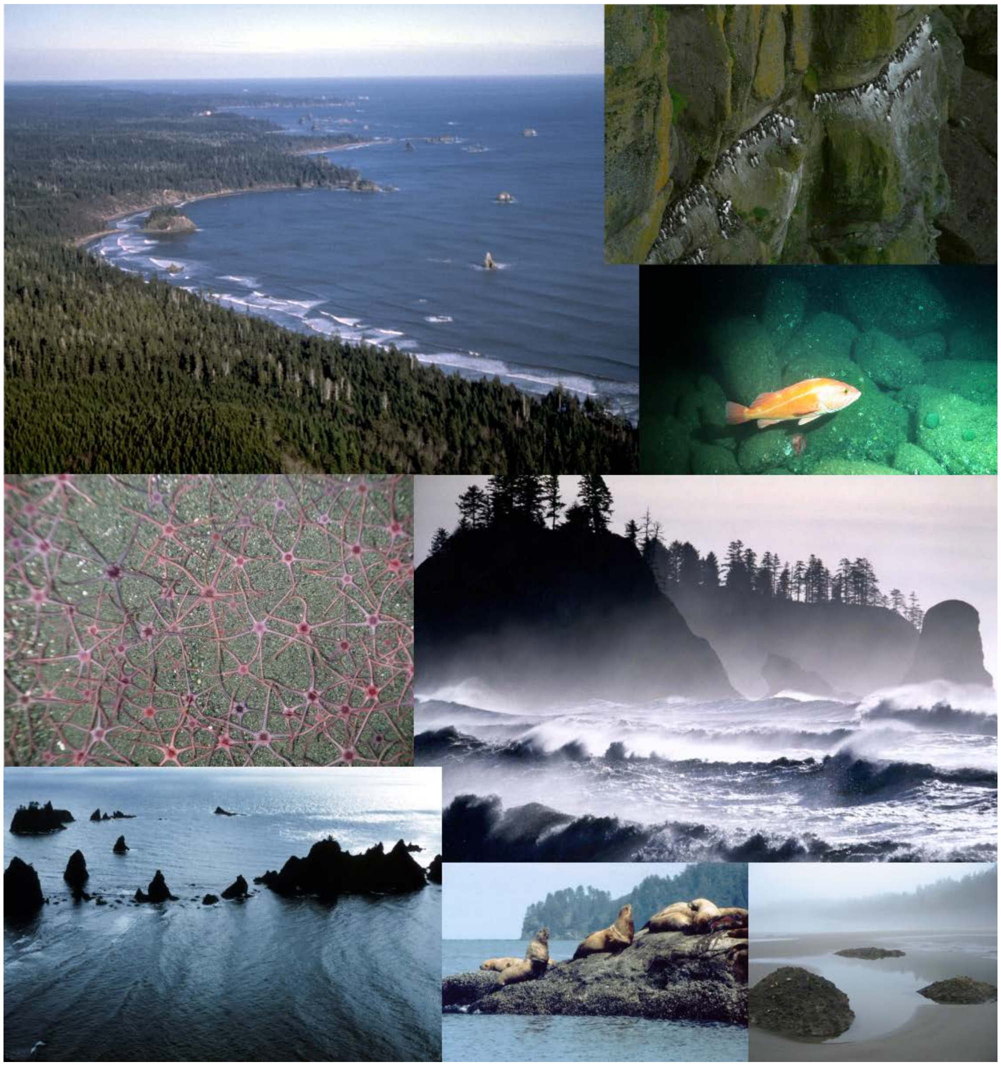

Marine Sanctuaries Conservation Series (ONMS-13-01)

Climate Change and the Olympic Coast National Marine Sanctuary: Interpreting Potential Futures



U.S. Department of Commerce
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Office of National Marine Sanctuaries

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About the Marine Sanctuaries Conservation Series

The National Oceanic and Atmospheric Administration's National Ocean Service (NOS) administers the Office of National Marine Sanctuaries (ONMS). Its mission is to identify, designate, protect and manage the ecological, recreational, research, educational, historical, and aesthetic resources and qualities of nationally significant coastal and marine areas. The existing marine sanctuaries differ widely in their natural and historical resources and include nearshore and open ocean areas ranging in size from less than one to over 5,000 square miles. Protected habitats include rocky coasts, kelp forests, coral reefs, sea grass beds, estuarine habitats, hard and soft bottom habitats, segments of whale migration routes, and shipwrecks.

Because of considerable differences in settings, resources, and threats, each marine sanctuary has a tailored management plan. Conservation, education, research, monitoring and enforcement programs vary accordingly. The integration of these programs is fundamental to marine protected area management. The Marine Sanctuaries Conservation Series reflects and supports this integration by providing a forum for publication and discussion of the complex issues currently facing the sanctuary system. Topics of published reports vary substantially and may include descriptions of educational programs, discussions on resource management issues, and results of scientific research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and cultural sciences, education, and policy development to accomplish the diverse needs of NOAA's resource protection mandate. All publications are available on the Office of National Marine Sanctuaries Web site (http://www.sanctuaries.noaa.gov).

Climate Change and the Olympic Coast National Marine Sanctuary: Interpreting Potential Futures

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Cover

A mosaic of perspectives on the ecosystems and organisms within the boundaries of Olympic Coast National Marine Sanctuary. All images: OCNMS

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Executive Summary

Due to global climate change, the Intergovernmental Panel on Climate Change (IPCC; www.ipcc.ch) projects a high likelihood that marine ecosystems around the globe will be measurably altered in the coming century (Bernstein et al. 2007). In some cases, the collapse of entire ecosystems is viewed as possible, or even likely. These projections are valuable in terms of describing the global implications of climate change and clarifying the role that anthropogenic emission of greenhouse gases plays in large-scale ecosystem change. However, they are less useful for assisting managers and policy-makers at the regional or local scale in their efforts to prepare for and, where possible, adapt to climate-related changes.

The Olympic Coast National Marine Sanctuary (OCNMS) encompasses 572 square kilometers of marine and near-shore waters and intertidal habitat off of Washington State's Pacific Ocean coast. As one of 14 national marine sanctuaries managed by the National Oceanic and Atmospheric Administration (NOAA), OCNMS is provided protected status because of extraordinary ecological and maritime heritage values. The Office of National Marine Sanctuaries developed its "Climate-Smart Sanctuary" program in order to facilitate the process of climate adaptation in these special marine waters. This assessment is designed to assist OCNMS in adapting to climate change by bridging the gap between the global projections provided by the IPCC, and the regional and local implications of climate change by 2100.

The direct consequences of climate change on the physical environment in OCNMS were considered and, where possible, the direction and magnitude of change was estimated (Section 2). These physical effects were divided into seven categories: Increasing ocean temperature, ocean acidification, sea level rise, increasing storminess, changing ocean current patterns (with a focus on upwelling), increasing hypoxia or anoxia and altered hydrology in rivers draining into OCNMS. These are summarized here:

- Based on the literature reviewed for this assessment it is considered likely that in the Pacific Northwest (including the habitats within OCNMS) average air and ocean temperatures will rise measurably by 2100, probably outside of the contemporary range of variability. Downscaling of multiple global climate models for the Pacific Northwest coastal zone suggests that ocean water could warm by approximately 1°C by 2050. (Section 2.2).

- The magnitude and extent of corrosive ocean water (the term used in this report to describe ocean water with pH reduced relative to contemporary values and reduced availability of carbonate ions for calcifying organisms) is also expected to increase. Corrosive ocean water is currently associated with deeper water in OCNMS and is probably only drawn to the surface during periods of intense upwelling. By 2050, however, shallower areas within OCNMS will be exposed to corrosive water with greater frequency (Section 2.3).

- Due primarily to the warming of the ocean and melting of land-based ice, mean sea level rise in OCNMS could exceed 1.0 m by 2100, but variable rates of vertical land movement associated with tectonic forces will cause variations in the rate of relative sea level rise. Relative sea level is expected to be greater along the southern coast of shoreline within OCNMS as compared to the northern coast (Section 2.4).

- Climate model projections suggest that the tracks of storms in the northeast Pacific Ocean will migrate, on average, further north due to climate change, but it is not clear if the magnitude or duration of storms will change. Observational evidence from locations in the northeast Pacific Ocean suggests the possibility that the ocean adjacent to OCNMS has become stormier in the last 50 years, though it isn't clear if the trend is related to long-term climate trends (Section 2.5).

- Projections regarding the possibility of increased upwelling favorable winds in OCNMS are mixed, and based on the contemporary variability in the timing, duration and intensity of upwelling favorable winds it is considered unlikely that climate change will cause measurable changes by 2100 (Section 2.6). Other factors besides upwelling favorable wind, notably warming of the surface layer of the ocean (Section 2.2), may also influence the timing and magnitude of upwelling and, by extension, productivity in OCNMS.

- Concentrations of dissolved oxygen in the northeast Pacific Ocean are expected to decrease as the upper ocean warms and becomes more stratified. Based on the dynamics of water masses influencing ocean areas within OCNMS, dissolved oxygen concentrations in the ocean waters in OCNMS also may decline. Long-term declines in dissolved oxygen have been observed at numerous locations in the northeast Pacific, including coastal locations near OCNMS (Section 2.7).

- Future warming in the Pacific Northwest region of the United States is projected to alter regional rainfall patterns and trigger more 100-year magnitude floods and lower summertime low flows among some basins that drain to OCNMS, including the Sol Duc, the Hoh, the Queets and the Quinault Rivers (Section 2.8).

The ecological implications of these likely or possible changes to the physical environment in OCNMS were analyzed in three different ways. First, the general ecological consequences of the suite of changes expected in OCNMS were examined (Section 3.2). These focused on the various ways in which marine ecological systems respond to change - by shifting species' ranges or by altering the timing of life history stages (phenology) for example – or on the consequences of these responses, which include changes in the composition of biological communities in OCNMS and increasing interactions between native and non-native species. Given the magnitude of some projected climate-related change and evidence from distant and neighboring marine ecosystems it is likely that the marine ecosystem in OCNMS will experience all of these responses or consequences of climate change by 2100. However, there is a great deal of uncertainty regarding the specific responses of ecosystems in OCNMS to climate-related changes, specifically the magnitude or direction of change. There is some empirical, quantitative evidence from the northeast Pacific Ocean that some of these responses or consequences are likely already influencing communities in OCNMS, however (Section 3.2).

Next, the cumulative impacts of multiple changes to the physical environment were assessed for four broad habitat categories: Nearshore and shallow water; deep-sea benthic; pelagic; and freshwater habitats. All habitat categories were vulnerable to various aspects of climate-related change. Chemical-biological impacts due to the changing properties of ocean water within OCNMS (i.e., increased ocean temperature, decreased oxygen concentration, increased acidity) are likely to interact directly with biota in all habitats. By contrast, the potential “mechanical” consequences of climate change, related to higher or lower streamflow, sea level rise, larger waves, or changes in the magnitude, intensity or location of storms are likely to influence freshwater and nearshore and shallow water habitats most directly. In all cases, though, there was no clear trend related to these changes due to the likely interaction between complex physical and biological systems. For example, in pelagic habitats primary productivity may increase under some climate change scenarios due to higher CO_2 concentrations in ocean water and possibly increased nutrient delivery from enhanced upwelling, but rising ocean temperature would be expected to partly or entirely counteract that response by increasing stratification and reducing mixing in the shallow surface ocean.

Finally, the implication of climate-related changes on a select group of species or species assemblages, including phytoplankton, zooplankton, deepsea corals, intertidal mussels, sea urchins (*Stronglyocentrotus spp.*), Dungeness crab (*Metacarcinus magister*, formerly *Cancer magister*), fish, seabirds, cetaceans, pinnipeds and sea otters, was analyzed. There were clear implications of climate-related changes for all species analyzed. In some cases, those implications are due to the direct interaction between the organism and the changing environment, as is the case for some deep-sea coral species whose ability to maintain calcium carbonate body structures may be compromised by ocean acidification (Section 4.4). In other instances, the implications of climate-related change are via ecological interactions that mediate projected changes in the physical environments within OCNMS through other species. For example, given their role as mid- to upper-trophic level predators, the susceptibility of seabirds to climate-mediated changes may depend in large part on the impacts that their prey species experience (Section 4.9). In some instances, the documented consequences of climate cycles (Section 6.3) in the northeast Pacific Ocean are used to suggest the overall impact of climate change on particular species. For example, decreased ocean survival of Chinook and Coho salmon is likely based on observations made during conditions of unusually high water temperatures and reduced or delayed upwelling (Section 4.8).

Despite these very clear implications of climate change, very little certainty could be ascribed to the magnitude or direction of change for a given species or species assemblage, or to the overall consequence of ecological change. For example, despite the clear physical consequences of ocean acidification on some species of deep-sea corals, some capacity to adapt to corrosive ocean water has been demonstrated for species in OCNMS (Section 4.4). In some cases, possible or likely shifts in community composition may not have clear ecological consequences. For example, resident forage fish including northern anchovy, Pacific herring, and smelts (surf and whitebait), may become less abundant in OCNMS (Section 4.8). The abundance of these species is currently highly variable, though. Additionally, migratory fish species, including Pacific hake, jack and Pacific chub mackerel, and Pacific sardine, are likely to become more abundant. Upper trophic-level species, like cetaceans (Section 4.11) and seabirds (Section 4.9), may have some capacity to adapt to these changes by altering their feeding behavior and targeting new or more abundant species. Even in instances in which conditions during El Nino-Southern Oscillation (ENSO; Section 6.3) warm phases, for example, are used as representatives of future conditions, it is not entirely clear that these short-term events are perfect analogs for projected long-term climate trends.

Adapting to climate change within the boundaries of OCNMS will be shaped in part by the need to decide if, when, and where adaptation should be directed at helping species and ecosystems increase their resistance, resilience, or ability to respond to climate change. In some cases these choices will be made based on what is required to meet the mission of the sanctuary and other directives governing the activities within the sanctuary. How those directives are interpreted may simultaneously be influenced by climate change as well (Section 5).

There are several tenets or guiding principles related to “climate-smart conservation” that can be used to frame adaptation thinking in the sanctuary. These include: protect adequate and appropriate space, manage for uncertainty and expect surprises, reduce non-climate stresses, mainstream climate adaptation, plan for both climate variability and climate change, and reduce the rate and extent of climate change. These guiding principles can be used to frame decisions about adaptive actions related to the four management focal points detailed in the 2011 Management Plan and OCNMS Terms of Designation (water, habitats, living resources, and maritime archaeological resources).

Key Words

Climate Change, Olympic Coast, Olympic Peninsula, Washington Coast, Marine Ecology, Climate Impact, Climate Assessment

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Preface

This report provides a review of the "state-of-the-science" as it relates to the implications of climate change on the resources in the Olympic Coast National Marine Sanctuary (OCNMS). To accomplish this, a working group of experts drawn from federal and state agencies, consulting firms, universities and tribes was assembled to summarize data and conclusions drawn primarily from peer-reviewed studies. The goal of the working group was to identify those impacts that were relevant to the unique biological and physical resources in OCNMS. In addition to the working group members themselves, input was sought from experts from a variety of disciplines and institutions. These outside experts provided relevant references, directions for new investigations, and content and figures. Finally, the working group leaned heavily on a few notable prior assessments and reports for analysis, insight and sources. While referenced throughout this report, these assessments and reports were also used for general guidance. They include:

- The Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report, published in 2007 and available through http://www.ipcc.ch/

- The North Pacific Landscape Conservation Cooperative's report titled, *Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region*, published in 2011 and available through http://www.fws.gov/pacific/Climatechange/nplcc/

- A Joint Working Group of the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries Advisory Councils published a report titled, *Climate Change Impacts* in 2010, available at http://farallones.noaa.gov/manage/climate/pdf/climate_report.pdf

- The Pew Center on Global Climate Change published a report titled, *Coastal and Marine Ecosystems and Global Climate Change* in 2002, available through http://www.pewtrusts.org/our_work_detail.aspx?id=327744

- The Washington Department of Fish and Wildlife's *Summary of Climate Change Effects on Major Habitat Types in Washington State: Marine and Coastal Habitats*, published in 2010

- The Climate Impacts Group at the University of Washington report titled *The Washington Climate Change Impacts Assessment*, published in 2009 and available at http://cses.washington.edu/cig/res/ia/waccia.shtml

1 Introduction

The Pacific coast of the Olympic Peninsula, at the northwest corner of Washington State, is a place regarded as unique by visitors, and both sacred and productive by those living adjacent to it. Much of the near-shore and off-shore coastal waters are designated as Olympic Coast National Marine Sanctuary (referred to throughout the remainder of the report as OCNMS) and also fall within the treaty-reserved “Usual and Accustomed” areas of the Hoh, Makah, and Quileute Tribes and the Quinault Nation. The shoreline is a mix of National Park wilderness area, U.S. Fish and Wildlife-managed Wildlife Refuges, and tribally-owned and/or managed lands. The tribal communities of the Olympic Peninsula, including those of the Hoh, Makah and Quileute Tribes and the Quinault Nation, actively utilize the coastal zone and are also co-managers with both the state of Washington and the federal government of marine resources. The coastal waters of the Olympic Peninsula support tribal, commercial, and recreational fisheries, commercial shipping operations, whale- and wildlife-viewing and other recreational activities.

The climate of the planet, and of the Olympic Peninsula coast, is changing and the ongoing resilience of OCNMS depends, in part, on anticipating and adapting to climatic shifts expected to affect Washington’s coastal areas. The Intergovernmental Panel on Climate Change (IPCC) has provided, since 1990, periodic summaries of the state of the science regarding climate (see www.ipcc.ch), and most recently stated that observed warming of the planet is “unequivocal” and that much of the increase since the mid-20th century is “very likely”[1] due to rapidly increasing greenhouse gas emissions from human activities. Furthermore, the rate of change may be accelerating (Bernstein et al. 2007). The IPCC’s “best estimate” range for projected increases in average annual global temperature is +3.2 to +7.2°F (+1.8 to +4.0°C) by 2100. These projected increases exceed the +1.3°F (+0.7°C) warming observed during the 20th century and suggest a rate of change that could exceed the ability of many ecosystems and species to adapt.

The IPCC’s projections are important for detailing the overall direction of our global climate system and large sub-regions (e.g., continents). However, the resolution of the climate models issued by the IPCC to date are too coarse to capture the nuanced expression of projected climate changes over a smaller, climatically complex region like the Pacific Northwest, where climate is strongly influenced by the region’s multiple mountain ranges and proximity to marine influences. This discrepancy in scale presents challenges for natural resource managers attempting to directly use the IPCC’s results to identify and address the impacts of climate change for their resource of interest.

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[1] The IPCC defines the term “very likely” as having a greater than 90% chance of being true. The use of “very likely” in this case means there is a less than 10% chance that the primary cause of observed warming is something other than increasing greenhouse gases from human activities. Note that uses of “very likely” or “likely” in other parts of this document in statements unrelated to IPCC findings are not defined in this manner.

Our collective challenge is to first understand these changes in the hopes that strategies can be developed to efficiently respond to and manage them. The Office of National Marine Sanctuaries addresses this challenge through the "Climate-Smart Sanctuary" Initiative. The goal of this initiative is to, "organize and implement a climate action plan at each (marine sanctuary) site" (Office of National Marine Sanctuaries 2010). To support this goal, this analysis will

- Describe the state of knowledge of a suite of climate-related physical parameters that may influence the management of marine resources broadly and OCNMS specifically over the coming 50 to 100 years.
- Analyze the responses of marine ecosystems in OCNMS to projected physical changes.
- Summarize sources of vulnerability and relevant adaptation strategies that can potentially be employed by OCNMS to improve the resilience of resources of concern.

In accomplishing these objectives this document will also facilitate the certification of OCNMS as a "Climate-Smart Sanctuary".

1.1 Regional Climate Change Context

In an effort to provide more decision-relevant data and information to Pacific Northwest resource managers, the Climate Impacts Group at the University of Washington statistically downscaled 20 of the global climate models released by the IPCC to determine the regional implications of climate change for Pacific Northwest regional climate (e.g. Mote and Salathe 2010). The downscaled climate models apply two greenhouse gas emissions scenarios that incorporate assumptions about future changes in population growth, technological advances and energy sources and usage: B1 is a low emissions scenario and A1B is a moderate scenario (see Section 6.1). The key climatic variables regionally downscaled under these two emissions scenarios are temperature and precipitation.

The downscaled projections of temperatures for the 21st century in the Pacific Northwest show warming across all decades, with the greatest increases in annual temperature occurring in the latter part of the century (Figure 1-1). Compared to the historical baseline (1970 – 1999), projected average annual temperature increases averaged over the two emissions scenarios (and their respective ranges) are 2° F (1.1° – 3.4° F) by the 2020s, 3.2° F (1.6° – 5.2° F) by the 2040s and 5.3° F (2.8° – 9.7° F) by the 2080s. The warming trends are projected to occur across all seasons with the greatest increases occurring during the summer months. By the mid-21st century, projected temperature increases are expected to exceed the 20th century's range of natural variability attributable, in part, to El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).

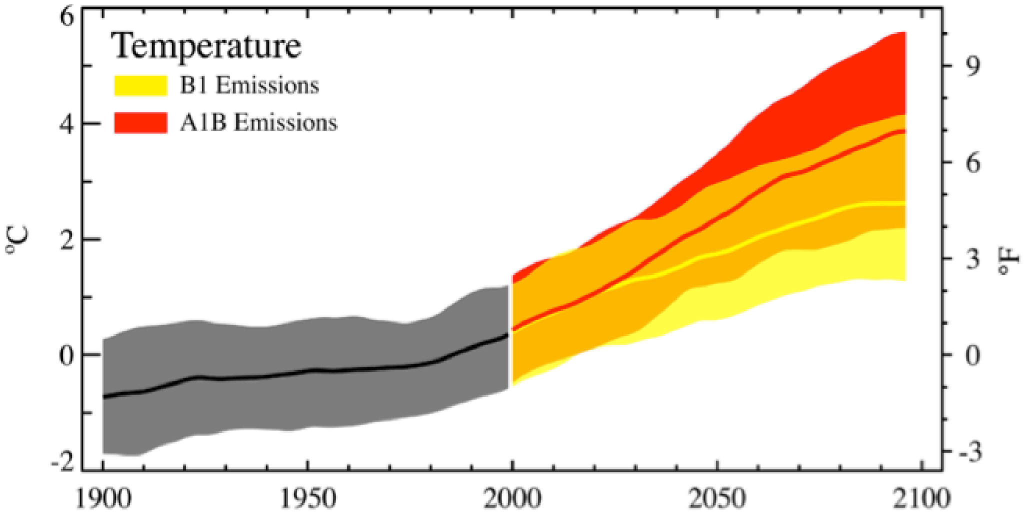

Figure 1-1. Projected increase in Pacific Northwest mean annual temperature for the 21st century, compared to the historical baseline (1970 – 1999). Solid lines represent the mean of downscaled projections averaged over the 20 global climate models examined for the historical (black), the B1 (yellow) and A1B (red) future emissions scenarios. Colored swathes around the means show the 5th to 95th percentiles, representing the range of global climate model projections. Figure source: Mote and Salathé (2010).

Projected changes in annual Pacific Northwest precipitation are less clear than temperature (Figure 1-2). This is both a function of the large range of natural variability in Pacific Northwest precipitation, which is still expected in projections of 21st century climate, and technical challenges in modeling precipitation changes at both the global and regional scale. Both the B1 and A1B scenarios produce only modest increases in average annual precipitation (+1 to 2% by mid-century , +4% by end of century)(Mote and Salathe 2010). However, current seasonal patterns of precipitation (wet winters and dry summers) may be enhanced by climate change. By 2080, just over half of the scenarios show winters getting wetter while most models show drier summers (Figure 1-3).

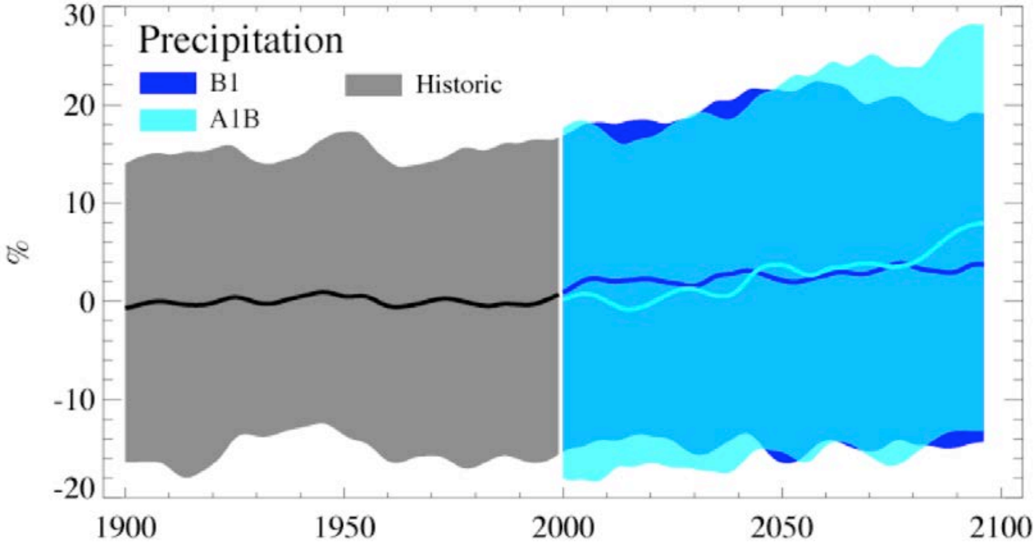

Figure 1-2. Projected increase in Pacific Northwest mean annual precipitation for the 21st century, compared to the historical baseline (1970 – 1999). Solid lines represent the percent change in the mean of downscaled projections averaged over 20 GCMs for the historical (black), the B1 (light blue) and A1B (dark blue) future emissions scenarios. Colored swathes around the means show the 5th and 95th percentiles, representing the range of global climate model projections. Figure source: Mote and Salathé (2010).

Understanding how global and regional projections of climatic changes will affect the marine environment is difficult to determine. The oceans have absorbed most of the added energy related to warmer temperatures from rising greenhouse gas emissions (see Section 2.2), leading to observable warming of 1.1°F (~0.6°C) in the ocean's upper layers over the past century (Hoegh-Guldberg and Bruno 2010). In addition to providing a heat sink service for the planet, the oceans have also absorbed about one-third of the anthropogenic carbon dioxide emitted to the atmosphere (Canadell et al. 2007; Doney et al. 2009b). The ocean's absorption of heat and carbon dioxide has changed its chemistry, particularly in regards to rising acidity levels (Sabine et al. 2004; Solomon et al. 2007). The shifts in oceanic conditions can manifest in a number of disparate ways and the IPCC now asserts that there is "*high confidence*, based on substantial new evidence, that observed changes in marine and freshwater biological systems are associated with rising water temperatures, as well as related changes in ice cover, salinity, oxygen levels and circulation. These include: shifts in ranges and changes in algal, plankton and fish abundance in high-latitude oceans; increases in algal and zooplankton abundance in high-latitude and high-altitude lakes; and range changes and earlier fish migrations in rivers."

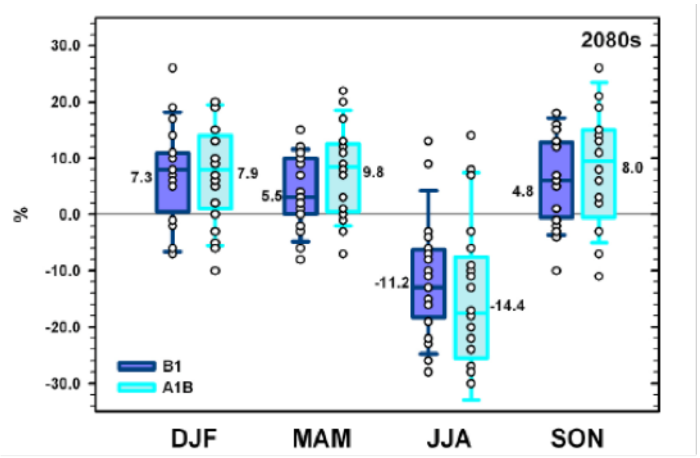

Figure 1-3. Projections of percent change in seasonal precipitation for the 2080s compared to historical conditions (1970 – 1999). The x-axis represents the seasons based on month (i.e., DJF stands for Dec-Jan-Feb, MAM stands for March-April-May, etc.). The horizontal lines indicate 0% change from the historical; the areas above and below the lines indicate increases and decreases in precipitation, respectively. The boxes represent the 25th – 75th percentiles, the "whiskers" extending from the ends of the boxes represent the 10th – 90th percentiles, and the dots are the individual model results. The average over all the model results (the dots) for each scenario is indicated by the numbers to the left or right of the boxes. Figure source: Mote and Salathé (2010).

In the coastal ocean of OCNMS (Figure 1-4) projections suggest that wave and weather patterns may shift, almost imperceptibly, with time. Changing sea level and changing precipitation patterns on land alter sediment delivery and transport in the coastal zone and can evolve the shoreline in unpredictable ways. Changing ocean temperature and chemistry may create conditions untenable to some fish and wildlife (while also creating conditions that favor new species) within OCNMS, potentially driving a cascade of ecological change impacting marine ecosystems and the human communities that utilize them.

1.2 Description of OCNMS

OCNMS is a marine protected area, one of 14 sites designated by the U.S. federal government and managed as the National Marine Sanctuary System by the Office of National Marine Sanctuaries. National marine sanctuaries are special places in the ocean or Great Lakes that are provided protected status because of extraordinary ecological and/or maritime heritage values. OCNMS is overlapped by the treaty-reserved "Usual and Accustomed" areas of the Hoh, Makah and Quileute Tribes and the Quinault Indian Nation.

Designated in 1994, OCNMS' mission is to protect the Olympic Coast's natural and cultural resources through responsible stewardship, to conduct and apply research to preserve the area's ecological integrity and maritime heritage, and to promote understanding through public outreach and education.

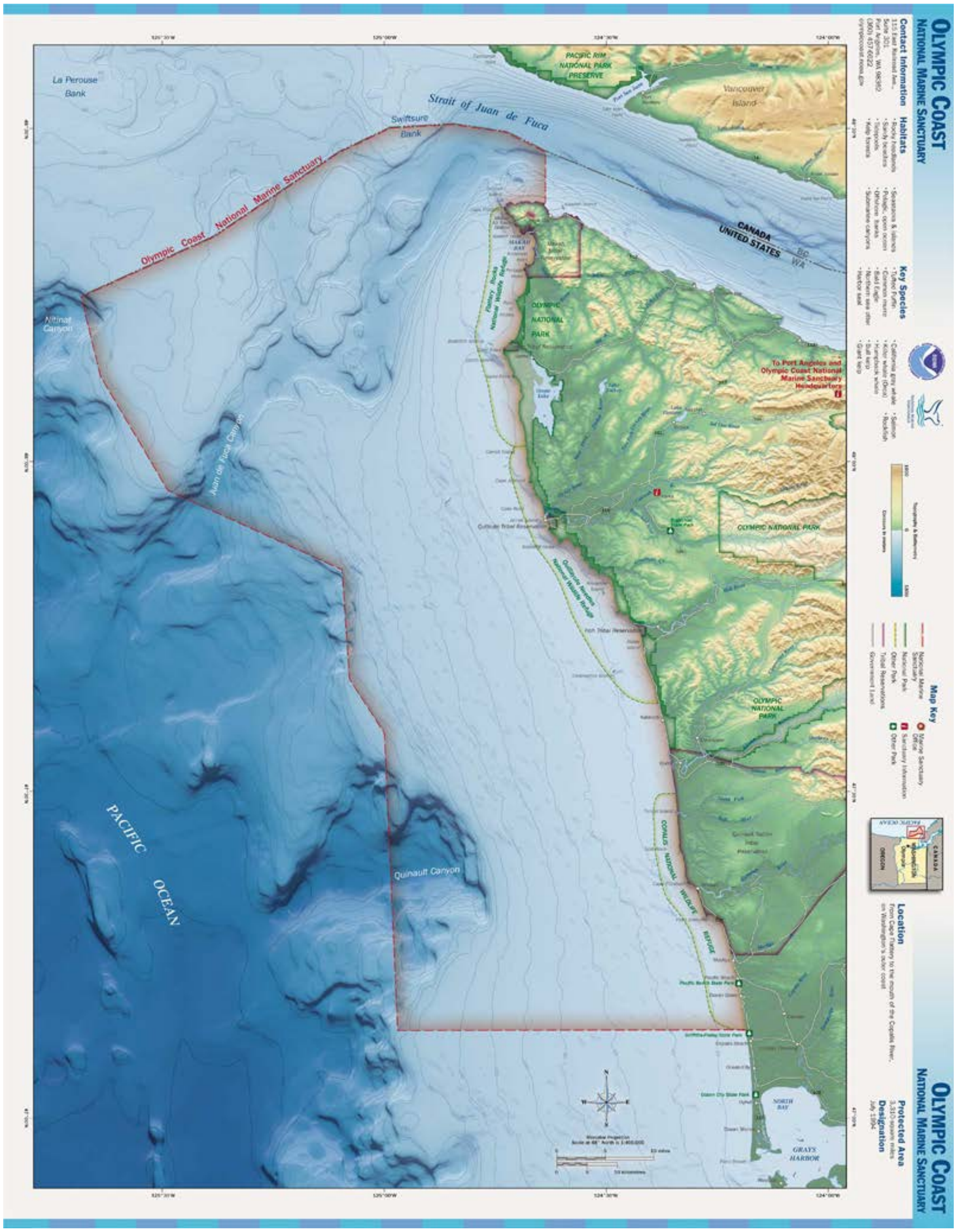

Figure 1-4. Map of the Olympic Coast National Marine Sanctuary and adjacent areas. Figure: OCNMS

OCNMS spans 8,572 square kilometers (2,408 square nautical miles) of marine waters off Washington State's rugged Olympic Peninsula coast (Figure 1-4). Extending seaward 40 to 72 kilometers (22 to 39 nautical miles), the sanctuary covers much of the continental shelf and the heads of three major submarine canyons, in places reaching a maximum depth of over 1,400 meters (4,500 feet). These canyons are dynamic areas where massive submarine landslides occur on the steep side walls and canyon bottoms collect sediment deposited from above. These canyons also serve as conduits for dense, cold, nutrient-rich seawater that is seasonally pulled toward the surface, an upwelling that feeds surface productivity at the base of the food web. The sanctuary borders one of the longest stretches of undeveloped coastline in the contiguous U.S., enhancing protection provided by the 90-kilometer long (56-mile) wilderness of the Olympic National Park's coastal strip and the 600 offshore islands and emergent rocks within the Washington Islands National Wildlife Refuges. Superimposed on a nutrient-rich upwelling zone with high primary productivity and composed of a variety of marine habitats, the sanctuary is home to numerous marine mammals and seabirds, diverse populations of kelp and other marine algae, and prosperous fish and invertebrate communities.

OCNMS lies in the northern portion of the Oregonian biogeographic province extending from Point Conception, California, to Cape Flattery, Washington (Airame et al. 2003). The province is characterized by a narrow continental shelf, mountainous shoreline, steep rocky headlands, sandy pocket beaches with sea stack islands, many small and a few large rivers, and small estuaries with barrier islands. The province also notably exhibits the greatest volume of upwelling in North America. This nutrient-rich upwelling zone drives high primary productivity and supports a multitude of marine habitats. The sanctuary is at the Northern end of the California Current System (referred to throughout this report as the CCS) and represents one of North America's most productive marine ecosystems.

The area around the sanctuary is characterized by distinct patterns in oceanographic circulation, winter storms, water flows influenced by topography and land-sea interactions. Large-scale processes are the predominant controlling factors for seasonal upwelling-downwelling fluctuations that produce a highly dynamic oceanographic environment. Large-scale movements of oceanic water masses, such as the California Current, which flows southward beyond the continental shelf, connect the sanctuary with the broader seascape of the eastern North Pacific Ocean and influence climate and marine productivity for the region.

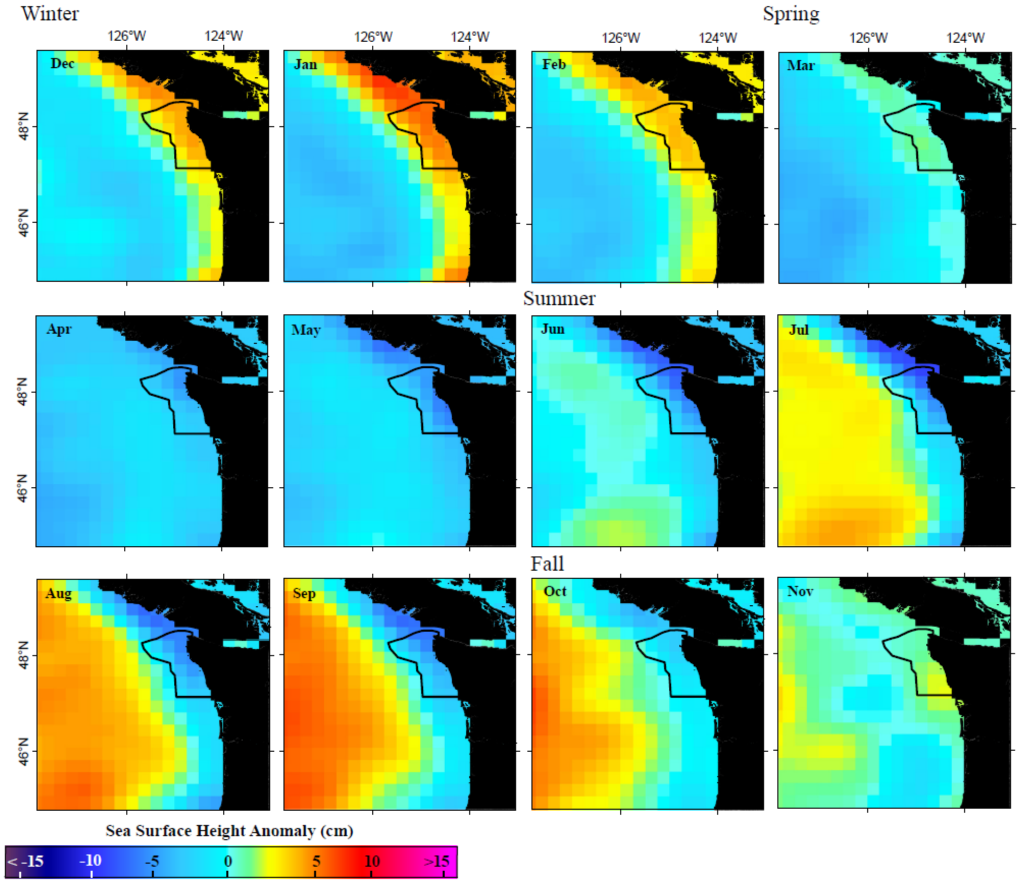

Figure 1-1-5. Monthly average sea surface height anomalies in OCNMS and adjacent waters based on remotely-sensed data from the AVISO (www.aviso.oceanobs.com) satellite altimeter (1996-2006). Figure from Pirhalla et al. (2009)

A general characterization of oceanographic and meteorological conditions for the sanctuary region was developed from satellite imagery (Pirhalla et al. 2009). Winter months (November-mid-February) are characterized by strong winds from the south (which forces downward transport of surface waters and elevated sea surface height; Figure 1-1-5), heavy rainfall, and northward transport of the Columbia River plume of fresh water and suspended materials. A spring transition period with variable conditions typically occurs in March. A spring/early summer plankton bloom period occurs in April-June, when strengthened upwelling, increased surface water temperatures, and the Juan de Fuca outflow encourage increased plankton growth. During the summer/early fall period, offshore transport of surface waters, continued upwelling, increased light and temperature, with available nutrients out of the Juan de Fuca Strait combine to promote chlorophyll (phytoplankton) production along the entire Olympic Coast. A relaxation in upwelling, decrease in nutrients and chlorophyll, and shift toward northward flow of surface waters typify the fall transition period.

OCNMS remains distant from crowded, dense and developed centers of human society, a place where wildlife and the natural environment dominate, and humans seem to have left a relatively small imprint. Native Americans of Hoh, Makah, Quileute and Quinault lineages have been resident on the outer coast of Washington since time immemorial. Their cultures, knowledge, and practices are integral to the ecosystem of the Olympic Coast. Recent history of human migration into the area, however, dates back only about 150 years, and the current population of coastal communities immediately adjacent to the sanctuary totals a few thousand people. Today, the economies of outer coast communities, tribal and non-tribal alike continue to have a strong basis in fisheries and forestry, as well as tourism and recreational uses.

OCNMS is an ecological entity where a dynamic balance of physical, chemical, and biological processes sustains life in this portion of the California Current Ecosystem. After decades of modern scientific research and ever-improving technologies to help humans better understand ecological processes on and below the water's surface, oceans of the Earth remain largely a place of mystery. In OCNMS, the majority of the seafloor and water-column habitats have not been viewed by humans. Oceanographic data is in short supply. Population estimates for many species are imprecise or lacking. OCNMS has no ecosystem model to support analysis of different scenarios and future conditions. We are still piecing together the information to help us understand what we have and how it all works and fit together. Compounding this uncertainty is a new consideration – climate change.

In the context of the challenges presented by climate change, OCNMS seeks to be a focal area for research into impacts of climate change on coastal oceanographic and ecological systems. OCNMS also seeks to be a regional leader in public outreach to promote improved understanding of these ecological and social impacts and the adaptations humans might make to a changing and uncertain future.

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Increasing Frequency and Severity of Storms	Ian Miller[2]	Nick Bond[7]
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- Steven Fradkin, Coastal Ecologist at Olympic National Park
- Jennifer Hagen, Marine Biologist for the Quileute Tribe
- Deanna Lynch, US Fish and Wildlife Service
- Rob Young, Western Carolina University

2 The Physical Effects of Climate Change in OCNMS

2.1 Introduction

This section describes and explores a suite of potential or observed effects of climate change that could influence OCNMS over the coming century. Atmospheric warming (Section 1.1) is expected to have far-reaching implications for global and regional marine ecosystems, as are changes in the chemistry of ocean water, driven by the increasing concentration of carbon dioxide in the atmosphere. The projected changes discussed here are all physically derived from changes in the global climate due to increased greenhouse gases. These physical impacts of climate change will be used as the basis for exploring the implications of these physical effects to biological communities or particular marine organisms, covered in Chapters 3 and 4.

Based on a review of scientific literature, government reports and consultation with experts and marine resource managers the following potential impacts of climate change that are relevant to OCNMS were identified:

- Increasing ocean temperature
- Acidification of ocean water
- Sea level rise

- Increasing frequency and severity of storms
- Changing ocean current patterns
- Increasing occurrence of coastal hypoxia and anoxia
- Altered hydrologic patterns

These impacts will be discussed in individual sections in the order shown above. Each section will be identically organized. A **summary** will highlight three or four conclusions drawn from the evidence compiled in the section. A short **introduction** will define the impact, place it into a global context and briefly describe the processes controlling projected or observed trends or changes. **Projections** are then described that have been made at the smallest known spatial scale possible regarding the impact, and finally describe contemporary **observations**, relevant to the physical impact, made in or near to OCNMS.

2.2 Increasing Ocean Temperature

2.2.1 Summary

- Ocean heat content and water temperature is expected to increase throughout the global oceans over the next century, with average projected warming of 1.5° to 2.6° C by 2100.
- The coastal waters of Washington State are expected to roughly follow global projections, with one study projecting an increase in sea surface temperature of at least 1° C by 2050 for the coastal marine waters of the Pacific Northwest.
- Some investigations identify a significant increasing trend in ocean temperature for data records from inside or adjacent to OCNMS, while others find that temperature variability is too high, and the data record too short, to identify trends.

2.2.2 Introduction

The observed and projected warming of the global atmosphere (Meehl et al. 2007) is associated with an increase in the heat content of the global ocean as surplus atmospheric heat is mixed into the ocean (Figure 2-1). In general, it is expected that the upper layer of the ocean, which is most readily exposed to the atmosphere, will absorb heat most rapidly (and therefore warm the fastest). Warming in the deep ocean will take longer, occurring over centuries as relatively warm shallow water is mixed into the cold ocean depths in association with global ocean circulation patterns.

Surplus heat in the ocean can have a variety of regional impacts. The temperature of ocean water masses drives water circulation patterns, influences regional weather patterns and can alter surface productivity by increasing stratification and reducing mixing between deep cold and warmer surface waters. Also, the thermal expansion of warmer water is one of the primary components of global sea level rise.

2.2.3 Projections

The warming of the Earth's atmosphere is expected to continue during the current century (Meehl et al. 2007) with global climate models projecting between 1° and 4° C of warming (over 2000 levels) by 2100. There is little uncertainty regarding the physical mechanisms that cause this warming; radiative forcing due to increasing concentrations of greenhouse gases in the atmosphere drives this temperature increase. The range in temperature projections is due primarily to uncertainty in future carbon emissions (Meehl et al. 2007).

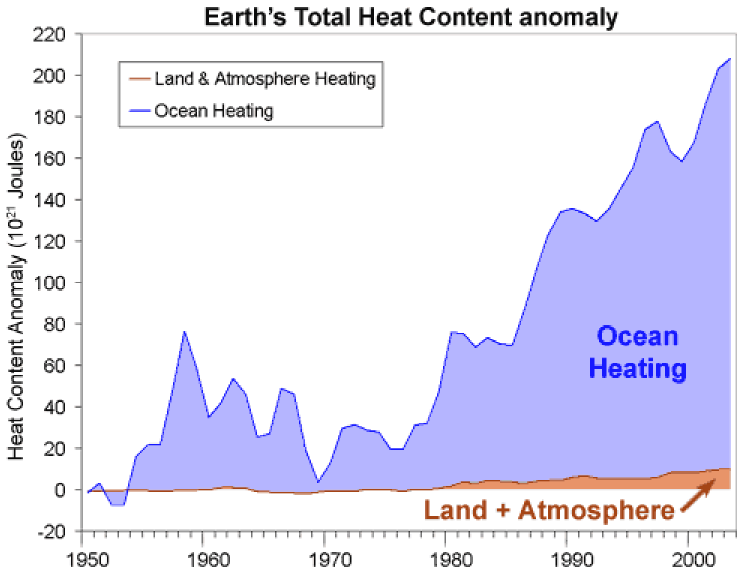


Figure 2-1. Change in Earth's total heat content budget since 1950. Figure from Cook (2010) with data from Murphy et al. (2009).

The oceans are a massive sink for atmospheric heat, and 90% of the heat added to the atmosphere will eventually be absorbed by the global ocean (Church et al. 2011b). Heat flux to the ocean is expected to continue a trend of rising ocean heat content through the present century (Figure 2-1). There is virtual certainty that the global ocean will warm in the future, with estimates of the global average sea surface temperature increase varying from 1.5 to 2.6^{o}C by 2100 depending on the emission scenario under consideration (Nicholls et al. 2007). Mote and Salathe (2010) analyzed global climate model results for the Pacific Northwest, and project approximately 1.2°C of sea surface warming in the coastal ocean of the Pacific Northwest by 2050 relative to the 1970-1999 average. Their results suggest little seasonality in the temperature increase; rather it is evenly distributed over the annual temperature cycle (Figure 2-2). However, the resolution of global climate models, from which the results of Mote and Salathe (2010) are derived, are generally insufficient to resolve fine-scale coastal upwelling processes. Summertime sea-surface temperature on the Washington coast is a function of the strength and duration of upwelling, and therefore projections of summertime ocean temperatures are associated with lower confidence than projections of average temperature.

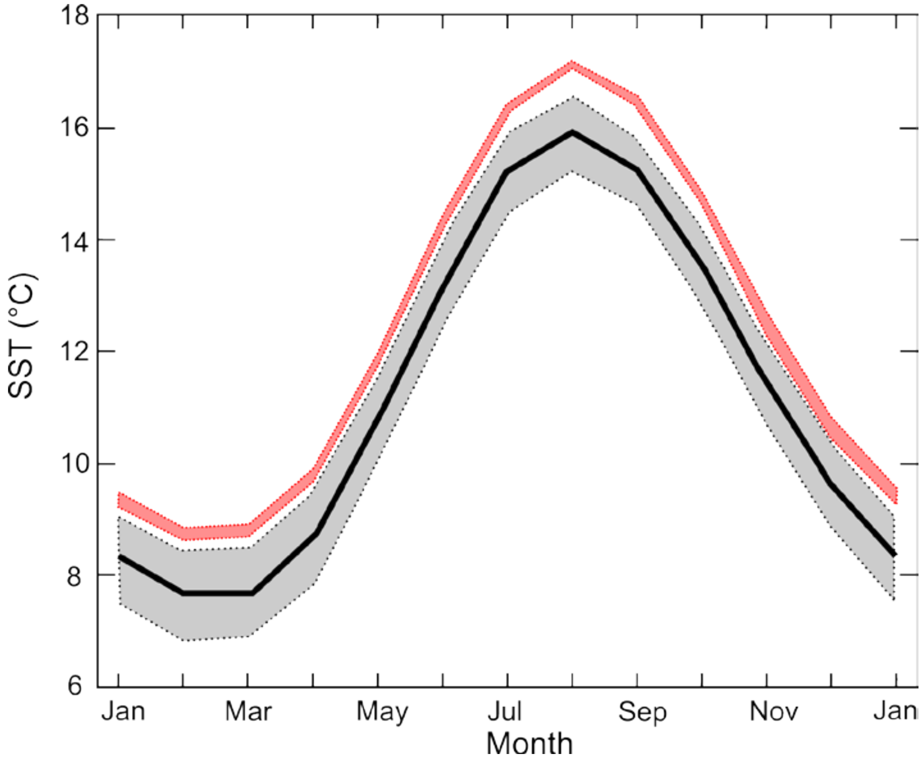


Figure 2-2. Simulated annual cycle of sea surface temperature for the coastal waters of the Pacific Northwest for 1970-1999 (black line/gray shading) and 2030-2059 (red line). Grey shading represents ±1 standard deviation around the 1970-1999 mean modeled temperature. The red shaded area shows the range of means for 2030-2059 for three emissions scenarios (A2, A1B and B1; see Section 6.1 for a summary of emissions scenarios). Note that the projected 1.2°C warming is outside of the 20th century variability. Figure and caption adapted from Mote and Salathe (2010).

2.2.4 Observations

Climate models project that the heat content (and therefore the temperature) of the ocean will increase over the next century, driven by the uptake of surplus heat in the atmosphere. Due to the high specific heat of water, however, this energy uptake by the global ocean results in only modest water temperature increases. Analysis of global ocean temperature datasets show, however, that the total heat content of the oceans has risen measurably since mid-century (Figure 2-1), with most of the heat stored in the uppermost 700m of the ocean (Church et al. 2011b).

