northerly winds off northern and central California. Both model and data analyses support this assertion. Further, given that this region is characterized by upwelling processes and populations, the impact of any change in upwelling (and thus nutrient delivery) will ripple through the whole ecosystem.

In contrast to cooler waters over the shelf, surface waters are warming outside of the active upwelling zones – which means both offshore waters and nearshore waters in bays and estuaries are warming. In addition to direct thermal effects on organism physiology, warmer surface waters result in enhanced stratification being observed offshore (and in sheltered bays) and a reduction in the vertical mixing that underpins offshore primary production.

The primary cause of sea level rise is the global increase in ocean temperatures. In addition to being well documented in IPCC assessments, data at the mouth of San Francisco Bay show a 20 cm rise in sea level over the last century. Sea level rise directly affects intertidal communities in estuaries as well as on rocky and sandy shorelines, but it also increases the damage associated with storm wave events, which heavily impact human activities and shoreline ecosystems.

Finally, the acidification of ocean waters has recently been called "the other CO_2 problem" in recognition of the immensity of this threat. Alone, acidification may seriously alter coastal ecosystems as we know them. Decreasing pH (increasing acidity) will preclude many organisms from forming calcium carbonate structures, like shells and exoskeletons. Deep upwelled waters are more acidic than most of the surface ocean and this region is thus threatened by the double effect of increased dissolved CO_2 in the ocean plus increased upwelling in this region. It is quite possible that the "saturation horizon" will shoal to depths where it can significantly impact the marine ecosystem, which is predominantly near-surface, making this region uninhabitable for numerous key invertebrate populations.

Although we highlight these parameters, it is important to realize that we may yet be surprised and find that changes in other parameters like fog and cloud cover, or dissolved oxygen, or dispersal patterns, or trophic landscape connectivity plays a critical role in the trajectory of ecosystem change. Clearly, in understanding a changing system, one has to reduce the complexity of analysis and focus on the high-risk phenomena (but one cannot completely ignore other phenomena).

9.2 Working Group Recommendations

The question that now arises is, "what should we do?" Based on the immensity of ocean systems (even small coastal ones), and aware of the uncertainty in anticipating how global changes will downscale to regional and local change, the working group recommends that GFNMS and CBNMS pursue five lines of action. Each of these lines of action will require an allocation of resources, and enhanced collaboration with other agencies and non-governmental organizations.

- ***Educate society** – inform people to allow for optimum decisions.*
  Use the opportunities inherent in the National Marine Sanctuary System to educate both local residents and federal/state/local decisions makers. Education is not intended to prescribe options, but to provide people with the insight that will optimize difficult decisions, including use of public funds and regulation of activities in developing a strategy for minimizing disruptions to ecosystems and socio-economic systems due to climate change.
    - Promoting stewardship, including citizen science and monitoring
    - Outreach through exhibits & lectures
    - Outreach through web sites and portals

- ***Put ecosystems in context** – link greenhouse gas emissions with marine ecosystem health.*
  The IPCC has made it clear that observed changes in global climate are due to a buildup in greenhouse gases (GHG). Further, there is a long-term commitment to climate change due to the delay between increases in GHG concentration and responses in atmosphere and ocean conditions. Our actions now can have significant benefits in mitigating climate change impacts on human society and ecosystems decades from now.
    - Work to understand and elucidate links between global climate assessments and threats to local ecosystems
    - Work with partners regionally and globally to address the increase in greenhouse gas concentrations
    - Educate public on the link between greenhouse gas emissions and marine ecosystem health

- ***Anticipate change** – obtain best available information on changing and future conditions.*
  The primary antidote to uncertainty in predictions of the future is to improve certainty in the assessment and understanding of present conditions. The most critical action is to know how the environment and ecosystems are changing, and to know how these changes relate to global climate change (as opposed to other local drivers of environmental change). Available information and modeling may not be perfect, but it can be much improved with strategic investment in monitoring and assessment. Given that sanctuaries are seen as sentinel sites, this is where GFNMS and CBNMS can play a leadership role in collaboration and community building with other federal, state, and local agencies, academia, and regional groups.
    - Identify priority concerns and develop expectations of change in order to direct monitoring efforts and to identify early opportunities for reducing ecosystem risk
    - Monitor the environment. Through collaboration with other groups, develop a set of strategic monitoring activities that can reasonably track the pulse of the environment. This would include fixed stations, boat-based surveys and remote sensing (e.g., satellites and HF radar) to monitor water properties, currents and plankton.

  - o Monitor populations. Through collaboration with state/federal/non-governmental resource agencies and research groups, develop annual assessments of changes in fish, bird and mammal population. In addition, develop collaborative assessments of habitat-defining populations such as krill and macrophytes (e.g., kelp & seagrass).
  - o Regular assessment. Building on updated global and eastern Pacific regional assessments of climate change, develop a regular assessment of changing conditions and anticipated future change for the study region that can resolve interannual and interdecadal changes. These assessments will include data on environment and ecosystem conditions in addition to the results of down-scaling models. The initial assessment should include a schematic view of the ecosystem components and processes.
  - o Capture an up-to-date understanding of environment and ecosystem in a model that can be used to anticipate possible future changes.
  - o Pursue funding and collaboration to develop this program.

- ➢ ***Mitigate impacts on the ecosystem*** **–** *reduce manageable stressors that compromise system resiliency.*

  While climate change cannot be diverted in the short-term, we can mitigate the impact on local ecosystems by enhancing the resiliency of coastal ecosystems to handle this environmental change. Resiliency suggests a complex system that can adapt to change – typical attributes of such a system include being modular and heterogeneous, and having tight feedback loops and redundancy. This system understanding is developing rapidly through the promotion of ecosystem-based management (EBM). The sanctuaries are important players in developing EBM for this region and can play an increased leadership role if supported in this.
  - o Develop an assessment of ecological goods and services in this region.
  - o Develop an assessment of stressors that are constraining the “breathing room” of these coastal ecosystems.
  - o Identify strategic opportunities to reduce manageable stressors and motivate this action in terms of the reduced risk of losing critical ecological goods and services.
  - o Work with regional partners to develop EBM for this region.

- ➢ ***Adapt to change*** **–** *create policies and management strategies that are flexible to future changes.*

  As we identify future problems, we need to adapt management to minimize future impacts. For example, within sanctuary jurisdiction, policies such as a preference for removal of shoreline armoring could be developed to help nearshore and estuarine habitats adapt to sea level rise. Further, partnerships with state and local government and non-governmental groups should be strengthened even more to ensure that appropriate mitigative and adaptive legislation, regulations and strategies are maximized among the relevant groups.

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

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

The National Marine Sanctuary System consists of 14 marine protected areas that encompass more than 150,000 square miles of marine and Great Lakes waters from Washington State to the Florida Keys, and from Lake Huron to American Samoa. The system includes 13 national marine sanctuaries and the Papahnaumokukea Marine National Monumen t (ONMS 2006). The study region for this document are the waters off north-central California, from Point Arena to Año Nuevo, within which Gulf of the Farallones and Cordell Bank national marine sanctuaries are found. The boundaries of these sanctuaries are also located within the California Current ecosystem, one of four major eastern boundary currents in the world, that stretches along the western coast of North America from southern Canada to northern Mexico. Due to a high degree of wind-driven upwelling, there is a ready supply of nutrients to surface waters and the California Current ecosystem is one of the most biologically productive regions in the world.

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

Designated in 1981, Gulf of the Farallones National Marine Sanctuary (GFNMS) spans 1,279-square-miles (966 square nautical miles) just north and west of San Francisco Bay, and protects open ocean, nearshore tidal flats, rocky intertidal areas, estuarine wetlands, subtidal reefs, and coastal beaches within its boundaries. It is a globally significant, extraordinarily diverse and productive marine ecosystem that supports abundant wildlife and valuable fisheries. The sanctuary provides breeding and feeding grounds for at least twenty-five endangered or threatened species; thirty-six marine mammal species, including blue and humpback whales, and seals; over a quarter-million breeding seabirds; and one of the most significant white shark populations on the planet. In addition, GFNMS has administrative jurisdiction over the northern portion of the Monterey Bay National Marine Sanctuary, from the San Mateo/Santa Cruz County line northward to the existing boundary between the two sanctuaries and maintains offices in both San Francisco and Half Moon Bay.

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

Glossary

Accretion: the accumulation of sediment, deposited by natural fluid flow processes

Advection: the transport of something (e.g., temperature, moisture) from one region to another

Amplitude: the magnitude of change in a wave; one half the wave height

Anthropogenic: effects, processes or materials derived from human activities

Aragonite: a carbonite mineral; one of the two common (the other is calcite) naturally occurring polymorphs of calcium carbonate

Biodiversity: the variation of life forms within a given ecosystem, biome, or for the entire Earth

Bottom-up: nutrient supply and productivity and type of primary producers (plants and phytoplankton) are controling the ecosystem structure

C_3 plants: over 95% of earth's plant species; use the enzyme rubisco to make a three-carbon compound as the first stable product of carbon fixation; flourish in cool, wet, and cloudy climates, where light levels may be low, because the metabolic pathway is more energy efficient, and if water is plentiful, the stomata can stay open and let in more carbon dioxide, however, carbon losses through photorespiration are high