Despite the evidence for an increase in the heat content of the global ocean, discerning a pattern within the relatively small slice of ocean occupied by OCNMS is difficult because of a lack of long-term temperature measurements. There are no published investigations of temperature trends or heat content from within the marine area encompassed by the boundaries of OCNMS, and very few published temperature observations. An investigation by Freeland (1990) analyzed a decades long water temperature data set composed of daily measurements made at British Columbia's network of lighthouses and found that 18 of the 19 stations showed positive sea surface temperature trends, though only 10 of the trends were statistically significant. Of the four stations closest to OCNMS (Figure 2-3), two stations (Amphitrite Point and Sheringham Point) showed a statistically significant increasing temperature trend. These temperature records are particularly valuable because of their length; many of the temperature records analyzed by Freeland (1990), including those collected at Amphritrite Point (initiated in 1934) and Race Rocks (initiated in 1921), exceed 50 years of daily measurements. The coastal waters of the Pacific Northwest are subject to large variations in temperature due to seasonal patterns, events like El Nino-Southern Oscillations (ENSO), and decadal scale climate variability related to the Pacific Decadal Oscillation (See Section 6.3) that can obscure long-term trends. Long records (many decades) may therefore reveal longer-term climate-related trends. No re-analysis of these data, including data from after 1989, has been published.

Figure 2-3. Four British Columbia Lighthouses (red squares) closest to OCNMS (outlined in white) included in the sea surface temperature analysis of Freeland et al (1990). Image: Google Earth

Gower (2002) analyzed water temperature records collected near the surface (~ 1 m depth) on nearshore and open ocean buoys maintained by NOAA's National Data Buoy Center (NDBC) and Canada's Department of Fisheries and Oceans. The 26 buoys included in the investigation are distributed around the northeast Pacific Ocean with data records covering 1977-1999 for off-shore buoys (including NDBC 46002, 46004 and 46005 adjacent to OCNMS; See Figure 2-4) and 1990-1999 for nearshore buoys (including NDBC 46041 within OCNMS). Nineteen of the 26 stations showed a positive temperature trend, though the trend was statistically significant for only three of the longest time-series (spanning ~22 years), including NDBC 46004 adjacent to OCNMS (Figure 2-4). NDBC Buoy 46041, within the boundaries of OCNMS was included in this investigation and showed a positive temperature trend, but the trend was not statistically significant.

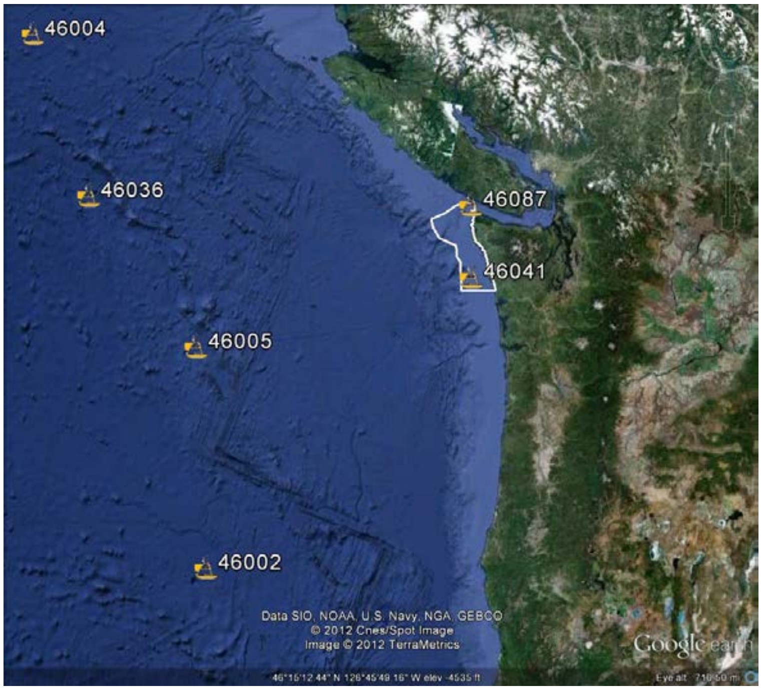


Figure 2-4. Locations of permanent oceanographic buoys "adjacent" or "within" OCNMS. The boundaries of OCNMS are shown in white. NDBC Buoy 46087 lies on the northern boundary of OCNMS, while NDBC buoy 46041 is within OCNMS. Image: Google Earth

Masson and Cummins (2007) assembled and analyzed vertical temperature profile data collected approximately quarterly between 1970 and 2005 from the continental shelf offshore of Vancouver Island, including data collected within the boundaries of OCNMS. They found a statistically-significant warming trend throughout the water column (to a depth of ~400 m), and observed a greater rate of warming in surface waters (<100 m) than at depth (Figure 2-5). The observed surface warming trend of approximately 0.02 °C/yr is approximately the trend expected for a total temperature increase of 1.2° C by the middle of this century, as projected by Mote and Salathe (2010) for the coastal waters of Washington State.

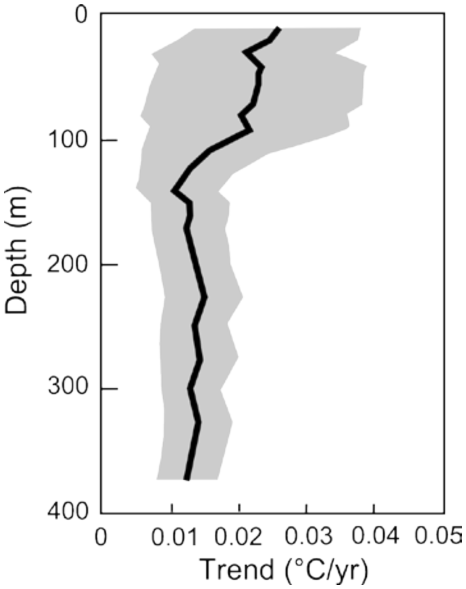


Figure 2-5. Mean (black line) linear temperature trend off-shore of Vancouver Island for the period 1970-2005. Gray shaded areas are 95% confidence intervals. Figure adapted from Masson and Cummins (2007).

Despite projections for warming in the coastal waters of the Pacific Northwest, the evidence to support a contemporary warming trend in OCNMS is mixed. Several published investigations find significant trends in some temperature records, whereas other published analyses, and our own preliminary analysis of additional NDBC Buoy data, cannot detect a significant trend. In general, all available observations cover too short a time span to confidently exclude the influence of variability related to annual to decadal scale cycles like ENSO or the PDO. Observational platforms within OCNMS, including the OCNMS mooring program (Olympic Coast National Marine Sanctuary 2012) as well as the Northwest Enhanced Moored Observatory (NEMO) (Applied Physics Laboratory 2012) will, over time, help to clarify trends related to warming and other climate-related factors.

Box 2-1: A Re-Examination of Sea Surface Temperature in OCNMS

Temperature data from buoys 46041 and 46005 (Figure 2-4) were re-analyzed using the methods outlined in Gower et al. (2002) but with an extended data record (to 30 December 2011 for both data sources). No significant temperature trend was detected in either buoy (Figure 2-6). This preliminary result is not unexpected given the large variations in temperature in the northeast Pacific Ocean. In the context of that variability, even a relatively steep trend would be difficult to detect with such a short observational record. These results are considered preliminary. In particular, data gaps in the temperature record were not accounted for and may potentially introduce bias. Furthermore, the results have not been subjected to a rigorous review.

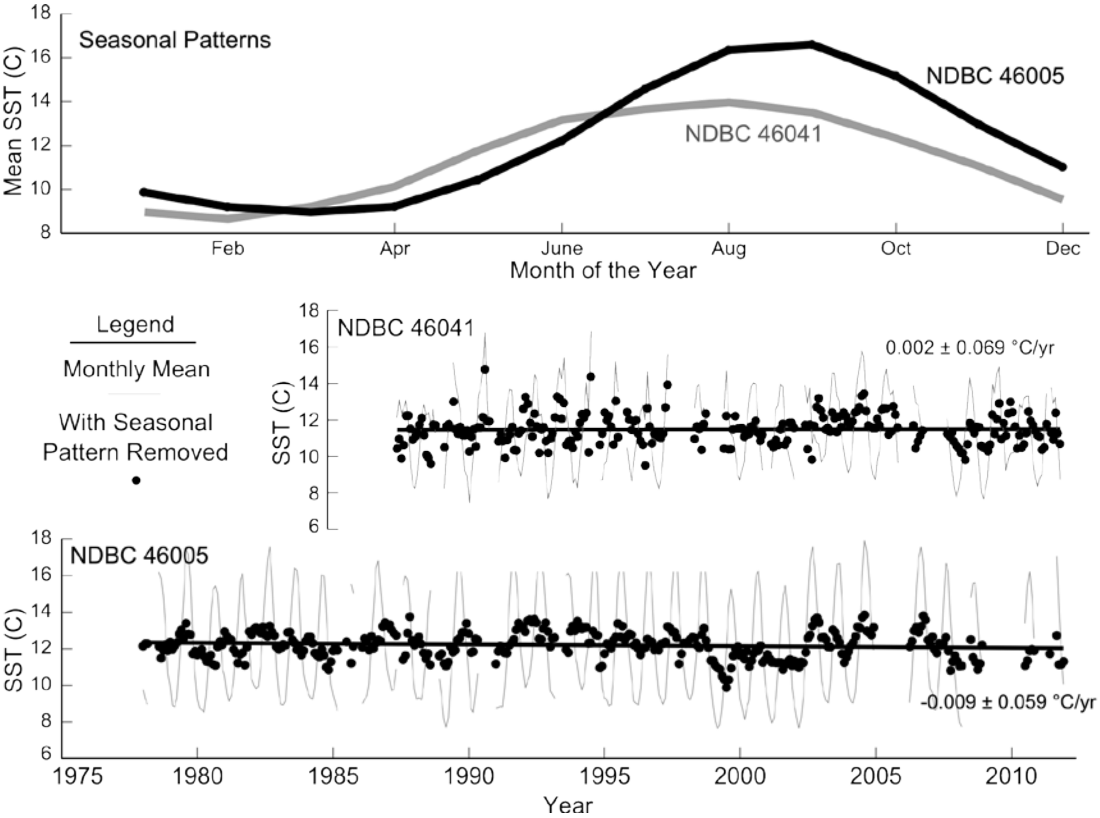


Figure 2-6. Sea-surface temperature seasonal patterns (top panel) and trends of monthly means at Buoy 46041 (middle panel) and 46005 (bottom panel). See Figure 2-4 for buoy locations relative to OCNMS. Data from NOAA National Data Buoy Center.

2.3 Acidification of Ocean Water

2.3.1 Summary

- The ocean's absorption of anthropogenic CO_2 is causing changes to seawater chemistry, referred to as ocean acidification." The Pacific Northwest coast is likely to be particularly vulnerable to ocean acidification.

- Observations along the Pacific Northwest coast, including sites within OCNMS, suggest that the coastal ecosystem is seasonally exposed to corrosive waters. Corrosive is the term used in this report to describe ocean water with lower pH and reduced availability of carbonate ions relative to a historical baseline. Exposure to corrosive waters can result in the degradation of the body parts of some marine organisms and may impact the survivability of those organisms.
- Model projections suggest that corrosive waters will expand in both spatial and temporal extent over the coming century.

2.3.2 Introduction

For more than three decades, oceanographers have documented carbon chemistry throughout the global ocean. This work has led to a recognition that ocean chemistry is changing as a result of human release of carbon dioxide (CO_2) into the atmosphere. The atmosphere and ocean exchange gases between one another, and the ocean is absorbing 25% of the annual anthropogenic CO_2 released into the atmosphere (Sabine et al. 2004; Le Quere et al. 2009).

When CO_2 from the atmosphere dissolves in the surface ocean, pH and the concentration of carbonate ions (CO_3^{2-}) in seawater decrease. These chemical changes in the ocean resulting from increasing anthropogenic CO_2 are referred to as “ocean acidification.” Surface seawater pH has decreased by 0.1 units since the beginning of the industrial revolution (Caldeira and Wickett 2003; Orr et al. 2005a). The pH scale is logarithmic, like the Richter scale that measures the strength of earthquakes, so this change represents a 30% increase in acidity of the ocean (Figure 2-7). Since preindustrial times, the average concentration of CO_3^{2-} in the surface ocean has also decreased, by approximately 16% (Figure 2-7) (Feely et al. 2009b).

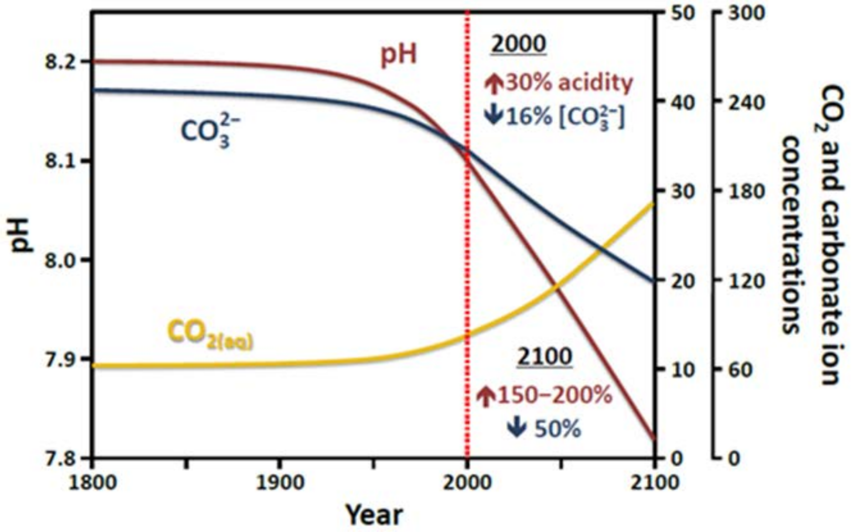


Figure 2-7. Surface ocean carbonate chemistry from pre-industrial times to 2100 with projections based on the IPCC WG2 IS92a scenario (See Section 6.1 for a summary of emissions scenarios). Units for CO_2 and carbonate ion concentrations are μmol/kg. Figure courtesy of Simone Alin, NOAA PMEL; adapted from Wolf-Gladrow et al. (1999).

Marine calcifiers, organisms that build calcium carbonate shells and skeletons, will likely be the most vulnerable to the impacts of ocean acidification. The saturation state of calcium carbonate minerals, including aragonite and calcite, is an important parameter for assessing whether ocean conditions are favorable to calcification. Saturation state (represented by the symbol Ω) describes the amount of these minerals available in solution based on the physical characteristics of the water and the solubility of the carbonate mineral. When Ω is greater than 1, the water is considered "supersaturated," and there are excess mineral constituents for organisms to build calcium carbonate shells and external skeletons. When Ω falls below 1, waters are "undersaturated," and organisms typically must expend more energy to extract those skeletal building blocks from seawater. Ω is a useful indicator, but not all organisms respond the same to varying saturation states. Some organisms, like many shallow water tropical corals (Hoegh-Guldberg et al. 2007), only thrive in conditions well above saturation, whereas some organisms are able to maintain their structures in undersaturated waters at an energetic cost. Other examples of economically and ecologically important marine calcifiers include shellfish, deep-sea corals, sea urchins, and calcareous plankton.

In addition to reduced calcification, other potential impacts of ocean acidification include altered reproduction and survival, reduced olfaction in fish, increased photosynthesis, acoustic disruption, and various potential responses to altered trace metal and nutrient speciation (Fabry et al. 2008; Doney et al. 2009a; Hutchins et al. 2009). Marine organisms are also exposed to other stressors in the contemporary marine environment (e.g., increasing ocean temperature and fishing pressure) that may exacerbate or counteract the impacts of ocean acidification. Impacts to organisms that play a vital role to the ocean food chain (e.g., calcareous plankton) may reverberate throughout the marine ecosystem, threatening the health of our oceans and coasts and the services those ecosystems provide. Research on the biological implications of acidification is in its early stages, and potential impacts relevant to the OCNMS are discussed in greater detail in Sections 3 and 4.

2.3.3 Projections

Under the "business-as-usual" CO_2 emission scenario used in the IPCC 3rd Assessment Report (Scenario IS92a; see Section 6.1), average ocean pH is predicted to decrease as much as an additional 0.3 units by 2100 (Caldeira and Wickett 2003; Orr et al. 2005a), which is approximately a 150 to 200% increase in the acidity of oceans over pre-industrial levels. Under similar high-emission scenarios (IS92a and SRES A2; Section 6.1), carbonate ion concentrations in the global ocean are also predicted to decrease by approximately 50% by the end of this century (Figure 2-7) (Wolf-Gladrow et al. 1999; Feely et al. 2009a).

Surface ocean waters are currently supersaturated across most of the global ocean with respect to aragonite and calcite minerals. Deep ocean waters are naturally high in CO_2, low in pH, and undersaturated with respect to calcium carbonate minerals due to the accumulation of the products of respiration and the lack of ventilation with the atmosphere. The saturation horizon is the ocean depth where supersaturated surface waters and undersaturated deep waters meet, or where the saturation state is equal to 1. Since the beginning of the industrial revolution, the aragonite saturation horizon has migrated 40–200 meters closer to the surface in the North Pacific Ocean due to ocean uptake of anthropogenic CO_2 (Feely et al. 2004; Orr et al. 2005a; Feely et al. 2012).

The California Current System (CCS) may be vulnerable to ocean acidification due to a combination of the anthropogenic shoaling of the saturation horizon and the natural process of upwelling. Upwelling occurs in the CCS when winds from the north push surface waters offshore and are replaced by water drawn to the surface from intermediate depths (a few hundred meters). Feely et al. (2008) estimate that, along the coast of Washington, these upwelled waters were last in contact with the atmosphere 30-50 years prior. Therefore, in addition to the CO_2 added to upwelled waters due to biological respiration, these waters are also increasingly carrying increased CO_2 loads supplied from the atmosphere as well.

Upwelling also brings nutrient rich waters to the surface and supports high primary productivity in the CCS. Because of the chemical and physical properties of the system and the importance of the services the ecosystem provides, the CCS has been a region of interest for ocean acidification observations and modeling work. Hauri et al. (2009) used an eddy-resolving ocean current model coupled with a biogeochemical model to assess ocean chemistry changes in the CCS. Their results support present day observations that surface seawater pH and aragonite saturation states have decreased by 0.1 units and 0.5 respectively and that undersaturated waters shoal closer to the surface during periods of summer upwelling. Using a similar model, Gruber et al. (2012) suggest that the saturation horizon ofaragonite (Ω_{arag}) has shoaled by about 150 m in the CCS since 1750, and they predict a further shoaling of 100-150 m by 2050. This may lead to a reduction in CCS habitat remaining in supersaturated waters over time. Models suggest that in 1750 no waters in the euphotic zone were exposed to undersaturated conditions; however, by 2005 seasonal undersaturation (i.e. due to summer upwelling) was projected and by 2050 half of the euphotic zone may be exposed to undersaturated conditions (Figure 2-8a). This evolution to undersaturated conditions is even more prevalent deeper in the water column and may currently be impacting bottom habitat on the continental shelf (Figure 2-8c).

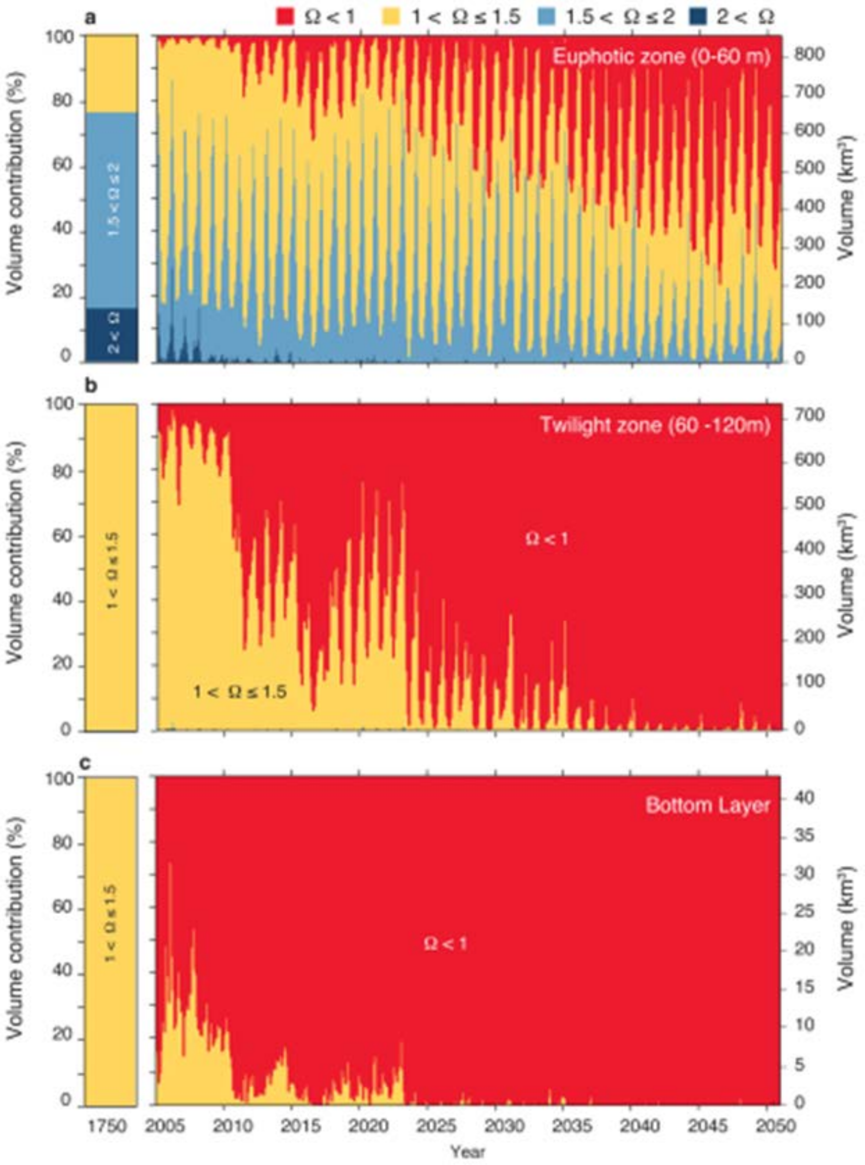


Figure 2-8. Change over time in the volume of seawater off of the Northern California coast with different levels of Ω_{arag} for a) the euphotic zone above 60 m, b) the twilight zone between 60-120 m, and c) the bottom layer below 120 m. Projections based on the SRES A2 scenario (See Section 6.1). Figure from Gruber et al. (2012).

The predictions in Figure 2-8 were made for the region between Point Conception and the California/Oregon border, but similar patterns are expected to occur throughout upwelling regions of the CCS, including in OCNMS. Changes in carbon chemistry are predicted to coincide with increasing hypoxic and anoxic conditions in the CCS (Bograd et al. 2008; Chan et al. 2008). Some work also suggests that wind-driven upwelling in many of the world's coastal upwelling regions may intensify due to increasing wind stress driven by a greater land-ocean temperature gradient as warming temperatures progress into the future (Bakun 1990) (see also Section 2.6). In summary, models predict that ocean conditions in the CCS are changing rapidly and marine organisms in this highly productive ecosystem are currently exposed to corrosive waters during upwelling.

2.3.4 Observations

Direct observations of ocean carbon chemistry in the CCS support many of the modeling results discussed above. In 2007, waters undersaturated with respect to aragonite upwelled onto large portions of the continental shelf and to the surface in one area along the northern California coast (Figure 2-9). At sampling stations within OCNMS, the depth of aragonite under-saturation occurred between 60 and 100 meters below the surface, suggesting that shallow seafloor habitats within the sanctuary were exposed to corrosive waters.

As a part of the first set of extensive carbon surveys undertaken in Washington State, stations in the northern section of OCNMS were sampled in the summer of 2008. In August 2008 much of the water column sampled on Washington shelf and into the Strait of Juan de Fuca were under-saturated with respect to aragonite (Figure 2-10). This PRISM/NANOOS (www.nanoos.org) cruise was repeated in October of 2011 and shows similar under-saturation of the entire water column at the entrance to the Strait (Alin and Feely, unpublished data). Some pH and carbon isotope measurements have also been made at Tatoosh Island off Cape Flattery in conjunction with ecological studies and are consistent with these hydrographic observations and the modeling predictions discussed previously (Wootton et al. 2008; Pfister et al. 2011).

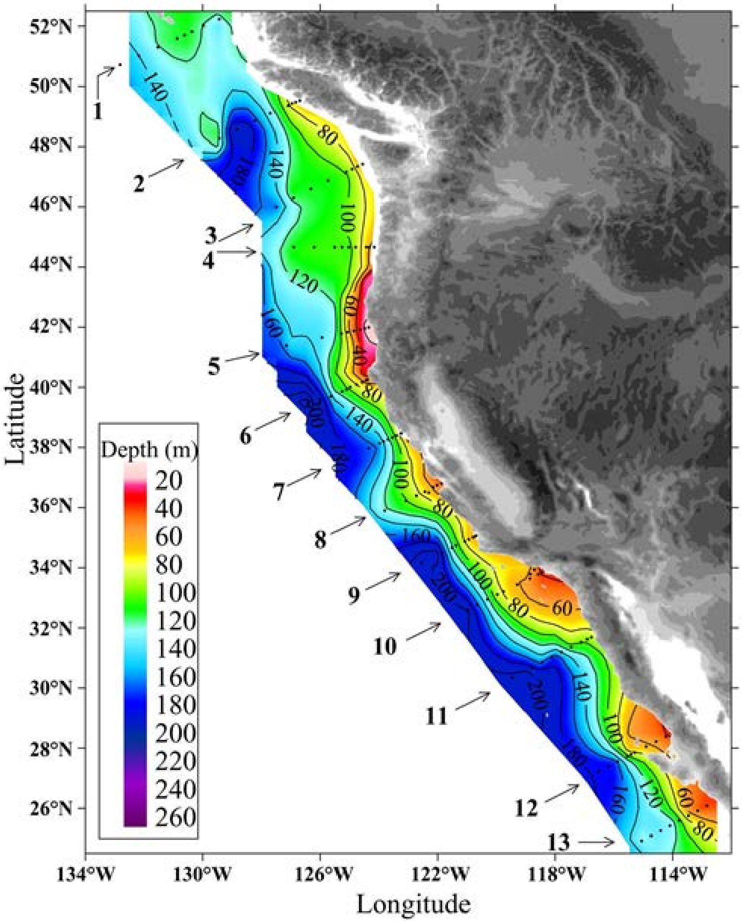


Figure 2-9. Depth of waters where Ω_{arag}=1 in May-June 2007. Figure from Feely et al, (2008).

In highly productive coastal and estuarine systems, CO_2, pH, and saturation states can vary substantially on timescales from hours to years due to tides, coastal currents and upwelling, daily patterns of photosynthesis, and river or groundwater inputs. Only a few studies in coastal systems have documented short-term variability of carbon chemistry (Gray et al. 2011; Yu et al. 2011). Separating these natural sources of ocean chemistry variation from anthropogenic sources of change is dependent on high-resolution, long-term monitoring. NOAA, in partnership with the University of Washington and other partners, has been measuring CO_2 and related parameters on two surface buoys within OCNMS; the NANOOS-NOAA-UW Chábă (Applied Physics Laboratory 2012) and NDBC 46041 Cape Elizabeth buoys (Figure 2-4). Observations show strong variability over short time periods in seawater pH and pCO_2 (partial pressure of CO_2; See Section 0) at Chábă. For example, in September 2010 values fluctuated as much as 200 µatm pCO_2 and 0.2 pH between 3-hour measurement cycles and >300 µatm pCO_2 and 0.5 pH within one day (Figure 2-11). Much of the variability at this site is likely due to a combination of high biological productivity and strong winds that can drive localized upwelling. In the Cape Elizabeth CO_2 time-series, the seasonal cycle becomes more apparent with minimum seawater pCO_2 values typically occurring in the spring/summer and maximum values in the fall/winter. Seasonal variation in surface seawater pCO_2 at this site is approximately 250 µatm (Figure 2-11b).

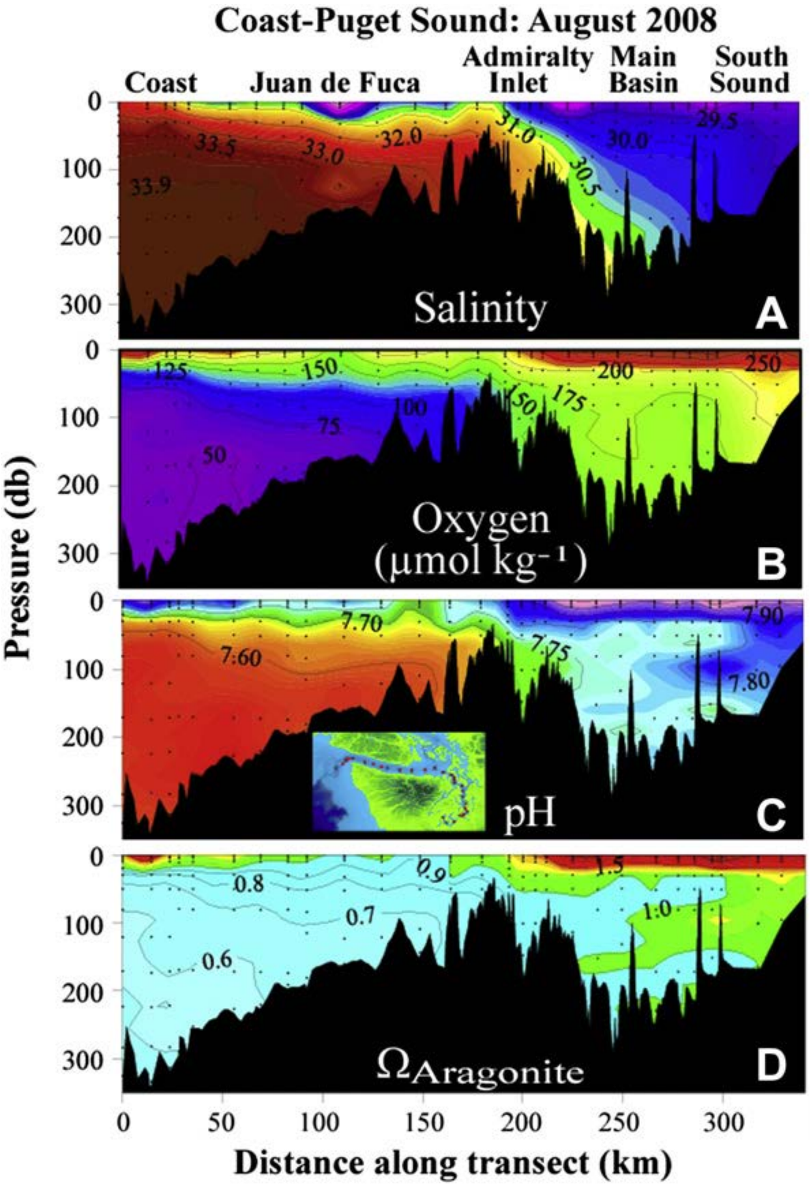
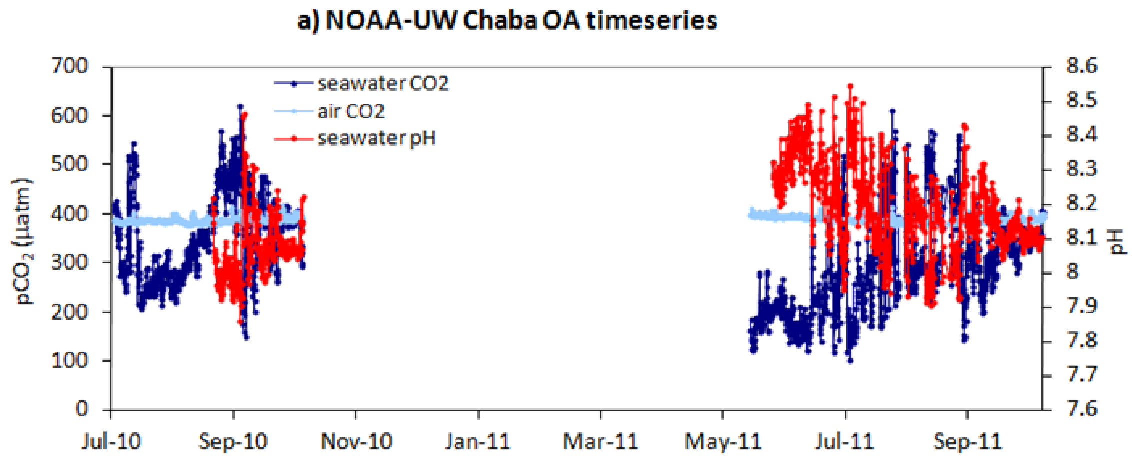


Figure 2-10. Coastal transect of A) salinity, B) oxygen, C) pH, and D) Ω_{arag} from the outer coast into Puget Sound (see inset map in C) in August 2008. Figure from Feely et al. (2010).

Current research is also focused on building proxy relationships for estimating ocean carbon chemistry using widely measured parameters such as oxygen and temperature. Juranek et al. (2009) collected data on transects in the northern CCS to develop an empirical relationship for estimating Ω_{arag} from temperature and oxygen observations. This relationship, when applied to temperature and oxygen profiles, indicated that undersaturated waters covered bottom habitat of the continental shelf in central Oregon throughout the entire upwelling season in 2007 (May – November). This approach is a powerful method to estimate ocean acidification conditions using commonly collected oceanographic data.



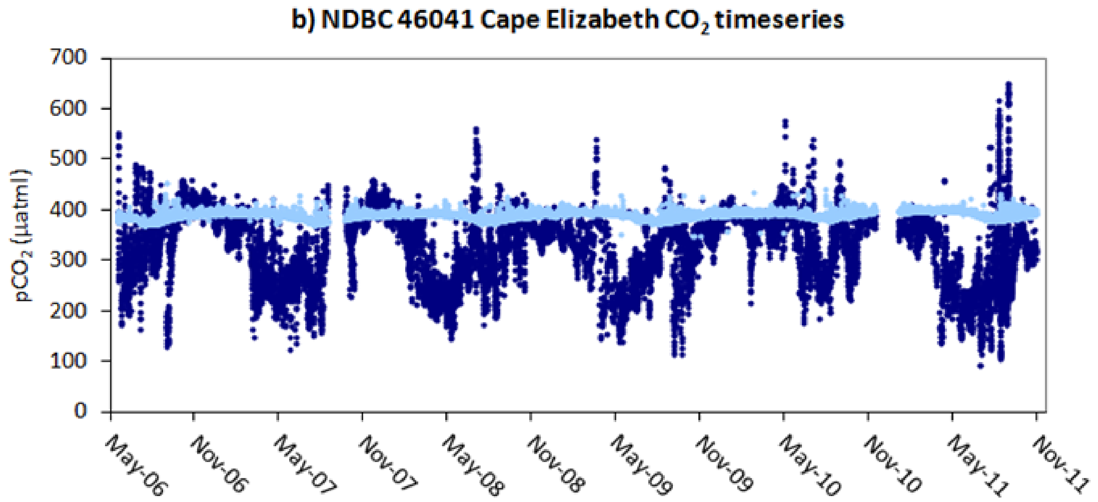


Figure 2-11. CO_2 and ocean acidification time-series from the a) NANOOS-NOAA-UW Chábă and b) NDBC 46041 Cape Elizabeth buoys (see Figure 2-4 for locations of buoys).

Historical carbon measurements along the U.S. West Coast have been limited in time and space. However, the scientific community is ensuring that high-quality observations of marine carbon are continued and extended along the West Coast and the resulting data are synthesized for use by the broader community. These efforts are particularly important to understand the potential impacts of ocean acidification on OCNMS.

2.4 Sea Level Rise

2.4.1 Summary

- Mean sea level is projected to increase throughout the northeast Pacific Ocean, though there remains debate regarding the magnitude of that increase. We suggest a planning horizon of 1.0 m by 2100 is reasonable, though both higher and lower rates are justified given the available evidence.
- Rates of sea level change relative to the shoreline varies from north to south within OCNMS due to variability in the rate of tectonically-driven vertical

land movement. Sea level rise is likely to impact the southern coast of OCNMS earlier and to a greater extent than along the northern coast.

- Sea level within OCNMS is highly variable, with pronounced seasonal variation due to oceanographic and meterologic effects and annual variation due to, for example, ENSO events. Despite this variability, there is evidence that observable sea level rise is already occurring within OCNMS.

2.4.2 Introduction

The mean level of the ocean's surface varies over short-time scales (days to months) due to a variety of factors, including tides, variations in atmospheric pressure (related to the passage of low-pressure and high-pressure air masses), and wind which can "pile" water up against coastlines. These short-term fluctuations in sea level are superimposed upon longer (years to decades) variations associated with climate cycles like the El Nino-Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO; See Section 6.3). Over much longer time-scales (multiple decades to centuries) mean sea level is determined primarily by the heat content of the ocean as well as the fraction of the Earth's water budget that is tied up in large, land-grounded ice masses. Of particular contemporary concern are projections suggesting increasing multi-decadal mean sea levels. The goal of this section is to describe the processes that drive long-term sea level variations, projections relevant to OCNMS and observations of sea level made in or near OCNMS.

The thermal expansion of the mass of water held in ocean basins and melting of land-based ice (the ice sheets covering Greenland, for example) combine to generate mean sea level rise over decades and centuries. However, land masses can also move vertically due to a variety of processes, and relative sea level takes into account the relative position of the water and the shore. Relative sea level is of greatest interest when considering impacts related to erosion and coastal flooding. For example, over the past two decades mean global sea level, as measured from satellites using radar altimetry and averaged over the surface of the global ocean, has risen at a rate of approximately 3.1 mm/yr (Figure 2-12). Despite this positive rate of mean sea level rise, relative sea level varies considerably at locations around the globe. For example, over the past two decades the relative sea level at Grand Isle on the Mississippi delta rose nearly three times faster than the mean rate of sea level rise (9.2 mm/yr) due to the effects of land subsidence. By contrast, relative sea level at Kodiak, Alaska is falling at a rate of over 10 mm/yr due to tectonically driven rapid vertical movement of the land relative to a more slowly rising sea (Zervas 2009). The Pacific Northwest coast of the United States sits adjacent to the tectonically-active Cascadia Subduction Zone, and subduction of the Juan de Fuca plate beneath the North American Plate drives variable rates of vertical land movement. As a consequence, observations made at tidal water level gauging stations show variable rates of relative sea level around the Pacific Northwest (Figure 2-13).

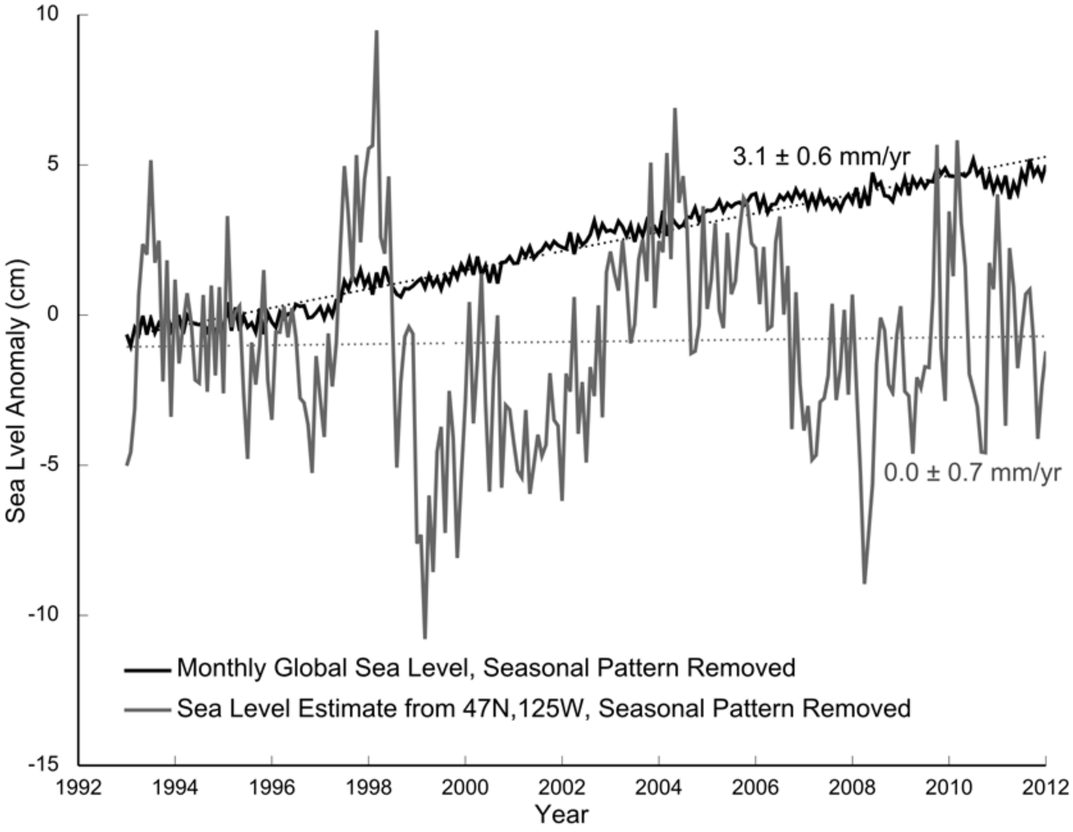


Figure 2-12. Monthly estimates of sea level, spatially-averaged over the world's oceans (black curve) and for a 1-degree grid cell at 47N, 125W within OCNMS (gray curve). Regressions, with standard error, are shown with dotted lines. Data from http://sealevel.colorado.edu.

A rising sea level is likely to impact the resources in OCNMS primarily through the erosion of shorelines and the physical restructuring of coastal habitats. For the coastal communities on the outer coast of the Olympic Peninsula, however, sea level rise can have direct and negative impacts on infrastructure.

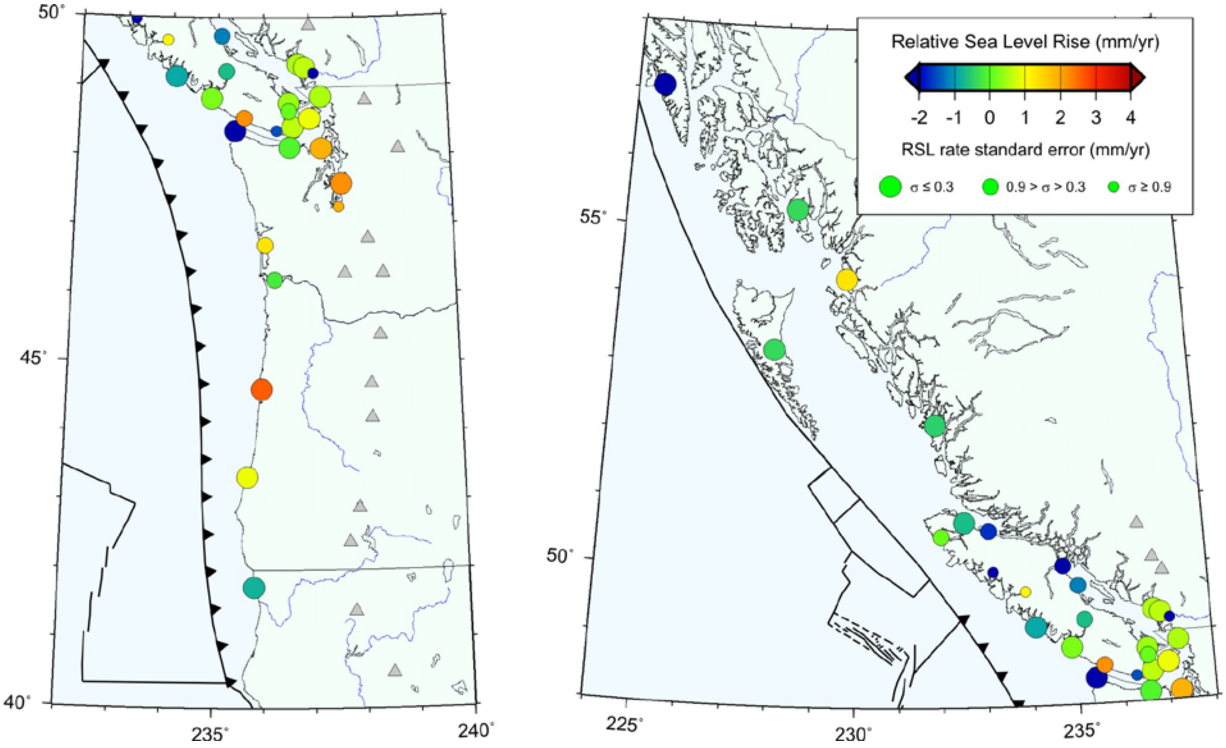


Figure 2-13. Rates of relative sea level change estimated from water level data collected at tidal gauging stations from around the Pacific Northwest. Figure from Mazzotti et al. (2008).

2.4.3 Sea Level Rise Projections

Global Projections of Mean Sea Level

As the atmosphere warms and heat is transferred to the global ocean, mean sea level is projected to rise as a result of thermal expansion of water. Additionally, the melting of land-based ice from, for example, Greenland and Antarctica will result in the addition of a substantial volume of water to the ocean basins. While the processes and mechanisms controlling thermal expansion are well understood and can be modeled with little uncertainty, the contribution of water to the ocean basins due to the melting of land-based ice is more difficult to constrain given present knowledge. As a result, the magnitude of the increase in global mean sea level is difficult to predict with great certainty. The 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; www.ipcc.ch) offered a range of expected increases in global mean sea level by 2100, ranging from 0.18 to 0.59 m (Bernstein et al. 2007). This widely reported range of estimates may be too low, however. To derive the IPCC estimates, the rate at which melting land-based ice contributed water to the oceans was assumed to continue for the next century at a rate equivalent to that estimated for the last decade of the 20th century. Some evidence suggests that the rate of ice melting may accelerate as the atmosphere warms (Bernstein et al. 2007; Meehl et al. 2007). At least one investigation has attempted to constrain the possible contributions of ice melt to sea level rise using a range of more complex melting models, and their results suggested the possibility of sea levels by 2100 of between 0.785 and 2.01 m (Pfeffer et al. 2008). A full summary of the limitations of the IPCC's numerical modeling approach used to provide the sea level rise estimates published in 2007 is given in Church et al. (2011a).

Given the limitations of physically-based numerical modeling approaches, a number of more recent sea level rise projections are based on a "semi-empirical approach" that links observations of near-surface atmospheric temperature with global mean sea level. The idea behind this approach is that, over long time periods (multiple centuries) the relationship between temperature and sea level incorporates thermal expansion and the complex processes governing the loss of land-based ice to the ocean. Results of one investigation suggest a strong relationship between global mean temperature and global sea level measured between 1881 and 2001. Furthermore, when extrapolated into the future using the IPCC's estimates of global temperatures change, the relationship suggests higher sea levels, between 0.50 and 1.40 m, than those projected by the IPCC for 2100 (Meehl et al. 2007; Rahmstorf 2007). A second analysis using a similar approach, but with an extended temperature and sea level record, suggested that global sea level by 2100 can be reasonably expected to exceed 0.9 m given projected atmospheric temperature increases (Grinsted et al. 2010). Despite some criticism of these semi-empirical approaches (Holgate et al. 2007; Church et al. 2011a), overall they suggest a probability that global sea level rise in the year 2100 may exceed the range published by the IPCC in 2007.

The National Academies of Science published sea level projections for the West Coast of the United States (California, Oregon and Washington) based on a combination of approaches (Committee on Sea Level Rise in California Oregon and Washington 2012). The contribution to global mean sea level from rising ocean water temperature was calculated using global climate models, but the contribution from melting land-based ice was extrapolated from updated observations of ice loss. Their analysis also suggest global sea levels are likely to exceed the estimates from the IPCC 4th Assessment Report (Figure 2-14), and approximate some published estimates using the semi-empirical approaches (Bernstein et al. 2007; Rahmstorf 2007).

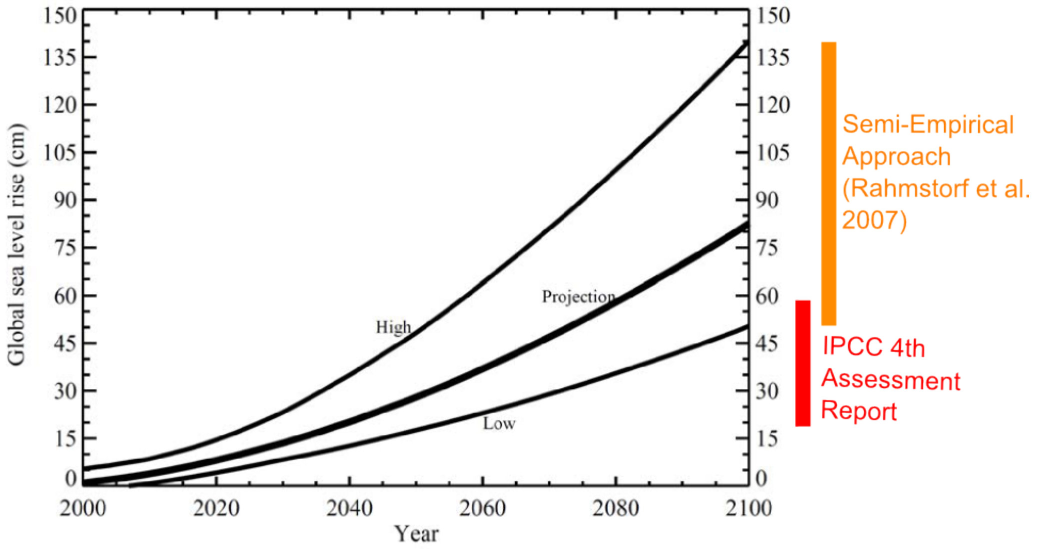


Figure 2-14. Global sea level rise projections to 2100 based on the results of the Committee on Sea Level Rise in California, Oregon and Washington (2012), compared to 2100 projections from the IPCC's 4th assessment report (Bernstein et al. 2007) and Rahmstorf et al. (Rahmstorf 2007). Figure adapted from the Committee on Sea Level Rise in California, Oregon and Washington (Committee on Sea Level Rise in California Oregon and Washington 2012).

Regional Projections of Relative Sea Level Rise

For estimates of future sea level rise to be valuable at the spatial scales relevant to OCNMS, global-scale mean sea level projections must be transferred into estimates of relative sea level for the stretch of coastline fringing OCNMS. Available evidence suggests that, over long time-scales (multiple decades), rates of mean sea level rise in the Pacific Northwest are nearly equivalent to global rates (Mazzotti et al. 2008; Komar et al. 2011) and that variation in space of rates of vertical land movement are the primary cause of observed variations in rates of relative sea level rise (Figure 2-13). Along the shoreline fringing the eastern edge of OCNMS vertical land movements vary from a rate of approximately 3-4 mm/yr along the northern boundary (Verdonck 2006; Mazzotti et al. 2008) to rates along the central and southern boundary of OCNMS that may be as low as -1 mm/yr (Verdonck 2006). Based on these estimates the total vertical land movement along the northern shoreline of OCNMS by the end of the century may be as high as 0.30 to 0.40 m, while the shoreline along the southern boundary may subside by ~ 0.10 m. This variability in vertical land movement across OCNMS will alter the shoreline impacts of relative sea level rise over the 100 year timeframe considered by this report. These rates of vertical land movement are assumed to be relatively stable, although subsidence associated with seismic events can abruptly change patterns of vertical land movement.

Table 1. 100-yr sea level projections from Mote et al. (2008). While no probability were assigned to the three scenarios by the authors, our interpretation of information published since this report suggests a greater likelihood of occurrence of the medium or very high scenarios (in green), while the "very low" scenario (red) is considered unlikely.