C_4 plants: less than 1% of earth's plant species; possess biochemical and anatomical mechanisms to raise the intercellular carbon dioxide concentration at the site of fixation, and this reduces, and sometimes eliminates, carbon losses by photorespiration; inhabit hot, dry evironments, have very high water-use efficiency, so that there can be up to twice as much photosynthesis per gram of water as in C_3 plants, but C_4 metabolism is inefficient in shady or cool environments

Calcite: the most stable polymorph of calcium carbonate

Carbon cycle: The carbon cycle is the biogeochemical cycle by which carbon is continuously exchanged among Earth's five major resovoirs of carbon (biosphere, pedosphere, geosphere, hydrosphere, and atmosphere)

Carbon sink: a natural or manmade reservoir that accumulates and stores some carbon-containing chemical compound for an indefinite period

Climate change: a change in the statistical distribution of weather over periods of time that range from decades to millions of years; it can be a change in average weather or a change in the distribution of weater events around an average (i.e., greater or fewer extreme weather events)

Congener: another organism within the same genus

Conspecific: another organism within the same species

El Niño: a condition of decreased westward winds over the equatorial Pacific. This results in warm waters in the eastern Pacific that reduce nutrient availability, having significant consequences for coastal fisheries of western North and South America.

Elevational range: the component of a species range in terms of the elevation or altitude it occupies

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

Fog: a cloud whose base intersects the ground and restricts visibility below 1 km.

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

Frontogenesis: the formation or strengthening of an atmospheric front.

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

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

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

Hyper-nutrified: a body of water containing high levels of nutrients such as nitrogen and phosphorus.

Insolation: a measure of solar radiation.

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

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

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

La Niña: a condition of unusually cold water temperatures in the tropical eastern Pacific, also the opposing condition to El Niño.

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

Macroalgae: large aquatic photosynthetic plants that can been seen without the aid of a microscope

Marine layer: an air mass that develops over a body of water and thus takes on the characteristics of both the moisture and temperature of the water. The air mass is trapped under a strong temperature inversion. Given that the marine layer is composed of very moist cool air, it can contain clouds either elevated off the surface, which are called marine stratus, or clouds intersecting the ground, which can be called sea fog.

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

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

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

North Pacific High (NPH): a semi-permanent, subtropical area of high pressure in the North Pacific Ocean; strongest in the Northern Hemisperic summer and displaced towards the equator during the winter when the Aleutian Low becomes more dominate

Oligotrophic: an ecosystem or environment offering little to sustain life; commonly used to describe bodies of water or soils with very low nutrient levels

Pacific Decadal Oscillation (PDO): a longer-term fluctuation in ocean climate that changes state approximately every 20-40 years

Phenology: the study of periodic plant and animal life cycle events and how these are influenced by seasonal and interannual variations in climate

Population Connectivity: the exchange of individuals between geographically isolated sub-populations through mechanisms such as larval dispersal or migration

Saturation depth (horizon): Surface ocean waters are supersaturated with respect to $CaCO_3$ (calcite or aragonite), which becomes more soluble with decreasing temperature and increasing pressure (hence depth). A natural boundary, the saturation horizon develops when the saturation states falls under unity and $CaCO_3$ readily dissolves (http://www.co2.ulg.ac.be/peace/intro.htm).

Saturation state: the degree to which seawater is saturated with respect to carbonate minerals (e.g., calcite, aragonite, and high-magnesium calcites).

Significant wave height (H_s): the average height of the one third highest waves.

Stratification: the building up of layers

Stratus: A cloud in the form of a gray layer with a rather uniform base. It seldom produces precipitation but if it does, it is in the form of drizzle. It is often seen in the summer months along the California coast. When this cloud comes in contact with the surface it is called fog.

Stressor: an agent, condition, or other stimulus that causes stress to an organism

Subsidence: a descending motion of air in the atmosphere, usually with the implication that the condition extends over a broad area.

Thermocline: a thin but distinct layer in a large body of fluid (e.g., water, such as an ocean or lake, or air, such as an atmosphere), in which temperature changes more rapidly with depth than it does in the layers above or below; in the ocean, the thermocline may be thought of as an invisible blanket which separates the upper mixed layer from the calm deep water below

Top-down: top predators are controling the structure/population dynamics of the ecosystem

Turbulence: the irregular or chaotic flow of a fluid (e.g., air or water).

Uptake: an act of taking in or absorbing

Upwelling: results from the offshore transport of near-surface water due to alongshore winds from the north and the influence of the earth’s rotation (known as Ekman transport), this water is replaced with cold, salty, nutrient-rich water from depths below.

Wind curl (stress): the drag or tangential force per unit area exerted on the surface of the earth by the adjacent layer of moving air

Wind shear: a change in wind direction and speed between slightly different altitudes, especially a sudden downdraft