Scenario	**NW Olympic Peninsula**	**Central and Southern WA Coast**
Very Low	-24 cm (-9")	6 cm (2")
Medium	4 cm (2")	29 cm (11")
Very High	88 cm (35")	108 cm (43")

Mote et al. (2008), using the IPCC's 2007 estimates of global sea level rise coupled with estimates of regionally-varying vertical land movement and projected changes in off-shore winds, provide a range of relative sea level rise projections for the Northwest Olympic Peninsula and the Central and Southern Washington coast. Three sea level rise scenarios ('Very Low', 'Medium' and 'Very High') were reported for these regions (

Table 1), but with no rigorous treatment of probability between scenarios. Consideration of the limitations of the IPCC sea level rise projections upon which Mote et al.'s (2008) scenarios were based suggests the likelihood that actual regional relative sea level rise will be in the range of their "medium" or "very high" estimate. In particular, Mote et al.'s (2008) "very high" sea level rise scenario uses the "worst-case" IPCC sea level rise projections and also incorporates an accelerating freshwater flux from land-based glaciers into the present century.

The consistency between the "very high" scenario projections of Mote et al. (2008), the most probable estimates (0.80 m by 2100) of Pfeffer et al. (2008), the recent projections of the National Academy of Science (Committee on Sea Level Rise in California Oregon and Washington 2012), and the range of estimates provided by semi-empirical approaches (Rahmstorf 2007; Grinsted et al. 2010) suggest the possibility of mean sea level rise of ~1.0 m in OCNMS by 2100, though both higher and lower estimates can be justified.

2.4.4 Sea Level Observations

Global mean sea level rose at a rate of approximately 3.1 ± 0.6 mm/yr between 1993 and 2011, based on observations made by radar altimetry from satellites (Figure 2-12). Sea level rise calculated from a network of tidal gauges suggest a slightly lower rate of 1.7 ± 0.3 mm/yr for the entire 20th century (Church and White 2006). In contrast to globally-averaged measurements of sea level, satellite altimetry observations from the northeast Pacific waters adjacent to OCNMS since 1993 suggest no significant regional mean sea level rise (Figure 2-15). Using a network of eight tidal gauge records from Oregon and Washington, some dating back to the early 20th century, Komar et. al. (2011) find, by contrast, that a regional mean sea level rise rate of ~2 mm/yr is necessary to align the relative sea level rise rates measured by tidal gauging stations (which measure the changing elevation of the sea *relative* to the land) with GPS-based measurements of vertical land movement. Their results suggest that over longer time-scales (multiple decades) regional sea level in the Pacific Northwest has been approximately equivalent to the global mean. The suppression of regional mean sea level since 1993 (Figure 2-15) has been tentatively attributed to variations in wind patterns in the northeast Pacific Ocean, (Bromirski et al. 2011) perhaps related to the Pacific Decadal Oscillation (Section 6.3).

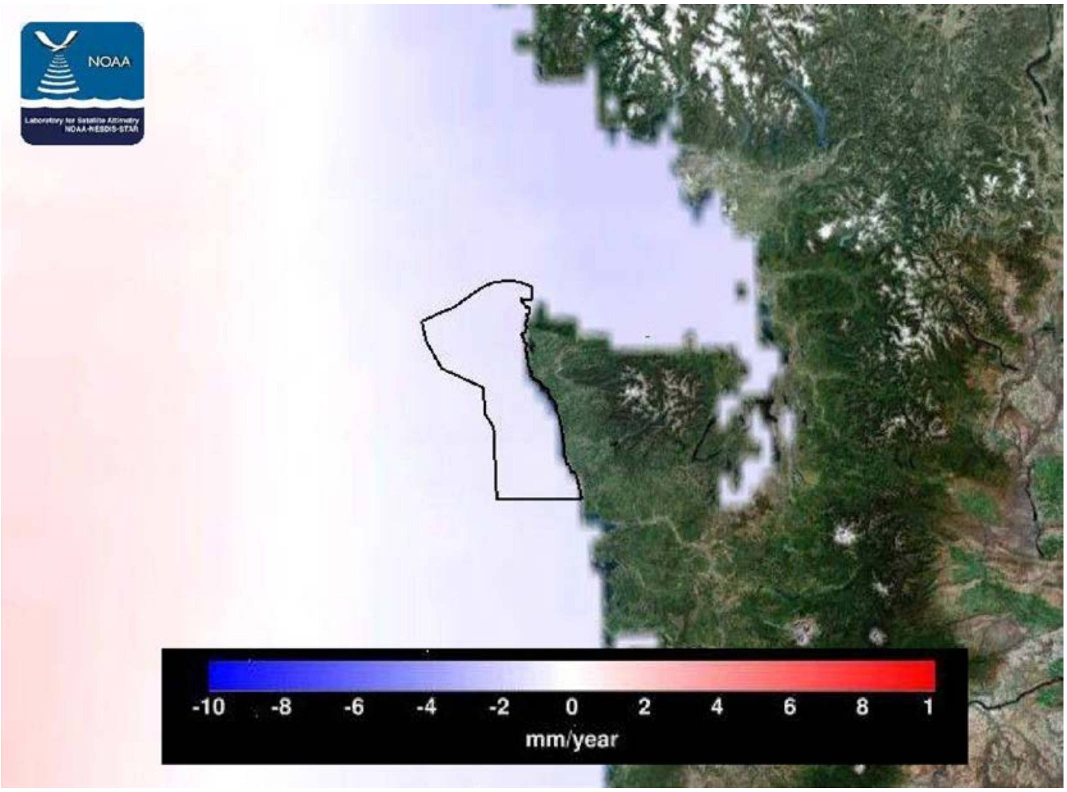


Figure 2-15. Sea level trend since 1993 for the waters in and adjacent to OCNMS estimated from satellite altimetry. The boundaries of OCNMS are given in black. Data from: http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/; image: Google Earth

Relative sea level rise is measured directly from tidal gauges in or adjacent to OCNMS at both NOAA Station 9443090 in Neah Bay, Washington and Station 9440910 at Toke Point in Willapa Bay, Washington (Figure 2-16). The station at Toke Point was originally installed in 1922, but data is only available from the early 1970's that is of adequate quality for the estimation of a sea level rise trend. There, NOAA's CO-OPS estimates a relative sea level rise rate of 1.60 ± 1.38 mm/yr (Figure 2-16). By contrast a data record extending back to 1934 exists from Neah Bay, Washington on the northern boundary of OCNMS, suggesting that relative sea level is falling at a rate of -1.63 ± 0.36 mm/yr (Figure 2-16). Two other NOAA water level stations are within or adjacent to the sanctuary: Station 9442396 at La Push and Station 9441102 in Westport, Washington. As of the publication of this manuscript there exists no published sea level trend estimate for either station.

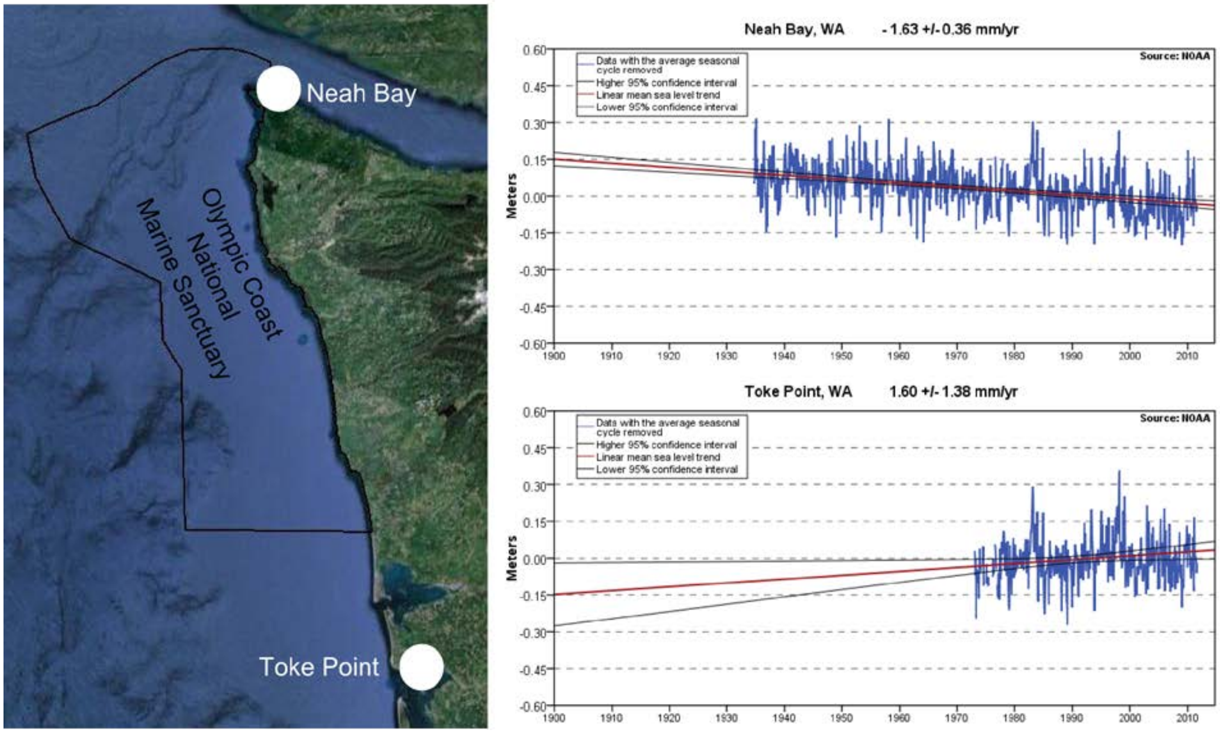


Figure 2-16. Relative rates of sea level change, estimated from tidal water level measurements, from stations on the northern and southern boundary of OCNMS. The boundary of OCNMS is in black. Data from the NOAA Center for Operational Oceanographic Products and Services (2012)

These estimates of relative sea level made adjacent to the northern and southern bounds of OCNMS suggest that vertical land movement plays a very important role in determining the vulnerability of the coastal zone within the sanctuary to sea level rise. At the northern boundary of the sanctuary rates of vertical land movement of ~4.0 mm/yr (Mazotti et al 2008, Verdonck 2006) outpaced the mean sea level rise of the 20th century (~2 mm/yr), whereas little or no vertical uplift at the southern boundary have combined with a rising sea to produce the observed sea level rise trend at Toke Point. Spatially-varying patterns of relative sea level rise can be correlated with spatial patterns of erosion and susceptibility to coastal hazards (Komar et al. 2011) and therefore it is prudent to assume that sea level rise will impact the southern shores of the sanctuary disproportionately during the upcoming century. Sea level impacts at the northern boundary of OCNMS cannot be discounted, though. An acceleration in the rate of mean sea level rise could overtake the observed vertical land movement towards the northern boundary of the sanctuary within the next century (Mote et al. 2008).

A Note on Sea Level Variability

Shorter-term variations in sea level (over years to decades) within OCNMS are extreme. For example, the range in monthly mean sea level measured by satellite in OCNMS between the winter of 1998 and 1999 was approximately 20 cm (Figure 2-12). This variability, often associated with climate cycles like ENSO or the PDO (See Section 6.3), almost certainly has more influence over time-scales of decades than the long-term sea level rise trend in regards to coastal impacts. In other words, sea level variability associated with climate cycles occurring over years or decades can strongly influence observed long-term sea level trends related to climate change. Over the long-term this sea level variability is expected to remain, and will be overlain on a rising mean sea level. It is important to take this variability into account when planning for the potential impacts of long-term sea level rise.

2.5 Increasing Frequency and Severity of Storms

2.5.1 Summary

- Climate models strongly suggest a shift in the tracks of storms in the northeast Pacific by 2100. Model results also tentatively suggest that the magnitude and frequency of storms in the northeast Pacific may increase by 2100.
- Observational evidence generally suggests increasing mean wind speed and wave height in and adjacent to OCNMS over the past 50 years, though there remains some debate regarding the veracity of those results.
- Other indicators of storminess, including storm surge patterns, are inconclusive due to extreme variability and the relatively short length of available data records.

2.5.2 Introduction

The 2007 report of the IPCC projects global increases in the frequency and intensity of extreme weather events (Bernstein et al. 2007). The impacts of such an increase in storm intensity and frequency on the resources of OCNMS could be varied. Large, energetic and sometimes destructive extra-tropical storms are common within OCNMS, particularly during the winter (Mass 2008). Those that are associated with high winds, ice and or large amounts of snow often receive extensive media attention due to damages to human communities or forestlands (Mass 2008). However, coastal flooding and erosion are associated with these storm events (Ollikainen 2012), and these storm events could have widespread impacts in shallow coastal habitats within OCNMS.

Even remote storms that do not directly impact OCNMS may have indirect consequences on marine habitats. Increasing mean or extreme wave heights or changes in wave direction can alter shallow marine and intertidal habitats through the erosion and re-distribution of sediment transported by waves. Wave “run-up” or the elevation on the beach that waves drive water, is strongly correlated with wave height (Allan and Komar 2006) and increasing extreme wave heights increase the risk of coastal flooding and erosion by raising the total water level associated with storms. Short-term, but relatively large, water level changes driven by low atmospheric pressure or wind associated with storm systems (generally known as “storm surge”) can also cause erosion. The combination of large waves, high tides and a large storm surge caused erosion and damage to the south jetty in La Push, WA in January of 2012 (Miller 2012; Ollikainen 2012).

This section will discuss three different facets of "storminess" relevant to OCNMS: Direct storm impacts associated in particular with extratropical cyclones, changes in the wave climate of OCNMS, and water level variability associated with storms.

2.5.3 Storminess Projections

There is general consensus amongst model ensembles that a decrease in winter surface pressure across the northern reaches of North America will act to shift the Aleutian Low northward and drive storm tracks northward over time (Yin 2005; Meehl et al. 2007). On the Olympic Peninsula and in OCNMS the intensity and severity of winter storms can be related to the regional position of low pressure centers as they make landfall (Mass 2008) since the extreme pressure gradients to the south of a low-pressure cell drive the high winds and ferocious winter storms that characterize the season. Wind storms in the Pacific Northwest (mid-latitude cyclones) are driven by large horizontal temperature differences between latitudes, and the strength of these storms can be characterized by the sea level pressure at the center, or "eye" of the storm. Mass (2008) shows that the location of landfall in the Pacific Northwest of strong low-pressure extra-tropical cyclones is a predictor of the locations where damage is most concentrated, and that storms that make landfall on Vancouver Island tend to concentrate wind energy and storm-induced damage on the northern Olympic Peninsula. Therefore, increases in the frequency or intensity of such storms in OCNMS, potentially associated with a northward shift in storm tracks, would increase the likelihood of intense winds.

While the mean track of storms may change, there remains some disagreement amongst global climate models with regards to the intensity and frequency of individual storm events (McDonald 2011). There is a consensus that the Pacific Northwest of the U.S. can expect increasingly intense storm events in terms of precipitation associated with those events (Salathe 2006; Christensen et al. 2007). For example, the average year will see more dry days but precipitation intensity during storms (the amount of rain falling on the average rainy day) is projected to increase (Meehl et al. 2007). These patterns are partially reflected in forecasts of changing hydrologic conditions for rivers on the Olympic Peninsula, where projections suggest higher winter flows and lower flows during the summer (Section 2.8). It is unclear, however, if and when changes in the intensity of individual storm events, as measured using wind power or atmospheric pressure for example, will be large enough to become apparent relative to the natural variability in storminess.

Changes in the intensity and frequency of storms in the northeastern Pacific Ocean could have three additional ramifications of particular interest to OCNMS due to their capacity to influence the marine environment. First, there is evidence to support a future of larger extreme wave heights in the mid-latitude ocean, driven by increasing wind speeds associated with mid-latitude storms of greater peak intensity (Meehl et al. 2007). Wave height, to a large extent, determines the energy contained in waves propagating along the ocean's surface, and larger storm waves could therefore be expected to increase nearshore sediment transport and coastal erosion. Second, biological communities may respond to an increase in storminess in complex ways. For examples, some connection has been made between the timing and intensity of storms and the survival of marine mammals (Lea et al. 2009). Finally, strong winter storm winds and/or low atmospheric pressure can generate large storm surges which can also influence coastal erosion and the reconfiguration of shallow water habitats. The lower winter atmospheric surface pressure projected by global climate models (Meehl et al. 2007) suggests the possibility of larger storm surges in the winter months in OCNMS.

2.5.4 Storminess Observations

Observations of surface wind speed made from buoys (Gower 2002) and via satellite altimetry (Young et al. 2011) show some statistically significant trends, though records are generally too short to determine the extent to which those trends are driven by longer-term climate changes versus shorter-term (annual to decades) climate fluctuations like the Pacific Decadal Oscillation (Section 6.3). Wind speed measured at NDBC buoy 46041 within OCNMS (Figure 2-4) increased at a statistically significant rate of 0.069 m/s/yr between 1987 and 1999, for example (Table 2). NDBC Buoys 46002 and 46036, adjacent to OCNMS (Figure 2-4), also showed statistically significant increasing wind speed trends for data collected between 1976 and 1999 (Table 2). Similarly, Young et al. (2011) identified a statistically significant trend in both the mean and extreme (90th and 99th percentile) wind speeds recorded at NDBC Buoys 46005 and 46002 (Figure 2-4) and via satellite altimeter over the period between 1991 and 2008 (Table 2). At NDBC 46005 the mean wind speed from both measurement platforms increased at a rate of approximately .04 m/s/yr (Table 2).

Table 2. Significant mean wind speed trends from buoy locations shown in Figure 2-4. No published analyses from Buoys 46004 or 46087 were identified. Referenced studies include Gower (2002) and Young et al. (2011). "NS" indicates that an analysis was conducted, but no significant trend was found.

NDBC Buoy	Trend (m/s/yr)	Time Range	Reference	Method
46036	0.091	1976-1999	Gower	Buoy
46005	NS	1976-1999	Gower	Buoy
	0.040	1991-2008	Young	Buoy
	0.043	1991-2008	Young	Altimeter
46002	0.020	1976-1999	Gower	Buoy
	0.020	1991-2008	Young	Buoy
	0.032	1991-2008	Young	Altimeter
46041	0.069	1987-1999	Gower	Buoy

Graham and Diaz (2001) utilized a suite of measured and interpolated sea level pressure and wind data from the Pacific ocean to analyze the frequency and intensity of north Pacific winter cyclones between 1950 and 1998. Their results suggest a pattern of "increasingly vigorous cyclone activity across much of the north Pacific since the mid-twentieth century," with increasingly frequent deep low-pressure cells, declining minimum sea level pressure and increasing extreme winds. The investigators hypothesize that these changes can be attributed to increasing sea surface temperatures in the tropical western Pacific Ocean, which is consistent with climate model predictions. However, the extent to which western Pacific sea surface temperature increases is due to global climate change versus shorter-term variability related potentially to El Nino-Southern Oscillations or the Pacific Decadal Oscillation (Section 6.3) remains unclear. There is tentative evidence that cycles of atmospheric and sea-surface temperature variability related to ENSO events may themselves be modified in association with climate change (Vecchi and Soden 2007), but the matter is far from settled.

Other storminess proxies, specifically analyses of wave heights and storm surges, suggest the possibility of contemporary trends in storminess in the northeast Pacific Ocean. Bromirski et al. (2003) analyzed storm surges in San Francisco Bay, derived from water level measurements made since 1858. Their results suggest an increase in the highest winter storm surges since about 1950. In other words, the few extreme events each year that generate large surges have grown increasingly frequent and longer since 1950. Since storm surge is generated by wind-driven water pile-up and by reduced sea level pressure, it may be useful as an indicator of broader storm and atmospheric pressure patterns in the northeast Pacific Ocean (see Box 2-2).

Waves provide perhaps the best-studied regional proxy for storminess. Allan and Komar (2006) analyzed trends in winter average significant wave heights calculated from measurements made by a set of NOAA NDBC buoys stretching from the Cape Elizabeth buoy (NDBC 46041; Figure 2-4) within the boundaries of OCNMS, to the Point Arguello buoy (NDBC 46023) north of Santa Barbara, CA. They found the greatest rates of change in mean wave height for buoys in the northern half of the study area, and significant increases for all buoys north of Point Arena, California. At NDBC Buoy 46005, adjacent to OCNMS (Figure 2-4), they report an increase in average winter significant wave heights of 3.2 ± 1.7 cm/yr between 1976 and 2002. Ruggiero et al. (2010) extended this analysis by examining the distribution of measured wave heights by decade to demonstrate that the most extreme wave heights, typically associated with storms, are driving the increase in average winter wave heights. Using a slightly longer wave measurement record, Ruggiero et al. (2010) were also able to identify a statistically significant increasing trend in the five largest significant wave height measurements made each year since 1976 for NDBC Buoy 46005 adjacent to OCNMS (Figure 2-4). The rate of increase of the largest winter waves, 7.1 cm/yr, is larger by more than a factor of 2 than the trend in average winter wave height, corroborating the hypothesis that increases in wave heights in the north Pacific are associated with winter storm events.

BOX 2-2: A Preliminary Assessment of Storm Surge Patterns in Neah Bay, WA

San Francisco’s water level record is the longest continuous set of water level measurements on the West Coast of the United States and no similar analysis of storm surge has been published using the shorter water level records from within or adjacent to OCNMS. It is therefore unclear if and how storm surge patterns identified in San Francisco Bay are relevant to OCNMS. In order to assess the possibility of a trend in patterns of storm surges adjacent to OCNMS we adapted the analysis of Bromirki et al. (2003) and examined the water level record from Neah Bay, Washington (NOAA/NOS CO-OPS 2012). Storm surges were calculated by differencing hourly predictions of the astronomic tide and observed water level using data collected between 1934 and 2011. Similar to the results of Bormirski et al. (2003) there is no significant trend in the mean wintertime (January – March) storm surge. Additionally, the duration (in hours) and magnitude (in cumulative meters) of storm surges that are “extreme” (that exceed the 98th percentile of all storm surge water levels, which is 0.44 m for Neah Bay) were calculated. Also similarly to the results of Bromirski et al. (2003) both of these parameters do show a positive trend with time, though neither trend is significant (Figure 2-17). It is therefore unclear if the trends identified by Bromirski et al. (2003) for San Francisco Bay are relevant to OCNMS.

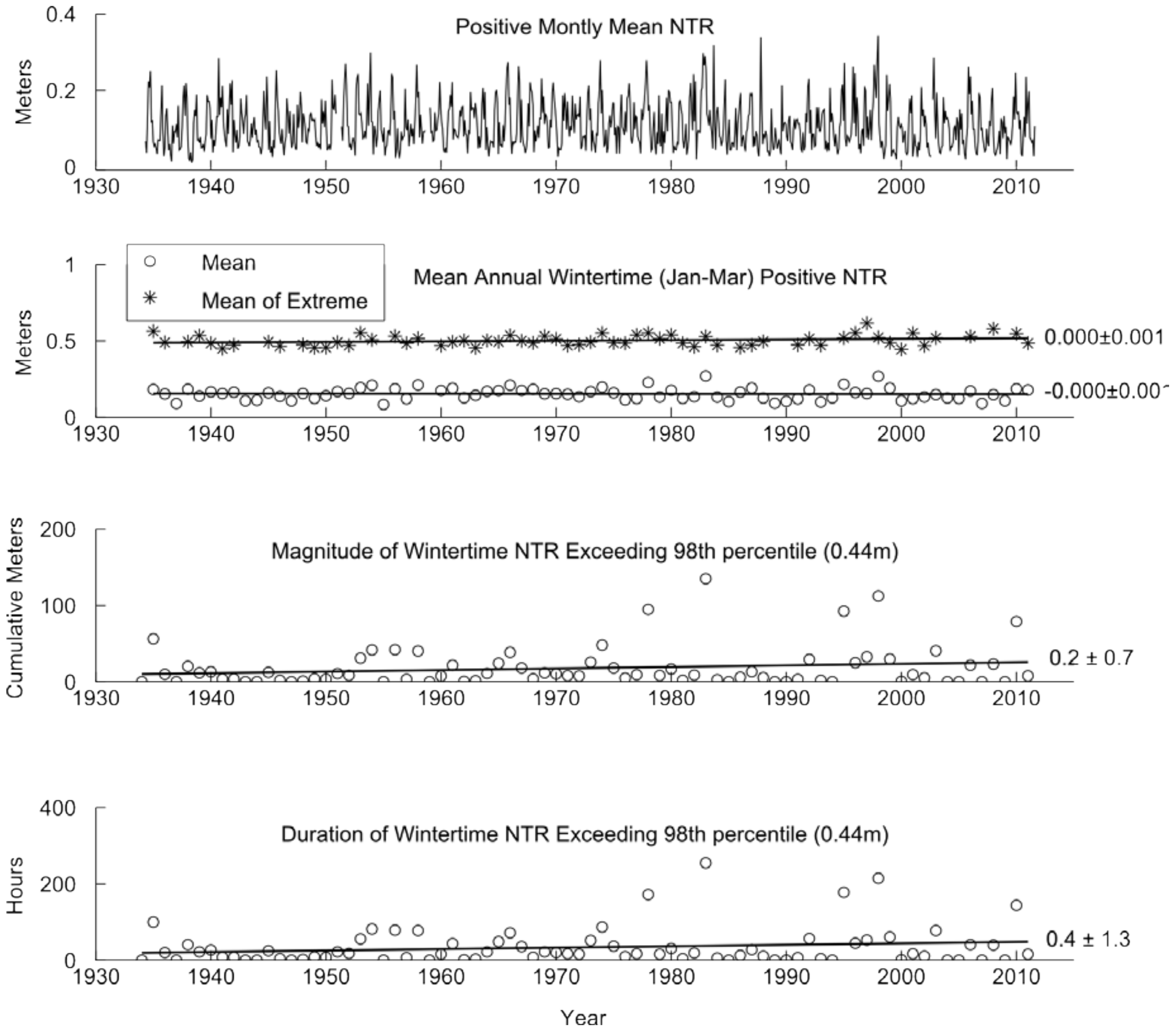


Figure 2-17. Trends in positive non-tidal residuals (“storm surge” in the text) calculated using hourly water level measurements made in Neah Bay Washington between 1934-2011, using methods described in Bormirski et al. (2003).

Table 3 Mean annual and winter wave height trends from buoy locations shown in Figure 2-4 and altimeter data collected near buoy locations. Referenced studies include Gower (2002), Allan and Komar (2006), Gemmrich et al. (2011) , and Young et al. (2011). "NS" indicates that an analysis was conducted, but no significant trend was found.

Buoy	Trend (cm/yr)	Parameter	Time Range	Reference	Method
46004	NS	Average Winter	1976-2010	Gemmrich	Buoy
	1.8	Annual Mean	1976-1999	Gower	Buoy
46036	NS	Average Winter	1976-2010	Gemmrich	Buoy
	NS	Annual Mean	1976-1999	Gower	Buoy
46005	3.2	Average Winter	1976-2002	Allan and Komar	Buoy
	2.3	Average Winter	1976-2007	Ruggiero	Buoy
	~1.0	Average Winter	1976-2010	Gemmrich	Buoy
	NS	Mean Annual	1976-2010	Gemmrich	Buoy
	NS	Mean Annual	1985-2007	Young	Buoy
	NS	Mean Annual	1985-2007	Young	Altimeter
	2.1	Mean Annual	1976-1999	Gower	Buoy
46002	2.8	Average Winter	1976-2002	Allan and Komar	Buoy
	NS	Average Winter	1976-2007	Ruggiero	Buoy
	NS	Average Winter & Mean Annual	1976-2010	Gemmrich	Buoy
	NS	Mean Annual	1985-2007	Young	Buoy
	NS	Mean Annual	1985-2007	Young	Altimeter
	1.9	Mean Annual	1976-1999	Gower	Buoy
46041	NS	Average Winter	1987-2010	Gemmrich	Buoy
	NS	Annual Mean	1987-1999	Gower	Buoy
46087	NS	Average Winter	2004-	Gemmrich	Buoy

Some additional analyses of the data collected by oceanographic buoys corroborate these results. Bromirski et al. (2005) also detected an increasing trend in the long-period (swell) component of wave energy since 1980 using data collected from ten NDBC buoys (including NDBC 46005 and 46002; Figure 2-4). They interpret the results as suggestive of a general increase in storminess in the northeast Pacific. In particular, wave energy data collected at NDBC Buoy 46005 shows an increasing trend in wave energy across the entire wave energy spectrum (Figure 2-18). Menendez et al (2008) took a slightly different approach, analyzing wave measurements since 1983 using an extreme wave height methodology, and also expanded the spatial extent of their analysis into the waters of British Columbia and Alaska. Their results also suggest a trend of increasing extreme wave heights for waves off of Northern California, Oregon and Washington, but found a decreasing extreme wave height trend for waves off of British Columbia.

By contrast, a recent paper by Gemmrich et al. (2011) finds that much of the statistically significant positive trend in mean and extreme wave heights derived from buoy data may be attributable to instrument uncertainties and data processing methodology. After correcting for poor data quality for the wave records from eight Canadian and U.S. buoys from Oregon to northern B.C., they report a statistically significant positive trend for winter wave heights at NDBC 46005, but no significant trend for other buoys adjacent to OCNMS (Table 3). Additionally, the magnitude of the trend in winter mean wave heights at NDBC 46005, 1.0 ± 0.5 cm/yr, is lower than those calculated by Ruggiero et al. (2010) and Allan and Komar (2006) after correcting for instrument biases.

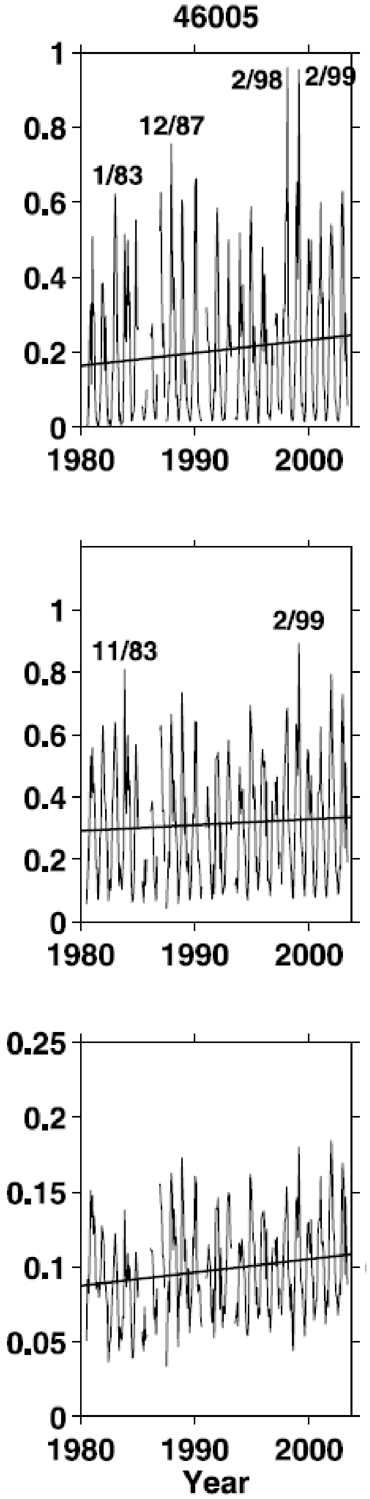


Figure 2-18. Mean monthly wave energy at NDBC Buoy 46005 in the long period (top panel), intermediate period (middle panel) and short period (bottom panel) bands. Annotated dates identify the extremes in the time-series. The extremes in the long period band (top panel) are tentatively associated with major El Nino/La Ninas, whereas the increasing trend in energy in the short period band (bottom panel) may be due to increasing storminess in the central NE Pacific Ocean (Bromirski et al. 2005). Figure from Bromirski et al. (2005)

Given the potential data inconstancies in NDBC buoy data identified by Gemmrich et al. (2011), a global analysis of wave patterns using satellite altimetry (Young et al. 2011) provides a valuable corroborating source of information. Using data collected between 1985-2007 Young et al. (2011) describe a global trend in increasing mean and extreme wave heights, and extract time-series for comparison to NDBC buoys, including 46002 and 46005 adjacent to OCNMS (Figure 2-4). In keeping with the results of other investigators (Allan and Komar 2006; Menendez et al. 2008; Ruggiero et al. 2010; Gemmrich et al. 2011), Young et al (2011) identify a statistically significant increase in the largest waves at NDBC 46005 (Figure 2-4).

The identification of statistically-significant trends in a variety of storm-related parameters is compelling, and suggests the possibility that model projections of a stormier future are already impacting OCNMS. However, the short-length of the record of storminess proxy data (wave height, water level, storm metrics) from the West Coast of North America (the earliest wave-measurements are from the mid-1970's) and the high inherent variability in the climate of the north Pacific (Bromirski et al. 2005) makes it difficult to separate the influence of climate-related trends like the Pacific Decadal Oscillation (Section 6.3) from the observations discussed above. Ruggiero et al. (2010), for example, state that while wave height increases "are most likely due to Earth's changing climate, uncertainty remains as to whether they are the product of human-induced greenhouse warming or represent variations related to natural multi-decadal climate cycles." In an attempt to address this short-data record Graham and Diaz (2001) analyzed hind-cast wave height estimates dating to 1948. The overall trend of increasing extreme wave heights persisted across the northeast Pacific throughout the longer data record, with an estimated growth in extreme (99th percentile) wave heights of approximately 5% for the region adjacent to OCNMS over the last half of the 20th century (Figure 2-19). This longer hind-cast wave height data record suggests the possibility that trends in wave height may not be related to decadal-scale variability (Section 6.3) but instead adds weight to the interpretation that these are longer-term climate-related trends.

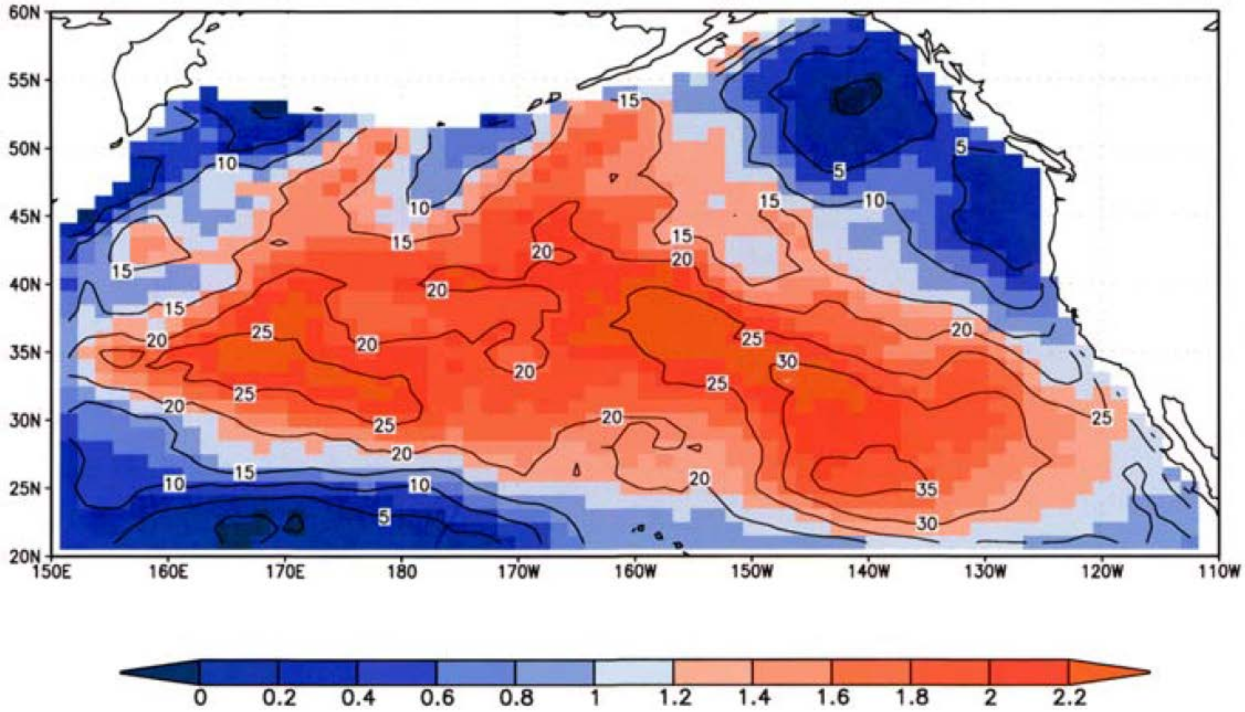


Figure 2-19. Trends in hindcast winter extreme (99th percentile) wave heights for 1948-1998 (units of meters/50yrs). Black contour lines show the trend expressed as a percentage of the long-term mean wave height. Figure from Graham and Diaz (2001)

2.6 Upwelling and Upwelling Favorable Winds

2.6.1 Summary

- Global climate model projections are mixed regarding changes to upwelling-favorable winds along the entire Pacific Northwest coast.
- Historical analyses suggest enhanced upwelling favorable winds for southern portions of Pacific coast (coastal Oregon and south), but no similar pattern is yet evident from the Washington coast.
- Considerable variability from year-to-year in the timing, duration and intensity of upwelling favorable winds suggests that any small trends due to climate change will not on their own markedly impact average annual productivity in OCNMS.
- Increases in upwelling favorable winds, if they were to occur, may be counteracted by increased stratification due to rising ocean temperature. Therefore, overall changes to upwelling or upwelling-driven productivity in OCNMS are difficult to project.

2.6.2 Introduction

The coastal waters of the Pacific Northwest are at the northern end of the California Current System (CCS), a wind-driven coastal current which is partly responsible for the biological productivity in OCNMS (Ware and Thomson 1991). Productivity in the CCS is driven in part by equator-ward (from north to south) surface winds over the ocean's surface which push surface water offshore via Ekman transport as a consequence of the

Coriolis force (Pond and Pickard 1983; Open University 2000). The advected surface water is replaced by water from intermediate water depths (typically between 80-200 m depth; Section 2.7), and is referred to as coastal upwelling (Figure 2-20). The upwelled water is typically colder, saltier, carbon-rich, nutrient-rich, and oxygen-depleted than the surface water it replaces (Smith 1995). A reversal in wind direction (from north to south) causes the opposite phenomenon – downwelling – to occur. The CCS can experience upwelling favorable wind conditions at any time of year, but they are most frequent between March and September (Section 1.2). The intensity of upwelling at any given location within the CCS can vary over days or weeks. By contrast, during October-February winds are generally down-welling favorable (Hsieh et al. 1995; Pirhalla et al. 2009), and the transition between persistent upwelling and down-welling favorable conditions in both spring and fall are considered to be relatively abrupt (Huyer et al. 1979; Pirhalla et al. 2009).

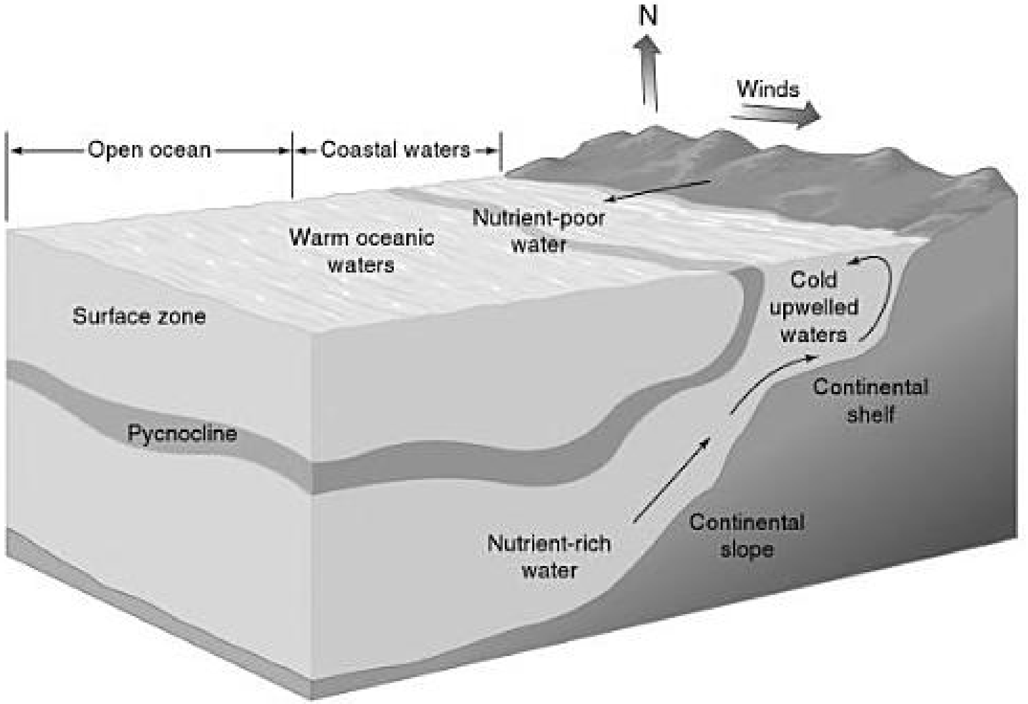


Figure 2-20. Illustration of upwelling in a coastal context similar to the northeast Pacific Ocean. Winds blowing towards the south force surface water off-shore, drawing water from depth to the photic zone. Figure from Abel and McConnell (2010)

Upwelling within OCNMS generally follows the temporal pattern of the CCS as a whole, though the duration and intensity of upwelling winds are greatest in northern California and southern Oregon, and least in the OCNMS region and off Vancouver Island (Hickey and Banas 2008). Satellite observations of sea surface height, sea surface temperature and chlorophyll suggest that the transition between upwelling and down-welling states occurs most frequently in April, and typically reverses state by early October (Pirhalla et al. 2009). Climate variability (Section 6.3) has an influence on the timing and intensity of the annual upwelling/down-welling patterns (Schwing et al. 2006; Pirhalla et al. 2009).

ENSO events, for example, are associated with elevated sea surface heights, higher sea surface temperature and reduced primary productivity in OCNMS (Pirhalla et al. 2009). It is unclear if ENSO-related anomalies in productivity are related to reductions in the magnitude or duration of upwelling favorable winds or increased stratification due to higher sea surface temperature.

The northern section of the CCS usually experiences weaker upwelling-favorable winds than those further south, but still achieve high levels of productivity due to intensive tidal mixing and eddy generation through the Strait of Juan de Fuca, freshwater inputs from the Fraser and Columbia Rivers, and broad coastal shelves up to 100 km wide off the coast of Vancouver Island which significantly extend the residence time of upwelled water (Botsford et al. 2003, 2006; Hickey and Banas 2008). Primary productivity is enhanced as upwelled water reaches the photic zone, and heavily influences the composition and vitality of biota at all life stages (Ware and Thomson 1991; Mackas et al. 2001; Barth et al. 2007).

2.6.3 Projections

It has been suggested that wind-driven upwelling in many of the world's coastal upwelling regions may intensify due to increasing wind stress driven by increasing atmospheric temperatures and a greater land-ocean temperature gradient (Bakun 1990). However, climate model projections regarding the timing and magnitude of upwelling favorable winds for the coastal waters of the Pacific Northwest are mixed. In general the localized effects of upwelling are not adequately captured by the coarse resolution of global climate models (Mote and Mantua 2002). A meta-analysis of climate model forecasts off the coast of Vancouver Island suggests that upwelling favorable winds could increase in magnitude by 5-10% by 2100, and could be accompanied by a clockwise rotation in wind stress (Merryfield et al. 2009). However, Wang et al. (2010) assessed the efficacy of a variety of global climate models used as part of the IPCC's Fourth Assessment Report (www.ipcc.ch) in projecting future conditions in large marine ecosystems. Their results suggested that there was too much uncertainty to draw relevant conclusions regarding upwelling in the northern CCS (specifically off of the Oregon Coast). Regional Climate Models (RCMs), which employ a finer resolution than global-scale models, suggest future increases in upwelling-favorable wind stress, but have only been applied to latitudes below 46 degrees on the West Coast of North America (Snyder et al. 2003; Auad et al. 2006). Similar modeling investigations using RCMs have not been used to project potential changes in upwelling favorable winds for the coast of Washington.

2.6.4 Observations

Detecting trends in historical observational wind stress data is difficult due to the variability in the data itself and the brevity of the historical records (Merryfield et al. 2009). Large variations in wind stress magnitude and timing over years to decades is such that any published trend in either phenomenon tends to be relatively small. However, the CCS as a whole has exhibited increases in upwelling favorable winds over the 1946-1988 period (Bakun 1990). More recent analysis using buoy stations off the coast of California also found significant increases in the magnitude of upwelling favorable winds, and some evidence of an earlier onset of the upwelling season between 1982 and 2008 (Garcia-Reyes and Largier 2010). Time series analysis of the Comprehensive Ocean-Atmosphere dataset (COADS) wind stress data from Washington State to southern California show significant increasing trends in upwelling favorable winds up to the Oregon coast. However wind stress at Neah Bay in particular showed no discernible trend over the 1946 to 1990 period (Schwing and Mendelssohn 1997).

BOX 2-3: A Preliminary Assessment of Upwelling Winds in OCNMS

Wind data for 1979-2010 from the North American Regional Reanalysis (NARR) (NOAA Earth System Research Laboratory 2012) were retrieved for the OCNMS region to characterize the behavior of coastal winds. Specifically, NARR wind data was analyzed to detect any temporal trends in the onset, duration, or intensity of the upwelling seasons within OCNMS. NARR meteorological data are interpolated from nearby observations via advanced earth-ocean-atmosphere models. The onset and duration of the upwelling season was determined based on the proportion of total equatorward wind stress occurring each year. The onset was chosen to be the day in which 10% of total yearly upwelling had occurred, and the end of upwelling as the day when 90% of total upwelling had occurred; the time (in days) in between was defined as the duration. Upwelling intensity was defined as the sum of total equatorward wind stress occurring during the upwelling season defined above. Internannual variability exists between 1979 and 2010 and there is no significant temporal trend for the onset, duration, or intensity of upwelling within OCNMS (Figure 2-21). The high interannual variability apparent in Figure 2-21 is common to the entire Pacific Northwest, and suggests that any small future changes in coastal upwelling due to climate change will not on their own produce any noticeable effects on marine life in OCNMS over the next 50 to 100 years.

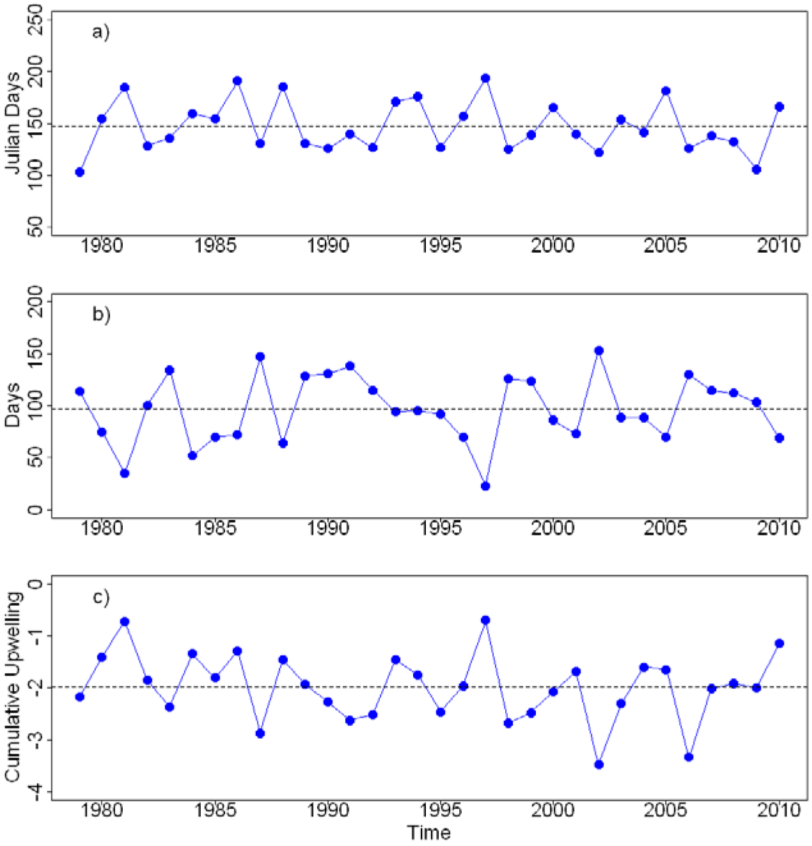


Figure 2-21. Start (a), duration (b), and intensity (c) of the summer upwelling season in OCNMS from 1979-2010. The start of the summer is shown as the number of days since January 1, and is defined as the time of year when over 10% of total upwelling has occurred for the given year; the duration of the summer seasons is calculated in days; the intensity of upwelling is shown as the cumulative total wind stress over the summer. The dashed line in each plot is the mean value for the entire record. The results above are based on North American Region Reanalysis (NARR) data retrieved from the shelf break adjacent to OCNMS.

2.7 Increasing Occurrence of Coastal Hypoxia and Anoxia

2.7.1 Summary

- Concentrations of dissolved oxygen in the northeast Pacific Ocean are expected to decrease as the upper ocean warms and becomes more stratified.
- Although hypoxia is a seasonal occurrence in OCNMS, severely hypoxic concentrations during a summer of unusually strong upwelling in 2006 were unprecedented in previous historical data.
- Long-term declines in dissolved oxygen have been observed at numerous locations in the northeast Pacific, including coastal locations near OCNMS.

2.7.2 Introduction

During the summer upwelling season, low concentrations of dissolved oxygen (DO) are a common feature in the subsurface waters of OCNMS. Hypoxia, defined as DO concentrations low enough to cause stress to aquatic animals, has been observed throughout the historical record of the past sixty years. However, unusually severe hypoxia has been associated with mortality of fish, crabs and other marine life off the coasts of Washington and Oregon in recent years. The frequency and severity of hypoxia in OCNMS are governed by large scale ocean circulation and productivity, as well as local processes such as coastal upwelling. Under global climate change, hypoxic regions are expected to expand due to warming of the ocean surface and changing circulation patterns.

Concentrations of DO are governed by physical transport, biochemical processes and air-sea interactions (Figure 2-22). During late spring through early fall on the Washington coast, coastal upwelling transports high-nutrient, low-DO water from intermediate depths (~80-200 m) towards the surface near the coast (Hickey 1989). This stimulates production of large phytoplankton blooms which support a rich marine food web and result in dead cells and fecal pellets that sink through the water towards the bottom. Bacteria break down (or “remineralize”) this organic matter, respire and further deplete DO. Nutrients influence DO in coastal waters by supporting phytoplankton blooms. Elevated nutrient concentrations in OCNMS result from numerous natural factors, including turbulent mixing in the Strait of Juan de Fuca and coastal upwelling (Hickey and Banas 2008). Nutrients from rivers do not drive high productivity in the OCNMS (Hickey and Banas 2008), unlike many other hypoxic regions such as the Gulf of Mexico.

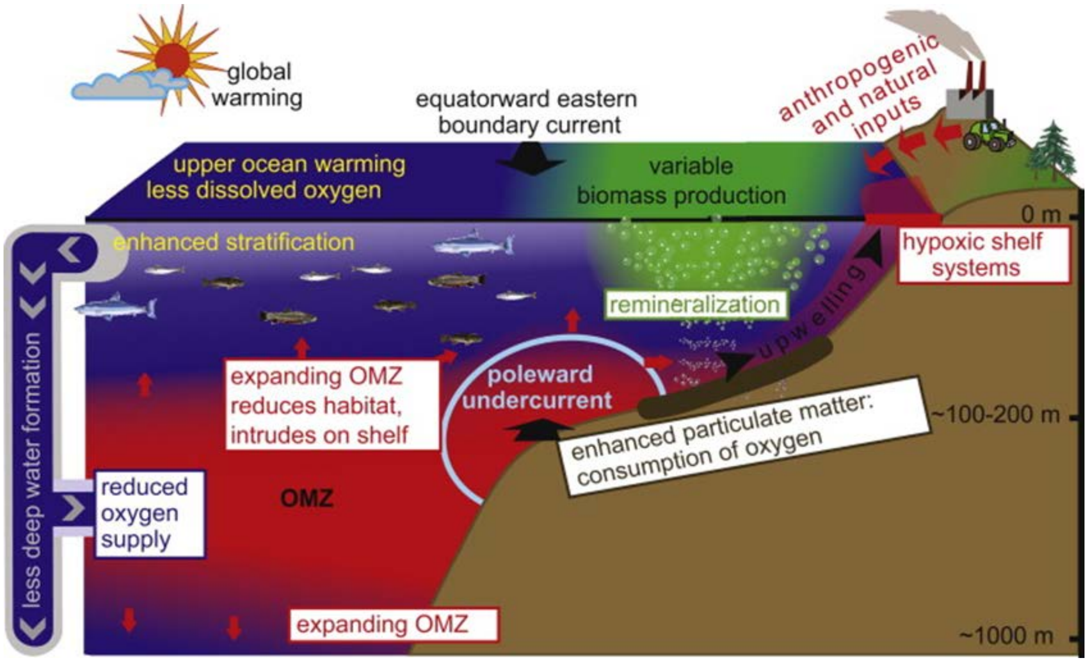


Figure 2-22. Schematic of interactions of open ocean oxygen minimum zones (OMZ, red) with hypoxic shelf systems and dead zones (Diaz and Rosenberg 2008) on continental shelves of eastern ocean boundaries. Figure from Stramma et al. (2008).

The severity of hypoxia is largely governed by DO concentrations in the upwelling source water at the edge of the continental shelf. Source water DO concentrations are determined by ocean currents that cover thousands of kilometers and vary at interannual time scales. For upwelling source waters in OCNMS, equatorial water masses are warmer, saltier and have lower DO concentrations than subarctic water masses from the north. Over the Washington continental slope, deep source waters for upwelling at 200m typically contain ~40% equatorial water and ~60% subarctic water (Thomson and Krassovski 2010). In shallower water at 100m, the equatorial contribution drops to ~30%. Much lower DO concentrations occur over the continental slope at ~850 m depth in the “oxygen minimum zone” (Sverdrup et al. 1942; Pierce et al. 2012), but these waters are too deep to influence the continental shelf in OCNMS. Bacterial respiration can further reduce DO concentrations over the continental shelf and is necessary to bring hypoxia to severe levels.

Terminology and thresholds have been developed to describe the severity of low DO concentrations. Based on reviews of marine species' stress response to low-DO conditions (Davis 1975; Tyson and Pearson 1991; Gray et al. 2002), a widely-used threshold for defining hypoxia is 2 mg L^{-1} (= 1.4 mL L^{-1} = 62.5 μmol kg^{-1} ≈ 20% saturation for salinity of 32 psu and a temperature of 7 ºC; see call-out box). However, lethal concentrations vary widely between species. Organisms, such as echinoderms and cnidarians, are generally able to tolerate lower concentrations and more prolonged exposure to hypoxia than mobile organisms like fish and crustaceans (Vaquer-Sunyer and Duarte 2008). Fish typically show avoidance reactions in the range 1.4-2.8 mg L^{-1}, which can cause mortality if they move towards the surf zone and wash ashore (Tyson and Pearson 1991). Under certain circumstances, fish can benefit from hypoxia by feeding on stressed benthic organisms, but this short-lived situation only occurs in a narrow range of relatively mild hypoxic conditions (Diaz and Rosenberg 1995). In the range 1.4-2.0 mg L^{-1}, benthic organisms typically exhibit stress responses. Crabs move towards shallower water and other organisms raise parts of their bodies to reach higher into the water column (Tyson and Pearson 1991). Mortality typically occurs in the range 0.7-1.4 mg L^{-1} and few animals survive exposure to concentrations < 0.7 mg L^{-1}. This threshold is often referred to as "severe hypoxia" (Diaz and Rosenberg 1995; Chan et al. 2008). The term "anoxia" indicates a complete absence of DO.

2.7.3 Projections

Climate models that incorporate simple representations of ocean biogeochemistry consistently suggest decreasing DO throughout the global ocean (Keeling et al. 2010). Projected DO declines result mostly from decreased solubility of oxygen due to warmer water temperatures and reduced ventilation of subsurface waters with increased stratification. If lighter water is present at the ocean surface due to warming or freshening, mixing between the atmosphere and the lower thermocline becomes restricted. Denser water cannot be ventilated with atmospheric oxygen at the surface, and experiences longer time periods of respiration at depth, which reduces DO concentrations. Regionally, these processes are projected to cause declines of DO in the subarctic north Pacific (Bopp et al. 2002; Frolicher et al. 2009). Furthermore, because aerobic respiration also produces nitrate, declines of DO in the north Pacific are expected to coincide with increased nitrate concentrations in upwelling source waters (Rykaczewski and Dunne 2010). The resulting increase in upwelling-driven primary productivity could further reduce surface water DO concentrations by providing more organic material for respiration over the continental shelf.

The frequency and severity of hypoxia may also be affected by potential changes in the strength of upwelling-favorable winds (Section 2.6). Bakun and Weeks (2004) proposed a mechanism where increased upwelling-favorable winds lead to a tipping point and phytoplankton production cannot be consumed by higher trophic levels. As a result a greater amount of sinking organic matter leads to depletion of DO. Increased stratification near the coast due to warming, or freshening associated with changes in the hydrologic cycle, may also affect upwelling circulation and therefore hypoxia. Increased stratification can decrease primary productivity by reducing exchange of nutrients between the surface and deeper water (Roemmich and McGowan 1995), which would mitigate future declines in DO over the shelf. However, it has also been suggested that increased stratification could reduce supply of DO to the deeper waters over the shelf by reducing vertical mixing (Bograd et al. 2008). Downscaled regional climate models that include ocean biogeochemistry could help address such questions, but have not yet been developed for OCNMS region.

In general, increased severity and frequency of hypoxia is associated with reduced species diversity, smaller organism size and decreased efficiency of energy transfer between trophic levels (Diaz and Rosenberg 1995). The ecosystem response to any long-term declines of DO in OCNMS will be complicated due to the presence of high seasonal and interannual variability in DO concentrations, and the shorter term response to wind relaxations and downwelling events over the inner shelf. As discussed below, severely hypoxic events on the continental shelves of Washington and Oregon appear to be a new phenomenon (Chan et al. 2008; Connolly et al. 2010), but there is little baseline data on benthic communities in this region to make definitive predictions of the lasting effects of such events on coastal ecosystems (Levin et al. 2009).

2.7.4 Observations

Hypoxia on the Washington shelf

The Washington coast experiences a strong seasonal cycle in DO concentrations (Landry et al. 1989). During winter, when biological productivity is low and downwelling-favorable winds occur frequently due to passing storms, relatively high dissolved oxygen concentrations occur near the bottom (Figure 2-23). During summer, when prevailing winds are upwelling-favorable and biological productivity is high, near-bottom DO concentrations decrease, often to hypoxic levels (Figure 2-23). The inner shelf (bottom depths < 40 m) experiences a broad range of DO concentrations during summer because currents respond more strongly to wind reversals and relaxations in shallower water (Figure 2-23).

Maps of near-bottom DO suggest that the lowest oxygen concentrations over the Washington shelf occur near Grays Harbor and Copalis Beach (GH and CB, respectively, in Figure 2-24), with higher concentrations further north (Figure 2-24). However, these data were collected from ships over periods of 5-7 days so these spatial patterns may result from brief reversals in upwelling-favorable winds. Most historical measurements occurred near Copalis Beach and few historical data from summer months are available for the northern Washington shelf (Connolly et al. 2010). Therefore, it is not certain whether lower concentrations to the south are part of a consistent pattern. Further north, on the British Columbia shelf, hypoxic concentrations occur within the Juan de Fuca eddy, a retentive upwelling feature that persists and strengthens throughout the summer (Freeland and Denman 1982; MacFadyen et al. 2008). Hypoxia does not extend to the inner shelf near the Vancouver Island coast because of the Vancouver Island Counter Current, which flows to the northwest from the Strait of Juan de Fuca and downwells on the inner shelf of British Columbia (Bianucci et al. 2011).

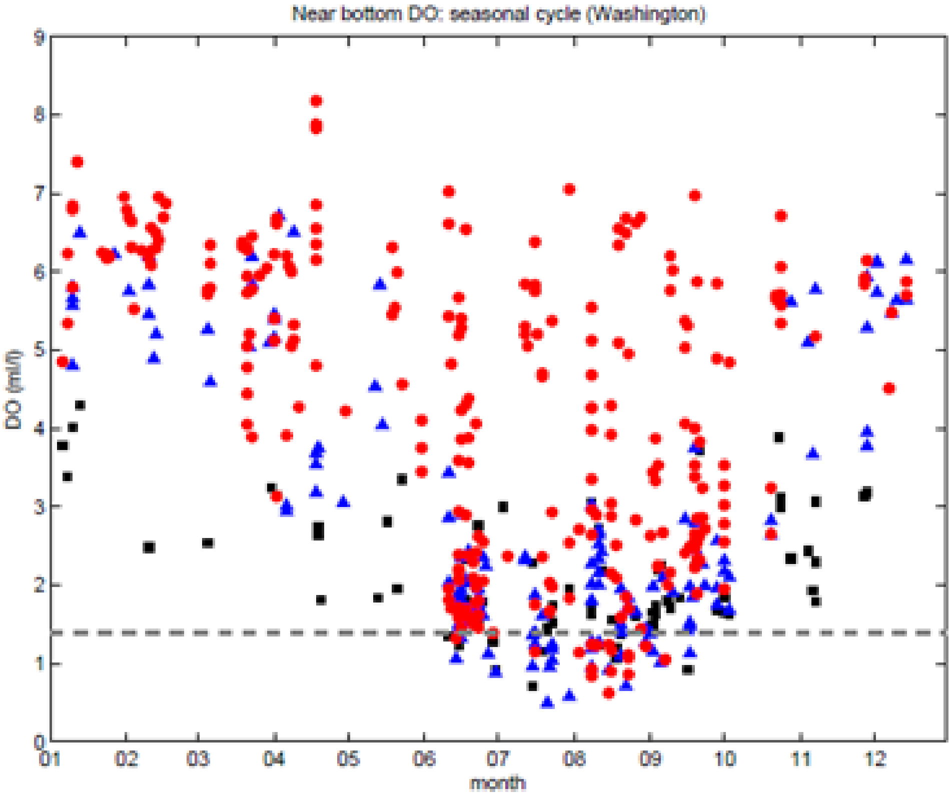


Figure 2-23. Seasonal cycle of historical near- bottom DO over the Washington shelf. Dashed line indicates the 1.4 mL/L (equivalent to 2.0 mg/L) definition of hypoxia. Data are divided into three depth categories: inner shelf (0– 40 m; red circles), midshelf (40– 80 m; blue triangles), and outer shelf (80– 130 m; black squares). Figure adapted from Connolly et al. (2010).

Upwelled water also influences water properties and circulation in coastal estuaries (Hickey and Banas 2003). Near the mouth of the Grays Harbor estuary in the 1950's, Pearson and Holt (1960) measured DO concentrations as low as 2 mg L^{-1}. Water properties were consistent with upwelling-derived water coming into the estuary, and concurrent DO concentrations as low as ~0.7 mg L^{-1} were observed just offshore in at 15-m depth. Low-DO water associated with upwelling has also been observed in the Columbia River estuary (Roegner et al. 2011), and in the Yaquina River estuary near Newport, OR (Brown and Power 2011).

Historical observations from 1950–1986 suggest that hypoxic DO concentrations (< 2.0 mg L^{-1}) over the Washington shelf are not unusual (Connolly et al. 2010). Even on the inner shelf where DO concentrations are more variable, measurements of hypoxia occur throughout the available record. However, these DO concentrations do not fall into the severe category associated with mass mortality. The presence of seasonal hypoxia, and high rates of organic matter supply to the bottom, allow for the presence of low-DO tolerant species of benthic macrofauna in Washington shelf sediments (Jumars and Banse 1989).

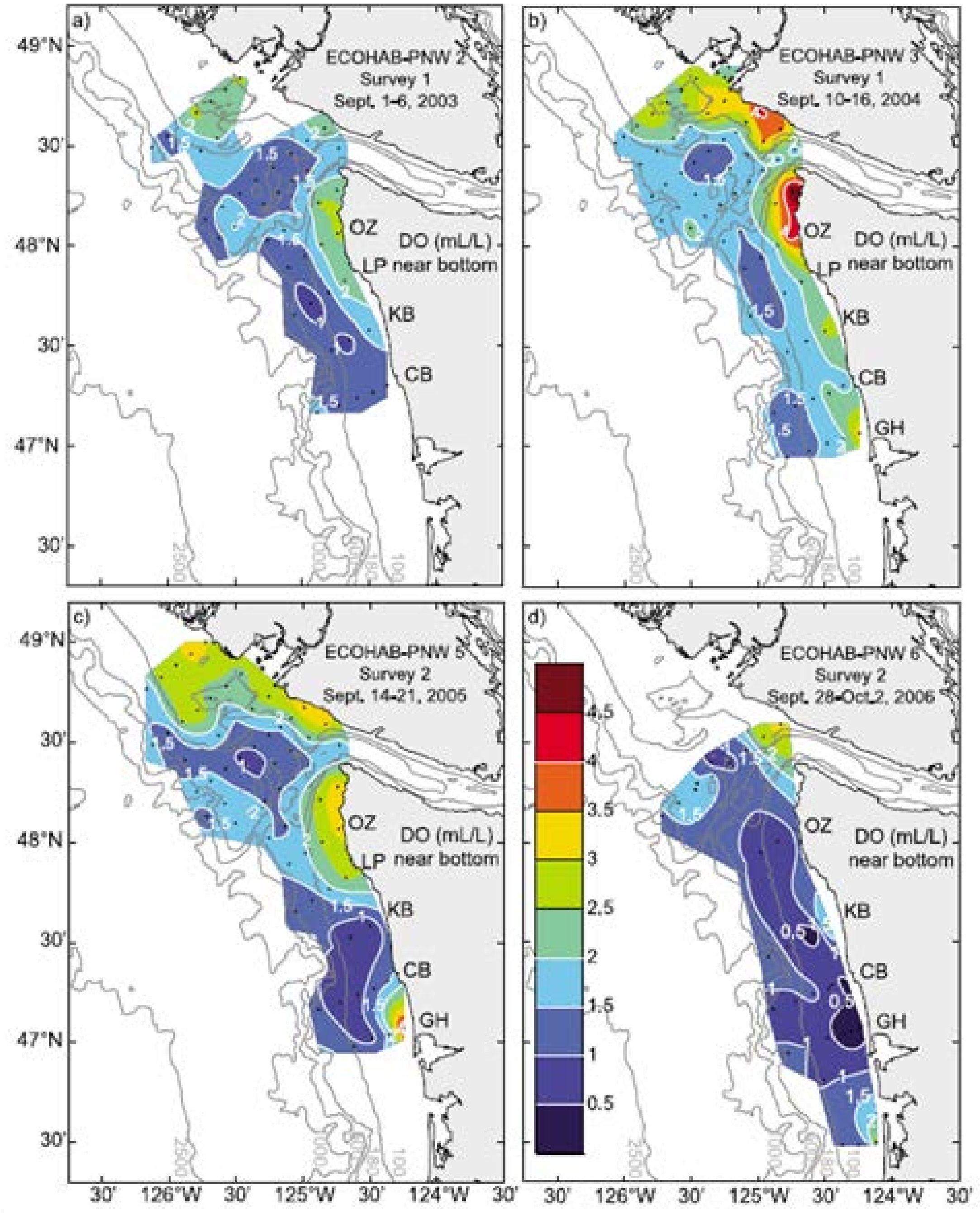


Figure 2-24. Near- bottom dissolved oxygen during late summer/early fall from 4 different years: (a) 2003 (b) 2004, (c) 2005, and (d) 2006. DO contours, shown in the color bar in (d), represent increments of 0.5 mL L^{-1}. Isobaths are indicated by gray contour lines. Station locations are shown as black dots. Figure from Connolly et al (2010).

Severe hypoxia (< 0.7 mg L^{-1}) was first observed in near-bottom water over the Washington shelf during summer 2006 (Figure 2-24d). Fish and crab mortality from Westport to Kalaloch were reported in the news media (Doughton 2006). During the same summer, severely hypoxic concentrations also occurred over the Oregon shelf (Chan et al. 2008; Pierce et al. 2012). Remotely operated vehicle surveys of benthic communities off the Oregon coast revealed mass mortality of crabs and other invertebrates (Chan et al. 2008), which coincided with low historical catch (Keller et al., 2009). Severe hypoxia during 2006 was associated with unusually strong seasonal upwelling-favorable winds (Connolly et al. 2010). Anomalous transport of warm, oxygen-poor water in the California Undercurrent may have also played a role in this extreme event.

Although the historical data suggest that seasonal hypoxia on the inner shelf is more common off Washington than northern Oregon (Connolly et al., 2010), the 2006 event was unprecedented at both locations (Chan et al., 2008; Connolly et al., 2010). Severe hypoxia was also documented on the Oregon shelf during summer 2002, which was associated with mortality of rockfish and crabs (Grantham et al. 2004). No measurements of DO are available from the Washington shelf during the same time period for comparison. The 2002 event off Oregon was associated with anomalous transport of nitrate-rich subarctic water from the north and high chlorophyll concentrations (Wheeler et al. 2003). This situation differs from summer 2006 when oxygen-poor equatorial water from the south contributed more to the properties of upwelling source water (Connolly et al. 2010). Therefore, there are several types of ocean anomalies that can potentially exacerbate the effects of seasonal upwelling-favorable winds on shelf hypoxia in this region. The regional scale of severe hypoxia during 2006 indicates that DO concentrations off the coasts of Oregon, Washington and British Columbia respond in a similar manner to year-to-year variability in atmospheric and oceanic processes.

Observed trends in the northeast Pacific

Patterns in DO concentrations suggesting long-term declines have been observed at several sites in the north Pacific, both in coastal locations close to OCNMS and in remote locations that may be indicative of broader-scale changes in upwelling source waters (Figure 24). Note that trends are often reported as DO changes at a certain water density (rather than at a particular depth), since water tends to flow along layers of constant density. Denser water tends to be colder and saltier, and lies at greater depths.

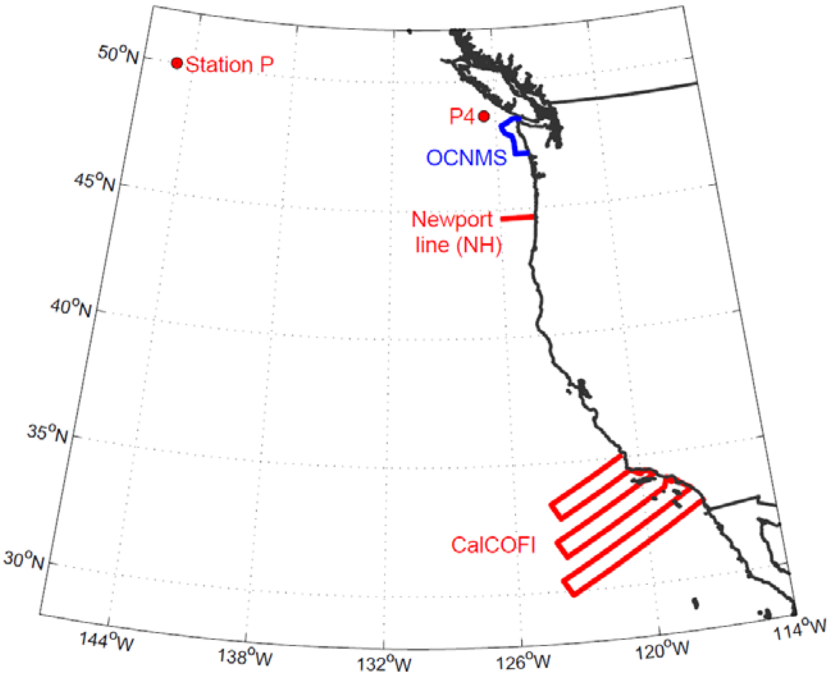


Figure 2-25. Location of long-term oxygen data sets

The long-term time series closest to OCNMS is located over the southern British Columbia slope, ENE from the mouth of the Strait of Juan de Fuca (Station P4 in Figure 2-25). DO has been measured at this location a few times per year since 1987. In waters at ~200-300-m depth, Whitney et al. (2007) found declines of - -0.040 mg L^{-1} yr^{-1} over the ~20 yr record (black triangles in Figure 2-26). Comparing the two periods 1960–1971 and 1998–2009 at the Newport hydrographic (NH in Figure 2-25, Pierce et al. (2012) found declines of ~0.02 mg L^{-1} yr^{-1} over the upper slope (Figure 2-27), Declining DO concentrations over the shelf and slope were primarily attributed to changes in source water characteristics or biological activity, rather than shoaling of deeper water. Although decadal variability may be present, these studies both suggest that a long-term decline of DO has influenced upwelling source waters near OCNMS.

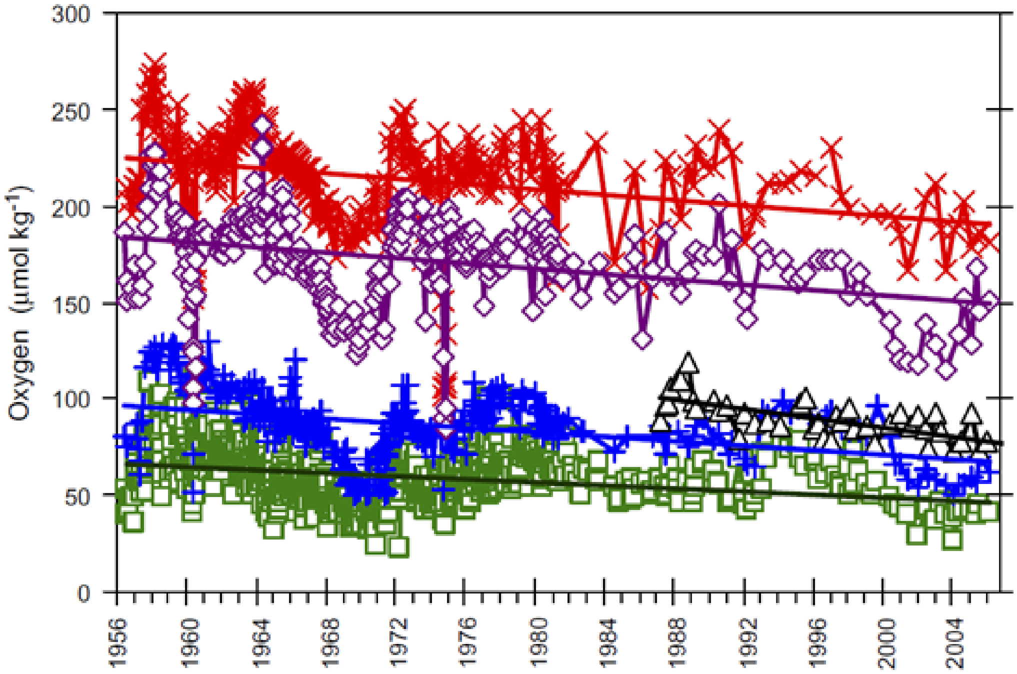


Figure 2-26. Oxygen trends at Ocean Station P on the 26.5 (×), 26.7 (◊), 26.9 (+) and 27.0 (□) isopycnal surfaces and at station P4 (Δ) on the 26.7 surface. Dissolved oxygen at P4 is declining at 0.04 mg L^{-1} y^{-1}. Figure from Whitney et al. (2007).

Declining DO has also been observed over a 50-yr period (1956-2006) at Station P (Figure 2-25) at rates of up to -0.022 mg L^{-1} yr^{-1} (Whitney et al. 2007). DO decreases on the surface were also observed throughout the subarctic north Pacific during the 1980s and 1990s (Emerson et al. 2004). The model study of Deutsch et al. (2011) attributed this decline to increased stratification in the western Pacific, which reduces the transfer of oxygen from the surface to deeper waters. Freshening of surface waters in the subarctic north Pacific (Wong et al. 2001) may also contribute to increased stratification.

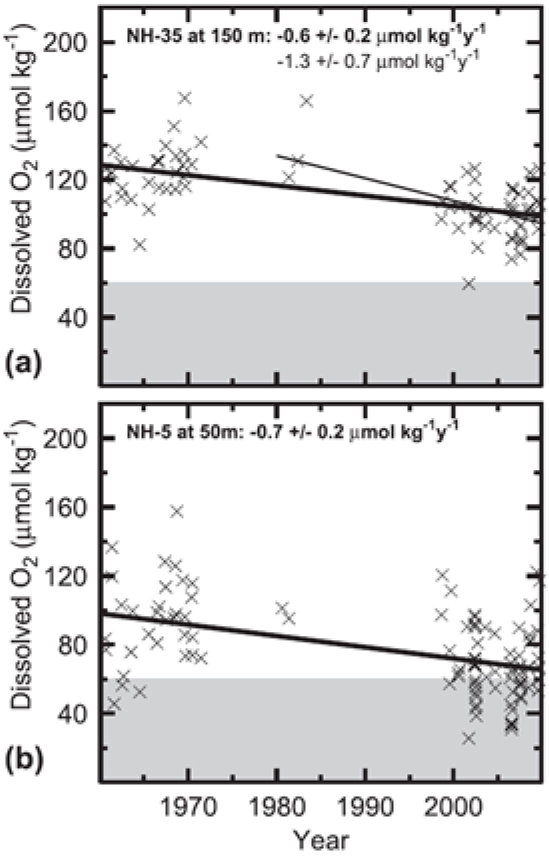


Figure 2-27. Time series of dissolved oxygen at (a) the upper slope station NH-35 at 150-m depth and (b) the shelf station NH-5 at 50-m depth. Linear regression lines with 95% confidence intervals are shown. The thin line in (a) only uses data after 1980, for the purpose of comparing with some other studies. Figure from Pierce et al. (2012).

Changes in DO in the equatorial Oxygen Minimum Zone (OMZ) and other locations along the path of the northward-flowing California Undercurrent (Figure 2-22) can also affect the Washington coast. Bograd (2008) analyzed trends in DO over the period 1984–2006 in the coastal ocean off southern California. Significant declines were found at all depths analyzed (50-300 m). At 200-m depth, an average decline of - -0.033 mg L^{-1} yr^{-1} was measured. However, recent DO concentrations at these locations are similar to those measured in the late 1950s and early 1960s, indicating that decadal variability may be at least partially responsible for these trends (McClatchie et al. 2010). Further south, the OMZ in the eastern tropical Pacific has expanded since 1960 (Stramma et al., 1960), indicating that both equatorial and subarctic source waters for upwelling have already experienced long-term declines in DO concentrations.

BOX 2-4: Unit Conversion for Dissolved Oxygen

In this assessment we provide dissolved oxygen measurements in units of mg/L, but other units are reported in the literature. In this document some figures also include alternate units, and differing units are also discussed in the section on the biological implications of reduced dissolved oxygen (Section 4). A general conversion between units is given here:

$$1 \text{ mg/L} = 0.70 \text{ mL/L} = 31.26 \text{ mmol/m}^3 = 30.5 \text{ umol/kg}^*$$

*for seawater with density 1026.5 kg/m^3

2.8 Altered Hydrologic Patterns

2.8.1 Summary

- Future warming and increased precipitation intensity is projected to trigger greater flood magnitudes for the 100-year flood among some basins on the west side of the Olympic Peninsula, including the Sol Duc, the Hoh, the Queets and the Quinault Rivers.
- Late summer low flows are expected to decrease for basins feeding into OCNMS due to warmer temperatures and less snow accumulation at higher elevations.
- Water temperatures are expected to remain within favorable thresholds for salmon migration and rearing habitat for basins on the western coast of the Olympic Peninsula.

2.8.2 Introduction

Hydrologic regimes, including stream temperatures, streamflow timing and magnitude, are highly correlated to the prevailing climatic conditions. Exposure to warmer or cooler air temperatures results in higher or lower stream temperatures. The influence of climate on streamflows is particularly perceptible in the Pacific Northwest where winter temperatures and precipitation play a key role in watershed hydrology. When winter temperatures are warmer, precipitation falls predominantly as rain, producing instantaneous runoff and elevated water levels. Conversely, cooler winter temperatures induce snow accumulation at higher elevations that subsequently contributes to springtime streamflows as temperatures warm and the snow melts.

The predominant precipitation regime that drives streamflows in the Pacific Northwest can be used to identify three characteristic basin types. *Snow dominant* basins are higher in elevation and experience colder average temperatures during the winter months. The majority of the runoff in snow dominant basins is produced by melting snow in the late spring/early summer. *Rain dominant* basins are found at lower elevations on the western slopes of Pacific Northwest mountains, where rainfall-driven runoff lead to highest flows in the fall/winter months. Thirdly, *transient*, or mixed rain and snow basins at moderate elevations produce runoff from both rain and snowmelt processes. Transient basins typically have two peaks, one in fall from precipitation falling as rain, and one in spring from combined snowmelt and precipitation as rain. The relative size of the fall or spring peak flow depends largely on mid-winter temperature regimes, with warmer transient basins having a larger peak flow in fall and a smaller peak flow in spring. Watersheds draining the western coast of the Olympic Peninsula are considered *rain dominant,* because they are primarily sustained by rainfall, with relatively small snowmelt inputs from higher elevations in the headwaters of some basins.

For basins draining to OCNMS the interaction of climate and geographic features plays a role in shaping extreme stream flow events. The Olympic Mountains create diverse climatic conditions in different areas of the peninsula: While the rain-shadowed southeastern slopes of the Olympic Mountains are relatively dry, the western side of the peninsula is characterized by a wetter, maritime climate, averaging about 400 cm/year of rainfall. The mountainous ridges of the western Olympics are among the wettest areas in the continental United States, receiving > 600cm/year of precipitation (Peterson et al. 1997). When a sufficiently large and intense precipitation event occurs simultaneously with warmer temperatures, the resulting rainfall will generate flood conditions for basins draining into OCNMS. The combined effects of retreating glaciers, loss of snow cover, increased winter precipitation, and elevated soil moisture on steep slopes is also hypothesized to increase the frequency and intensity of mass wasting and debris flows, which can result in increased sediment loads and geomorphological changes affecting river channels, such as channel aggradation downstream (Benda and Dunne 1997). On the other end of the hydrologic spectrum, extreme low flows typically occur in the late summer, when there is little precipitation and reduced snowmelt contributions to streamflows along the western margin of the Olympic Peninsula. In some cases, groundwater moderates the low flow response in the late summer season, when the bulk of in-stream flows are maintained by baseflows for watersheds draining into OCNMS (Halofsky et al. 2011).Projections

Global climate models (GCMs) project rising annual air temperatures in the Pacific Northwest in the 21st century across all seasons, with the most significant warming occurring in the summer months (Mote and Salathe 2010). Precipitation projections are more variable for the region, although seasonal signals emerge: summers are expected to be drier whereas more precipitation could fall in the winter (Figure 1-3). Projections of warmer temperatures throughout the year are expected to reduce spring snowpack regionally and induce earlier spring snowmelt (Hamlet and Lettenmaier 1999; Hamlet et al. 2005; Elsner et al. 2010). Mid-elevation (< 3000 ft), transient basins are most prone to reductions in snowpack because they are highly sensitive to the shift from snow to rain as temperatures increase (Hamlet et al. 2005; Elsner et al. 2010).

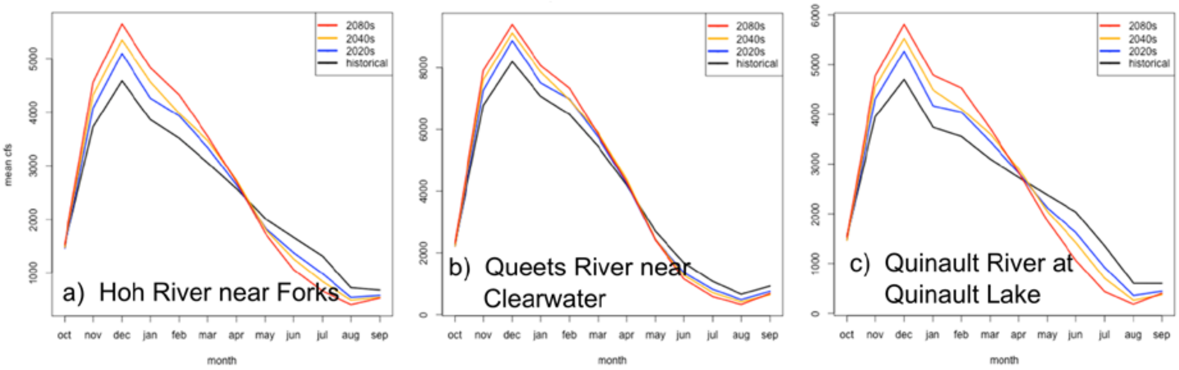


Figure 2-28. Monthly hydrographs for the historical (black lines) and three future time periods (colored lines) for the Hoh (a), Queets (b) and Quinault (c) Rivers. Note difference in the y-axis for each plot. Figure: Climate Impacts Group using data from Hamlet et al. (2010)

Streamflows for the basins emptying into OCNMS are predominantly rain-fed with small snowmelt contributions in the late spring/early summer. Hamlet et al. (2010) used climate change scenarios to determine how streamflows are projected to change with rising temperatures and shifts in precipitation. Monthly hydrographs from the results of this study are shown for three of the major basins draining to OCNMS illustrating the historical timing of streamflows and their respective responses to a warmer climate during three future time periods, the 2020s, the 2040s and the 2080s (Figure 2-28). The Hoh (Figure 2-28a) and the Quinault (Figure 2-28c) River basins historically demonstrate the behavior of rain dominant basins with minor snowmelt contributions in the summer. However, streamflow projections for both basins indicate a greater proportion of runoff generated earlier in the water year (October to September) for consecutive future simulations. This timing shift in streamflow is a result of more precipitation falling as rain, rather than being stored as snow. The Queets River basin shows a similar shift in its hydrograph (Figure 2-28b), but with less snowmelt contributions initially.

Hydrologic extremes (floods and extreme low flows) are projected to change markedly in response to changing future climate conditions. Downscaled global climate models project increases in winter precipitation, and both statistically downscaled global models and regional climate models project an elevated intensity of precipitation events in the 21st century, specifically along the western coast of the Olympic Peninsula (Salathe 2006; Mote and Salathe 2010; Salathe et al. 2010). Increasing winter precipitation (and storm intensity) coupled with warmer winter temperatures and rising freezing elevations (increased contributing basin area during storms) results in projections of increased flooding (Hamlet and Lettenmaier 2007; Mantua et al. 2010). During summer, projected reductions in snowpack and warmer, drier weather suggests reduced summer low flows and low flow extremes (Hamlet et al. 2010; Mantua et al. 2010).

In a project completed for the Olympic National Park and U.S. Forest Services (Tohver et al. 2012), flood and low flow statistics were estimated for basins throughout the peninsula using data from Hamlet et al. (2010). Changes in flood risk for the 2040s are presented as maps showing the ratio of the future-to-historical 100-year flood (Q_{100}) for small basins on the Olympic Peninsula (Figure 2-29). For example, if the ratio is 1.75, the future Q_{100} magnitude is projected to be 75% greater than the historical estimate. These changes also imply that Q_{100} for the historical condition will occur more frequently in the future. The headwaters of several major basins draining to the OCNMS are found at higher, snow-fed elevations, including the Sol Duc (feeding into the sanctuary via the Quillayute coastal drainage), the Hoh, the Queets and the Quinault Rivers. As noted earlier, the largest increases in flood risk, a 20-30% increase in the magnitude of Q_{100} (Figure 2-29), are projected to occur in the headwaters of these basins due to the combined effects of warming (increased contributing basin area) and increased precipitation intensity. Smaller shifts in flood risk, a 0-20% increase in the magnitude of Q_{100} (Figure 2-29), are projected for rain-dominant basins at lower elevation areas due to projected increases in storm intensity (Salathe et al. 2010).

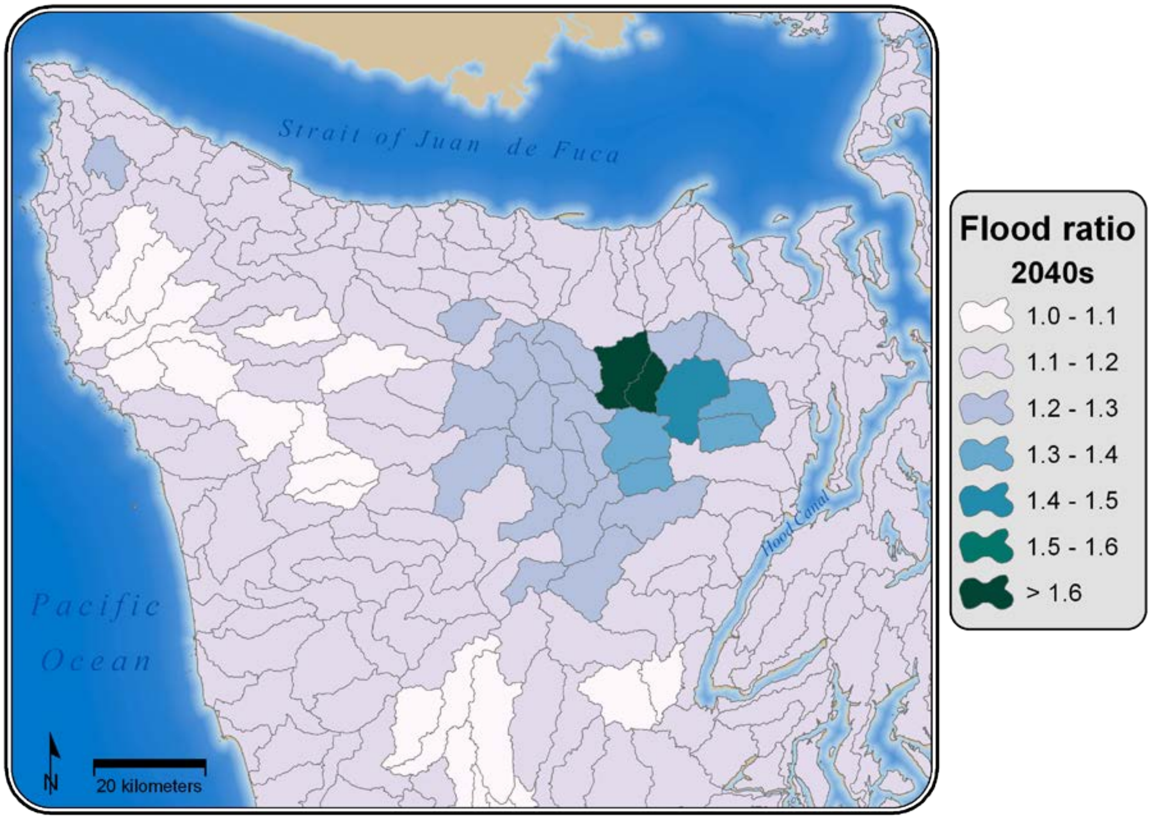


Figure 2-29. Ratios of the 100-year flood (future/historical) for watersheds in the Olympic Peninsula at the 12-digit Hydrologic Unit Code (HUC) spatial resolution.

On the other end of the hydrologic spectrum, the severity of low flows in the late summer months is expected to rise for watersheds throughout the Olympic Peninsula. Low flow statistics, estimated as the 7-day lowest flow with a 10-year return interval (7Q10), are presented as a ratio of the future-to-historical values. The 7Q10 estimates shown in Figure 2-30 depict the spatial distribution of watersheds vulnerable to more intense low flows during the summer months, when the precipitation and snowmelt contributions to streamflows are at their lowest. Again, projections for the 2040s indicate that the headwaters of western Olympic Peninsula basins are more susceptible to low flow severities, declining by as much as 40% compared to the historical period due the combined effects of loss of snowpack and warmer, drier summers. Lower summer in-stream flows can create both uninhabitable conditions for juvenile salmon that spend the summer rearing in freshwater and migration barriers for adult salmon returning to spawn in the fall.

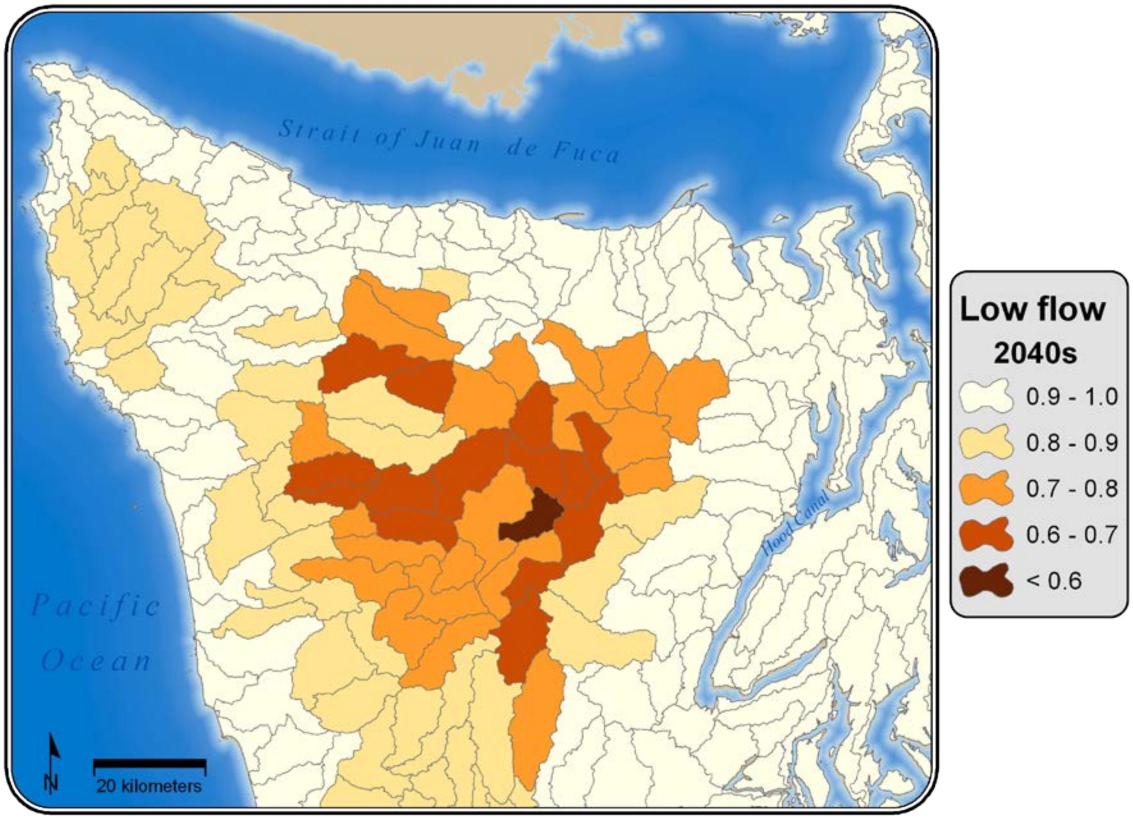


Figure 2-30. Ratio of the future-to-historical 7Q10 (7-day lowest flow with a 10-year return interval) estimate for the Olympic Peninsula at the 12-digit HUC spatial resolution

Strong observed correlations between air and streamtemperatures allows freshwater habitat studies to apply the former to estimate the latter via non-linear regression approaches (Mohseni et al. 1998). Although air and water temperatures are projected to increase throughout Washington State (Mantua et al. 2010), water temperature projections for the 2040s in the Olympic Peninsula remain in the favorable ranges for salmon habitat for all but a few sites (Figure 2-31).

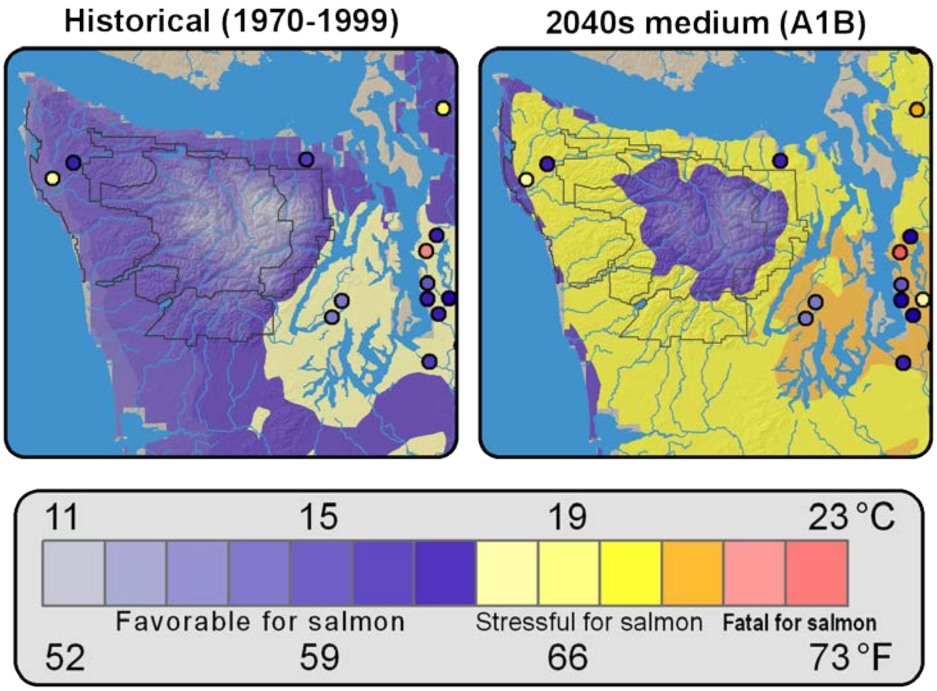


Figure 2-31. Mean weekly August air temperatures (continuous colors) and water temperatures (colored dots) for the historical (left panel) and the 2040s (right panel). Figure from Halofsky et al. (2011)

Using air temperatures as a proxy for water temperatures is an effective method of determining freshwater thermal responses to climate change over large spatial scales, but many other local factors affect stream temperatures. Among the proximate, physical characteristics that affect water temperatures, but not captured in the above study, are connections to side channel refugia and historical floodplains, riparian vegetation, changes in groundwater inputs and channel depth and width (Bilby 1984; Sedell et al. 1990; Torgersen et al. 1999; Crozier and Zabel 2006). In terms of summer habitat for coldwater fish, it is important to take into account that more extreme summertime low flow may further increase stream temperatures, due to increased residence time and decreased thermal mass. It is also noteworthy that while warmer water temperatures in the cool season could boost metabolic and growth rates for juvenile salmon and improve their overall fitness (Beckman et al. 1998); an earlier spring snowmelt may offset the timing of downstream migration with the timing of food availability in the marine environment (Mantua et al. 2010).

2.8.3 Observations

Changes in climatic conditions across the western United States, including the Pacific Northwest, have been documented by several studies. The western United States has undergone an increase in temperatures, leading to a greater proportion of precipitation falling as rain as opposed to snow and a lower snowpack (Mote et al. 2005; Hamlet and Lettenmaier 2007). Mote et al. (2003) evaluated temperature data from the 113 U.S. Historical Climate Network stations in the Pacific Northwest and estimated that temperatures rose by about 0.82 °C during the 20th century. The western United States as a whole has experienced increases in temperatures (with the largest changes focused in early spring), leading to a greater proportion of precipitation falling as rain as opposed to snow (McCabe and Wolock 2002; Mote et al. 2003; Hamlet et al. 2005), lower spring snowpack (Hamlet et al. 2005; Mote et al. 2005) and changes in streamflow timing (Stewart et al. 2005). Observations from the 20th century also suggest that warming and changes in precipitation have resulted in higher winter runoff, earlier spring snowmelt, diminished summer water availability, intensified summer evapotranspiration, and changes in soil moisture recharge (Hamlet and Lettenmaier 2007).

3 Ecological Responses to Climate Change in OCNMS

3.1 Introduction

The direct physical effects of global climate change are expected to stress ecosystems, and it is likely that the resilience of many ecosystems will be exceeded this century (Bernstein et al. 2007). Generalized global changes in "ecosystem structure and function, ecological interactions between species and shifts in species geographical ranges, with predominantly negative consequences for biodiversity and ecosystem goods and services (like water and food supply)" are projected (Bernstein et al. 2007). The objective of this chapter is to examine the degree to which these global generalizations are relevant to the complex and variable marine ecological environment of OCNMS. First, general ecological responses to climate change that are likely to occur in OCNMS are summarized. Next, we synthesize a selection of climate change impacts relevant to particular broad habitats categories within OCNMS.

3.2 General Marine Ecological Response to Climate Change

Physical and chemical changes in the ocean have direct and indirect effects on the physiology, behavior, and productivity of marine organisms. These changes can lead to population and community level alterations including shifts in ecological structure, spatial range of species and communities, seasonal life history patterns, and species interactions (Doney et al. 2012). These responses may, taken together, result in marine ecosystems that function very differently from the way they do now (Kennedy et al. 2002). Here we summarize a group of those ecological responses, including shifts in community composition, altered phenology, non-native species interactions and range shifts.

3.2.1 Shifts in Community Composition, Competition and Survival

The assemblage of species in an ecological community is a product of the interactions among species as well as between the organisms and their abiotic environment (Walther et al. 2002). Likely and possible alterations in the abiotic environment, described for the OCNMS in Section 2, can be therefore be expected to change in some way the composition of biological communities. Changes in community structure, meaning differences in the mix of predators, prey, parasites, and competitors within a given area, could consequently alter the function and productivity of that ecosystem (Kennedy et al. 2002). For locations in the southern California Current System (CCS) climate related shifts in marine ecological communities, rocky intertidal invertebrate (Barry et al. 1995) and seabird (Hyrenbach and Veit 2003) communities, for example, have already been documented (Doney et al. 2012).

Rocky intertidal populations are generally vertically structured by thermal stress from above and from below by organisms that cannot tolerate prolonged exposure to high air temperatures or direct sunlight. In addition to potential acidification responses, climate change may therefore narrow the suitable range of some intertidal species by permitting the upward excursion of marine predators due to sea level rise even as higher air temperatures force some species lower into the intertidal zone. Higher wave energy could directly influence intertidal communities due to the higher forces directly delivered to organisms under larger breaking waves, while increased erosion or delivery of sediment by rivers during winter high flows in combination with higher wave energy may promote abrasion and burial of intertidal and sub-tidal organisms. The acidification of ocean water bathing shallow-subtidal and intertidal organisms can potentially compromise the vitality of both adults (Spicer et al. 2011b) and larvae (Barton et al. 2012) of species found in OCNMS, suggesting that the species composition of these communities may be modified over time if the duration and extent of the incursion of acidified water on to the inner shelf increases. In fact, within OCNMS Wootton et al. (2008) observed shifts in community composition from mussels to algae dominance in the rocky intertidal community on Tatoosh Island in correspondence with declining pH. Based on these interactions it seems reasonable to expect that the composition of biological communities will change within OCNMS due to climate change. What is more difficult to assess, given a lack of information on the interactions between species and with their environment, is the overall direction of that change.

The entire suite of mechanisms that drive these changes in community composition across the ecosystems and habitats within OCNMS are not entirely clear. However, potential changes in large-scale circulation patterns (Section 2.6) can affect species that depend on ocean currents for larval dispersal and recruitment success (Scavia et al. 2002) or due to changes in large-scale patterns of productivity. Some organisms are expected to shift their range in response to changes in ocean temperature (Section 2.2), which in ONCMS could mean that certain species are lost, while others move in. Several studies have observed that increasing atmospheric and ocean temperatures can also increase consumption rates of predators such as sea stars on their prey (Sanford 1999), benthic herbivores on algae (O'Connor 2009), zooplankton feeding on phytoplankton (O'Connor 2009), and benthic predators feeding on bivalves (Philippart et al. 2003). It is conceivable that the mortality of certain species due to ocean acidification (Section 2.3) or possibly hypoxia (Section 2.7) may remove certain species from OCNMS either seasonally or permanently (Occhipinti-Ambrogi 2007). The net effect of these various processes on the assemblage of species that currently utilize OCNMS is difficult to predict, though, and a variety of responses, including adaptation, migration or local extinction are possible (Parmesan 2006).

3.2.2 Altered Phenology

Organisms may change the seasonal timing of certain phases of their life cycle (phonological adaptation) in response to changes in the physical environment. This has been documented for spawning in kelps (Section 10.3) and the timing of blooms of phytoplankton (Section 10.1). However, phonological adaptation can often lead to mismatches in trophic synchrony between predators and prey (Brander 2010) and subsequent ecosystem level changes (Edwards and Richardson 2004). Temperate marine environments may be particularly vulnerable to these changes because the recruitment success of higher trophic levels is highly dependent on synchronization with blooms of plankton production (Hjort 1914; Cushing 1990; Edwards and Richardson 2004). For example, the success of migrating juvenile salmon depends on these timed pulses of plankton production because they undergo critical life-history transitions over a very narrow phenological window (Doney et al. 2012).

The net ecological effect of numerous species adapting to changes in the physical environment associated with climate change isn't clear, but mismatches in phonological timing have been shown to have deleterious consequences in the marine ecosystem of OCNMS. A delay in the initiation of upwelling in the Pacific Northwest in 2005 resulted in a delay in phytoplankton production and was associated with a failure of recruitment of many rockfish species, low survival of some salmon species, nesting failure of the seabird, Cassin's Auklet, and mortality of other seabirds (Peterson and Schwing 2008). While variability in the timing of upwelling is typical in OCNMS (Section 8.6), this example suggests that there are limitations in the ability of the ecosystem to adapt to sudden change, and that the rate of climate-related changes projected for the OCNMS could stress the ecosystem.

3.2.3 Non-native Species Interactions

In addition to invasive species transported through human-mediated pathways (i.e. ballast water, hull fouling, exotic/aquarium trade), other non-native species from adjacent areas may begin to shift their geographic ranges to new territory in response to changing abiotic conditions. Invasive species can have profound ecological and economic consequences. Documented invasions in four well-studied marine areas have shifted food webs toward domination by suspension and deposit feeders (Byrnes et al. 2007). Several studies have implicated the interaction between climate change and invasive species in measurable alterations in several marine ecosystems (Harris and Tyrrell 2001; Stachowicz et al. 2002; Frank et al. 2005). In Willapa Bay, WA, Reusink et al. (2006) observed that non-native bivalves have colonized empty niches and added novel ecological processes to the environment. Although most studies concentrate on the negative effect of climate change and invasive species, non-native species also have the ability to fill an ecological void left vacant by a previous species that has already been pushed out by climate change.

3.2.4 Range Shifts

Species are generally adapted to a specific range of environmental variability. As the climate changes and environmental parameters tend towards the extremes of tolerance, species that have the capacity to shift their distribution will do so. By contrast, species that have limited ability to disperse may face local extinction (Kennedy et al. 2002). Movement in response to environmental changes is most well documented for changes in temperature. Retrospective studies have shown that some species of fish change their spatial and depth distributions in response to interannual and long-term changes in temperature. The North Sea warmed by 1.05 C between 1977 and 2001 (Perry et al. 2005). For this 25 year period, species distribution centers (mean latitude) and northern or southern range boundaries (maximum or minimum latitude for species with a range boundary in the North Sea) shifted in response to interannual temperature variation for many of the 36 demersal species examined (Perry et al. 2005). Nearly all correlations between latitude and temperature were positive (i.e., farther north in warmer years) and nearly all latitude shifts over the 25 year period were from south to north. The mean rate of range boundary movement for the six species whose range boundaries shifted significantly in relation to both interannual temperature variation and time was 2.2 km per year. Many of the species that moved north in response to warming also moved to deeper water, and some additional species moved deeper but did not shift latitude.

Other North Sea studies similarly documented fish distributional responses to warming including movement to deeper water (Dulvy et al. 2008) and increases in occurrence and abundance of species with southern biogeographic affinities (Beare et al. 2004; Hiddink and ter Hofstede 2008). Murawski (1993) found significant correlations between mean (or maximum) latitude and temperature (surface or bottom) during 1967-1990 for many northwest Atlantic fish species. Many eastern Bering Sea fishes and large crustaceans moved north as winter sea ice cover retreated and summer bottom temperatures warmed (the former was thought to have caused the latter) during 1982-2006 (Mueter and Litzow 2008). Significant northward shifts over time and (or) significant positive correlations between distribution centers and summer bottom temperatures were documented. Across all 40 species examined, the northward shift averaged 34 km over the 25 year period, including species that didn’t shift significantly.

BOX 3-1: Range Shift Projections for the Northeast Pacific Ocean

Range shift projections have been made based on species preferences coupled with predictions of climate-driven changes in environmental conditions. Cheung et al. (2009) projected changes in the distributions of 1066 exploited marine fish (836 species) and invertebrates (230 species) from around the world. Species preferences were inferred from their current distribution, representing the average pattern of relative abundance in recent decades (1980-2000). Environmental variables accounted for were temperature (surface and bottom), depth, salinity, ocean advection, coastal upwelling, sea ice cover (distance from), and habitat type (coral reef, estuary, and seamounts). Larval dispersal and adult migration processes were included in the forecast model. Three climate change scenarios representing high, medium, and low-range greenhouse gas emissions (SRES A1B, SRES B1, and a “committed” scenario where forcing agents were stabilized at late twentieth century levels, respectively; Section 6.1) were simulated. Range predictions were made for 2050 (mean of 2040-2060) and compared to 2003 (mean of 2001-2005). Local extinction intensity, defined as the number of species that disappeared from an area divided by the initial (2003) number of species in the area, was projected to be greatest for the tropics, the Southern Ocean, the north Atlantic, and of relevance for our report, the northeast Pacific coast. Roughly 5-10% of initial species were projected to be lost from the northeast Pacific coast, compared to a global average of 3%, under the high emissions scenario. Projected species invasion intensity, defined as the number of new species that appeared in an area divided by the initial number of species in the area, was highest at high latitudes (Arctic and Southern Ocean). Invasion intensity projected for the northeast Pacific coast was near the global average but was nonetheless considerable. The number of new species in the area was projected to be 15-60% of the initial number of species under the high emissions scenario. Distribution centers and range limits were projected to shift poleward for most species. Projected median range limit shifts were 291 km under high emissions and 231 km under low emissions. Projected range limit shifts were greater for pelagic species (median under high emissions = 600 km) than for demersal species (median under high emissions = 223). Across all emission scenarios, projected median rate of range limit shifts was 45-59 km per decade.

3.2.5 “Cumulative” Implications

Attempts are being made to incorporate additional climate-sensitive environmental variables in range shift forecasts. Cheung et al. (2011) accounted for effects of ocean acidification, reduction in ocean oxygen content, and changes in phytoplankton community structure to project shifts in range and maximum catch potential for 120 exploited marine fish (99 species) and invertebrates (21 species) from the northeast Atlantic Ocean. Environmental variables included in the forecast model were temperature (surface and bottom), oxygen and hydrogen ion concentration (surface and bottom), depth, salinity, ocean advection, and small and large phytoplankton production. A decrease in large phytoplankton relative to small phytoplankton might result in less efficient energy transfer to fish and large invertebrates because of the need for additional trophic levels (e.g., small zooplankton to eat small phytoplankton and be eaten by large zooplankton). Range predictions were made for 2050 under the high emissions scenario (SRES A1B; See Section 6.1) and compared to 2005. Projected distributions shifted north for most species. The mean rate at which projected distribution centers shifted north was 15% greater with biogeophysical variables (oxygen and hydrogen ion concentrations; phytoplankton community size structure) included than with them excluded. Projected maximum catch potential was substantially less with biogeophysical variables included than with them excluded, and was more sensitive to changes in oxygen and hydrogen ion concentrations than to changes in phytoplankton community structure. The authors acknowledge that the magnitude of changes projected by the model is uncertain, in part because the underlying biological hypothesis linking fish and invertebrate response to acidification and reduced oxygen has not been considered before.

Two studies reviewed for this assessment attempt to project cumulative effects of climate-driven changes on Pacific Northwest coastal marine ecology. Ainsworth et al. (2011) projected climate change effects on marine foodweb structure in northeast Pacific shelf ecosystems using trophic flow models (Christensen and Walters 2004) coupled with climate models (SRES A1B; See Section 6.1). They simulated effects of climate-driven changes in (1) mean annual primary production, (2) zooplankton community size structure (decrease of large relative to small-bodied species) (3) range shifts of exploited marine fish and invertebrates, (4) ocean acidification (only on crustaceans, echinoderms, and mollusks), and (5) ocean deoxygenation (on all species except birds, mammals, and plants). These five effects were simulated separately and in combination (cumulatively) for the 50-year period from 2010-2060. The response of fisheries landings, biomass of fish and benthic invertebrates (total of fished and unfished biomass), and ecosystem characteristics (diversity and trophic indices) was assessed. Five models with different spatial extents provided nearly continuous coverage from Cape Mendocino, California, to Yakutat Bay, Alaska, and also included Prince William Sound.

In the northeast Pacific as a whole (results averaged across spatial models), cumulative impacts of the five climate change effects reduced fisheries landings by 77%. The impact of range shifts alone (54% reduction in landings) was greater than the cumulative impacts of the other four effects (20% reduction; note that the sum of the individual impacts doesn’t necessarily equal the cumulative impact). Cumulative impacts of all five effects reduced total biomass (fished and unfished) by 30%. Cumulative impacts were greater for pelagic fish (57% reduction in biomass) than for benthic invertebrates (29% reduction) or demersal fish (no change). The impact of range shifts was again greater than the impact of the other four effects. Cumulative impacts of the five effects also reduced ecosystem biodiversity and mean trophic level. Cumulative impacts simulated with each of the regional models produced a wide range of possible outcomes but some generalities were evident. Forage fish fisheries consistently declined and most of the other fisheries (shellfish, rockfish, flatfish, and salmon) were vulnerable to decline depending on the assumed strength of climate effects (conservative, moderate representing the best available estimate, or substantial). Total biomass (fished and unfished) of pelagic invertebrates (mainly squid) could double, whereas biomass of demersal fish tended to remain at current levels. Final biomass of small pelagic fish ranged from near zero to near current levels depending on assumed effect strength but did not increase. Outcomes from the regional model most relevant to the OCNMS, the northern California Current from Cape Mendocino to the U.S.-Canada border, were in agreement with general trends shown by the other regional models. The authors caution that their results are best interpreted in a qualitative way (for example, the types of community response that occur, not their magnitude) given the substantial process and model uncertainty.

King et al. (2011) took a different approach to forecasting climate-driven changes to fish throughout the CCS. They developed conceptual models describing the potential pathways linking climate forcing, oceanography, and species' responses and projected warmer surface and near-surface waters, potential changes in productivity, a deepening thermocline in coastal waters, particularly in the north, increased coastal stratification, (particularly in the south of Point Conception, California), and increasing incidence of hypoxia in shelf waters. Reduced secondary production in the south and a northward shift of the southern copepod community, replacing and reducing the biomass of boreal shelf and Subarctic oceanic copepods, were also projected. They concluded that species like Pacific sardine and Pacific hake, which are associated with warm water and typically spawn in southern California, will respond by expanding their ranges northward. Salmon species, which prefer cool water, may move north out of the California Current ecosystem. Deep water groundfish such as Dover sole may not be measurably affected by moderate warming. Recruitment success may be impacted for forage fish and Pacific hake which in the past have experienced recruitment failures and rapid population declines. In contrast, long-lived, highly fecund species like Dover sole, sablefish, and rockfish can withstand many years of poor recruitment. These demersal fish may be able to move offshore into deeper water to maintain preferred temperatures assuming sufficient oxygen concentrations.

3.3 Implications for Selected Habitats of OCNMS

The physical climate-related changes discussed in Section 2 could have a variety of implications for the habitats of OCNMS. In some instances these changes may have fairly direct effects. For example, a link has been made between annual variability in storminess and the success of weaning of fur seal pups in the Bering Sea (Lea et al. 2009). This suggests the possibility that an increase in the magnitude and duration of storms, discussed as a possibility in Section 2.5, may directly influence the suitability of habitats within the OCNMS for some or all types of marine mammals. In other cases the causal links between projected or observed changes in the physical environment and the implications for certain habitat types are clouded by complexity or inadequate ecosystem models. There is some observational evidence to suggest that kelp biomass is exported to deeper water where it may fuel the metabolisms of deep-water invertebrates. Consequently changes to shallow water habitats that lessen the suitability of those habitats for kelp could have an indirect effect on deeper ecosystems. While such interconnections may be important to the ecological functions of marine habitats in the future OCNMS, it is currently impossible to model the ecosystem at an adequate resolution to project the direction or magnitude of changes with any degree of certainty.

Here we discuss some of the potential implications for four broad habitat categories within OCNMS: nearshore and shallow water, deepsea benthic, water column/pelagic and freshwater habitats. This sections is not intended to be comprehensive, but instead is used to highlight some of the potential interactions between the changes in the physical environment discussed in Section 2.

3.3.1 Nearshore and Shallow Water Habitats

Nearshore and shallow water habitats in or adjacent to OCNMS include kelp forests, sandy beaches, rocky intertidal zones, shallow-water reefs and sea stacks and islands (Office of National Marine Sanctuaries 2008). These environments will be exposed to a wide range of climate-driven changes. The various shallow water habitats of OCNMS provide a suite of ecological services and functions. For example, sand beaches support prey for foraging birds, spawning habitat for forage fish and haul-out areas for marine mammals. Kelp forests support a unique biological community and can dampen wave energy impinging on the shoreline. Rocky intertidal zones are hotspots for biodiversity, and rocky benches provide haul-out areas for marine mammals. Off-shore sea stacks and islands strongly influence near-coastal currents and waves, protecting the shoreline and providing complex habitat for a range of species. Many bird species are strongly dependent upon sea stacks for nesting.

Climate change implications for nearshore and shallow water habitats can be broadly divided into "mechanical" impacts that will alter the physical environment, as well as what can be thought of as a group of "chemical-biological" impacts. The "chemical-biological" impacts, which will influence biota in all habitats due to changes in seawater temperature, acidification, productivity and hypoxia, are generalized to multiple habitats and discussed in a variety of sections, including 3.2.1 and 3.2.4. These are not discussed further here. "Mechanical" impacts to these nearshore and shallow water habitats under changing climate conditions are derived from increasing sea level, potential changes in wave energy or direction, and increasing frequency or duration of storm surges. Together, these mechanical impacts may:

1) Increase erosion of the shoreline and sedimentation of shallow water habitats
2) Directly impact biota due to increasing wave energy and elevated sea level
3) Restructure soft sediment shallow sub-tidal or intertidal habitats
4) Narrow intertidal habitat through thermal stress and increased "bottom-up" pressure by lower intertidal predators as sea level increases

Sea level rise, changes in storminess, and changing hydrologic patterns will influence nearshore and shallow water habitats via the erosion and redistribution of coastal sediment, resulting in the landward migration of the shoreline, sedimentation of some existing hard bottom habitat types, steepening and coarsening of beaches, and an increase in the amount of sediment transported to shallow water as material is eroded from coastal bluffs and beaches, which may cause changes in the distribution of soft-sediment habitats.

Tebaldi et al. (2012) formally project the changes in the probability of extreme high water, incorporating sea level and storm surge, using water level observations from Neah Bay and Toke Point, Washington (Figure 3-1) combined with a "semi-empirical" sea level rise model (Section 2.4). Their results suggest that by 2050 water levels that are currently considered extreme (i.e. occur, on average, every 100 years) will occur much more frequently. At Toke Point, for example, the contemporary 100-year return water level of approximately 2.0 meters above mean high water (MHW) may occur, on average, approximately every 20-25 years by 2050 (Figure 3-1). Tebaldi et al (2012) also point out that their estimates may also be conservative, since they assume that there will be no change in the magnitude of storm surges over that time period (See Section 2.5). Additionally, their analysis only considered the "still water level;" water level due to mean sea level, tides and storm surge. It did not incorporate the possibility of increasing wave heights (Section 2.5), which can drive the total water level higher up the beach face and increase the frequency of interaction with beach-backing cliffs or berms. However, their analysis is one of the first for the Pacific Northwest that formally examines changes in return interval for extreme water levels.

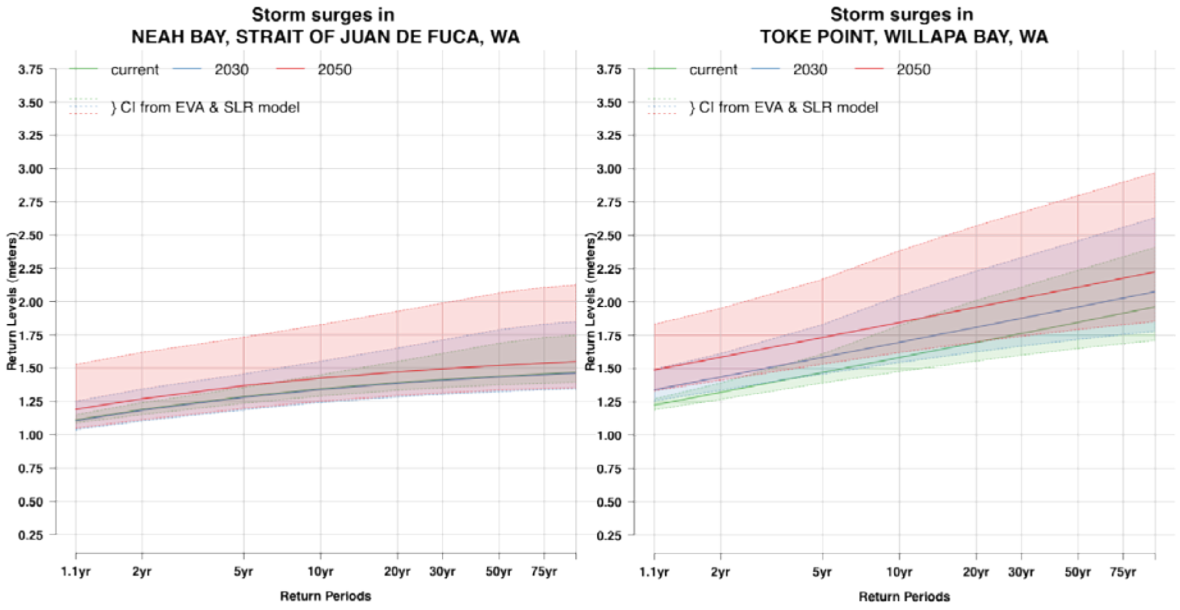


Figure 3-1. Return interval projections for total still water level relative to mean high water at Neah Bay and Toke Point. Estimates of uncertainties (95% confidence intervals) are derived from an extreme value analysis (EVA) and projections of sea level rise (SLR Model). Figure courtesy of Dr. Claudia Tebaldi, Climate Central Inc. using methods described in Tebaldi et al. (2012)

The shoreline fringing OCNMS is relatively undeveloped. Much of it is publicly owned and managed, while coastal tribes directly manage intermittent sections of shoreline associated with their reservations. The lack of development removes a significant pressure on the shoreline that would otherwise exacerbate the effects of climate change: under intense development, shoreline armoring can prevent the shore moving with changing ocean conditions, so beaches will be increasingly "squeezed" between land development and a rising ocean. While the shoreline fringing OCNMS is lightly developed, the rocky beach-backing bluffs and cliffs may mimic shoreline "squeeze." As a result, some intertidal beaches in or adjacent to OCNMS may coarsen and steepen leading to a reduction in spawning habitat for forage fish, prey for beach-foraging birds, and beach areas for marine mammal haul-outs.

BOX 3-2a: A Preliminary Assessment of Bluff Erosion Potential

To assess the potential that shoreline erosion may alter or restructure nearshore habitats, the elevation of beach-backing shore forms (berms and cliff toes) were quantified using aerial LiDAR (from 2002) along the southern boundary of OCNMS (Figure 3-2). For shorelines covered by the LiDAR survey and within OCNMS, the dominant shore form was the cliff-backed coast, represented by both hard cliffs and soft bluffs. Cross-shore profiles (N=175) were extracted from these LiDAR data, and the elevation of the toe of the cliff estimated from each profile. For all cliff-backed profiles, the mean elevation of the cliff toe was 3.55 m relative to MLLW.

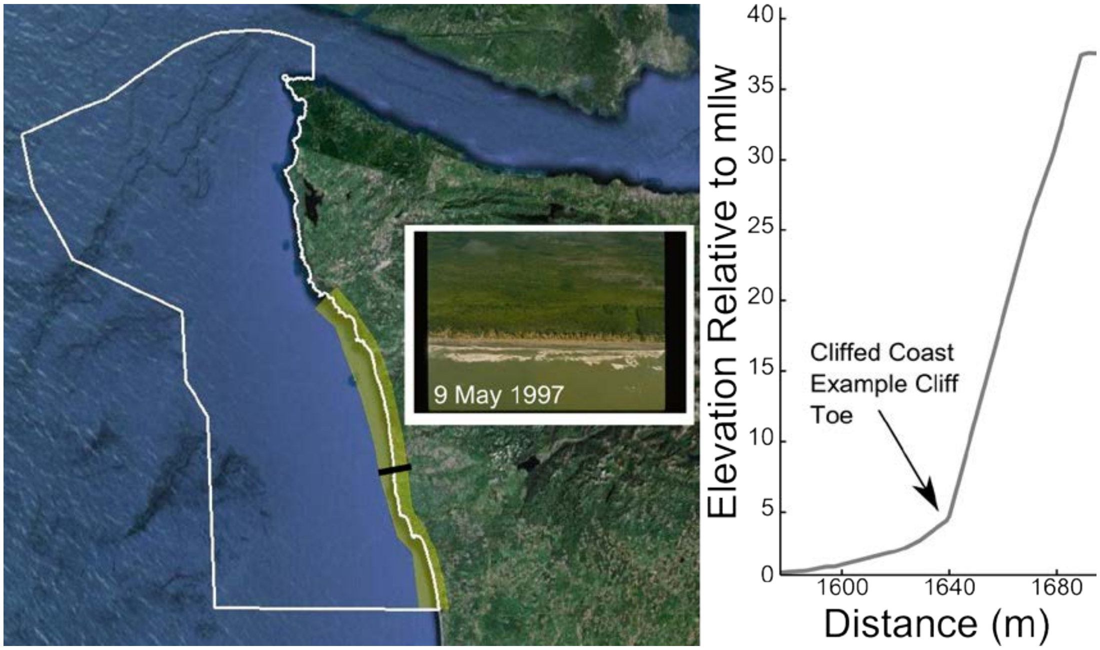


Figure 3-2. Map of the Olympic Peninsula showing the extent of coastal LiDAR (yellow area) collected in 2002 relative to the boundaries of OCNMS (white line). A representative cross-shore transect is shown in black, and the inset photo shows the coastal bluffs in the area of the representative transect. The extracted profile from the representative transect is shown at right.

The elevation of the toe of coastal bluffs and sea cliffs is a critical threshold for erosion – if the combined total water level, including the "still" water level (incorporating sea level, tides, and storm surge) and run-up from waves, exceeds that elevation for a significant amount of time erosion or sliding of the bluff is likely to result. The sediment contributed from this sliding is added to the shallow water littoral transport cell, and may alter or restructure existing soft-bottom habitat. The erosive action also moves the shoreline landward, potentially altering existing intertidal and shallow water habitats. Interestingly, the potential for increasing wave heights, depending on their magnitude, may be more important than sea level rise in the total water levels observed in the Pacific Northwest (Ruggiero 2008).

BOX 3-2b: A Preliminary Assessment of Bluff Erosion Potential

To evaluate the possibility of a changing total water level, and therefore the possibility that the toe of cliff-backed beaches adjacent to OCNMS may come into contact with the ocean more frequently, we estimated total water level for the period between 1987 and 2010 for the southern coast of OCNMS. Total estimated water level was calculated using the observed still water level from the NOAA tidal gauging station at Toke Point, WA (9440910), and wave run-up was added to the still water level (Baron 2011). Wave observations (significant wave height and dominant period) from NDBC Buoy 46041 (Figure 2-4) were utilized for this calculation. We estimate that total water level (the elevation reached by the water due to tides, storm surge and other factors, plus wave run-up) exceeded the mean elevation of the cliff toe (3.55 m above MLLW) approximately 0.8% of the time between 1987 and 2010 (Figure 3-3). The projected rise in sea level for the southern shore of OCNMS, combined with the potential for higher waves, would be expected to increase the probability of exceedance of the mean cliff toe elevation (Figure 3-3), though a formal quantification of that change in probability is beyond the scope of this report.

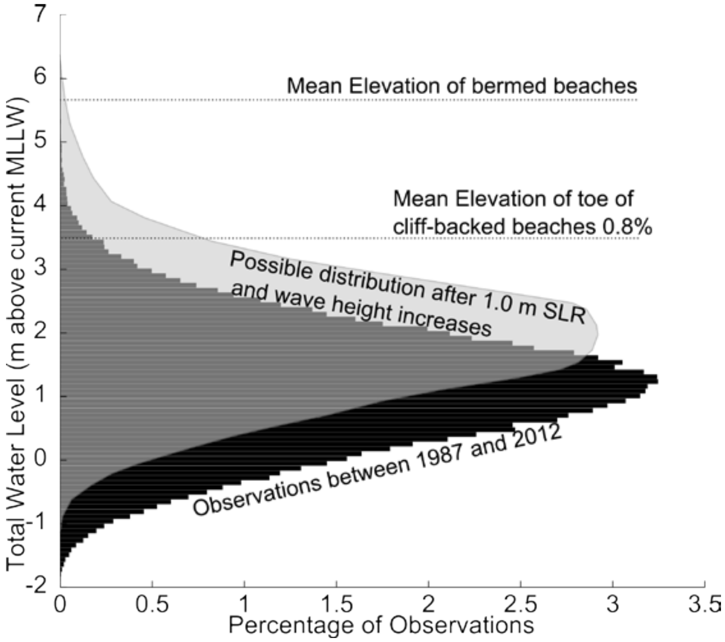


Figure 3-3. Histogram (black bars) of the estimated total water level along the southern coast of OCNMS between 1987 and 2010, incorporating storm surge, tidal amplitude and wave run-up. The shaded gray area is a hypothetical histogram of total water level after 1.0 m of sea level rise and extreme wave height increases.

3.3.2 Deep-sea Benthic Habitats

Deep-sea bethic habitats, defined for the purposes of this analysis as those occurring in waters below the euphotic zone, will primarily be influenced by changes in ocean temperature, acidification of ocean water, hypoxia/anoxia and changes in surface productivity. These habitats in OCNMS are utilized by biota such as deep-sea corals and groundfish species like Pacific cod, halibut and rockfish. The ecological roles played by these species, as well as the numerous lesser known and understood species that make deep-sea habitats of OCNMS their home, are poorly understood.

In OCNMS particular interest is focused on deep-sea corals (also known as “cold-water corals”), and particularly those species that may create habitat for fish and other invertebrates (Roberts et al. 2009; National Oceanic and Atmospheric Administration 2011). Three variables that determine habitat suitability for deep-sea corals are water temperature, aragonite saturation state and salinity (Davies and Guinotte 2011), all of which may change in OCNMS with a changing climate. The northeast Pacific is already thought to be marginally suitable as habitat for some deep-sea corals (scleractinian corals, for example) (Davies and Guinotte 2011), suggesting the possibility that changes in ocean temperature (Section 2.2) and aragonite saturation states (Section 2.3) in particular may further reduce the suitability of deepwater benthic habitats in OCNMS for some corals.

An expansion of anoxic or hypoxic zones, or an increase in the frequency of hypoxic or anoxic events, could also influence the habitat suitability of deepwater benthic habitats in OCNMS. For some organisms this physical response to climate change would result in a loss of available habitat and reduced populations of, for example, deepwater fishes (Koslow et al. 2011). Other species may benefit from the expansion of hypoxic/anoxic zones (Diaz and Rosenberg 1995); a northward range expansion of Humboldt squid in the northeast Pacific Ocean over the last decade has been attributed, at least in part, to reduced oxygen in some water masses in the northeast Pacific Ocean (Bograd et al. 2008).

The interaction between variables important to deepwater habitats may change over the coming century as a result of climate change. These changes may stress organisms, making them more susceptible to disease (Danovaro et al. 2011) or reducing food availability; however, these same changes may benefit other organisms. Ecological modeling of marine foodwebs in the northern California Current suggests that changes in primary productivity, species ranges, zooplankton community structure, acidification and hypoxia/anoxia will increase the biomass of benthic and pelagic invertebrates, as the biomass of benthic fish decreases (Ainsworth et al. 2011). Beaugrand (2012) notes however, that ecological modeling efforts are often based upon empirical relationships between the biomass of functional groups and environmental variables, and that those relationships could break down suddenly and unexpectedly in response to climate change. Based on this, the results of ecological models should be interpreted cautiously.

3.3.3 Water Column/Pelagic Habitats

Climate changes may alter communities utilizing pelagic habitats in the OCNMS due to shifts in metabolism from changes in ocean temperature (Section 2.2), the physiological effects of acidification (Section 2.3), and periods of reduced oxygen (2.7). Additionally, changes in patterns of storminess or waves (Section 2.5) may influence the distribution and survival of pelagic organisms, as has been suggested for marine mammals (Lea et al. 2009).

As with changes in other habitats, interactions between variables are complex and their consequences to habitat suitability are difficult to project with certainty. Overall primary productivity is expected to decline across the global ocean (Hoegh-Guldberg and Bruno 2010), but whether this will hold true for OCNMS is uncertain. Higher surface-water temperature may reduce primary productivity by increasing stratification whereas increases in upwelling winds could partially counteract this by increasing mixing (e.g., King et al. 2011). Certain members of the plankton community, such as larval oysters (Barton et al. 2012) and pteropods (Fabry et al. 2008) might be negatively impacted by ocean acidification as their shells are made from calcium carbonate, whereas some species of euphasiids may benefit from the increased water temperatures projected for OCNMS (Letessier et al. 2011).

The effect of possible changes in the zooplankton community on pelagic fishes is unclear. Pink salmon in the Gulf of Alaska rely on both pteropods and euphasiids for prey (Armstrong et al. 2005). Reduced oxygen in the California Current is associated with reductions in the populations of most pelagic fishes (Koslow et al. 2011), suggesting that the direct consequence of reduced oxygen may outweigh the indirect effects of changing prey availability in determining the populations of some pelagic fish. Ecological modeling of the northern California Current suggests that the combined impacts of climate change will lead to a reduced biomass of pelagic fish by 2060, and an increase in the biomass of pelagic invertebrates like squid (Ainsworth et al. 2011).

3.3.4 Freshwater Habitats

While there are no freshwater habitats within the boundaries of OCNMS, there are two implications to the resources of the sanctuary from alterations in connected streams and rivers. First, anadromous fish, particularly salmonids, utilize the rivers adjacent to OCNMS for spawning and nursery habitat. Changes in stream temperature for some rivers draining into OCNMS may not reach thresholds unfavorable for salmon by 2100 (Section 2.8). However, projections of greater flood magnitudes and increased turbidity of these streams due to changing atmospheric temperature and precipitation patterns (Section 2.8) could have detrimental effects on salmon habitat and water quality. For example, higher velocity flows associated with higher magnitude winter flooding can reduce salmon egg survival and sweep juveniles downstream before they are ready to migrate (Mantua et al. 2010).

Next, two processes may increase the sediment flux from rivers to the coastal zone, potentially altering intertidal and shallow sub-tidal sediment budgets and driving changes in coastal habitats. The combination of snow cover loss and higher velocity flows along steep slopes may also accelerate mass-wasting processes and increase sediment delivery to rivers (Benda and Dunne 1997). Additionally, increased flood magnitudes may result in an intensification of river sediment transport capacity (Leopold et al. 1964). These processes could result in sediment deposition in lower river reaches, deltas and floodplains, and the coastal zone near river mouths. There is a potential benefit to this effect: an increased sediment supply to the coastal zone may help to mitigate the projected erosion of the shoreline due to climate change (Section 3.3.1). However, sediment fluxes to the coastal ocean are also associated in some cases with habitat degradation, reduced water quality and an overall reduction in habitat suitability.

4 The Response of Selected Species or Communities

A subset of species or communities was selected for more detailed consideration. The species and groups were selected based on extensive discussion within the working group who compiled this report, with OCNMS staff, and consultation with the OCNMS Advisory Council. The selected list includes zoo- and phytoplankton, marine algae and seagrass, deep-water benthic corals, intertidal mussels, urchins of the shallow sub-tidal zone (*Stronglyocentrotus sp*.), Dungeness Crab (*Metacarcinus magister, formerly Cancer magister*), fish (including salmon, forage fish, and groundfish), seabirds and cetaceans. Where literature was available, authors considered and attempted to summarize the direct consequences of the projected changes described in Section 2, and also in some cases attempted to consider the cumulative or synergistic effects of climate changes on species.

4.1 Phytoplankton

4.1.1 Summary

- Unusual phytoplankton activity correlated to warming ocean temperatures has been documented at a variety of locations around the globe including unprecedented blooms, decreases in phytoplankton size, reduced peak biomass, and declines in photosynthetic capabilities.
- Changes in ocean current patterns may also affect harmful algal bloom (HAB) dynamics. The Juan de Fuca eddy is a major site where the toxic Pseudo-nitzschia that affects the Washington Coast is initiated. Changes in this eddy dynamic could lead to a large HAB biomass transported on-shore increasing unprecedented occurrences of toxic phytoplankton events.

4.1.2 Importance

Phytoplankton provide more than half of the global primary production and as a result are a fundamental element of marine food webs (Falkowski et al. 1998). Changes in phytoplankton abundance, distribution, or density could “ripple” through groups and species at higher trophic levels. For example, most zooplankton populations are limited by the availability of phytoplankton (“bottom-up control”); therefore, if phytoplankton biomass is significantly reduced or altered, secondary production will likely be limited (Richardson and Schoeman 2004) and consequently higher trophic level assemblages such as fish which depend on the zooplankton for early development will also be reduced (Cheung et al. 2008).

Phytoplankton also influence biogeochemical cycles and play a role in stabilizing changes in climate (Schlesinger 2005; Rost et al. 2008). Climate change not only affects phytoplankton, but changes in phytoplankton assemblages also have the ability to affect the climate through associated biogeochemical cycles (i.e. the flux of carbon to the deep ocean via the sinking of phytoplankton biomass) (Rost et al. 2008). According to Schlesinger (2005) phytoplankton have played a central role in mitigating and amplifying changes in paleo-climate and may have contributed to climate stabilization by influencing the partition of CO_2 and other climate-relevant gases between the ocean and atmosphere. Additionally, through the process of photosynthesis, phytoplankton act as a major consumer of CO_2 which is then converted into particulate organic matter which can then be buried in the deep ocean (the "Biological Pump"), thereby providing a mechanism for the oceans to act as a global carbon sink.

4.1.3 Phytoplankton and Climate Change

In the context of climate change, phytoplankton can be distinguished into three functional types: silicifiers, calcifiers, and diazotrophs (Rost et al. 2008). The silicifiers are largely comprised of diatoms that, due to their high sinking velocity relative to other phytoplankton, play a major role in determining vertical fluxes of silicate and organic carbon (Rost et al. 2008; Sommer and Lengfellner 2008). Increased stratification due to thermally induced changes in density in the surface ocean may reduce nutrient availability in the productive sunlit surface of the ocean, and therefore could have strong effects on this group (Rost et al. 2008). The group known as "calcifiers," phytoplankton that build "tests" or exoskeletons of calcium carbonate, are much more susceptible to changes in seawater alkalinity due to ocean acidification. Finally, potential climate change effects on the "diazotroph" group, that includes N_2-fixing cyanobacteria, is projected to have a variety of consequences. While recent studies have found that some species of diazotrophs are extremely sensitive to changes in carbonate chemistry, other studies have observed that cyanobacteria may benefit from climate change due increases in the concentration of CO_2 in the photic zone of the global ocean (Badger et al. 1998).

Phytoplankton and climate change are also important in the context of HABs, which occur in OCNMS (Office of National Marine Sanctuaries 2008). Although HABs have naturally occurred throughout recorded history, within the past three decades, HAB occurrences appear to have become more prevalent, more frequent, and more intense globally, perhaps due to climate-related changes (Hallegraeff 1993; Van Dolah 2000). HABs of greatest importance in the Pacific Northwest are those that produce neurotoxins such as paralytic shellfish poisoning (PSP) caused by dinoflagellates in the genus *Alexandrium* and domoic acid, a neurotoxin produced by diatoms in the genus *Pseudo-nitzchia*. These can have a significant impact on human health as tribes on the coast rely on shellfish for subsistence as well as other tribal fisheries. In addition, a number of valuable higher trophic level species including whales and porpoises can also be affected when they ingest the biotoxins through contaminated fish or zooplankton. According to Hallegraf (2010), a number of California pelicans and sea lions have been increasingly exposed to anchovies contaminated with a HAB species (possibly *Pseudo-nitzschia*) that contributed to erratic and often unusual behavior. Expansive diversity in taxonomy and life strategy makes it difficult to predict how climate change will affect HABs. As a result, only a scattered number of publications have addressed HABs and climate change and are usually focused on single environmental factors or a single species. Therefore, there is an express need to continue to addresses HABs in the context of a changing climate.

Below various investigations exploring the potential implications of climate change to phytoplankton in OCNMS are summarized.

Increasing Ocean Temperature

Projected increases in ocean temperature (Section 2.2) are likely to influence primary production, and could therefore alter the spatial distribution, community composition, and phenology of phytoplankton. A number of studies document unusual phytoplankton activity correlated to warming ocean temperatures in other parts of the global ocean, including unprecedented blooms (Stockwell et al. 2001), decreases in phytoplankton size (Hoegh-Guldberg and Bruno 2010), reduced peak biomass (Sommer and Lengfellner 2008), and declines in photosynthetic capabilities (Hare et al. 2007).

Globally distributed plankton data suggest that a number of phytoplankton assemblages are undergoing community changes including poleward range shifts and alterations in the magnitude and timing of peak biomass most likely due to increasing warming trends (Beaugrand et al. 2002; deYoung et al. 2004; Richardson and Schoeman 2004; Hays et al. 2005). These changes may alter the temporal synchrony between phytoplankton blooms and phenology of secondary consumers (the 'match-mismatch hypothesis') (Edwards and Richardson 2004). Winder and Schindler (2004) found that a warming trend in Lake Washington, WA (Figure 4-1) advanced the annual spring bloom 20 days between 1977 to 2002, which was associated with declines in secondary consumers. Similarly, in the North Sea the mismatch of clam (*Macoma balthica*) spawning and the spring phytoplankton bloom has reduced the amount of food available during the pelagic phase of the clam's life cycle, resulting in increased mortality (Philippart et al. 2003). Warming is also likely to increase consumption rates and interaction strengths of consumers as metabolic rates increase. Therefore, we may also expect that phytoplankton will experience increased predatory pressure from zooplankton (O'Connor 2009) which could further exacerbate alterations to trophic dynamics if coupled with changes in phenology.

Figure 4-1. Lake Washington, in Washington State (white arrow) is shown in geographic relationship to OCNMS (outlined in white). Increasingly warm springs since the early 1960's have been associated with a shift in the timing of the spring phytoplankton bloom in Lake Washington (Winder and Schindler 2004).

Increasing ocean temperature may lead to increased vertical stratification of the surface ocean, which would be expected to influence phytoplankton (Rost et al. 2008). Highly stratified waters are depleted in essential nutrients (phosphate, silicate, and nitrate) and therefore generally contribute to a reduction in phytoplankton abundance and primary production (Behrenfeld et al. 2006). Bopp et al. (2005) proposed that an increase in stratification due to ocean warming could contribute to reduced silicate availability in surface waters which may be detrimental to silicifiers such as diatoms (which are a contributor to primary production in OCNMS). Others have suggested, though that vertical stratification may lead to greater light availability (Sarmiento 2004), which could promote productivity (Bopp et al. 2001; Doney 2006) in some cases where light is a limiting factor (such as in the northeast Pacific Ocean)(Alexander et al. 2008). According to Tyrell and Taylor (1996), vertical stratification can facilitate the growth of coccolithophore species (i.e. *Emiliania huxleyi*), over other phytoplankton groups such as diatoms. However, this particular species has also been demonstrated to be extremely susceptible to ocean acidification that could negate any potential growth benefits conferred by the vertical stratification. In general, little work has been done to isolate effects of light and temperature because there is an extremely close coupling between the two variables (Sommer and Lengfellner 2008) and further research is needed to uncover the contribution of each factor to phytoplankton dynamics in a changing environment.

Ocean temperature also plays a role in HAB dynamics, especially for those species that form cysts. Paralytic shellfish poisoning PSP producing dinoflagellates genera (such as *Alexandrium* and *Pyrodinium)* rely on benthic resting cysts as part of their life-cycles, which allows them to persist through unfavorable conditions (Hallegraeff 2010). Many of these cysts are sensitive to temperature and nutrient conditions for germination. The raphidophyte *Chattonella* is able to vertically migrate even in highly stratified water columns, which may provide it with a competitive advantage in a climate-altered ocean (Imai et al. 1998). According to (Hallegraeff 2010)), increasing sea surface temperatures are also expected to generate longer-lasting bloom windows (Figure 4-2), which could have implications for OCNMS. For example, the dinoflagellate *Alexandrium catenella* in Puget Sound blooms in a well-defined seasonal temperature window that typically lasts 68 days when temperatures are >13ºC (Moore et al. 2008); however, with warming waters, this window is expected to increase significantly, providing a wider window for accelerated growth.

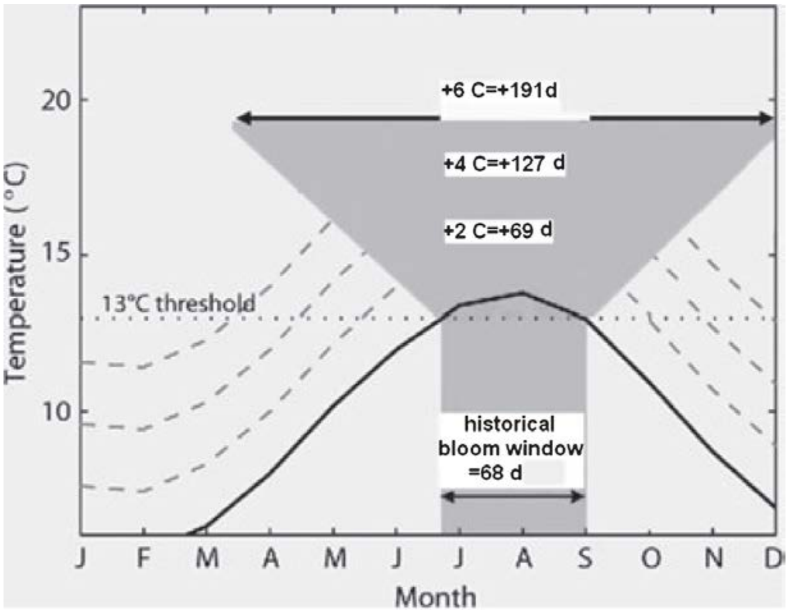


Figure 4-2. Projected scenarios for warmer sea surface temperature conditions in Washington's inland marine waters by 2, 4, and 6ºC would widen the annual window (in gray) of accelerated growth (occurring at temperatures >13ºC) for the dinoflagellate *Alexandrium catenella*, potentially increasing the occurrence of HABs associated with this species. From Hallegraeff (2010) using data from Moore et al. (2008).

Ocean Acidification

The effect of ocean acidification (OA) on phytoplankton is likely to be species specific and may elicit both positive and negative effects on assemblages. Berge et al. (2010) speculated that phytoplankton assemblages in oceanic regions are more susceptible to reductions in pH compared to phytoplankton in coastal regions like the OCNMS that regularly experience large variations in pH. Aside from coccolithophores, however, data are relatively scarce on the responses of marine phytoplankton to lower pH. Increased CO_2 concentrations in marine waters could potentially benefit phytoplankton (Kim et al. 2006). However, other studies highlight negative responses to OA including reductions in nutrient uptake rates in the diatom *Thalassiosira pseudonana* (Yan et al. 2012), decreased growth rates of *Phaeocystis globosa* (Hoogstraten et al. 2012) and *Navicula directa* (Torstensson et al. 2012), and increased susceptibility to UVB-related photoinhibition in *P. globosa* (Chen and Gao 2011). Additionally, shifts in phytoplankton assemblages away from dominant diatoms (including *Phaeodactylum tricornutum*, *Thalassiosira pseudonana,* and *Skeletonema costatum*) have been observed in areas of increased CO_2 saturation and light exposure in the South China Sea (Gao et al. 2012).

Ocean acidification may also affect the toxicity of certain HAB genera. In an ocean acidification study on the species *Pseudo-nitzschia fraudulenta*, Tatters et al. (2012) found that when *P. fraudulenta* is both silicate-limited (as described above under "Increasing Ocean Temperature") and exposed to acidified waters, the rate of toxin production increased. At pCO_2 levels equivalent to those projected for 2100 in the California Current System (CCS) under some emissions scenarios, the domoic acid production of silicate-limited *P. fraudulenta,* more than doubled (Tatters et al. 2012).

In the pelagic ocean, the standing stock of particulate inorganic carbon (PIC) is contributed by calcifying marine organisms including coccolithophores, foraminifera, pteropods, and a number of other larval species of calcifying invertebrates (Balch and Fabry 2008). Coccolithophores are one of the most well-studied groups of phytoplankton with respect to OA; different studies have observed both increases in shell calcification (Tyrrell and Taylor 1996; Halloran et al. 2008) and decreases in shell calcification, including deformation (Riebesell et al. 2000; Zondervan et al. 2002; Bach et al. 2012) due to ocean acidification. However, the number of studies which found negative effects on shell formation outweighed those that found any positive effects, either directly or indirectly. Furthermore, a number of studies (Langer et al. 2006; Rickaby et al. 2010) report that OA effects are highly species dependent and others (Rost et al. 2008; Langer et al. 2009) have also observed further inconsistent reactions within the same species.

Coccolithophores may benefit from an increase in pCO2 concentrations due to the reduced energetic demands of harvesting CO_2 from the environment for photosynthesis (Riebesell 2004). Accordingly, several studies have observed positive effects on weight (Iglesias-Rodriguez et al. 2008), growth rates (Lohbeck et al. 2012), and even calcification (Halloran et al. 2008; Irie et al. 2010). Contrary to the majority of studies that observed reduced calcification of coccoliths in response to OA, Rost et al. (Rost et al. 2003) stated that an observed increase in calcification could be attributed to an increased availability of CO_2 in the coccilthophores species *Emiliania huxleyi.*

Sea Level Rise

Hallegraeff (2010) hypothesized that rising sea levels will marginally increase the extent of the continental shelf, providing additional shallow, stable water column habitats favorable to phytoplankton production and growth.

Upwelling and Upwelling Favorable Winds

The seasonal upwelling pattern characteristic of the OCNMS strongly influences phytoplankton assemblages by advecting nutrient rich water into the photic zone (Pitcher et al. 2010). Wind stress determines the incidence of upwelling and downwelling, which in turn influences the supply of macronutrients to the surface (Section 2.6). Wind-driven currents can transport phytoplankton away from a region and affect the size and frequency of formation of mesoscale features such as fronts and eddies. Wind intensity also strongly influences depth and intensity of vertical mixing on the ocean surface, thereby affecting phytoplankton access to nutrients, and light required for photosynthesis.

Potential changes in ocean current patterns can alter patterns of HAB occurrence. Areas where circulation is retentive, such as the Juan de Fuca Eddy (Office of National Marine Sanctuaries 2008), can support blooms of the diatom *Pseudo-nitzschia* (Trainer et al. 2002; Trainer et al. 2009) and high concentrations of domoic acid (Hickey and Banas 2003). The Juan de Fuca eddy is a cyclonic gyre located off the coast of Washington State near the mouth of the Juan de Fuca Strait and persists through the summer as water is upwelled onto the continental shelf. MacFayden et al. (2005) developed a model that describes the conditions under which high concentrations of domoic acid are exported from the Juan de Fuca eddy to shallow habitats in the OCNMS (Figure 4-3): A HAB initiates in the eddy, exports to the southeast during upwelling favorable winds, and then is advected on-shore during periods of downwelling favorable winds (Trainer et al. 2002; Hallegraeff 2010). While this assessment concludes that the timing, magnitude or duration of upwelling favorable winds are not likely to exceed current variability by 2100 (Section 2.6), such changes would be expected to influence the residence of HABs in the eddy, and the pattern of export to the coastal zone. Overall, unprecedented occurrences of toxic phytoplankton events may result (MacFadyen et al. 2005).

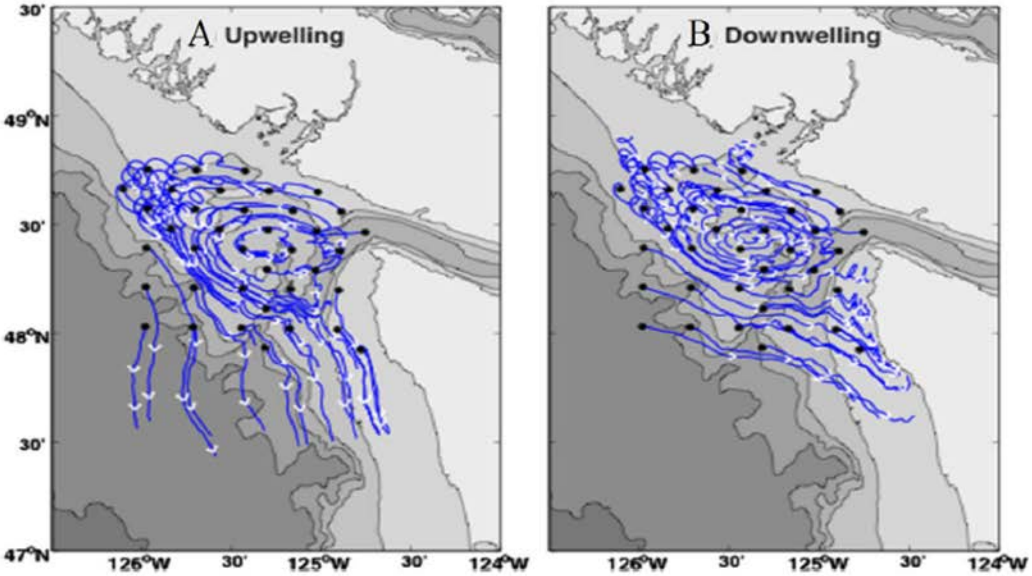


Figure 4-3. Modeled circulation patterns around the Juan de Fuca Eddy, a source of *Pseudo-nitzschia* blooms. (a) Upwelling scenario that allows phytoplankton (i.e. *Pseudo-nitzschia*) to escape the eddy (b) Downwelling scenario which pushes escaped phytoplankton on-shore, possibly transporting masses of toxic blooms. Figure from MacFayden et al. (2005).

Altered Hydrologic Patterns

Although diatoms appear to be negatively affected by water column mixing associated with river discharge, dinoflagellates often benefit from the increased nutrient availability (Granéli and Moreira 1990; Doblin et al. 2006), suggesting the possibility that increasingly severe winter flooding may impact phytoplankton assemblages. Increases in river discharge have also been linked to blooms of the dinoflagellates *G.catenatum* and *A.tamarense*, both of which can produce HABs (Hallegraeff 2010).

4.2 Zooplankton

4.2.1 Summary

- Zooplankton range-shifts, changes in timing of peak abundance, and differences in community composition may be expected in OCNMS due to climate change, and in particular increasing ocean temperature.
- As ocean waters acidify, a number of zooplankton will be affected by the decline in pH including foraminfera, pteropods, and many larval forms of calcifying species such as mussels, seastars, and urchins. However the response by

individual zooplankton species to increasing ocean acidification is likely to be variable.

4.2.2 Importance

As secondary consumers, zooplankton are the principle pathway for the movement of energy from primary producers to higher trophic levels (i.e. fish, marine mammals, and seabirds). Zooplankton therefore facilitate ecosystem services such as fishery production and nutrient cycling and regulate long-term climate via the "biological pump." Some of the CO_2 fixed by phytoplankton eventually sinks to the seabed, a process mediated by zooplankton through the production of fast-sinking fecal pellets and through daily vertical migrations during which they respire CO_2 at depth.

4.2.3 Zooplankton and Climate Change

Increasing Sea Surface Temperature

Increasing temperature and water column stratification require more energy to mix deep nutrient rich water into the photic zone. The resulting reduced nutrient loading to the surface ocean could decrease primary productivity and, therefore, zooplankton abundance. Zooplankton community composition may also change to one increasingly dominated by gelatinous zooplankton (e.g. salps, doliolids, ctenophores) under lower nutrient conditions (Richardson 2008).

Range-shifts of important zooplankton species, due to changes in temperature, are also projected. For example, in a study of copepods in the North Sea, Beaugrand et al. (Beaugrand et al. 2003) observed that the dominant zooplankton species, *Calanus finmarchicus,* has been replaced by *Calanus helgolandicus*, a copepod typically found in warm-water assemblages which has a lower biomass and is less nutrient rich than *C.finmarchicus*. In addition, *C finmarchicus* abundance peaks in spring whereas *C.helgolandicus* abundance peaks in autumn (Bonnet et al. 2005). These phenological differences are potentially important to higher tropic-level species that are timed to take advantage of increasing secondary production following the spring bloom. In the North Sea, Atlantic cod spawn in the spring and their larvae benefit from a diet of large copepods. Where *C.finmarchius* abundance is reduced cod recruitment has been shown to be negatively affected (Beaugrand et al. 2003).

A similar shift in peak abundance has also been observed in the north Pacific Ocean where the copepod *Neocalanus plumchrus* typically dominates the zooplankton biomass during spring and early summer (Mackas et al. 1998). The timing of the annual maximum in abundance of this copepod shifts by up to 60 days earlier during warm water years (associated with, for example, ENSO events or the "warm" phase of the PDO; See Section 6.3) as compared to cold years (Mackas et al. 1998). This shift in the timing is ecologically significant because it will likely influence the amount of food available to economically important higher trophic level species such as salmon, herring, hake, and seabirds. Both the predator and prey communities involved in this changed phenology do not appear to respond to ocean warming synchronously, resulting in predator-prey mismatches that negatively affect higher trophic levels (Edwards and Richardson 2004).

Changes in copepod communities have also been documented off the central Oregon Coast from 1997 to 1998 (Peterson et al. 2002). In 1997, anomalous warming associated with an ENSO event caused prolonged changes in the copepod community which resulted in an increase in subtropical species and a near disappearance of the dominant temperate species.

Acidification of Ocean Water

As ocean waters acidify, a number of zooplankton species will be affected including pteropods, foraminifera and many larval forms of calcifying species such as mussels, seastars, some crustaceans and urchins (Brierley and Kingsford 2009). Pteropods are marine planktonic molluscs that are very important in temperate and polar food webs and are believed to be susceptible to ocean acidification because of their thin and soluble aragonitic shells. Increases in ocean acidification will affect both larval and adult form of pteropod species (Bednarsek et al. 2012; Seibel et al. 2012). At a pH of 7.82 (projected by 2100 under some emissions scenarios; see Figure 2-7) larval pteropods exhibited malformations and reductions in shell growth and at a further reduced pH of 7.51, the pteropod larvae were not able to repair or manufacture new shell material (Comeau et al. 2010). In the Pacific Northwest, most pteropod species form aragonite shells (Mackas and Galbraith 2012). Impacts to pteropods due to ocean acidification may radiate through the food web since pteropods are an important source of nutrition for salmon and other fish species (Armstrong et al. 2005).

Foraminifera are amoeboid zooplankton which produce a calcium carbonate shell and are responsible for a large proportion of the global deep-ocean flux of calcite (Schiebel 2002). Foraminifera produce an elaborate shell made of calcium carbonate, the formation of which could be affected by the acidification of ocean waters. In a study of two foraminifera species (*Orbulina universa* and *Globigerinoides sacculifer*), Lombard et al. (Lombard et al. 2010), found that calcification rates significantly declined, by 6 to 13%, in acidified conditions projected under the IPCC's IS92a emission scenario (See Section 6.1). Similarly, in a study of the foraminfera species *Marginopora kudakajimensis*, (Kuroyanagi et al. 2009) found that at a pH of 7.7, both the shell diameter and shell weight significantly declined.

Copepods are one of the most abundant multi-cellular animals on Earth and serve as important linkages in marine foodwebs, especially to larval fish (Turner 2004; Schminke 2007). Ocean acidification studies conducted on a number of different copepod species have led to varying results. While some species are able to increase their respiration and feeding rate to compensate for the increased metabolic demands associated with increasing acidity (Li and Gao 2012), others were unable to undertake such compensatory mechanisms (Pascal et al. 2010). After observing responses by the copepod *Tisbe battagliai* to declining pH levels, (Fitzer et al. 2012) created a multi-generational model and projected a gradual decline in naupliar production over a 100 year timeline. A study by (Rossoll et al. 2012) showed that OA may also affect copepod populations through food web dynamics; the authors observed that under increased pCO_2 scenarios, the fatty acid composition of the diatom *Thalassiorsira pseudonana*, a primary prey for the copepod *Acartia tonsa*, decreased, resulting in decreased growth and reproduction of the copepod. Changes in these fundamental trophic linkages (i.e. diatom-copepod) form the base of many food webs and therefore may influence the entire trophic system.

Increasing Frequency and Severity of Storms

In the Pacific Northwest, winter storms may cause down-welling—the wind-driven movement of warm, surface ocean water toward the coast (Section 2.6). In summer, down-welling events interrupt seasonal upwelling, temporarily capping nutrient inputs and collapsing the productive region towards shore. Breaks in upwelling are necessary for maximum ecosystem productivity because they allow the build-up of phytoplankton and zooplankton populations that would be flushed offshore with continuous upwelling (Botsford et al. 2003). Changes in the frequency and severity of summer storms may, therefore, partly determine whether total productivity increases or decreases in the future: downwelling events that are too long or too frequent decrease total production. The effects of increasing winter storms, which occur during the downwelling season, are less clear.

Upwelling and Upwelling Favorable Winds

Conditions prevalent during patterns of climate variability (see Section 6.3) may be useful as indicators of long-term climate change. Peterson and Schwing (2003b) found that during the PDO "warm" phase, upwelling in the California Current System (CCS) diminishes and warm conditions prevail associated with a northward expansion of warm water species, declines in the dominant copepod biomass, and also a reduction in Coho salmon abundances occurs. Keister et al. (2011), who explored mechanistic linkages between the PDO and changes in zooplankton communities in the northern CCS, found that a large proportion of the multiyear variability in zooplankton communities could be attributed to PDO-related changes in the magnitude and timing of onshore-offshore surface flow associated with upwelling. More specifically, they observed that during "warm" phases of the PDO, warmer waters and the associated warm-water zooplankton community was transported onshore whereas during "cold" phases, cold-water taxa dominated due to enhanced upwelling. Because cold-water and warm-water zooplankton communities differ in the size of individuals and their lipid content, these changes in advection have the potential to alter trophic dynamics.

ENSO events also affect zooplankton. During positive ENSO events, primary production is reduced and downwelling conditions predominate (Section 6.3). In 1997-98 there was a strong and prolonged El Niño event which resulted in a significant decrease in copepod biomass and a shift from cold water copepod species to a shelf dominated by warm water copepods off Oregon (Peterson et al. 2002). The investigators suggested that the disappearance of the local cold water copepods was not the result of mortality, but rather the copepods were advected to the north by poleward surface flows. This shift in species composition has consequences for the rest of the food web because warm water species are typically less nutritious (less fatty acids) than the local cold water species (Keister, pers comm.).

Increasing Occurrence of Coastal Hypoxia and Anoxia

A number of studies have documented changes in the distribution, abundance, and community composition of zooplankton in response to repeated episodes of hypoxic/anoxic conditions in estuarine and coastal environments (Marcus 2001; Powers 2001; Purcell 2001). The mortality of a number of zooplankton species increases markedly at dissolved oxygen concentrations that are < 1.43 to 2.0 ml l^{-1} (Marcus 2001). Extreme shifts in zooplankton community structures due to hypoxia/anoxia could alter predator-prey interactions and affect population dynamics on long time scales. Roman et al. (Roman et al. 1993) suggested that hypoxic conditions could interrupt the phytoplankton-zooplankton linkage by decreasing recruitment to the zooplankton population. Then, in a positive feedback loop, during the time of peak phytoplankton bloom decreased zooplankton recruitment would lead to reductions in grazing, thereby increasing the volume of phytoplankton exported to the benthos. The decay of this productivity contributes to further dissolved oxygen depletion (Roman et al. 1993).

Additionally, the presence of hypoxic zones may make zooplankton more susceptible to predation by forcing zooplankton to move into more well-oxygenated areas and restricting vertical movement (a typical predator avoidance strategy) (Judkins 1980). However, Ekau et al. (Ekau et al. 2010) also suggested that hypoxia tolerance and threshold values are highly species and stage specific and can vary. In addition, species that can tolerate low oxygen zones may benefit by using them as predator refuges. Additionally, it is possible that over time some coastal species of zooplankton will adapt to repeated low oxygen concentrations (e.g. Ekau et al. 2010); however the rate at which oxygen decreases in the coastal zone may determine whether the current zooplankton community is able to adapt before being significantly altered.

4.3 Marine Algae, Seagrasses and Salt Marsh Vegetation

4.3.1 Summary

- A diversity of marine algae (seaweeds, kelps), benthic marine vascular plants (seagrasses) and salt marsh vegetation are found in the nearshore environment of OCNMS.

- Of these, kelp, seagrasses and surfgrasses and salt marsh vegetation can be broadly classified as foundation species, which have a large effect on community structure.

- While there are implications of changes to these foundation species to the marine ecosystems of OCNMS, the uncertainties associated with not only the interaction of a single species with the environment, but also with multiple species and non-liner interactions with multiple factors, makes our ability to predict resulting changes in this ecosystem very difficult.

4.3.2 Introduction

Salt marsh vegetation, benthic marine vascular plants (seagrasses), and a diversity of marine algae species (seaweeds, kelps) are found in the nearshore environment of OCNMS. Of these, kelp seagrasses and surfgrasses and salt marsh vegetation can be broadly classified as “foundation species,” defined as “having a large effect on community structure by modifying environmental conditions, species interaction, and resource availability through their presence” (Bruno and Bertness 2001). In general, the loss of these groups from an ecosystem may have implications out of proportion with their relative abundance. This section examines the status of these species groups within OCNMS, and examines their potential responses to climate change.Salt marsh vegetation, benthic marine plants and marine algae play a variety of often unquantified roles within the marine ecosystem of OCNMS. They are major primary producers in intertidal and near-coastal systems, and their contribution of detritus into both deepwater and upper intertidal habitats is a significant source of energy (Duggins 1988; Duggins et al. 1989; Britton-Simmons et al. 2009). The relative role played by this primary productivity source, versus primary productivity due to phytoplankton in the photic zone, is not clear, though.

Marine algae (particularly kelps and coralline algae) and benthic marine vascular plants also create biogenic habitat, or habitats formed by the physical structures of living organisms. These types of habitats can provide a full range of functionality: substrate for attachment of eggs, larvae, or adults, refuge from predation or camouflage for predators, sediment and larval trapping, and surfaces to support feeding on epiphytic biota (Duggins et al. 1990; Eckman and Duggins 1998; Eckman et al. 2003). Since marine algae and benthic marine plants likely provide these two functions in the Sanctuary- biogenic habitat (the physical beds), as well as primary production means that climate change-related impacts to the marine algal or plant community could have far-ranging effects in the rest of the ecosystem. (Schiel et al. 2004; Parmesan 2006; Connell et al. 2011; Johnson et al. 2011; Marzloff et al. 2011; McClanahan et al. 2011; Wassmann et al. 2011; Wernberg et al. 2011a; Chan et al. 2012; Menge 2012; Wernberg et al. 2012).

Trying to project changes in marine algae, benthic marine vascular plants and salt marsh vegetation due to global climate change is confounded by at least five poorly understood sets of interactions (Griffis and Howard 2012). First, the interactions between each of the direct global climate changes (sea level rise, temperature, ocean acidification); second, the interactions between indirect effects (i.e. consumer effects vs producer effects) and the resulting trophic cascades. (Connell et al. 2011). Thirdly, these interactions may not simply alter existing communities, but instead lead to entirely new or novel communities. “Short-term” human pressures such as harvest, pollutants, and eutrophication may interact with the effects of climate change (Wernberg et al. 2011b). Finally, diseases, parasites, and epiphytes are also thought to possibly play a major role in shaping algal communities, and the rate or processes by which they do so may change under increasing atmospheric or ocean temperature. Research must move away from the so called “climate envelope” approach (Zarnetske et al. 2012), focusing on single species and their interactions with the changing environment, to include all the multiple aspects of the biota and environment in order to adequately address and prepare for climate related changes.

In the absence of complex ecological models robust enough to explore ecosystem-scale changes, existing El Niño/La Niña patterns may give some inkling of the effects of changing ocean currents and upwelling. For example, kelp do well in cold nutrient-rich water during periods of upwelling (La Niña), and conversely do poorly in warm nutrient-poor waters (El Nino). A shift towards conditions similar to current extremes (i.e. El Nino) may predictably shift kelp communities (Glynn 1988).

Here a short summary of the status of benthic marine vascular plants, algae and salt marsh vegetation relative to OCNMS is provided. This is followed by an analysis of the impacts of the potential effects of climate-related changes on these foundation species.

Benthic Marine Vascular Plants- Seagrasses (Zostera marina) and Surfgrasses (Phyllospadix spp.)

Occurrence and distribution of eelgrass (*Zostera* spp.) in OCNMS are poorly documented and probably not widespread. Suitable sandy or muddy substrate needed for eelgrass may not be present due to high wave energy. In the Strait of Juan de Fuca, adjacent to OCNMS, many occurrences of what appear to be eelgrass beds are in reality a mixture of eelgrass and the surfgrass *Phyllospadix scouleri*. These two species are difficult to positively identify without samples of rhizomes and roots, as blades morphology can be quite similar. (Helen Berry, DNR, pers. comm.)

Phyllospadix species in OCNMS are also important. *P. scouleri* is a foundation species (Shelton 2010) and its loss would impact tide pool communities, biodiversity, and food web dynamics. Experimental removal of *Phyllospadix*, for example, led to increased water temperature in tidepool habitats, loss of crustose coralline algae and lowered diversity (Shelton 2010). *P. serrulatus* and *P. torreyi* are found in the lower intertidal and shallow subtidal on rocky substrates. All of these primary producers also provide biogenic habitat.

Marine Algae- Kelp

Species of kelp (Phaeophyceae, Order Laminariales) in OCNMS create a major biogenic habitat (kelp “forests” or beds) for nearshore adult organisms and spawning/ larval habitats for juvenile fish and invertebrates. Kelps are a source of nutrition for many organisms, not only within the kelp beds themselves, but also in intertidal (wrack) and deep water habitats. Over twenty species of kelp occur within OCNMS. Kelp abundance is variable over time in OCNMS (Figure 4-4 and Box 4-1), but significant and persistent changes in the distribution, abundance and species composition due to climate changes could have far reaching ecological effects.

BOX 4-1: Kelp Canopy Monitoring in OCNMS

Washington Department of Natural Resources monitors kelp canopies in the marine waters of Washington State, including within the boundaries of OCNMS, using near-vertical aerial photography, a method that efficiently censuses large areas. DNR has measured substantial increases in kelp canopies between 1989 and 2010 within its monitoring area, which spans from the Columbia River to Port Townsend. Increases within index polygons are common along the outer coast and the western Strait of Juan de Fuca, whereas stable and declining areas are more common along the eastern Strait.

The OCNMS management area reflects the same general trend as observed along the outer coast and western Strait - kelp canopy area has increased in the majority of index polygons (Figure 4-4). Two areas where losses have been observed within the OCNMS management area include:

- In Neah Bay - a small Macrocystis bed was present along the western shore in 1990 and 1991, with canopy-area less than 1 ha (Figure 4-4).
- On the shoreline South of Lake Ozette, declines have been measured in a small beds located south of Yellow Banks and north of Norwegian Memorial. The canopy ranged from less than 1 ha to 3 ha between 1989 and 2000, and was composed predominantly of Nereocystis, with some Macrocystis present. Kelp was absent in the area between 2001 and 2007, then Nereocystis was found there in 2008 and 2009 (Figure 4-4).

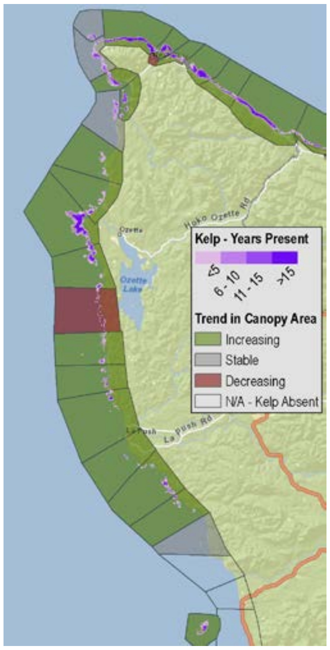


Figure 4-4. Trends in canopy-forming kelp between 1989 and 2010 within OCNMS. Persistence of kelp canopies (ie., number of years present) are shown in purple. Trends in total kelp canopy area within index polygons were assessed using regression analysis (p-value < 0.10). Figure courtesy of Helen Berry, WA Dept of Natural Resources

The kelp life cycle consists of a large sporophyte stage (the large "plant" that we see at the shore) that produces single-cell motile spores that germinate to become microscopic filamentous female or male gametophytes. Motile sperm fertilize the immotile eggs that then produce the sporophyte. Details of this life history are well understood and involve chemical pheromones, light intensity, light color, nutrient, and temperature cues (Bartsch et al. 2008; Bolton 2010). Understanding the effects of global climate change on kelp and kelp communities requires an understanding not only of the biology and ecology of the conspicuous sporophyte but also the cryptic and poorly understood gametophyte phase and the motile stages linking both (Figure 4-5).

Marine Algae- Coralline Algae

Coralline algae are a group of red algae (Rhodophyta) with strongly calcified cell walls containing calcium carbonate ($CaCO_3$). Coralline species are either crustose or upright, with some species having both morphologies (basal crustose holdfast with upright fronds). Crustose coralline algae interact with many invertebrates (abalone- recruitment; urchin- herbivory; chitons- herbivory) and are both influenced by and influence many organisms. They are also some of the deepest occurring marine plants- some are found in Washington at depths of over -35 m relative to mean lower low water.

Ocean acidification affects these plants in several ways. It will change the plant's ability to photosynthesize and uptake carbon (Cornwall et al. 2012), the ability to build and maintain calcification in the cell walls, resulting in changes in susceptibility to herbivory (Harley et al. 2012), and changes in other metabolic pathways.

Marine Algae- Other

While there is no exhaustive list of marine algae found in the Sanctuary the number of species may easily exceed 400 (Gabrielson et al. 2012). This is an enormously diverse group, not only in numbers, but in ecological roles, productivity, and ecosystem and trophic linkages. Understanding the effects of climate change in the marine ecosystem is complicated by the variety of unique phenologies, life history attributes, habitat requirements, and physiological responses to climate changes of these myriad marine algal species (Mumford et al. 2007).

Salt Marsh, Spit/Berm, and Dune Vegetation

Salt marshes are those areas populated with emergent salt-tolerant wetland plants such as pickleweed (*Salicornia virginica*), saltgrass (*Distichlis spicata*), and sedge (*Carex lyngbyei*) and the non-native *Spartina* spp. (Saliskar and Gallagher 1983). These areas commonly consist of sand or mud substrates. Spit and berm plant communities are those areas dominantly covered with plants such as dune grass (*Elymus mollis*), gumweed (*Grindelia integrifolia*), and yarrow (*Achillea millefolium*), which generally occur above the highest tides, but still receive salt influence. The substrate is usually sand or gravel, and drift logs commonly accumulate in this community (Berry and Ritter 1997). Salt marshes in OCNMS are relatively sparse, found in small patches near the mouths of streams and river. Spit berm vegetation is found in a narrow band in the high intertidal and is often associated with the log line. Salt marshes provide functions such as carbon sequestration, nutrient cycling, detritus export, sediment filtering, and critical habitat for shorebirds and out-migrating salmonids. Spit/berm and dune vegetation provides substrate anchoring and nesting habitat for various birds such as oystercatchers and snowy plovers.

4.3.3 Possible Climate Change Impacts

Increasing Ocean Temperature

Increasing ocean temperature may result in altered physiology, growth, and reproduction of kelps, as well as changes to competitive interactions. The timing and duration of changes in temperature will also be important; changes that are more pronounced during the early spring sporophyte growth burst or during dormant winter months may disproportionately influence the overall life history of marine algae. Harley et al. (2012) summarizes the effects of temperature and acidification on the various phases in the life history of the giant kelp, *M. pyrifera* (Figure 4-5) and concludes that most effects are likely deleterious. However, uncertainties about temperature and acidification related changes, during fertilization and dispersal primarily, are numerous (Wernberg et al. 2011b).

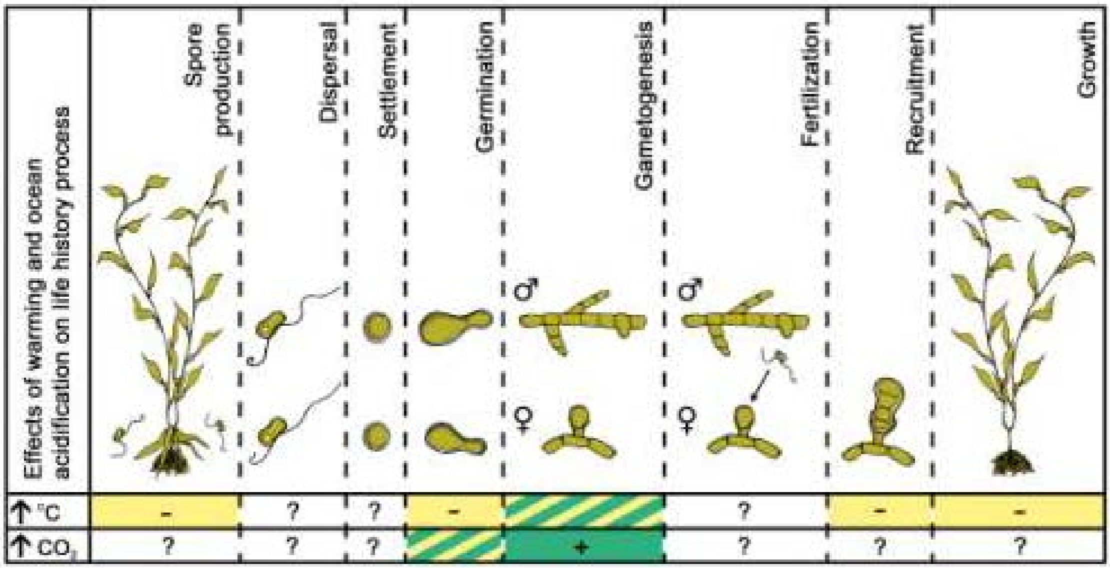


Figure 4-5. Generalized consequences of increased temperature and ocean acidification on the life history phases of the kelp *Macrocystis pyrifera.* Yellow boxes with '-' suggest that the effect is deleterious to the algae, green boxes with '+' suggest a beneficial effect, boxes with hatches suggest no net effect, and white boxes with '?' suggest that there is inadequate knowledge to determine the net consequence. Figure from Harley et al. (2012)

In some species of kelp it has been shown that reproduction can only take place within narrow temperature thresholds (Mumford et al. 2007). Changes in temperature may allow non-native species that are already in OCNMS (such as *Sargassum muticum*) to increase their abundance (Miller et al. 2011; Philippart et al. 2011) , or other species to recruit. The invasive kelp *Undaria pinnatifida* ("wakame") has been introduced into the San Francisco and San Diego areas of California, for example. It tends to occur in slightly warmer waters than are currently observed in OCNMS, suggesting the possibility that under increasing ocean temperature this kelp may move into OCNMS (Thornber et al. 2004; Macreadie et al. 2011; Miller et al. 2011). Additionally, investigators studying algae and invertebrate assemblages around the warmer water of a coastal power plant discharge in California reported that, “the communities were greatly altered in apparently cascading responses to changes in abundance of several key taxa, particularly habitat-forming subtidal kelps and intertidal foliose red algae. Many temperature-sensitive algae decreased greatly in abundance, whereas many invertebrate grazers increased. The responses of these benthic communities to ocean warming were mostly unpredicted and strongly coupled to direct effects of temperature on key taxa and indirect effects operating through ecological interactions” (Schiel et al. 2004). These various processes may drive shifts in the range of marine algae and lead to changes in the composition of the algae community within OCNMS. A northward shift in the distribution of marine algae species is correlated with increasing sea surface temperatures (Parmesan 2006).

Kelps and marine algae in the California Current System (CCS) are already exposed to considerable variability in ocean temperature and may therefore be somewhat resilient to climate-related forcing. In California research suggests that gametophytes of the kelp *Macrocystis* can delay reproduction in the face of high temperatures/low nutrients (during El Niño for example). Under more “ideal” conditions, however, the algae can quickly produce sporophytes (Kinlan et al. 2003; Carney 2011).

Increase in seawater temperature has already been implicated as a cause of major losses of eelgrass (Short and Neckles 1999; Moore and Jarvis 2008; Waycott et al. 2009; Franssen et al. 2011; Carr et al. 2012; Moore et al. 2012). However, the interactions between eutrophication, salinity, temperature and light levels on eelgrass are poorly understood (Short and Neckles 1999; Moore and Jarvis 2008; Moore et al. 2012). *Phyllospadix* appears to be nutrient limited in its more southern range (Ramirez-Garcia et al. 2002) suggesting that temperature changes may have less influence on distribution, at least in parts of the species’ range. An increase in frequency and severity of storms and increase in sea level will present an additional stress - these communities may be compromised due to increased erosion and overwash of berm tops.

Ocean Acidification

Increasing concentrations of CO_2 in seawater may benefit marine algae by making the raw materials for primary productivity more readily available (Raven 1997; Roleda et al. 2012) (Doney et al. 2009b). Similarly, an increase in available CO_2 has been found to increase the productivity of benthic marine plants (Thom 1996). The interaction between ocean acidification (OA) and temperature, though, has been shown to be important for some marine algae (Diaz-Pulido et al. 2012), and it isn’t clear that the relative benefits of higher CO_2 concentration will outweigh the negative benefits of increasing temperature.

OCNMS, at the northern end of the CCS, is characterized by a highly dynamic and productive upwelling ecosystem. Contemporary pH and CO_2 concentrations vary with periodic intrusions of deep, high CO_2 water. However, current conditions may not be severe enough to influence abundances, and other factors are likely to interact with OA, possibly enhancing or negating the expected effects of high CO_2 on calcification (Menge 2012). Calcareous coralline algae (CCA) is considered to be highly susceptible to OA due to the incorporation of calcium carbonate in its tissues. Harley et al. (Harley et al. 2012), for example, suggest that OA may result in the loss of calcified organisms (including CCA's), and an increase in turf algae and kelp species. Diaz-Pulido et al. (Diaz-Pulido et al. 2012) show that the interactive effects of OA and increasing temperature are underestimated for CCA's, and that combined interactive effects will compromise CCA's at much lower levels of acidification than might otherwise be expected. However, some field experiments in intertidal tidepools suggest that the high variation in microenvironments found near CCAs may promote acclimatization to extreme pH conditions (Guenther et al. 2011).

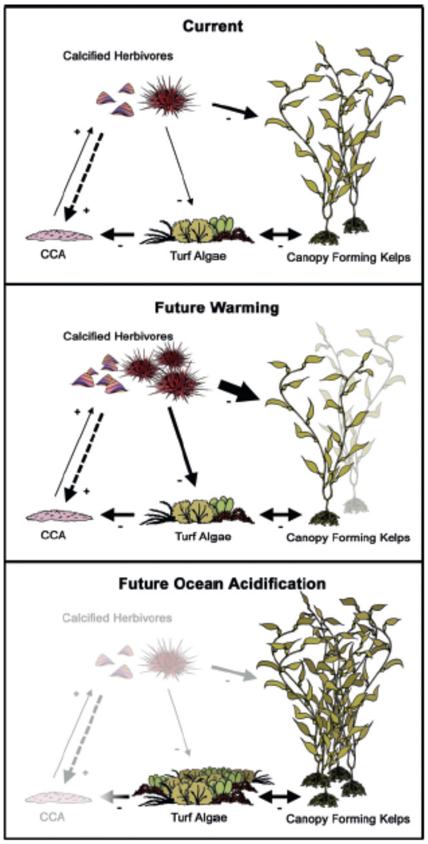


Figure 4-6. Changes in calcified herbivores, crustose coralline algae, turf algae, and canopy forming kelps under changes in temperature and ocean acidification regimes. Figure from Harley et al. (2011).

Sea Level Rise

Sea level rise may decrease the amount of light available to marine algae and benthic plants, due to light attenuation through the increased length of the water column. In some instances vegetation may compensate by moving into shallower water, but whether this is possible will depend on the geomorphology of the shoreline and the rate of change. Increased water depth may also change patterns of desiccation in the intertidal zone and vertical distributions of intertidal algae and benthic plants. The interaction of sea level rise and increased turbidity from winter floods may further compromise eelgrass beds (Stevens and Lacy 2012).

Similarly, increasing seawater and air temperature will likely change the vertical distribution (zonation) and geographic range of saltmarsh plants. Sea level rise, though, may simultaneously change the habitat configuration for this community, which is already confined to a very narrow vertical tidal range. In some areas salt marshes are backed by upland areas, so landward movement of the marshes is restricted. In estuaries and marshes, sea level rise can be expected to cause inundation of existing salt marsh habitat unless the rate of sediment accumulation can keep up with the sea level changes.

Increasing Frequency and Intensity of Storms

Frequent severe storms have been shown to decrease kelp forest food web diversity and complexity (Byrnes et al. 2011). Additionally, kelp depend on the availability of large hard substrates (bedrock, boulders and cobble) to provide a stable substrate for attachment (Emery and Tschudy 1941). The availability of these substrates may depend on nearshore sediment dynamics (erosion or burial of bedrock and boulders) that could be influenced by changes in sea level or increasing wave energy. CCA's may be similarly influenced by storms. An increase in frequency and severity of storms may affect coralline algae as they tend to occur on boulders and cobble and the degree to which these substrata are rolled and disturbed will determine what organisms can grow on them. Finally, wave action can directly damage seagrasses via uprooting or blade breakage, and indirectly through re-suspension of sediment and subsequent reduction of light levels. (Duarte 2002). Therefore, increases in storm intensity may impact the suitability of shallow water habitats for all classes of marine algae, benthic marine vascular plants and salt marsh vegetation.

Altered Hydrology

The timing of fresh water discharge from coastal streams appears to influence the distribution of the giant kelp *Macrocystis* (Druehl 1978; Watson and Estes 2011). The discharge of fine sediment into the coastal zone from glacers has been shown to decrease marine algae species richness due to changes in salinity, light, and increased sedimentation (Spurkland and Iken 2011). Further, it is becoming clear that the Fraser River in British Columbia, the Skagit River in Puget Sound, and the Columbia River can influence salinity, nutrients, turbidity, and hypoxia in OCNMS (Hickey et al. 2010). Therefore, large-scale climate-related changes to hydrology in the region's rivers may have subtle but important effects on marine algae and benthic marine plants in OCNMS.

4.4 Deepsea Corals

4.4.1 Summary

- The most potentially damaging effect of climate change on deep-sea corals is ocean acidification, which could compromise skeleton formation and may have other sub-lethal impacts.
- Deep-sea corals live at lower carbonate saturation states than shallow tropical species, and some can tolerate long-term under-saturation; however changing conditions may cause a loss of those species already close to their tolerance limit, resulting in alterations to community structure.

- Changing ocean temperature and oxygen concentration may both influence deepsea corals, but neither is projected to be as detrimental to corals as acidification.

4.4.2 Introduction

The term ‘coral’ is most commonly associated with tropical shallow reef ecosystems, but over the past decade, corals that live in deep waters have come to the attention of scientists, legislators and the general public. Deep-sea corals are found in all the world’s oceans. Many deep-sea coral species are very slow-growing and long lived; for example a black coral specimen from Hawaii was recently aged at 4265 years and another from the Gulf of Mexico at over 2000 years (Roark et al. 2009). In some regions precious corals (such as black, gold or red corals) are harvested for their decorative skeletons, which are used to make jewelry and curios. Their slow growth and long lifespans make deep-sea corals vulnerable to overharvesting, physical damage and climate change.

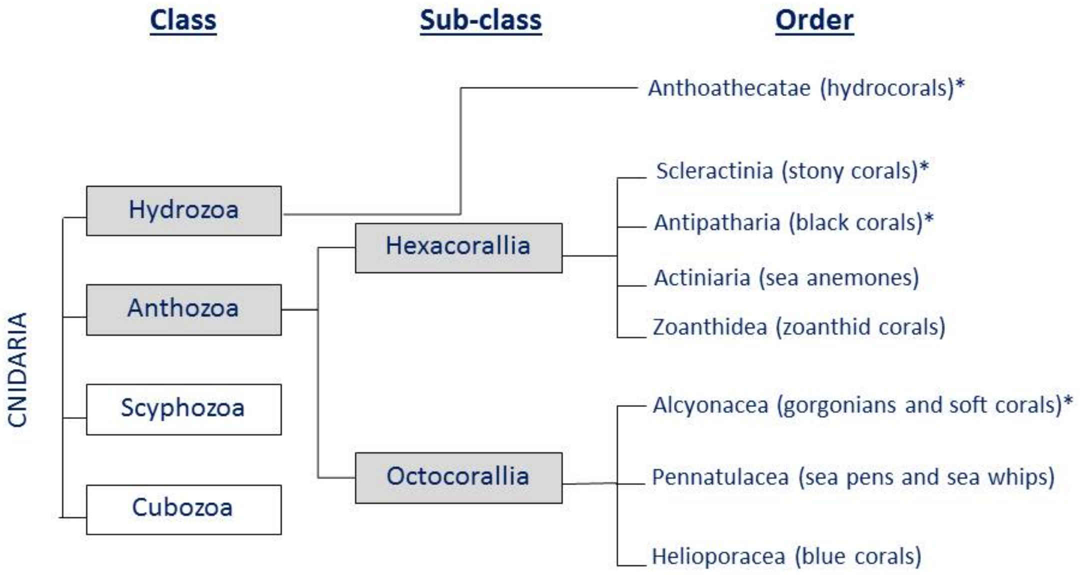


Figure 4-7. Relationships among major coral taxa; deep-sea corals fall into two main categories, the Hydrozoa and Anthozoa, and four Orders (marked with ‘*’).

Corals (phylum: Cnidaria; Figure 4-7) are marine animals that fall within the taxonomic classes of Hydrozoa and Anthozoa. The hydrozoa, or hydrocorals (order: Anthoathecatae) usually form small compact colonies with a brittle skeleton made of calcium carbonate (Figure 4-8a). They can be very diverse and abundant in some regions, creating complex structure for other invertebrate fauna. Within the Anthozoa there are two subclasses, the

Hexacorallia (whose polyps have multiples of six tentacles) and the Octocorallia (which have multiples of eight tentacles). Deep-sea corals fall into the same functional categories as their shallow counterparts. Stony corals (order: Scleractinia) have hard calcified skeletons and can form large colonies that coalesce to create massive geological structures such as reefs or bioherms (large structures formed from dead coral skeletons and sediment). Some stony corals do not form colonies, but exist as individuals; these solitary or ‘cup’ corals do not contribute greatly to reef structure, but may be very abundant locally (Figure 4-8b). The most diverse corals in both shallow and deep waters are the gorgonians (order: Alcyonacea, formerly Gorgonacea); these are commonly known as sea fans or tree corals (Figure 4-8c). As the name suggests, they create tree-shaped colonies with branches in various configurations. Gorgonian skeletons are much more flexible than stony corals as their skeletons are made primarily of a protein called gorgonin. Gorgonian tissue also contains small calcareous supportive structures called sclerites. In some cases, the gorgonin skeleton is absent, and the colony is supported completely by these densely packed sclerites. Skeletons of the gorgonian family Isididae are composed of ‘nodes’ of gorgonin interspersed with “internodes” of calcium carbonate, giving the corals the appearance of bamboo, and the common name “bamboo coral.” Similar in appearance to the gorgonians, but more closely related to the stony corals, the black corals (order: Antipatharia) form tree-like structures but with skeletons made of protein and chitin (Figure 4-8d). All of the above groups are found in rocky habitats as they need hard substrate to anchor the colonies. Sea pens and sea whips (order: Pennatulacea) colonize soft sediment, and can form large dense patches or ‘groves’ in some locations (Figure 4-8e).

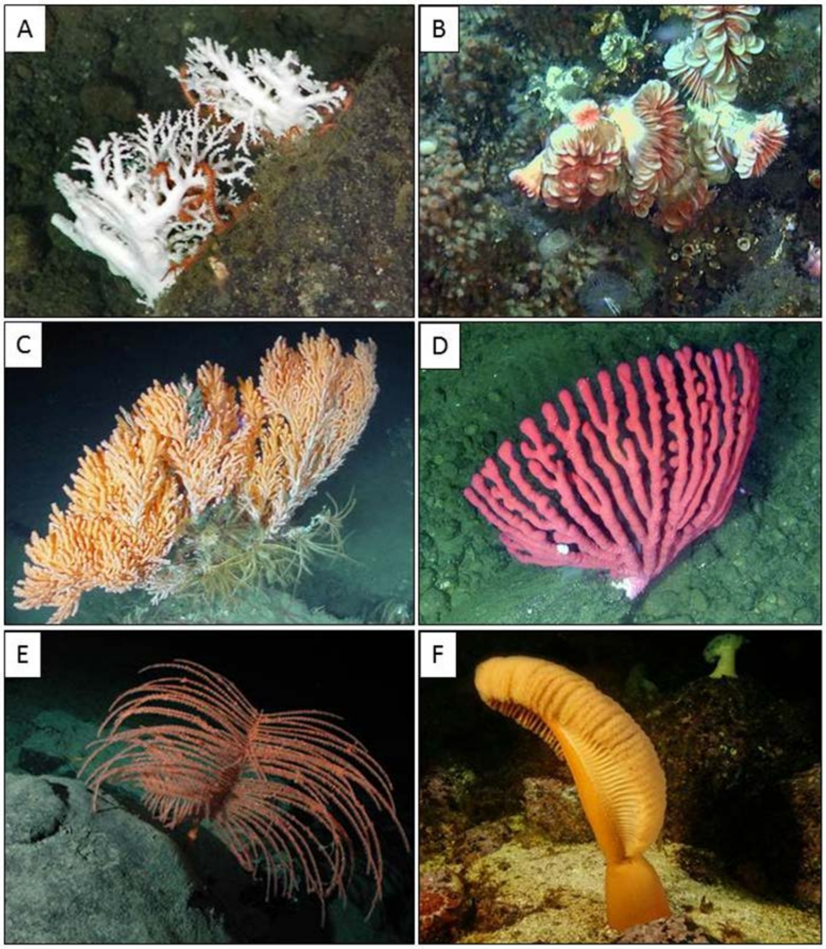


Figure 4-8. Images of representative groups of deep-sea corals that occur along the Pacific northwest deep shelf a) hydrocorals (*Stylaster* sp.); b) stony corals (*Desmophyllum dianthus*); c) and d) gorgonians in the OCNMS (*Primnoa resedeformis* and *Paragorgia arborea*); e) Black coral (*Bathypathes* sp.); sea pens (*Ptilosarcus* sp). Image credits. A-D: OCNMS; D: Marine Conservation Institute; E: David Wrobel Photography.

Deep-sea corals in the OCNMS

In 2004 a research cruise aboard the NOAA Ship *McArthur* surveyed offshore hard bottom areas of the OCNMS (147-265 m depth) in search of coral and sponge communities. During this cruise, the stony coral *Lophelia pertusa*, a relatively rare species in the northeast Pacific, was documented for the first time within the OCNMS (Hyland et al. 2005), together with several other species of stony corals, gorgonians, and hydrocorals. Subsequent expeditions (2006, 2008) discovered additional *L. pertusa* colonies (Figure 4-9) and dense patches of gorgonians. The discovery of *L. pertusa* and other corals within the OCNMS boundary was a contributing factor to the establishment of the Olympic 2 Conservation Area, which prohibits non-tribal trawling in approximately 7% of the sanctuary. In all, more than 40 species of sponges and 18 species of corals have been documented from within the OCNMS boundaries (Brancato et al. 2007), and these numbers will probably increase with further exploration. Below, the potential effects of three climate change-related impacts in OCNMS, increasing ocean temperature, ocean acidification, and hypoxia, are summarized for the deep-sea coral communities of OCNMS.

4.4.3 Climate Change and Deepsea Corals

Increasing ocean emperature

Temperature is thought to be one of the primary drivers of distribution of deep-sea corals (Roberts et al. 2009). For example, *Lophelia pertusa* has been observed in temperatures from 4 – 14^{o}C (Rogers 1999; Freiwald et al. 2009); however the upper thermal limit for this species is not currently known. Generally, however, thermal tolerances are not documented for the vast majority of deep-sea coral species. As with other types of stressors, increasing temperature would initially cause sub-lethal effects, and would ultimately result in mortality if the stressor became more severe or lasted for extended periods of time. In addition, corals may be more vulnerable to unusual temperature regimes if already under stress from other factorst is not clear that projected changes in ocean temperature for OCNMS (Section 2.2) would affect deep benthic communities. However, if unusually warm conditions were to reach the deep corals, it could cause sub-lethal stress and ultimately shift the distribution of the coral communities into colder water.

Ocean Acidification

Over the past decade, concern over rapidly increasing atmospheric CO_2 levels has stimulated a great deal of concern amongst the scientific community on how changing ocean chemistry will affect marine organisms, particularly those with calcified structures such as corals. Almost all of this research however has focused on shallow tropical corals, and their deep-sea counterparts have been neglected by comparison. Although some of the responses of shallow corals may be similar to those from the deep-sea, the environmental conditions are very different between the shallow and deep coral habitats. For example, according to Kleypas et al. (1999a; 1999b) the average aragonite saturation state (Ω_{arag}) of shallow tropical reefs is 3.83, and the authors postulated that reef growth will cease when $\Omega_{arag} < 3.3$.By contrast,many deep-sea corals live in environments that are naturally at much lower saturation states than those found in shallow tropical waters (Thresher et al. 2011). However, deep-sea corals may be particularly vulnerable to further reduced saturation states caused by anthropogenic changes (Guinotte et al. 2006; Turley et al. 2007). The reduction in availability of biogenic carbonates (aragonite and calcite) is expected to negatively affect skeleton formation (Langdon and Atkinson 2005; Cohen and Holcomb 2009), cause shifts in community composition away from calcified species and generally reduce the viability of both shallow tropical and deep-sea coral reefs in the long term (Hoegh-Guldberg et al. 2007; Guinotte and Fabry 2008; Riegl et al. 2009). hose corals that live on continental slopes can colonize shallower substrate, but may ultimately be constrained by temperature or other critical environmental conditions. Current predictions on the fate of corals under elevated atmospheric CO_2 conditions were derived primarily from modeling studies and short-term laboratory exposures (mostly on shallow tropical corals). Although these data are useful, they do not provide information on long-term effects of reduced carbonate saturation state, or on adaptation capacity in deep-sea corals. Field observations may provide insight into how carbonate saturation states may affect coral distribution and biology. Thresher et al. (2011) studied distribution, skeletal density and growth of various deep-sea coral taxa on a seamount off Tasmania, from 941 to 4011 m depth, where Ω_{arag} ranged from 1.24 to 0.61. The study showed no carbonate-dependent distribution of taxa with either aragonite or calcite skeletons; the maximum depth of those with aragonite or HMC (high magnesium calcite) skeletons did not differ statistically from those with no calcified structures. Corals of various taxa could therefore survive long-term conditions of up to 30% under-saturation with no discernible impact on distribution, growth rates or skeleton density and structure. There were two exceptions to this overall pattern: two colonial structure-forming stony corals (*Solenosmilia variabilis* and *Enallopsammia rostrata*) were always clustered on or above the aragonite saturation horizon (ASH), and the deepest bamboo coral collected (4011 m) showed evidence of compromised growth patterns and eroded outer surfaces. At this depth Ω_{arag} was approximately 40% under-saturated and the coral could no longer maintain normal skeletal deposition. Laboratory experiments have shown a non-linear response to 'acidified' conditions by temperate shallow-water corals (Holcomb et al. 2010; Ries et al. 2010), indicating that these taxa can compensate for low carbonate levels up to a point, beyond which there are signs of biological stress.

The distributional findings by Thresher et al (2011) are supported elsewhere in the literature; both solitary (cup) scleractinians and bamboo corals have been reported well below the aragonite and HMC saturation horizons at 6 km (Fautin et al. 2009) and 4 km (Roark et al. 2005) depth. The distribution of most structure-forming scleractinians however generally coincides with the approximate depth of the ASH (Guinotte et al. 2006), so these corals may have more stringent carbonate saturation requirements than other coral taxa. There is a fundamental difference between the reef building species and those that grow as individual colonies. In the latter, the entire colony is usually alive and covered with tissue, but dead coral skeleton is a vital component of deep-sea coral reefs as it provides the underlying support structure that allows the reefs to grow. This may explain why these ecosystems are generally found in carbonate-saturated environments; exposed skeleton would dissolve in under-saturated conditions and undermine the entire reef structure.

The globally distributed reef-building coral *Lophelia pertusa* (Figure 4-9) was exposed to elevated atmospheric CO_2 conditions for 6 months in the laboratory (Ω_{arag} treatments = 1.4, 1.0, 0.9), and showed no reduced calcification or increased metabolism (an indicator of stress) in any of the treatments (Form and Riebesell 2012); however the lowest of these treatments was close to aragonite saturation, so how the corals would have responded to more severe under-saturation is unknown.

Figure 4-9. A photograph of *Lophelia pertusa* (upper field) from OCNMS, along with a Rosethorn Rockfish (*Sebastes helvomaculatus*; field left) and a Redbanded Rockfish (*Sebastes babcocki*; field right). Image: OCNMS

Field studies suggest a more optimistic outlook for deep-sea corals than some of the experimental work, as it appears that many species can survive under-saturated conditions. This observed tolerance may be explained by the protective layer of tissue that covers coral skeletons (the calicoblastic layer or coenenchyme). The tissue controls the internal chemistry of the animal and not only creates skeletal structure, but provides a barrier between ocean conditions and the vulnerable skeleton (McConnaughey 1989; Adkins et al. 2003; Cohen and McConnaughey 2003). Skeleton formation is an energetically expensive process (consuming up to 30% of available energy in shallow-water corals), but normal calcification rates can be maintained under sub-optimal carbonate conditions providing there is sufficient food to offset the additional energy costs (Cohen and Holcomb 2009). Although these observations were based on shallow coral taxa, elevated food supply could similarly compensate to some extent for low carbonate saturation conditions in deep-sea species (Thresher et al. 2011).

Increasing energetic costs of skeleton formation under an unchanging food regime may result in energy allocation away from other processes such as reproduction. Experimental research on shallow coral species has shown no impact of reduced pH on gametogenic cycles; however a recent study (Holcomb et al. 2010) shows that during spawning, female colonies are more susceptible to reduced pH than males. Producing gametes is energetically expensive, particularly for females as eggs have a high lipid content. The energetic demands of producing eggs, therefore may limit the energy available for normal skeleton formation under acidified conditions. The effects of acidification on coral reproduction and early life history stages were reviewed by Albright (2012); two studies showed reduced sperm motility, fertilization success and settlement rates (Albright et al. 2010; Morita et al. 2010), but the greatest impact was on the skeletal deposition of early juvenile stages (Cohen and Holcomb 2009; Suwa et al. 2010; Albright and Langdon

2011; de Putron et al. 2011). Elevated CO_2 levels reduced post-settlement growth rates of *Porites astreoides* by up to 78% (at 720 atm CO_2) (Albright et al. 2008). Reduction in the viability of early life history stages will ultimately cause coral populations to decline as older colonies die off but are not replaced by younger recruits.

As with any biological system, compensation for deteriorating conditions will not continue indefinitely and the corals will begin to manifest signs of stress. Sub-lethal effects generally occur first, followed by mortality. Species will undoubtedly differ in their ability to tolerate and adapt to changes to their ambient environmental conditions. Synergies between stressors (predation, increased temperature, disease) will also reduce the ability of corals to compensate.

Most of the corals in the OCNMS are gorgonians (Brancato et al. 2007), which for the most part do not have heavily calcified skeletons but still need carbonate to make spicules. Hydrocorals are also common; some use calcite to make skeletons and other species use the more soluble aragonite. The most vulnerable of the corals within the sanctuary are probably the scleractinians, particularly the colonial *Lophelia pertusa*. Off the Pacific West Coast, this species does not appear to form the large bioherms found elsewhere in the US (Brooke and Schroeder 2007; Ross and Nizinski 2007), but rather occurs as small aggregations of individual colonies. The reasons for this are not understood, but may be a function of sub-optimal environmental conditions, such as low carbonate, limited food, or high temperatures. The very limited experimental data and the in situ observations indicate that deep-sea corals have a higher tolerance to low carbonate concentrations than shallow tropical corals; however what is not clear is how much change each species can tolerate from their current “normal” carbonate state or how quickly they can adapt to long term changes. The water washing over the continental shelf will become more acidified over time, exposing deep-sea corals to increasingly frequent low carbonate conditions. The aragonite saturation horizon has shoaled by 40-200 m since the beginning of industrial revolution (Feely et al. 2004; Orr et al. 2005a). The most likely scenario for these deep species is that they will begin to exhibit signs of sub-lethal stress in compromised growth and skeletal density. Assuming current trends in aragonite saturation horizons persist, the corals may ultimately be unable to overcome the multiple effects of low pH conditions. In conclusion, if the projected changes in ocean chemistry become a reality they could result in changes to species’ distributions and the composition of deep coral communities in the OCNMS; however the timescale and extent of these impacts is difficult to predict.

Upwelling and Upwelling Favorable Winds

Changes in upwelling extent and frequency could impact deepsea benthic communities by further increasing the frequency or extent of corrosive waters flowing onto the continental slope and shelf (Section 2.6). Oceanographic models suggest the possibility of an increase in upwelling for California and Oregon, but there is no certainty regarding changes in the timing, intensity of magnitude of upwelling in OCNMS (Section 2.6). As a result, impacts on benthic communities in OCNMS due to changes in upwelling are difficult to project.

Coastal hypoxia and anoxia

Some deep-sea corals appear to be quite tolerant of short-term hypoxia, though most marine fauna cannot tolerate extended periods without oxygen. Laboratory studies on *Lophelia pertusa* showed high survival for several hours under hypoxic conditions (Dodds et al. 2007); however apart from this study there are virtually no data on tolerance of deep coral species to low oxygen. Increasingly frequent hypoxic or anoxic events on the continental shelf and slope (Section 2.7) suggest the possibility that more sensitive deepsea coral species could be negatively impacted, though the magnitude of that impact is unclear. If these events were to persist or recur beyond the ability of the deep coral communities to recover, then they would be lost, possibly permanently.

4.5 Mussels

4.5.1 Summary

- Under increasing atmospheric and ocean temperature, long-term consequences on mussel populations (i.e. *Mytilus californianus* and *Mytilus trossulus*) are likely to be both positive (increased growth) and negative (increasing/persistent thermal stress and exposure to predation).
- Ocean acidification is likely to have a negative impact on both adult and larval stages. Observations on the Washington coast suggest gradual shifts from mussel dominated communities to one dominated by fleshy algae corresponding with declines in pH (Wooton et al. 2008).
- When the effects from increased storm intensity and frequency are compounded with effects of ocean acidification (reduced shell thickness) and increased sea surface temperatures (reduced attachment strength), there may be increased mortality rates for mussels in the OCNMS.

4.5.2 Importance and Role in the Environment

Many benthic calcifying fauna such as mussels are prominent in nearshore communities and are economically and ecologically important. Mussels are “ecosystem engineers;” their beds are highly productive and provide essential habitat for a diversity of organisms (Gutierrez et al. 2003; Jones et al. 2009). At a given location, mussel beds can provide food and protection for up to 300 species (Suchanek 1992). Additionally, mussels serve as an important energy linkage between primary producers such as plankton and higher trophic level predators (Smith et al. 2006b). Given their ecological importance, any change in mussel abundance and productivity, regardless of the cause, is likely to cause numerous changes in ecosystem function.

On the open coast of Washington State there are two native bed-forming species of mussels, *Mytilus californianus* (California mussels) and *Mytilus trossulus* (blue mussels). *M.californianus,* the main bed forming mussel, is an ecologically dominant species in the rocky intertidal zones along the West Coast of North America (Paine 1966, 1974; Menge et al. 1994; Menge et al. 2004; Smith et al. 2006a). As an important prey item for the keystone species *Pisaster ochraceous* (Ochre seastar) and a competitive dominant species for space, *M.californianus* is also a key determinant of community structure in the intertidal zone (Menge et al. 2008). The second species, *M.trossulus* is usually found at a slightly higher elevation than *M.californianus*, typically forming a narrow band above the *M.californianus* bed, but zones of mixed species do frequently occur. A third species, *Mytilus galloprovincialis*, is an introduced mussel from the Mediterranean, which is common in Puget Sound but has not been documented on the high-energy outer coast (Steve Fradkin, ONP, pers. comm.).

4.5.3 Climate Change and Intertidal Mussels

Increase in sea surface temperature

Climate change will expose mussels to increasing ambient air temperature (see Section 1) and sea surface temperature (Section 2.2) conditions that may have a variety of consequences. Intertidal mussels are exposed to huge temperature ranges: in the Pacific Northwest, the intertidal zone is characterized by extreme conditions (freezing temperatures during winter night low tides and heat during summer daytime low tides)(Ricketts et al. 1985). Physiological performance of *M.californianus* is maximized at a body temperature of 17°-22°C and significantly declines at temperatures above 26°C (Bayne et al. 1976). However, according to a study by (Helmuth 1998), a solitary mussel can tolerate short-term exposure to internal (i.e. inside the shell) temperatures up to 40°C. Persistent exposures to higher temperatures associated with climate change may cause mortality (Jones et al. 2009) or stress. Mussels have a cellular-based mechanism to deal with thermal stress called heat shock response (Hsr). This heat shock response is characterized by the synthesis of heat shock proteins (Hsps) which function as molecular chaperones that are involved in the stabilization and refolding of denatured proteins and are expressed at high levels when the organism is exposed to thermal stress. Rising temperatures may require them to increase the frequency with which they activate this Hsr, incurring a metabolic cost (Place et al. 2008).

These negative consequences of elevated temperature may be mediated by at least one potential benefit. Several studies suggest increased ocean temperature is likely to promote mussel growth (Robles and Desharnais 2002; Menge et al. 2008). According to (Somero 2002), up to a certain point, warmer water temperatures will favor faster physiological rates which, holding all other factors (i.e. available nutrition, predation) equal, should promote increased growth in adult mussels.

Since increasing air temperature implies increased thermal stress during low tides, mussels may retreat to lower elevations in the intertidal zone (Menge et al. 2008) thereby reducing total available mussel bed habitat and increasing spatial competition in lower intertidal areas. Observations of a downward shift in the upper limits of marine invertebrates in conjunction with an increased warming trend have been observed in Victoria, British Columbia (Harley 2011) (Figure 4-10). Additionally, increasing temperatures are also projected to increase the metabolic rate and population size of sea stars such as *Pisaster ochraceous*, which could raise the predation activity (consumption per capita) that typically sets the lower limit of the mussel bed (Sanford 1999; Harley 2011). A significant increase in predation could directly eliminate large sections of the mussel beds before they can recover and indirectly displace the many other organisms dependent upon the mussels for food and shelter. Finally, because warmer temperatures may initially favor increased growth rates, lateral pressure within the mussel beds resulting from expanding mussel girth may also increase (Robles and Desharnais 2002). The increased lateral pressure will compound the spatial competition problem, as there will be less space for larger mussels. These lateral pressures are also likely to lead to a weakened attachment of the mussel to the underlying rock as they are pushed away from the bed surface by other larger mussels leaving them susceptible to dislodgment by storms (Seed 1992).

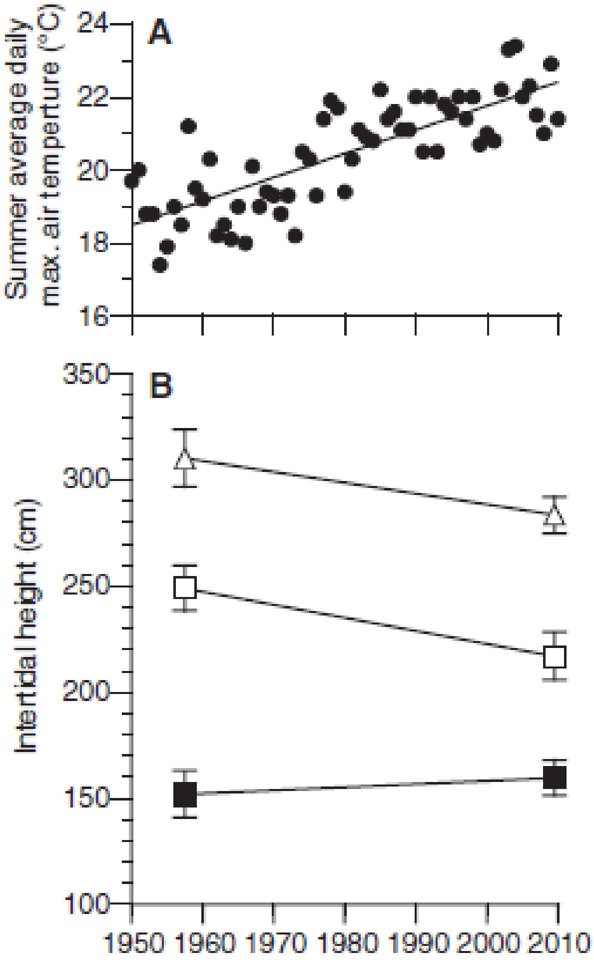


Figure 4-10. Changes in temperature and sessile invertebrate zonation over time. (A) Long-term trend in average daily maximum ambient temperature in Victoria, British Columbia for the summer months (June- August). (B) Upper limits of mussels (open squares) and acorn barnacles (open triangles) were significantly lower in 2009 to 2010. Mussel lower limits were not significantly different from historical limits. Taken from Harley et al (2011).

Climate change in the OCNMS may be associated with reduced primary productivity due to increased stratification and reduced mixing between warmer surface and cold, nutrient-rich water from depth (Corwith and Wheeler 2002). A warming trend along the California coast likely associated with shifts in climate regimes (See Section 6.1) has been linked to a decrease in overall biodiversity in mussel beds (Smith et al. 2006a). In a 2002 re-survey of mussel beds originally observed in the 1960s and 1970s, Smith et al.

(2006a) found a significant decline in mussel bed diversity at 22 sites along the coast of California. While the direct cause of this decline is speculative, the decline coincided with a PDO warm phase and was associated with drops in primary productivity (Smith et al. 2006a).

Although invasion by the non-native mussel *M.galloprovincialis* (documented in Puget Sound) is unlikely because of the high-energy environment of the wave swept outer coast, *M.galloprovincialis* has a greater heat tolerance than the native mussels and has already displaced the native *M.trossulus* from its former southern range limit up to Monterey Bay, California (Geller 1999). Therefore, while invasion may be unlikely, consideration of this invasive mussel should be noted especially in sheltered bays and harbors off the coast.

In summary, under a warming scenario, long-term consequences are likely to be both positive (increased growth) and negative (increasing thermal stress and exposure to predation). As a result there is no clear projection for future patterns of mussel abundance or distribution in OCNMS.

Ocean Acidification

Molluscs with calcium carbonate shells such as mussels are susceptible to ocean acidification. As pH decreases, so does carbonate availability, which may result in reduced rates of calcification (Gattuso et al. 1999), shell dissolution (Feely et al. 2004), reductions in protein synthesis and ion exchange (Portner et al. 2005), and depressed metabolic rates (Michaelidis et al. 2005). Calcification rates in the adult mussel *Mytilus edulis* (native to the Atlantic Ocean) decreased by approximately 25% when exposed to pCO_2 levels projected to occur by 2100 under the IPCC IS92a emissions scenario (Section 6.1) (Gazeau et al. 2007). Similarly the early larval stages of mussels, which contain aragonite (the most soluble form of calcium carbonate) in their shells also demonstrate a strong response to increased seawater pCO_2 and decreased pH (Weiss et al. 2002; Fabry et al. 2008; Gazeau et al. 2010). In seawater with both decreased pH levels and under-saturation of aragonite levels,*M.edulis* larvae exhibit significant decreases in growth, survivorship, and percentage of “normal” larvae at levels that may compromise the survivability of entire populations of the organism (His 1997; Gazeau et al. 2010).

The potential effects of ocean acidification on the rocky intertidal community of Washington’s outer coast (Tatoosh Island) are documented. Over a period of eight years, observed declines in pH corresponded with gradual shifts from a typically mussel dominated community to one dominated by fleshy algae and other non-calcareous species (Wootton et al. 2008). Additionally, results suggest a systematic decline in the abundance and mean size of *M.californianus* and *M. trossulus*, corresponding with declining pH (Wootton et al. 2008).

Sea Level Rise

Sea level rise may influence intertidal communities as a whole (Section 3.2.1) by increasing upward pressure by predators limited by exposure to air and dessication. This response may be mediated for intertidal organisms in general, and mussels in particular, if habitat is available for upwards migration. However, increasing thermal stress due to elevated air temperatures may, to a degree, serve to limit this migration, effectively "squeezing" intertidal organisms into narrower vertical bands.

Increasing Frequency and Severity of Storms

Frequent wave and storm damage creates discrete gaps in the mussel bed as wave-propelled logs batter the mussels and the shear stress of large waves rip the mussels off their substrate (Paine and Levin 1981). As the climate changes, these types of damaging storms may increase in both frequency and intensity. The native mussel *Mytilus trossulus*, which is typically adapted to calmer water environments and exists as a narrow band at the upper limit of the mussel bed, may be especially susceptible to physical forces. Although *Mytilus californianus* is much better adapted to turbulent environments, the increased frequency of high-intensity disturbances may be so pervasive that the recovery process (i.e. recolonization of mussel population) is compromised. When the effects from increased storm intensity and frequency are compounded with effects of ocean acidification (reduced shell thickness) and increased sea surface temperatures (reduced attachment strength), there may be increased mortality rates for mussels in the OCNMS.

Upwelling and Upwelling Favorable Winds

Upwelling and local advection processes play an important role in the dispersal and recruitment of marine larvae (Gaylord and Gaines 2000; Connolly et al. 2001; Menge et al. 2009). In a study of climate related oceanographic processes (Section 6.3) mussel recruitment was shown to vary as a function of a complex combination of large to local-scale processes (Menge et al. 2009). Since recruitment can be an important determinant of community structure (Underwood 1984; Menge and Sutherland 1987; Connolly and Roughgarden 1999; Gouhier et al. 2010), significant increases or decreases in mussel recruitment due to changing ocean patterns could have consequences for the intertidal community structure. An increase in recruitment does not necessarily mean increased abundance, though; before the mussel larvae are able to establish themselves as juveniles there are numerous pre-settlement (e.g. availability of facilitators such as filamentous algae or barnacles) and post-settlement challenges (e.g. predation, desiccation, and inter/intra-species competition) some of which are also likely to be altered by a changing climate. Additionally, changes in climate related oceanographic processes can also indirectly affect mussel recruitment success through changes in primary food sources (i.e. phytoplankton) and habitat availability (i.e. barnacle facilitators) (Menge et al. 2009; Menge et al. 2011).

4.6 Urchins (Stronglyocentrotus spp.)

4.6.1 Summary

- Increased ocean temperature in combination with changes in ocean currents may cause urchin populations to expand or be replaced by another species.
- Increases in ocean acidity, hypercapnia, and decreasing carbonate mineral saturation are intricately linked and have been shown to have negative impacts on all urchin life stages (pelagic larvae, juveniles and adults).

- Hypoxia is detrimental in sea urchins causing significantly lower feed intake and total feed consumption as well as a reduction in gonad growth.

4.6.2 Importance and Role in the Environment

Sea urchins (*Stronglyocentrotus spp.*) are calcifying benthic echinoderms who reside in the intertidal to shallow subtidal zones and play a major role in shaping the dynamics and community structure of coastal ecosystems (Pearse 2006; Lambert 2007). They are economically valuable in Washington State, supporting both a commercial and tribal fishery (Carter and VanBlaricom 2002). They are also important prey for many species, including sea stars, crabs, crows, gulls, wolf-eels and the sea otter (*Enhydra lutra*) (Lambert 2007), sometimes comprising over 60% of the latter's diet (Laidre and Jameson 2006).

To understand how climate change may affect urchins in the future it is important to understand not only their biology but also their present day status in Pacific Northwest coastal ecosystems. Sea urchins reproduce as separate-sex broadcast spawners. Eggs and sperms are shed directly into the seawater where fertilization takes place. Fertilized eggs and larvae are pelagic. Larvae feed within the water column until they metamorphose (4-6 weeks for most Pacific Northwest species, depending upon water temperature and food availability) and then descend to the sea floor (Lambert 2007). The three most common species of sea urchins (Family Strongylocentrotidae) in the northeastern Pacific are the purple (*Strongylocentrotus purpuratus*), green (*S.* droebachiensis), and red (*S. fransicscanus*) sea urchins. Purple sea urchins are found to a depth of 65 meters along shores with high waves and currents. In areas of particularly high waves they carve out depressions in rock to shelter from the force of waves. While in these shelters they rely on catching bits of drift algae as food. Red sea urchins are the largest urchins (maximum size of 30 cm in diameter). They occur from the intertidal zone to 125 meters deep and also rely heavily on drift algae though they will consume attached brown algae as well. The green sea urchin is found widely in sheltered locations away from direct surge and feeds primarily on attached algae. All three of these species are predominantly herbivores, preferring kelp above other seaweeds, although they will also feed on encrusting organisms and detritus (Lamb 2005; Lambert 2007).

They can be voracious grazers, capable of decimating entire kelp forests (Gutierrez 2010). Kelp forests are areas of high biodiversity and extremely important habitats for many species, including fish (especially during their larval and juvenile stages), other algae species, a variety of invertebrate species, seabirds and other marine mammals such as seals and sea lions. When there is a healthy sea otter population the urchin population is kept in check and kelp forests are allowed to prosper. When otters were hunted to near extinction, urchin populations exploded and kelp forests were replaced with areas known as "urchin barrens." These barrens are areas of low biodiversity and are dominated by crustose coralline algae which are more resistant to grazing (Behrens and Lafferty 2004). Due to this ability to catastrophically overgraze kelp forests and completely alter nearshore habitats it is imperative to understand how future climate change with effect the populations of this ecologically and economically important species.

4.6.3 Potential Response to Physical Changes

Increase in sea surface temperature (SST).

As a nearshore benthic species, sea urchins undergo daily, short-term tidal temperature fluctuations that exceed projected increases in ocean temperature due to climate change (Yu et al. 2011). Even so, chronic exposure to changes in seawater chemistry and temperature can impact all sea urchin life stages. For marine planktonic larvae Sheppard et al. (2010) considers temperature to be "the primary environmental factor controlling the physiology, phenology, planktonic larval duration and biogeography of marine invertebrates." Byrne et al. (2010) tested the thermo-tolerance of the planktonic larval stage of the sea urchin *Heliocidaris erythrogramma* at temperatures +3–4°C above ambient sea-surface temperature (approximately equivalent to temperatures projected for 2100 for the coastal area of Australia) and found that developmental success decreased with increasing temperature. However, the few larvae that developed normally at the highest temperatures metamorphosed successfully. These larvae developed more rapidly than those at cooler temperatures with a 25% decrease in the duration of the planktonic stage. This early settlement may be advantageous in reducing the predation that occurs during its vulnerable planktonic period and might help buffer some of the more negative effects of ocean warming. Their results also suggested differences in thermal tolerance between populations of the same species. Those coming from areas with historically warmer seawater were more tolerant to elevated temperature in the lab, showing that urchin species may be capable of adapting to warmer ocean temperature over time.

Increased ocean temperature in combination with changes in ocean currents may cause populations to expand or be replaced by another species. In SE Australia, the sea urchin *Centrostephanus rodgersii* was historically restricted to the coast of New South Wales but has recently extended its range to eastern Tasmania, where ~50% of all near-shore rocky reefs have now been converted to urchin barrens. This urchin's long-lived pelagic larval stage (100 days) in combination with warming SST temperatures and a strengthening of the East Australia Current has allowed it to extend its range poleward by ~160 km/decade for the past 40 years (Ling et al. 2009). Range extension may occur even within a relatively small area such as the vertical ranges in the subtidal to intertidal zones (Somero 2002).

Within any species population, changes in environmental temperatures can lead to increases in disease outbreaks. Infectious disease epidemics can seriously harm marine ecosystems, especially when the species affected is as ecologically important as the sea urchin. Disease outbreaks and mass mortalities have been directly linked to elevated temperature in several species of sea urchins. On the Atlantic Coast of Nova Scotia mass mortality of *S. droebachiensis* has been attributed to the pathogenic agent, *Paramoeba invadens,* during peak sea temperatures. Mortalities occurred down to ~25 meters but were mostly absent below the 20 meter depth where temperatures were lower (Brady and Scheibling 2006). Populations of the sea urchin *Paracentrotus lividus* in the intertidal waters of the Canary Islands experienced an outbreak of bald sea urchin disease only at their southernmost geographical limit at sites which coincided with the highest temperatures (Girard et al. 2012). Recent data from field studies in California suggest that warmer ocean temperatures may play a role in the disease epidemics of Pacific urchins

(Strongylocentrotus spp.). Disease prevalence of two pathogens was extremely rare or absent north of Point Conception at sites associated with strong upwelling and cooler temperatures but were common at warmer, southern sites (Lester et al. 2007).

Ocean Acidification

Sea urchins are a calcifying marine species that develops a high magnesium calcite (calcium carbonate) skeleton within its mesoderm. They may be more susceptible to ocean acidification than snails or bivalves due to: 1) a larger surface area to body weight ratio in combination with the direct connection of ambient seawater to their internal body compartments through their madreporites and thin overlying epidermis; and 2) high magnesium calcite is considerably more soluble than calcite (Shirayama and Thornton 2005; Spicer et al. 2011a). Increases in ocean acidity, hypercapnia, and decreasing carbonate mineral saturation are intricately linked and have been shown to have negative impacts on all urchin life stages (Kurihara and Shirayama 2004).

As a broadcast spawner that releases gametes directly into seawater, the sperm, eggs, fertilization and embryonic development may be particularly sensitive to changes in seawater chemistry (Havenhand et al. 2008; Reuter 2011). A statistically significant reduction in swimming speed and percent motility was found in the sperm of *H. erythrogramma* exposed to seawater with pH reduced by 0.4 (approximately equivalent to some projections for 2100; Figure 2-7). Fertilization success was also reduced by 25% (Havenhand et al. 2008). Once eggs were fertilized in the urchin *Paracentrotus lividus*, development of larvae appeared to be compromised (Moulin et al. 2011). Other studies, though, have shown fertilization to be robust to broader pH ranges, with impairment only at levels well in excess of 2100 projections (pH 7.1–7.4, Figure 2-7) (Byrne et al. 2010).

During the sea urchin's planktonic larval stage it produces a delicate calcite skeleton making it particularly vulnerable to ocean acidification. In both larvae and juvenile *H. erythrogramma* there was a decrease in calcification as seen in spine production at a lowered pH (7.6, 7.8) (Byrne et al. 2010). However, though *S. droebachiensis* larvae reared at lower pH (7.9 and 7.7) took longer to reach metamorphosis, they were more successful than those raised at control pH (8.0) Conversely, a longer planktonic stage can result in higher mortality due to increased predation and desynchronization with prey, thereby decreasing recruitment success (Moulin et al. 2011). Larvae of *Lytechinus pictus* reared in seawater with elevated CO_2 were smaller and had a more triangular body than those reared in normal CO_2 conditions. They also exhibited down-regulation in genes central to energy metabolism and biomineralization in response to the elevated CO_2 (O'Donnell et al. 2010). Another study found that *S. purpuratus* larvae exposed to seawater aerated with CO_2 gas (pH 7.96 and 7.88), experienced broad decreases in gene expression in four major cellular processes: biomineralization, cellular stress response, metabolism and apoptosis (Todgham and Hofmann 2009).

Other studies have indicated that some sea urchins are potentially resilient to near-future levels of ocean acidification. Yu et al. (Yu et al. 2011) raised larvae of *S. purpuratus* at elevated pCO_2 levels of 1000 ppm and 1450 ppm CO_2 (approximately pH 7.7 and 7.5 respectively) and found that larvae in the 1450 ppm CO_2 treatment were only 7-13% smaller than the control larvae. Clark et al. (Clark et al. 2009) observed that Antarctic sea urchin (*Sterechinus neumayeri*) larvae, which have evolved in an environment with historically higher levels of CO_2, were less affected by low pH compared to tropical and temperate sea urchin species. They postulate that *S. neumayeri* may be adaptable to higher CO_2 conditions (Clark et al. 2009).

Research has also been conducted to look specifically at OA effects on adult sea urchins. Adult *S. droebachiensis* were exposed to intermediate and highly elevated seawater pCO_2 for 10 and 45 days and feeding rates decreased by between 8%-30%. These urchins were able to regulate the chemical balance of their internal fluids for 45 days at the intermediate pCO_2 level. However, there was reduced growth and maturation of gonads (Stumpp et al. 2012). Juvenile *Hemicentrotus pulcherrimus* and *Echinometra mathaei* reared for six months in seawater with an elevation of CO_2 by only 200 ppm (–0.03 pH units) experienced both reduced growth and survivorship (Shirayama and Thornton 2005).

Hypoxia

Adult *S. droebachiensis*, that were reared in the lab for 54 days at reduced (but not hypoxic) oxygen levels of 4.0 and 6.0 mg l^{-1}, had significantly lower feed intake and total feed consumption as well as a reduction in gonad growth (Siikavuopio et al. 2007). Hypoxia commonly occurs simultaneously with hypercapnia in the field. Hypoxia alone is detrimental in sea urchins but the combined effects of hypoxia and hypercapnia might have an even more deleterious impact on energy acquisition (Stumpp et al. 2012).

Increasing Frequency and Severity of Storms

Storms can remove giant kelp (*Macrocystis pyrifera*) plants along the North American coast but understory kelps such as *Pterygophora californica* are more frequently spared. Both *S. franciscanus* and *S. purpuratus* reside in rocky areas protected from extreme wave action and heavily rely on drift algae as food. When there are no drift algae, they emerge from their shelters and actively forage on most living plants including the understory algae and young kelp recruits, thereby weakening the detritus-based food chain which in turn decreases biodiversity and urchin “barrens.” The exposed urchins can then be decimated by future storms, making the cleared rock surfaces available for kelp settlement (Ebeling et al. 1985; Pearse 2006).

As mentioned before, mass mortalities of sea urchins occurred in Nova Scotia due to the amoebic disease *Paramoeba invadens* and elevated seawater temperatures (Brady and Scheibling 2006). Further analysis found that these disease outbreaks appear to be connected with powerful tropical cyclones that pass close to the coast during the time when water temperature is optimal for disease transmission. The turbulent mixing caused by these storm conditions increases the likelihood of introduction and the spread of a water-borne pathogen (Scheibling and Lauzon-Guay 2010). However, similar disease outbreaks have not been documented in eastern Pacific urchins in relation to storm events.

4.7 Dungeness Crab

4.7.1 Summary

- Climate change is anticipated to affect Dungeness crab through every life history phase.
- Survival, growth, and development of larval and post-larval crab will be affected by increasing sea surface temperature and changes in food availability.
- Changes in ocean currents, while uncertain, could disrupt larval transport and influence recruitment of larvae to suitable settlement areas.
- Critical estuarine and nearshore habitat for Dungeness crab may be altered and/or degraded by a myriad of stressors, including increasing sea level, ocean acidification, and episodic hypoxia.
- Combined or possibly synergistic effects of multiple climate stressors have not been examined but may pose the greatest threat to Dungeness crab populations.

4.7.2 Importance/Significance

The Dungeness crab is an abundant benthic predator, cultural icon on the West Coast of the United States, and target of a valuable commercial and recreational fishery. The life history of Dungeness crab can be divided into four distinct phases characterized by changes in body type, behavior, and habitat. These include the larval phase, juvenile (0+ year class), subadult (1+ to 3+ year class), and adult (>3+ year class). While there is seasonal variation in life history across the range of the species from Unalaska, AK, to Santa Barbara, CA (Jensen 1995), the general pattern described below is consistent throughout this range. Climate change is expected to impact all of these life stages, as well as the concomitant fishery (Armstrong et al. 2010).

Dungeness crab, like many other marine invertebrates, are characterized by an ocean-going larval phase that can disperse long distances (>1,500 km or ~800 nm) (Park et al. 2007) relative to older, bottom-dwelling phases (Grantham et al. 2003). Newly hatched larvae enter the water column as zoeae, which spend an extended period (~90 days) floating in ocean currents (Buchanan and Millemann 1969). Early larval stages can be found 5-16 km offshore (Lough 1976; Orcutt 1977; Reilly 1983). Survival and the duration of larval development are dependent on ambient temperatures, salinities, and food availability and quality (Buchanan and Millemann 1969; Reed 1969; Lough 1976; Moloney et al. 1994; Sulkin et al. 1998a). The zoeae transition through five stages before metamorphosis to a short-lived post-larval megalops (Poole 1966). While megalopae are distributed widely offshore (up to 200 km), successful recruitment requires return to nearshore waters (Roegner et al. 2003). Cross-shelf and along-shelf dispersal are primarily the result of physical oceanographic processes (Jackson 1986; Shanks 2009), including seasonally predominant ocean currents and wind stress, with a small influence of larval behavior (Johnson et al. 1986; Shanks 1986; Moloney et al. 1994).

Subadult crab (1+ and 2+ year) in coastal waters typically occur in sandy nearshore areas less than ~18 m (or ~60 ft) but can be found up to ~37m (or ~120 ft) in depth (Tasto 1983). However densities of subadult crab are much lower in coastal habitats than in estuaries, so many studies have focused on their use of estuarine habitats. Some portion of the subadult crab population continues to utilize estuarine systems until they reach sexual maturity at about 2 years of age (~100 mm or ~ 4 in. carapace width [CW] for females, ~130 mm or ~5 in CW for males) (Gutermuth and Armstrong 1989) and then migrate to nearshore waters (Collier 1983). Overall growth is higher in warm estuarine systems, and subadult crab are larger and more abundant in estuaries than in adjacent coastal waters (Collier 1983; Emmett and Durkin 1985; Gutermuth and Armstrong 1989; Wainwright and Armstrong 1993; Wainwright 1994; Armstrong et al. 2003).

Adult crabs are less common in intertidal areas and shallow estuaries than their younger counterparts, and generally occupy subtidal habitats of coastal and inland waters. Anecdotal information on adult habitat comes primarily from commercial fishing that occurs in coastal waters less than ~183 m (or ~600 ft) deep on sandy and muddy habitats (Sweetnam et al. 2010; Marine Stewardship Council 2011), although directed mark-recapture studies have provided particular insight into female crabs (e.g., Diamond and Hankin 1985). While capable of long-distance movements (Collier 1983), most adult male crab are relatively sedentary and only migrate inshore to mate during spring and summer months (Gotshall 1978). Similar patterns have been observed for females; in a study conducted in northern California, Diamond and Hankin (1985) recovered about 46% of tagged female crab within ~2 km (or ~1 nmi) of their release location after one year. Observations from that study also indicate that females move inshore to shallow sandy areas during the spring, possibly because of molting, mating, or increased egg survival in this habitat (Diamond and Hankin 1985).

The sexes appear to exhibit more distinct seasonal patterns of movement and habitat use at the northern end of their range (Stone and O'Clair 2001). Egg-bearing female crab in southeast Alaska (Scheding K 2001; Stone and O'Clair 2002) and Ship Harbor, Anacortes, Washington (Armstrong et al. 1987) exhibit site fidelity and may annually return to the same brooding locations and form large partially buried groups in sand habitats. In general, adult female crab remain relatively inactive during winter months (November to mid-April), abruptly migrate into shallow water to release larvae in spring, and return to cooler deeper foraging areas in summer. Male crab movement patterns during winter months are similar to those of females with relative inactivity until migrating to shallower water in early spring (Stone and O'Clair 2001). In the area of OCNMS, male crabs are known to form dense molting aggregations in autumn (Gregory C Jensen, pers. comm.).

Dungeness crabs are culturally, commercially, and ecologically significant. The species was fished by early native coastal groups long before the arrival of European settlers (Dahlstrom 1983), and a valuable commercial and recreational fishery for adult male crab has occurred since the mid-19th century (Hankin et al. 2004). Along with being an important benthic predator of invertebrates and small fish (Butler 1954; Gotshall 1977), Dungeness crab represent a valuable prey resource (Reilly 1983). Larvae are eaten by a variety of predators, including planktivorous fishes (Stevens et al. 1982). The larger, more conspicuous megalopae are also vulnerable to predators, including Pacific salmon (Orcutt 1977; Hunt et al. 1999). Post larvae and bottom-dwelling juveniles are common in the diets of fishes (Reilly 1983), including tomcod (Haertel and Osterberg 1967), Pacific hake, sablefish, and Dover sole (Buckley 1999), staghorn sculpin (Armstrong et al. 1995) copper rockfish (Prince 1972). Birds, such as white-winged scoters (Grosz and Yocom 1972), and mammals, including river otters (Larsen 1984) and raccoons, opportunistically consume small crab in intertidal areas. By the end of their first or second year, Dungeness crab are too large for most predators. Nevertheless, they are still consumed by large fish, such as white sturgeon (McKechnie 1971) and cabezon (Waldron and Oregon. Fish 1958). Additional predators of adult crab include wolf eel, lingcod and various rockfish (Gray 1964). Dungeness crab have also been recorded in the diets of marine mammals such as sea otters (Garshelis et al. 1986).

4.7.3 Climate Change and Dungeness Crab

Increase in sea surface temperature

Previous assessments of climate change impacts on Dungeness crab have highlighted the sensitivity of planktonic larval stages (e.g. McConnaughey 1995). Survival, growth, and development of larval Dungeness crab are determined by temperature, salinity, and food availability and quality (Buchanan and Millemann 1969; Reed 1969; Lough 1976; Moloney et al. 1994; Sulkin et al. 1998a). Cloern et al. (2007) suggests that Dungeness crab recruitment along the West Coast is directly linked to periods of cooling because of higher egg survival and enhanced La Nina-type primary production (see Section 6.3). Temperature appears to elicit the most direct effect on growth, development, and survival because growth and development are a function of the thermal experience of larvae. Hatching success decreases from 10° to 17°C, yet optimal temperatures for larvae are 10-14°C (Pauley 1989); at these temperatures, growth is maximized and development duration is minimized, with a concomitant increase in survival (Moloney et al. 1994). Wild (1983) observed lower hatching success and larval survival during the 1970's associated with an extended warmer water regime.

The productivity of nearshore waters strongly affects diversity and abundance in coastal ecosystems. Projected future climate is expected to affect plankton productivity along the U.S. West Coast, and even contemporary fluctuations in conditions can have dramatic effects. For example, in years of strong El Niño events, low chlorophyll concentration (Strub et al. 1990) and reduced biomasses of zooplankton (Mullin and Conversi 1989) are common features along the U.S. West Coast. Increased temperature may affect the diversity and abundance of plankton by excluding constituent organisms with greater temperature sensitivity or through stratification of the water column that resists upwelling and limits primary productivity. During warm regimes of the Pacific Decadal Oscillation (Mantua and Hare 2002), lipid-poor zooplankton are carried with the California countercurrent (Hare et al. 2001). Dungeness crab zoeae and megalopae require planktonic prey throughout development, and growth is dependent on food quality (Sulkin et al. 1998a; Sulkin et al. 1998b). While these organisms are adapted to resist starvation (Sulkin et al. 1998b), insufficient nutrition can dramatically affect development and growth, which can reduce survival of larvae over time because of extended exposure to planktonic predation (Moloney et al. 1994).

Interannual variability in oceanographic conditions produces strong effects on larval survival and subsequent numbers of juvenile crab. The abundance of Dungeness crab larvae is lowest when winter sea surface temperatures are highest, as they are during El Niño events (Botsford 2001) but note that high sea surface temperatures also co-vary with low food availability (Mullin and Conversi 1989), and even unfavorable current patterns (Shanks and Roegner 2007). Regardless, if a future climate resembles El Niño conditions or warm PDO, then food available to larval Dungeness crab may be less abundant or of lower quality.

Growth of juvenile and adult Dungeness crab, as well as prey consumption, are strongly temperature-dependent (Holsman et al. 2003). A warming climate will therefore affect critical energetic processes, and such impacts may cascade through local food webs. Increased growth rates associated with higher temperatures can positively affect individual survival, as is the case for crabs reared in shallow estuaries (Gutermuth and Armstrong 1989). However, prey demand, which also increases with temperature, may outstrip production and lead to decreased carrying capacity. Reduced carrying capacity could exacerbate habitat-specific bottlenecks known to affect population size in Dungeness crab (Wainwright and Armstrong 1993).

Sea Level Rise

Estuaries of California, Oregon, and Washington are critical nursery areas for juvenile Dungeness crab (Gunderson et al. 1990; Emmett et al. 1991), provide critical foraging grounds for subadult crab (Holsman et al. 2003; Holsman et al. 2006), and disproportionately contribute to coastal crab fisheries (Armstrong et al. 2003). Estuarine beaches support the highest densities of juvenile Dungeness crab (McMillan et al. 1995), likely because predation pressure is more intense in deeper waters (Armstrong et al. 1995). Loss of intertidal habitat due to sea level rise would reduce this refuge and make it difficult for vulnerable metamorphosing crabs to avoid predators by occupying shallow tidal waters (Gibson 2003). Additionally, intertidal areas support living habitats, such as oyster beds and eelgrass meadows that are preferred rearing habitats for juvenile crab (Fernandez et al. 1993a). While early survival is sometimes considered a bottleneck to adult populations (Wainwright et al. 1992), loss of foraging habitat for subadult crab may also have dramatic consequences for overall estuarine production (Holsman et al. 2003) with impacts to coastal crab fisheries (Armstrong et al. 2003).

Rising sea levels will likely reduce the available area of intertidal habitat in most coastal estuaries (Kennish 2002). Moreover, rising sea level may restrict the maximum depth of eelgrass meadows and alter distribution of this important biogenic habitat (Short and Neckles 1999). While OCNMS does not contain significant areas of estuarine habitat, important estuaries of southern Washington and northern Oregon, including Willapa Bay, Grays Harbor, Columbia River, and Tillamook Bay, may lose >60% of available intertidal area according to recent analyses (Glick et al. 2007). Work by Galbraith et al. (2002) indicates that the intertidal area of northern and southern San Francisco Bay may be reduced by 40% and 70%, respectively. Considering the connectedness of Dungeness crab populations along the Pacific coast, loss of important nursery areas elsewhere may have ramifications for recruitment within OCNMS.

Ocean Acidification

Few published studies have specifically addressed the effects of ocean acidification on larval or adult Dungeness crab. Current investigations underway at the University of Washington and National Oceanic and Atmospheric Administration labs seek to understand the impact of high $_PCO_2$ on growth, development, and survival of larval Dungeness crab. While preliminary results suggest some deleterious effects on larvae, adult Dungeness crab have a greater capacity to regulate extracellular pH (Pane and Barry 2007), which is likely an adaptation to living in shallow, nearshore areas that experience variable conditions. Some investigators (Pane and Barry 2007; Fabry et al. 2008) suggest this adaption may also help adult crab cope with higher levels of pCO_2 projected under several model scenarios (Section 2.3). However, little is known about the combined or possibly synergistic effects of multiple climate change stressors. For example, work on a related species, *Cancer pagarus*, has demonstrated reduced tolerance to thermal stress and hypoxia associated with elevated pCO_2 (Metzger et al. 2007).

While direct effects of ocean acidification are uncertain, impacts to important biogenic habitats are clearly negative. Survival of juvenile Dungeness crab is high in biogenic habitats like oyster and sand dollar beds relative to mud and sand because complex structures afford refuge from myriad predators (Fernandez et al. 1993b; Armstrong et al. 1995; Eggleston and Armstrong 1995; Fernandez 1999)**.** For calcifying organisms, like oysters and sand dollars, ocean acidification poses a substantial threat to population viability (Orr et al. 2005b; Miller et al. 2009; Dupont et al. 2010). High pCO_2 levels promote dissolution of shell material, alter morphology and reduce survival of mollusc (e.g., Miller et al. 2009) and echinoderm (e.g., Chan et al. 2011) larvae. Since 2005, shellfish growers in California, Oregon, and Washington have noted recruitment failures of oysters in several estuaries (Dickson 2010), including many important Dungeness crab nurseries (Gunderson et al. 1990; Dumbauld et al. 1993). Similar patterns may be occurring in coastal sand dollar populations. Large beds of oysters and sand dollars may slowly disappear because new larvae are not available to replace senescing individuals. Loss of these habitats could have negative consequences to Dungeness crab.

Changing patterns of streamflow

Under some climate change scenarios, the intensity and seasonality of high winter streamflows may be affected in watersheds originating at moderate elevations (Elsner et al. 2010). Larvae originating in estuarine systems are typically advected by buoyant freshwater river plumes (e.g., Reilly 1983) so changes to the timing and magnitude of these plumes may areas affect cross-shelf patterns of distribution. Moreover, because successful import into large estuaries may be dependent on aggregations of megalopae coalescing in estuarine fronts prior to flood tide (Roegner et al. 2003), increased volume of freshwater exiting an estuary could disrupt recruitment. Strong plume dynamics of larger freshwater sources, such as the Columbia River, may also disrupt transport. The Columbia River plume may act as a partial barrier to northward transport of Dungeness crab larvae because of salinity gradients (e.g., Banas et al. 2009). Modeling efforts by Banas et al. (2009) also indicate that a strong plume increases cross-shelf dispersion of water; thus late-starge larvae and megalopae entrained in the plume would be carried away from adjacent nearshore settlement habitat (McConnaughey 1995). However, even under extreme projections of future climate conditions, the relatively smaller plumes generated by rivers of OCNMS, such as the Quinault, Hoh, and Queets, are unlikely to dramatically alter transport of larvae on the coastal shelf.

Salinity also affects larval development and survival. According to Buchanan and Millemann (Buchanan and Millemann 1969) highest survival and successful metamorphosis occur at salinities of 25-30 ppt. Increased winter streamflows forecasted under climate change scenarios for moderate-elevation watersheds (Stewart et al. 2005) may affect the development or survival of larvae in or near estuaries but larvae on the shelf are not likely to be affected, particularly within OCNMS waters.

Upwelling and Upwelling Favorable Winds

Because of the extended larval duration of Dungeness crab along the continental shelf, this life history phase is susceptible to changes in physical oceanographic conditions that may disrupt larval transport to settlement habitats. Along the West Coast, the spring transition marks the shift from a winter downwelling state to a summer upwelling state (Huyer et al. 1979; Holt and Mantua 2009). The timing of this transition to spring upwelling conditions varies, sometimes by months (Section 2.6), but when it occurs early and coincides with peak abundance of competent megalopae (i.e., late-stage post-larvae), shoreward movement of water at depth may aid in return to nearshore areas by megalopae that make substantial diel vertical (>70 m) migration (Shanks and Roegner 2007). While projections are uncertain, if climate change results in a later onset of the spring transition and increased intensity of upwelling (Mote and Mantua 2002; Snyder et al. 2003; Diffenbaugh et al. 2004), then larval transport may be compromised. For larval crab, longer intervals at sea translate to increased mortality (Moloney et al. 1994). In years when the spring transition is delayed, megalopae may remain on the continental shelf where they are exposed to increased predation risk, resulting in lower abundance (Shanks and Roegner 2007). Moreover, in the absence of a transition, the along-shore component of transport in the northward-flowing Davidson current continues and may carry larvae and megalopae beyond suitable settlement habitat (McConnaughey et al. 1992; McConnaughey et al. 1994). This ‘conveyor belt’ dispersal may result in larvae spawned off Oregon and Washington being carried as far north as Alaska (Park et al. 2007).

Upwelling pushes surface waters away from shore and may disperse larvae across the continental shelf. These organisms may require periods of wind relaxation in order to return to nearshore areas (Wing et al. 1995; Roegner et al. 2007). Intense, sustained upwelling projected under some climate change scenarios (e.g. Snyder et al. 2003) may push larvae and early megalopae too far from shore and prevent them from reaching shallow water settlement habitat.

Hypoxia and anoxia

While the conditions indicated above primarily affect distribution and survival of larvae, these same forces also impact adult crab. A dramatic example occurs as a result of upwelling-driven nearshore low-oxygen conditions along the Washington and Oregon shelf (Section 2.7). Dungeness crab are somewhat adapted to survive short-term hypoxia (Airriess and McMahon 1994). However, annual periods of low oxygen in 2002-2007 resulted in the near absence of Dungeness crab in some areas (likely as a combination of mortality and migration). Catch of remaining crab show a strong trend associated with declining oxygen conditions (Keller et al. 2010). Crab not killed by these conditions may orient along oxygen gradients and move away from affected areas (Bernatis et al. 2007; Keller et al. 2010). Under climate change scenarios involving increased stratification of the north Pacific, deep water currents approaching the U.S. West Coast will likely be characterized by water masses that are older and oxygen-poor relative to present conditions so widespread and severe low-oxygen conditions on the Oregon and Washington shelf may increase in frequency and/or duration (Section 2.7).

4.8 Fish

4.8.1 Summary

- Decreased ocean survival of Chinook and coho salmon in the coastal waters of Washington, Oregon, and California is likely based on historical and present day observations during conditions of unusually high water temperatures and reduced or delayed upwelling.

- Based on observations during conditions of unusually high water temperatures and reduced or delayed upwelling, highly migratory southern species including Pacific hake, jack and Pacific chub mackerel, and Pacific sardine will likely become more abundant and distributed closer to shore off Washington. In contrast, resident forage fish including northern anchovy, Pacific herring, and smelts (surf and whitebait) may become less abundant.

- Small pelagic fish (i.e. forage fish and mackerel) respond more rapidly to climate-related changes in ocean conditions than benthic fish. Distribution and abundance of benthic fish reflect average ocean conditions over periods of many years. A key question for groundfish is how long term, sustained changes in ocean conditions will affect the current spatial configuration of habitats and fish communities, and the productivity of those habitats and communities. Little is known about effects of ocean acidification on northeast Pacific fish; however, work with tropical reef fish suggests that increased acidity impairs larval fish behavior (their ability to find suitable reef habitat from olfactory and auditory cues) and ultimately their survival.

- Response of benthic fish in the OCNMS to future increases in hypoxia will likely be similar to those for fish off the central Oregon coast where hypoxia developed each summer starting in 2002. Abundance and condition of fish will decline in hypoxic areas. Fish will move inshore seeking higher oxygen concentrations. Species adapted to low oxygen environments, for example Dover sole, will be less affected.

4.8.2 Introduction

Many species of fish inhabit the OCNMS for at least part of their lives. Climate change will likely affect all of them but in different ways and to different degrees. This section focuses on coastal pelagic species (forage fish and small predators), groundfish, and salmon. A list of species from each of these groups that are important in the sanctuary is given in Table 4.

Species that are abundant in the sanctuary (based on fishery-independent surveys conducted in or near OCNMS), commercially important (based on management by the Pacific Fishery Management Council or the International Pacific Halibut Commission), classified as overfished in the Pacific Coast Groundfish Fishery Management Plan (2008), or listed as threatened or endangered under the Endangered Species Act are included.

Table 4 also provides information for each species including scientific name (common names are used throughout the text), adult habitat, size and age, life history characteristics, range relative to OCNMS, and utilization in OCNMS by life stage (spawning, larvae, juveniles, adults). Information is given on species size and longevity because response to climate change will be mediated by a species' life history (King and McFarlane 2003). For example, small, short-lived species may respond more quickly than larger, longer-lived species. Information is provided on whether the center of a species' range is north, south or centered on OCNMS because populations near the lower-latitude end of a species' range are more likely to be negatively impacted by warming than populations at higher latitudes (Hay et al. 2008). References for the information in Table 4 are given in Table 5.

Brief descriptions, and life history and habitat use information supplementary to the information in Table Table 4, are given below for coastal pelagic species, groundfish, and salmon. Two main sections follow. The first (Section 4.8.3) describes the observed response of fish communities to historical and present day variation in ocean conditions; particularly the response to periods of unusually warm temperatures and (or) decreased or delayed upwelling. The second (Section 4.8.4) discusses the potential response of fish to changes in each of the major physical drivers associated with climate change.

Table 4. Species that are abundant in the OCNMS, commercially important, or of special management concern. Adult habitat: P1 = pelagic surface (0-50 m), P2 = pelagic midwater (50-200), P3 = pelagic deepwater (>200), B1 = benthic nearshore (0-30), B2 = benthic shallow shelf (30-100), P3 = benthic deep shelf (100-200), P4 = benthic slope (>200). Range relative to OCNMS: S = abundant south of Point Conception California and north to Vancouver Island, C = range roughly centered on OCNMS, NC = abundant central California to the Gulf of Alaska, N = abundant Washington to the Bering Sea. The source for adult habitat, maximum age, maximum length, and range was Love (2011).Presence in the OCNMS: Y = yes (documented), L = likely, O = occasional (for example, spawning when spawning usually occurs in California), N = not present (documented), UK = unknown, NA = not applicable. For presence in the OCNMS, the number after a comma corresponds to a reference in Table 5. For anadromous species, the spawning column entry indicates whether spawning occurs in Olympic Peninsula rivers emptying into OCNMS.

Group	Common name	Scientific name	Adult habitat	Maximum length (mm)	Maximum age (years)	Range relative to OCNMS	Presence in the OCNMS			
							Spawn-ing	Larvae	Juven-iles	Adults
Coastal pelagics:										
Forage fish	Eulachon	Thaleichthys pacificus	P1-2	229	5	NC	O,1	UK	L,12	Y,1
	Northern anchovy	Engraulis mordax	P1	248	7	S	Y,2	Y,2	Y,2	Y,2
	Pacific herring	Clupea pallasi	P1	330	15	N	N,3	L,25	L,12	Y,4
	Pacific sand lance	Ammodytes hexapterus	P1	260	5	N	UK	L,26	L,5	L,5
	Pacific sardine	Sardinops sagax	P1	394	13	S	O,6	O,6	O,6	Y,6
	Surf smelt	Hypomesus pretiosus	P1	305	5	NC	Y,7	UK	UK	Y,4
	Whitebait smelt	Allosmerus elongatus	P1	229	UK	C	UK	UK	L,12	L,8
Coastal pelagics: Small predators	Jack mackerel	Trachurus symmetricus	P1	813	30	S	O,9	O,9	O,9	L,8
	Pacific chub mackerel	Scomber japonicus	P1	635	12	S	UK	UK	UK	L,8
Groundfish:										
Flatfish	Arrowtooth flounder	Atheresthes stomias	B3-4	840	15	N	L,11	UK	L,12	Y,10
	Dover sole	Microstomus pacificus	B3-4	710	49	C	L,11	L,26	L,12	Y,10
	English sole	Parophrys vetulus	B2-3	570	23	C	L,11	L,26	L,12	Y,10
	Pacific halibut	Hippoglossus stenolepis	B2-4	2670	55	N	UK	UK	UK	Y,16

	Pacific sanddab	Citharichthys sordidus	B1-2	410	13	S	L,11	L,26	L,12	Y,10
	Petrale sole	Eopsetta jordani	B2-4	700	25	C	L,11	L,26	L,12	Y,10
	Rex sole	Glyptocephalus zachirus	B3-4	610	29	C	L,11	L,26	L,12	Y,10
Groundfish: Rockfish	Black rockfish	Sebastes melanops	B1-2	690	56	NC	L,11	UK	UK	Y,14
	Blue rockfish	S. mystinus	B1-2	553	44	S	L,11	UK	UK	Y,14
	Canary rockfish	S. pinniger	B2-3	760	75	C	L,11	UK	UK	Y,10
	China rockfish	S. nebulosus	B1-2	450	79	C	L,11	UK	UK	Y,14
	Darkblotched rockfish	S. crameri	B3-4	595	105	NC	L,11	UK	L,12	Y,10
	Greenstriped rockfish	S. elongatus	B2-4	470	54	C	L,11	UK	L,12	Y,10
	Pacific ocean perch	S. alutus	B3-4	510	100	N	L,11	UK	UK	Y,10
	Redstripe rockfish	S. proriger	B2-4	610	70	NC	L,11	UK	UK	Y,10
	Rosethorn rockfish	S. helvomaculatus	B2-4	430	87	NC	L,11	UK	UK	Y,10
	Sharpchin rockfish	S. zacentrus	B3-4	490	73	NC	L,11	UK	UK	Y,10
	Shortspine thornyhead	Sebastolobus alascanus	B4	826	133	C	L,11	UK	L,12	Y,10
	Splitnose rockfish	Sebastes diploproa	B4	457	103	S	L,11	UK	L,12	Y,10
	Tiger rockfish	S. nigrocinctus	B2-4	610	116	C	L,11	UK	UK	Y,16
	Widow rockfish	S. entomelas	B2-3	590	58	C	L,11	UK	UK	Y,10
	Yelloweye rockfish	S. ruberimus	B2-4	910	117	NC	L,11	UK	UK	Y,14
	Yellowtail rockfish	S. flavidus	B3	660	64	C	L,11	UK	UK	Y,10
	Blackbelly eelpout	Lycodes pacificus	B2-4	460	5	C	UK	UK	L,12	L,13
Groundfish: Roundfish	Cabezon	Scorpaenichthys marmoratus	B1-2	990	19	C	L,11	L,26	UK	Y,14
	Kelp greenling	Hexagrammos decagrammus	B1-2	629	25	NC	L,11	L,26	UK	Y,14
	Lingcod	Ophiodon elongatus	B1-3	1520	20	C	L,11	L,26	L,12	Y,10
	Pacific cod	Gadus macrocephalus	B2-3	1000	11	N	L,11	UK	UK	Y,10
	Pacific hake	Merluccius productus	P2-3	800	23	S	O,15	O,15	O,15	Y,10
	Sablefish	Anoplopoma fimbria	B4	1140	113	C	UK	L,25	L,12	Y,10

	Longnose skate	Raja rhina	B2-3	1400	30	C	L,11	NA	UK	Y,10
Groundfish: Sharks, rays, ratfish	Spiny dogfish	Squalus suckleyi	P1-2	1600	100	C	L,11	NA	L,12	Y,10
	Spotted ratfish	Hydrolagus colliei	B2-3	1000	15	C	L,11	NA	L,12	Y,10
	Bull trout	Salvelinus confluentus	B1	757	9	C	Y,17	NA	Y,17	Y,17
Salmon and trout	Chinook salmon	Oncorhynchus tshawytscha	P1	160	8	NC	Y,19	NA	Y,4	Y,4
	Chum salmon	O. keta	P1	1090	7	N	Y,20	NA	Y,4	Y,20
	Coho salmon	O. kisutch	P1	1080	5	NC	Y,21	NA	Y,4	Y,4
	Pink salmon	O. gorbuscha	P1	760	3	N	Y,22	NA	Y,4	L,22
	Sockeye salmon	O. nerka	P1	840	7	N	Y,23	NA	Y,4	Y,23
	Steelhead	O. mykiss	P1	1120	8	NC	Y,24	NA	Y,18	Y,24

Table 5. References for Table 4, above.

Reference number	Reference
1	(Gustafson et al. 2010)
2	(Litz et al. 2008)
3	(Haegele and Schweigert 1985)
4	(Brodeur et al. 2005)
5	(Haynes et al. 2007)
6	(Emmett et al. 2005)
7	(Pentilla 2007)
8	(Emmett et al. 2006b)
9	(Brodeur et al. 2006)
10	(Bradburn et al. 2011)
11	(McCain et al. 2006)
12	(Toole et al. 2011)
13	(Zimmermann 2006)
14	REEF scuba surveys
15	(Phillips et al. 2007)
16	(Jagielo et al. 2003)
17	(Brenkman and Corbett 2005)
18	(Pearcy et al. 1990a)
19	(Myers 1998)
20	(Johnson 1997)
21	(Weitkamp 1995)
22	(Hard and Northwest Fisheries Science 1996)
23	(Gustafson 1997)
24	(Busby et al. 1996)
25	(Doyle 1992)
26	(Brodeur et al. 2008)

Coastal pelagic species: forage fish and small predators

Coastal pelagic species are small, schooling, pelagic fish that inhabit waters over the continental shelf and slope. Presence and abundance in the OCNMS (Table 4) were primarily determined from purse seine (1981-1985) and surface trawl (1998-2005) surveys conducted during summer (May-September) along the Washington and Oregon coasts (Brodeur et al. 2003; Brodeur et al. 2005; Brodeur et al. 2006; Emmett et al. 2006a).

Forage fish feed primarily on plankton and are an important food for other fish, seabirds, and marine mammals (Pentilla 2007; Hay et al. 2011). Forage fish are also relatively short-lived (Table 4), and their abundance can fluctuate widely from one year to the next. The most abundant forage fish in OCNMS are northern anchovy, Pacific herring, Pacific sand lance, Pacific sardine, surf smelt and whitebait smelt (Table 4). Eulachon do not occupy surface waters but rather are found in deep pelagic habitats in continental shelf waters with depths ranging from 50-200 m (Gustafson et al. 2010) and were regularly caught in summer bottom trawl surveys off Washington and Oregon (Brodeur et al. 2003). Eulachon populations in Washington, Oregon and California were listed as threatened under the Endangered Species Act in 2010.

Coastal pelagic species exhibit a variety of reproductive strategies. Eulachon are anadromous. They spawn in the lower mainstem and tributaries of the Columbia and Frazier rivers and have been reported to spawn occasionally in the Bear and Naselle rivers which enter Willapa Bay and in the Quinault, Queets, and Elwha rivers on the Olympic Peninsula (Gustafson et al. 2010). Eulachon larvae leave freshwater shortly after hatching. Pacific herring require specific nearshore substrates, usually aquatic vegetation (eelgrass, seaweeds, or salt marsh), upon which to lay their adhesive eggs (Pentilla 2007).

Herring probably do not spawn in the OCNMS because their spawning requires sheltered waters (Haegele and Schweigert 1985). Documented herring spawning areas near the OCNMS are Willapa Bay, Grays Harbor, eastern Juan de Fuca Strait, Puget Sound, Georgia Strait, and Barkley Sound (Haegele and Schweigert 1985).

Pacific sand lance and surf smelt deposit demersal eggs on beaches in the upper third of the intertidal zone (Pentilla 2007), and both surf smelt (Pentilla 2007) and Pacfic sand lance (Olympic National Park, unpublished data) have been documented to spawn on Washington's outer coast. Sand lance and surf smelt also spawn in Puget Sound, Georgia Strait, and Juan de Fuca Strait (Pentilla 2007); Hay 2011). Whitebait smelt spawn on subtidal sand banks (Eschmeyer and Herald 1983). The other coastal pelagic species listed in Table 4 spawn pelagic eggs, and all of the coastal pelagic in Table 4 have a planktonic larval stage.

Jack mackerel, Pacific chub mackerel, and Pacific sardine are highly migratory species that typically spawn offshore from California (and Baja California) and then migrate into Pacific Northwest waters with increasing temperatures in summer (Love 2011). Anchovy are capable of migrating long distances, and their north-south and onshore-offshore distributions in Washington and Oregon coastal waters frequently change from year to year (Litz et al. 2008), but they do not make seasonal long-distance migrations between spawning and feeding grounds. Most herring in the Georgia Strait migrate to outer coast feeding grounds in the spring as one or two year-old juveniles or after spawning, then mature fish return in late fall just prior to spawning (Gustafson et al. 2006), and some Puget Sound herring show the same migration pattern (Stick and Lindquist 2009). Sand lances do not appear to be highly migratory (Robards et al. 2002; Haynes and Robinson 2011). Less is known about migration behavior of the smelts (surf and whitebait smelts and eulachon).

Groundfish

Groundfish are fish that live on or near the bottom. Three sources of information were used to determine which groundfish species are abundant in the OCNMS. The first was fishery-independent bottom trawl surveys conducted in continental shelf and upper continental slope waters to monitor groundfish stocks and provide data for fishery management (Weinberg 1994; Jay 1996; Tolimieri and Levin 2006; Zimmermann 2006; Juan-Jorda et al. 2009; Keller et al. 2012). Most useful was a recent report summarizing the annual summer (May-October) abundance of groundfish species during 2003-2008 by depth stratum and International North Pacific Fisheries Commission (INPFC) statistical area (Bradburn et al. 2011). The shallow depth stratum (55-183 m) of the U.S.-Vancouver statistical area fell within the northern two thirds of the OCNMS, and the mid-depth stratum (183-549 m) included deeper parts of the northern two thirds of the sanctuary. The Columbia statistical area, which bordered U.S-Vancouver and extended south to Cape Blanco, Oregon, was also relevant. The second source of information was visual surveys, using submersibles or ROVs, that sampled rocky, high relief habitat inaccessible to bottom trawls (Jagielo et al. 2003; Brancato et al. 2007). The only available reference documenting groundfish in shallow water (< 50 m deep) was scuba surveys conducted by REEF volunteers specifically for monitoring in the OCNMS (http://www.reef.org/db/reports/geo/PAC/29010001). Groundfish found by at least one of these three survey methods to be at least moderately abundant in or near (offshore from Washington) the OCNMS are listed in Table 4.

Canary, darkblotched, widow, and yelloweye rockfish, and Pacific Ocean perch are considered overfished off the Pacific Northwest Coast (Pacific Fishery Management Council 2008). These species are also included in Table 4. All species commercially important in the OCNMS are represented in Table 4.

Most of the groundfish have relatively long life spans (Table 4). Most are strictly marine. A few inhabit brackish water, notably English sole which frequent estuaries as juveniles. Many of the groundfish spawn planktonic eggs. Eggs of blackbelly eelpout, cabezon, kelp greenling, lingcod, longnose skate, and spotted ratfish are demersal. Cabezon, kelp greenling, and lingcod need rocky substrate to deposite their eggs on. Spiny dogfish, and all of the rockfish except shortspine thornyhead bear live young. Larvae are planktonic for all of the groundfish except longnose skate, spiny dogfish, and spotted ratfish whose young hatch from eggs or are released by the mother at large sizes (>4 cm) as juveniles.

Like some of the coastal pelagic species, Pacific hake typically spawn off California during winter and then migrate to Pacific Northwest feeding grounds in summer. Spiny dogfish are highly mobile but tend to stay in the same general region (Love 2011). All of the flatfish except Pacific sanddab are in the same family (Pleuronectidae, the righteye flounders). Time of spawning and extent of associated offshore-onshore migrations differ among the righteye flounders, but they all tend to spawn sometime during winter (October-April) and all move offshore into deeper water to spawn and back onshore in summer (McCain et al. 2006; Love 2011). Pacific cod may also make seasonal offshore-onshore movements associated with spawning and feeding (McCain et al. 2006; Love 2011). The other groundfish species are more sedentary. Juveniles of most groundfish species first settle to the seafloor in water shallower than their characteristic adult habitat and then gradually move to deeper water as they grow.

Most of the rockfish live on, over, or near rocky substrates, as do cabezon, kelp greenling, and lingcod. Rosethorn rockfish are an abundant species on high relief, rocky habitat in the OCNMS (Jagielo et al. 2003; Brancato et al. 2007). Black, blue, canary, widow, and yellowtail rockfish often school in the water column tens of meters above rock structures (Love and Yoklavich 2006). Greenstriped rockfish are sometimes found on mud as well as rock bottoms (Jagielo et al. 2003). Darkblotched and splitnose rockfish, Pacific Ocean perch, and shortspine thornyhead, all deep water species (Table 4), are often found on mud or sand (Love 2011). As their morphology suggests, longnose skates and all of the flatfish are usually found on soft substrates. Pacfic cod, Pacific hake, sablefish, spiny dogfish, and spotted ratfish can be found over a variety of substrates although most typically over soft sediments (Love 2011). Pacific hake and spiny dogfish often spend time in the water column away from the seafloor. Both species are regularly caught in midwater trawls (Brodeur et al. 2005; Brodeur et al. 2006) as well as bottom trawls. Dover sole and sablefish adults frequent deep, continental slope habitats within the oxygen minimum zone (Love 2011).

Salmon and trout

Five salmon and two anadromous trout species appear in Table 4. All but pink salmon have spawning populations in rivers near the OCNMS that are listed under the ESA. Bull trout are listed as threatened throughout their United States range. Anadromous populations of bull trout occur in Puget Sound and Olympic Peninsula rivers including rivers entering the OCNMS. Sockeye salmon that spawn in tributaries of Lake Ozette are listed as threatened under the ESA. Lake Ozette is in Olympic National Park and drains into the OCNMS. Puget Sound Chinook salmon and steelhead, Hood Canal summer chum salmon, and Oregon coast coho salmon are listed as threatened. Several populations of Columbia River basin Chinook, chum, coho, and sockeye salmon, and steelhead are listed as threatened or endangered under the ESA.

Most rivers entering the OCNMS support spawning by bull trout (Wydoski and Whitney 2003), Chinook (Myers 1998), chum (Johnson 1997), and coho salmon (Weitkamp 1995), and steelhead (Busby et al. 1996). Sockeye salmon spawn in tributaries of Lake Quinault as well as Lake Ozette (Gustafson 1997). Pink salmon spawn in the Elwha River on the north side of the Olympic Peninsula and in rivers entering Puget Sound but do not regularly spawn in outer coast rivers south of Vancouver Island or in the Columbia River basin (Hard and Northwest Fisheries Science 1996). The salmon and trout develop through the larval stage in freshwater. Chum and pink salmon enter the ocean as fry, Chinook salmon as subyearlings or yearlings, coho salmon as yearlings, sockeye salmon at 1 or 2 years of age, and most steelhead and bull trout at age-2. Some steelhead survive spawning, reenter the ocean and return to spawn again. Bull trout from western Olympic Peninsula rivers only enter the ocean for a few months of the year, typically from September-March to May-July (Brenkman and Corbett 2005), and can reenter the ocean and return to freshwater several times during their lives (Brenkman et al. 2007).

Juveniles of all five salmon species were regularly caught in summer (May-September) purse seine (1981-1985) and surface trawl (1998-2005) surveys along the Washington and Oregon coasts (Pearcy et al. 1990b, a; Brodeur et al. 2005; Brodeur et al. 2006). Chinook and coho salmon were more abundant in these surveys than juveniles of the other three species. The origin of naturally produced juvenile salmon caught in these surveys was unknown, but they likely originated from a variety of source rivers, including local coastal rivers and large river systems to the north and south (Brodeur et al. 2004). Hatchery Chinook and coho salmon juveniles caught in the purse seine surveys originated mostly from the Columbia River and to a lesser extent from Oregon and Washington coastal rivers based on coded wire tag recoveries (Pearcy et al. 1990a). Steelhead composed a small fraction (< 3%) of the juvenile salmonids caught in the purse seine surveys (Pearcy et al. 1990a). They were most abundant in May-June, and absent in September which is not surprising since steelhead leave coastal waters soon after entering the ocean in late spring (Quinn 2004). Bull trout were not reported in the purse seine or surface trawl catches. Bull trout may have stayed too close to shore to be vulnerable to these gear; they are known to stay close to shore in Puget Sound (Hayes et al. 2011).

Maturing adult Chinook and coho salmon were also regularly caught in the summer surface trawl surveys. Maturing adults of these species spend more time in Washington and Oregon coastal waters than do maturing chum or pink salmon or steelhead (Quinn 2004).

4.8.3 Observed Responses to Variations in Ocean Conditions

Distribution, abundance, recruitment, and survival of fish off the Pacific Northwest coast vary with ocean conditions including water temperature, ocean currents, upwelling, and primary and secondary production. Climate change will likely result in changes to some or all of these conditions; therefore fish communities will likely change in some way as well. Knowing how fish communities in OCNMS vary with historical and present day conditions should therefore help anticipate future climate change effects.

Pelagic habitats

Variations in properties of ocean surface waters are known to affect coastal pelagic species and salmon. Such changes are sometimes associated with large scale, climate-driven processes. El Ninos (Section 6.3), which often last for only one year, lead to warmer than normal water temperatures and less upwelling off the Pacific Northwest coast. Longer-term regimes also affect conditions in the northeast Pacific. Regimes of warmer than average temperatures lasting decades are associated with positive values of the PDO (Section 6.3). Smaller scale, regional processes such as the timing or intensity of upwelling also affect ocean conditions.

Strong El Ninos affecting continental shelf waters off Oregon and Washington occurred in 1983 and 1998 (Pearcy 2002). A commonality between these years was high abundance of predatory nekton and low abundance of forage nekton (Figure 4-11 & Figure 4-12). Survival of maturing coho salmon during 1982-1983 (i.e., during their final year in the ocean) and their average body size in 1983 were both anomalously low, and survival of juvenile coho salmon shortly after entering the ocean in 1983 was also unusually low (Pearcy and Schoener 1987).

The northeast Pacific shifted from a cool to a warm regime (positive PDO) in about 1978 (Zwolinski and Demer 2012). A striking difference in the pelagic fish community off Oregon and Washington between 1981-1985 and 1998-2005 was that Pacific sardine were absent in the former time period (Figure 4-11) but often dominant in the latter (Figure 4-12). Sardine thrive and expand north from California to the Pacific Northwest Coast during warm regimes, then retract south during cool regimes (Zwolinski and Demer 2012). Sardine began to increase in abundance off California in 1978, but their arrival off Oregon and Washington was delayed until 1992, possibly triggered by an El Nino during 1992-1993 (Emmett et al. 2005).

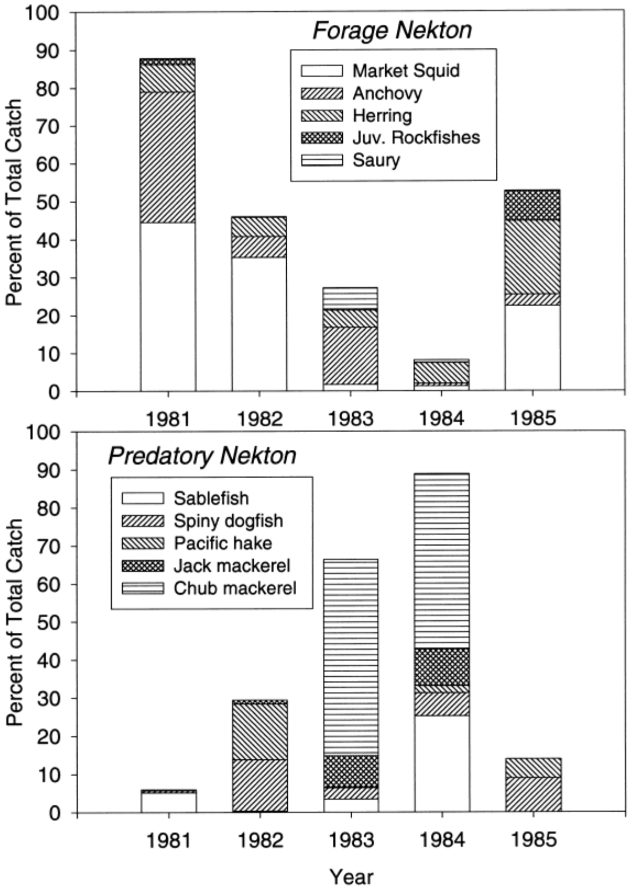


Figure 4-11. Summary of the catch during a purse-seine sampling campaign for the forage (top) and predatory (bottom) species (both expressed as a percent of total catch) collected off of Oregon and Washington from 1981 to 1985. Figure from Brodeur et al. (2003)

Regime shifts also have marked effects on salmon survival. Salmon catch records show that Chinook and coho salmon from Washington, Oregon, and California had consistently higher lifetime survival during a cool regime (1947-1977) than during the preceding or succeeding warm regimes (Mantua et al. 1997).

In 2005, the onset of coastal upwelling off Oregon and Washington was delayed by 2-3 months compared to normal (Schwing et al. 2006). Water temperatures were unusually high and chlorophyll levels unusually low in spring and early summer 2005 due to the delay (Schwing et al. 2006). Surface trawl catches in June 2005 were almost exclusively anchovy for forage nekton and jack and chub mackerel for predatory nekton (Figure 4-12). Catches in June 2005 were highly anomalous in terms of the presence of many unusual offshore species, more so than in any other year during 1998-2005 including the 1998 El Nino year (Brodeur et al. 2006).

Ocean conditions off Oregon and Washington changed dramatically following the 1998 El Nino. Upwelling-favorable winds strengthened, water temperatures cooled, and the PDO reversed sign from positive to negative (Peterson and Schwing 2003a). These conditions persisted through 2002 (Peterson and Schwing 2003a). Abundance was low for predatory nekton during 1999-

2002 and high for forage nekton in 2000-2002 although not 1999 (Figure 4-12& Figure 4-13), for the most part opposite to the pattern seen during the 1983 and 1998 El Ninos (high predator and low forage fish abundance). Ocean survival of Oregon and Washington Chinook and coho salmon also increased after 1998 (Peterson and Schwing 2003a). In 2003, the PDO reversed again (negative to positive) and the ocean became warmer. Night sampling in 2003 indicated that predator abundance increased compared to 1999-2002, especially for hake.(Figure 4-12). Among 1998-2003, hake became abundant in continental shelf waters in 1998 and 2003 when the transition to spring upwelling was moderately late (April rather than March) and temperatures at 50 m depth were warm in April-May(Emmett et al. 2006a). Also initiated in 2003 was a decline in coho salmon ocean survival off British Columbia, Washington and Oregon compared to 1999-2002 levels (Mackas et al. 2007).

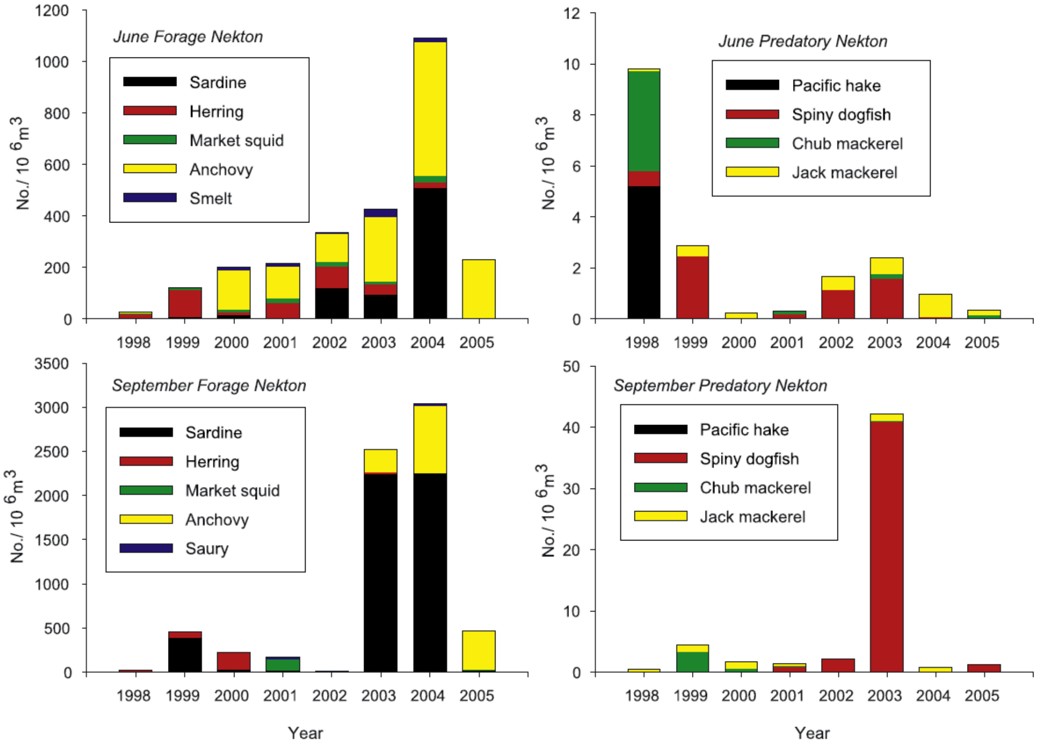


Figure 4-12.Time series of catches from daytime pelagic trawl surveys along the Washington and Oregon coasts from (top) June and (bottom) September 1998 to 2005 for (left) forage fishes and (right) predatory fishes. Figure from Brodeur et al. (Brodeur et al. 2006)

Three trends were apparent in Washington and Oregon coastal waters under conditions of unusually high water temperatures and reduced or delayed upwelling. First, presence and abundance of southern migratory species (hake, jack and chub mackerel, and sardine) and offshore species increased. Second, abundance of forage fish decreased. Third, ocean survival of Chinook and coho salmon decreased. Similar trends in the pelagic fish community might be expected under climate change to the extent that long-term climate trends result in similarly warm ocean temperatures or disrupted upwelling.

The mechanism causing reduced salmon survival during warm years is unclear. Some evidence supports the hypothesis that warm, unproductive ocean conditions reduce prey of juvenile salmon, resulting in slower early marine growth by salmon and greater susceptibility of salmon to size selective predation (i.e., smaller average body size of salmon results in high predation rates because small salmon are easier to catch than). Ocean survival, fish size at ocean entry, early marine growth rate, and ocean conditions indicative of strong upwelling were inter-correlated for a coho salmon population from the southWest Coast of Vancouver Island (Holtby et al. 1990). At a larger spatial scale, ocean survival, early marine growth, and indices of local and basin-scale ocean temperature anomalies were inter-correlated for coho salmon off British Columbia, Washington, and Oregon (Mackas et al. 2007). However, other evidence contradicts the productivity-growth hypothesis. Growth rates and stomach fullness of juvenile coho salmon caught off Washington and Oregon in early summer were as high in 1983 and 1984, years of very low ocean survival and low upwelling, as in 1981, 1982, and 1985, years of higher ocean survival and higher early upwelling, suggesting that a food limitation was not the cause of low ocean survival in 1983-1984 (Fisher and Pearcy 1988). Indications are that salmon were able to switch to alternate prey and maintain feeding and grow rates comparable to those under more productive conditions (Brodeur et al. 2007). An alternative hypothesis to explain low ocean survival in warm, unproductive years is increased size-independent predation on juvenile salmon due to greater spatiotemporal overlap of juvenile salmon and their predators or greater local abundance of predators(Pearcy 1992); however more work is needed to investigate this hypothesis. It is worth noting that hake and mackerel are probably not major predators of juvenile salmon in the northern California Current System (CCS) (Emmett and Krutzikowsky 2008)

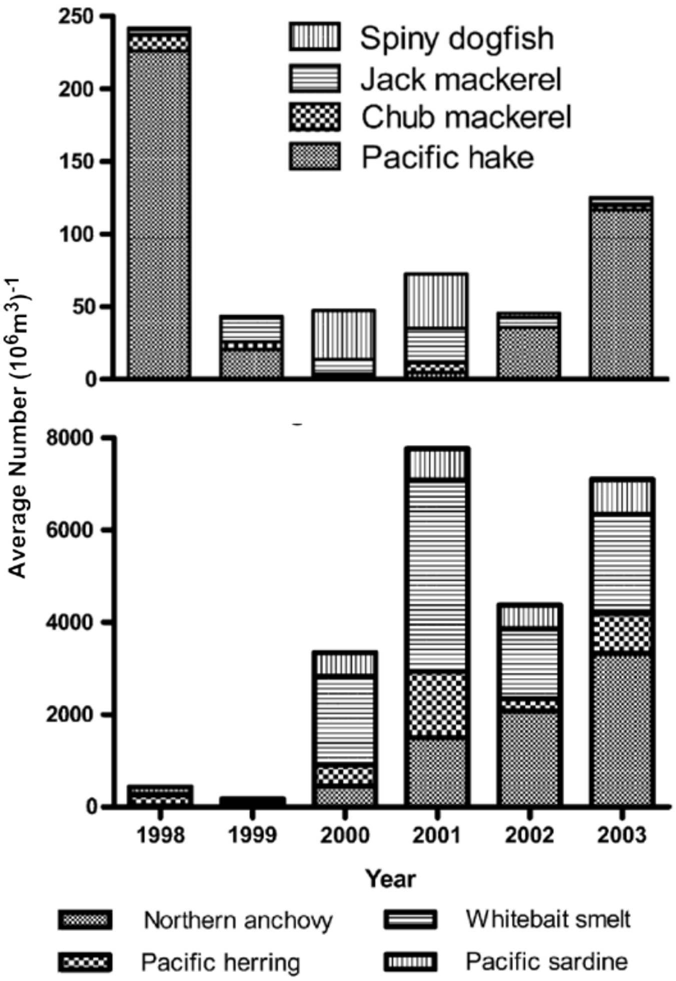


Figure 4-13. Average annual densities of (top) four pelagic predatory fishes and (bottom) forage fish collected at night by surface trawls off of the Columbia River during spring/early summer surveys 1998-2003. Figure from Emmett et al. (Emmett et al. 2006a)

Food web effects on other pelagic fish species from climate-driven changes are also unclear. Euphausiids are an important food of many coastal pelagic species and Pacific hake (Miller et al. 2010). However, a close dependence between euphausiid abundance and ocean conditions has not been demonstrated (Tanasichuk 2002). Furthermore, these pelagic fish exhibit a high level of omnivory and thus are not solely dependent on euphausiids (Miller et al. 2010). Jellyfish (small gelatinous zooplankton and large jellyfish) represent an energy loss pathway in the pelagic food web off Oregon and Washington in that they consume a large proportion of zooplankton production but are not in turn consumed by higher trophic levels (Ruzicka et al. 2012). However, among 2000-2007, large jellyfish were most abundant off Washington and Oregon in years of cool spring-summer condition (i.e., negative PDO anomalies), and low winter-summer Columbia River discharge (Suchman et al. 2012). It should be noted that large jellyfish are major consumers of eggs, larvae, and early juvenile stages of euphausiids and fish (Suchman et al. 2008), and therefore their increase could impact fish should it occur under climate change.

Many of the groundfish have planktonic eggs, nearly all have planktonic larvae, and many have pelagic juvenile stages as well. For these pelagic early life stages to succeed they must survive, grow, and arrive at habitat suitable for settlement to the bottom. Success of these life stages is very important because it often determines recruitment to the adult population (Field and Ralston 2005; Keller et al. 2012). In other words, high success in a year often translates into high abundance of adults born that year. Therefore, a key question with respect to climate change is how ocean conditions affect pelagic early life stage success (juvenile recruitment).

It is known that juvenile recruitment is often spatially synchronized over relatively long distances (on the order of 500-1000 km for West Coast rockfish) (Field and Ralston 2005). This suggests that ocean conditions that are synchronous over similarly large spatial scales may be affecting juvenile recruitment. Juvenile recruitment off the Pacific Northwest is often synchronized from northern Washington to Cape Blanco Oregon (Field and Ralston 2005). It is also known that juvenile recruitment is often uncorrelated among species, although it can covary for species with similar life histories (time of spawning, larval duration) and behavior (vertical stratification in the water column, thermal preference) (Carr and Syms 2006). Evidence also suggests that juvenile recruitment is probably set sometime during the larval stage (Bailey and Francis 1985; Ralston and Howard 1995).

Juvenile recruitment off the Pacific Coast has been shown to vary with a variety of ocean conditions but the specifics vary among species and other circumstances. Warm temperatures and poleward flow in late winter such as during El Ninos were detrimental to juvenile recruitment for black, blue, and yellowtail rockfish off northern California (Carr and Syms 2006; Laidig et al. 2007) but beneficial for a group of solitary, benthic rockfish species with shorter larval durations (Carr and Syms 2006). Strong upwelling hindered juvenile recruitment for Pacific hake (Bailey and Francis 1985), but was associated with high recruitment for some rockfish species off southern California although the mechanism was unknown (Caselle et al. 2010). Various aspects of cross-shore and along-shore current patterns were found to be important for juvenile recruitment of some rockfish species (Ainley et al. 1993; Yoklavich et al. 1996) and sablefish (Schirripa and Colbert 2006). No general trends applicable to a large number of species were apparent.

Another function of pelagic early life stages is dispersal. For sedentary benthic species, these early life stages may provide the primary means of shifting ranges to more suitable habitats under climate change. The effect of climate-driven changes to ocean conditions on dispersal of pelagic early life stages will therefore be important.

Benthic habitats

Interannual variation in distribution and abundance tends to be lower for benthic fish than for pelagic fish because many benthic species are long lived (Table 4) and non-migratory (King and McFarlane 2003). For example, interannual variation in abundance of groundfish species off Washington and Oregon during 2003-2008 (Figure 4-14) was much lower than for coastal pelagic species during 1998-2005 over roughly the same spatial extent (Figure 4-14). Benthic fish communities therefore do not track short-term changes in ocean conditions to the same extent as pelagic fish. Nevertheless, average ocean conditions over longer time periods vary spatially, and benthic fish communities reflect this variation.

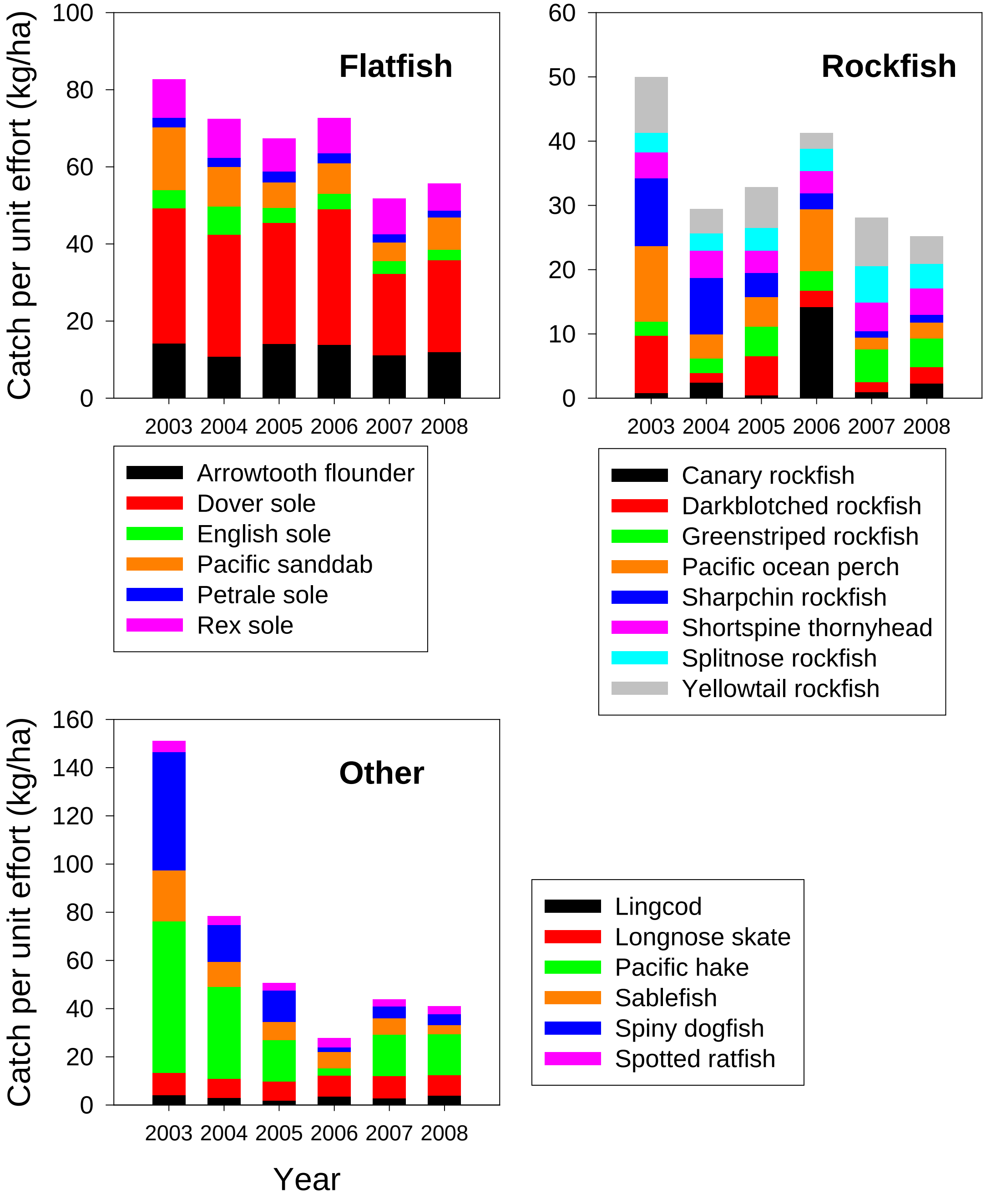


Figure 4-14. Abundance of the 20 most abundant groundfish species in 2003-2008 between the Washington-British Columbia border and Cape Blanco, Oregon (US-Vancouver and Columbia INPFC statistical areas), for the depth range 55-549 m. Data are from Bradburn et al. (2011)

Several studies have shown that for continental shelf and slope habitats off the U. S. West Coast, groundfish distribution and abundance vary with bottom temperature which in turn varies with depth and latitude (e.g. Tolimieri and Levin 2006; Zimmermann 2006). Bottom temperature generally decreases with increasing depth or latitude. Species maintain their preferred temperatures by occupying greater depths at lower latitudes.

Juan-Jorda et al. (2009) compared distribution and abundance of Pacific Northwest (Washington-northern California) groundfish in summer (March-October) 2004 to long term (19 year) summer averages and variation for surface, mid-water (50 m), and bottom temperature and salinity, and for surface chlorophyll-*a*. Five summertime oceanographic habitats with distinct physical and biological (fish community) characteristics were identified (Figure 4-15), three of which are present in OCNMS. "Highly variable habitat" occurred almost exclusively in the OCNMS. It had the highest variation in temperature and salinity, and the highest average temperature and lowest average salinity near the bottom, among the five habitats. Characteristic fish species for this and the other habitats are listed in Figure 4-15. "Upwelling habitat" was widely distributed from northern Washington to southern Oregon. It had cold temperatures and high salinities at the surface and mid-water, and relatively high surface chlorophyll-*a*. "Offshore habitat" was distributed from northern Washington to central Oregon. It covered the deepest waters of the study area and had the warmest surface temperatures, the lowest surface chlorophyll-*a*, and the highest bottom salinities. Three regions with both high chlorophyll-*a* concentrations and high abundances of particular groundfish species were also identified (but not shown in Figure 4-15): the Juan de Fuca Canyon in the OCNMS, the Columbia River plume, and Hecata bank off central Oregon (Juan-Jorda et al. 2009).

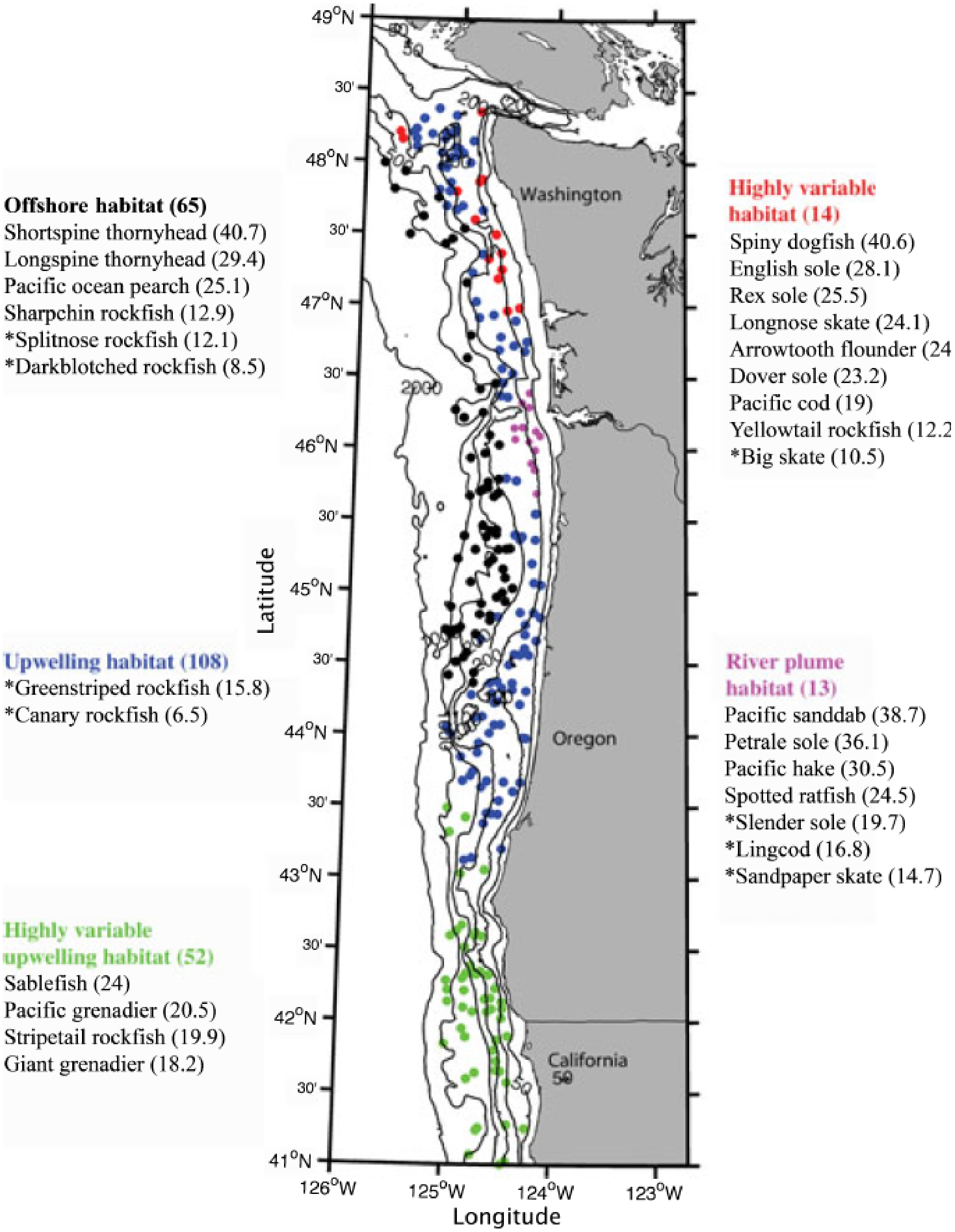


Figure 4-15. Geographic locations of the summer ocean habitats with different biological-physical characteristics. Species indicative of each habitat, along with values indicating their strength of association with the habitat, are also presented. An asterisk next to a species name denotes that the indicator value for that species was statistically non-significant. Bathymetric contours are at 50 m depth intervals. Figure from Juan-Jorda et al. (2009) .

Ware and Thomson (2005) showed that long term average annual yield (weight of commercial landings) of resident fish (primarily groundfish species) was positively correlated with regional primary and secondary production along the Pacific coast. Average resident fish yield in 11 North Pacific Anadromous Fish Commission (http://www.npafc.org/new/index.html) statistical fishing areas was correlated with mean annual chlorophyll-*a* from satellite observations. Interestingly, chlorophyll-*a* and fish yield were both highest in northern Washington-southern British Columbia. Chlorophyll-*a* was lower farther south, where upwelling was stronger, and farther north which is considered a downwelling zone. At a smaller spatial scale (British Columbia), average resident fish yield in six sub-regions was again correlated with chlorophyll-*a*. Zooplankton data were available for British Columbia and provided an intermediate trophic link between primary production and fish. Mean annual zooplankton biomass was correlated with chlorophyll-*a* and with resident fish yield.

Because groundfish are spatially distributed according to long term average conditions a key question for groundfish is how long term, sustained changes in ocean conditions from climate change will affect the current spatial configuration of habitats and fish communities, and the productivity of those habitats and communities.

4.8.4 Potential response to climate change

This section considers how fish will respond to changes in each of the major physical drivers associated with climate change: Temperature, ocean acidification, and hypoxia directly affect fish physiology. Brief descriptions of these effects are given. For fish, as with many other species and communities, many changes due to climate change are likely to be in response to multiple changes at an ecosystem scale. The reader is referred to Section 3.2 for a summary of potential generalized ecological implications of climate change for OCNMS.

Temperature

Because fish are ectotherms, their physiology is closely tied to water temperature. Fish have species (and sometimes population) specific upper and lower temperature thresholds beyond which they become stressed and their scope for aerobic activity is reduced (Portner and Knust 2007). Acclimation and short exposure times can mediate these effects but chronic exposure will reduce fish performance. The temperature range between the thresholds decreases with fish size and is narrower for adults than for juveniles but may also be narrow for larval fish (Portner and Farrell 2008).

Within the range of favorable temperatures where activity is unrestricted, temperature affects fish growth because temperature determines what portion of a fish's energy budget must be allocated to metabolism rather than to growth (Beauchamp et al. 2007). The energy required for metabolism increases with temperature. Metabolic costs also increase with fish size for any given temperature. Growth increases with food consumption (up to satiation) for a given temperature, but when food is limited (i.e., below satiation) maximum growth occurs at a lower temperature than when food is unlimited. Bioenergetic models are often used to examine relations among temperature, body size, food consumption, and growth (Beauchamp et al. 2007).

Temperature also affects reproduction and early development in fish (Pankhurst and Munday 2011). Rising temperatures cue initiation of reproductive development in spring spawning species and falling temperatures do the same for fall spawning species. Temperature increases from climate change could cause spring spawners to spawn earlier and fall spawners to spawn later. More extreme temperature increases could inhibit reproduction. An effect of temperature on embryos and larvae is to control development rate. Increased temperatures speed development and result in shorter duration embryonic and larval stages. Embryos are sensitive to temperature and often have lower maximum temperature tolerance limits than other life stages.

Fish might respond to temperature changes by moving to areas with more preferable temperatures, which for warming will likely result in moves to higher latitudes or greater depths. Life history and behavioral traits can affect the extent to which species shift their ranges in response to temperature changes. Maximum body size, age at maturity, and size at maturity were less for North Sea species that shifted their ranges in response to warming than for non-shifting species as would be expected if species with faster rates of population turnover more readily exhibited distribution changes (Perry et al. 2005). Northwest Atlantic migratory species often adjusted their spatial distributions to seasonal and interannual changes in temperature (Murawski 1993). In contrast, some sedentary (non-migratory) species inhabited areas with wide temperature fluctuations, implying that these species were relatively tolerant of temperature changes, and other sedentary species occupied deep, cold-water habitats that experienced little temperature variation (Murawski 1993).

Fish that are non-migratory, or are unable to shift their range due to lack of suitable habitat might experience increased mortality and population declines if temperature increases enough to impair aerobic activity or depress growth. For example, non-migratory common eelpout at the southern end of their range in the North Sea experienced increased summer mortality and decreased abundance from a gradual, long-term warming trend of 1.1 C over 40 years(Portner and Knust 2007). Bioenergetics modeling coupled with climate simulations indicated that growth of steelhead in the north Pacific would be depressed under climate change, assuming no range shifts and similar diet and consumption rate (Atcheson et al. 2012). Bioenergetics modeling also showed species differences in responses to increasing temperatures. Among sablefish, spiny dogfish, and yelloweye rockfish, increases in size at age-1 were greatest for yelloweye rockfish whereas decreases in age at 50% maturity were greatest for spiny dogfish (Harvey 2009).

Timing of fish reproduction and early development might also be altered by warming. The sockeye salmon summer spawning migration up the Columbia River is now 10.3 days earlier than in the 1940s, coincident with a 2.6 C increase in mean July temperature (Crozier et al. 2011). Up to two thirds of the change in migration timing may have been due to natural selection as opposed to a phenotypic shift, pointing out that responses to climate change will include both of these components.

Ocean acidification

Ocean acidification (OA) could directly affect fish physiology. Mechanisms used by fish to handle elevated pCO_2 include buffering of intra- and extra-cellular fluids, ion transport and exchange (osmoregulation), and transport of CO_2 in the blood (cardiorespiratory control) (Fabry et al. 2008). Most studies published before 2008 on effects of high pCO2/low pH on fish tested much higher pCO_2 levels than are projected for the OCNMS (Fabry et al. 2008; Ishimatsu et al. 2008). These studies indicate that marine fish have a high capacity for regulating internal pH, although such regulation may be energetically expensive (Ishimatsu et al. 2008). Gametes, zygotes, and early embryonic stages may be particularly susceptible to OA because they lack the physiological capabilities developed later in life to deal with high CO_2 levels (Melzner et al. 2009).

More recent studies have tested effects of smaller pCO2 increases/pH decreases in the range expected from OA in the next 100 years. Almost all of this work has been done with tropical coral reef fish rather than temperate fish. The most interesting results concern disruption of the ability to find suitable reef habitat and recognize predators or prey using olfactory or auditory cues. Larval reef fish use both of these senses to find suitable habitat for settlement and avoid predators (Munday et al. 2009b; Munday et al. 2010; Ferrari et al. 2011; Simpson et al. 2011). Older reef fish use olfaction to home on diurnal resting sites and find prey (Cripps et al. 2011; Devine et al. 2012). All of these olfactory and auditory discriminations were impaired by exposure to elevated pCO_2.Impairment of discrimination ability was usually present at 700 ppm and more extreme at 850 ppm. Furthermore, a link was demonstrated between impaired predator detection and mortality. Mortality from predation increased 5- to 9- fold when larvae exposed to elevated pCO_2 were transferred to natural reefs (Munday et al. 2010). Mechanisms by which OA disrupts olfactory and auditory discrimination are an area of contemporary research focus (Munday et al. 2009b; Domenici et al. 2012).

OA effects on performance measures other than sensory discrimination were not as consistent. No effect of elevated pCO_2 was found for embryonic duration, egg survival, size at hatching, maximum swimming speed of settlement-stage larvae, or juvenile growth or skeletal development of reef fish (Munday et al. 2009c; Munday et al. 2011a). In contrast, aerobic scope of adult reef fish decreased by 33-47% in acidified water (1000 ppm CO_2) compared to control water (Munday et al. 2009a). For temperate fish, Franke and Clemmeson (2011) reported no effect of OA on embryo genesis, hatch rate, or size of newly hatched Atlantic herring larvae, but the RNA/DNA ratio of larvae was inversely related to pCO_2. RNA concentration was reduced at higher pCO_2 levels could lead to decreased protein biosynthesis and growth rate.

Fish otoliths (ear bones) are made of aragonite and could therefore be influenced by increases in pCO_2/decreases in $CaCO_3$ saturation state projected under OA (Section 2.3). Otoliths from 7-8-day old white seabass larvae were larger under elevated pCO_2 rearing (993 and 2558 µatm pCO_2) than for control (Checkley et al. 2009)s. The authors speculated that the fish were able to control ion concentrations (H+ and Ca2+) but not CO_2 concentration in the endolymph surrounding the otolith, which would increase the $CaCO_3$ saturation state in the endolymph and the rate of otolith formation. Munday et al. (Munday et al. 2011b) also found that otolith size for reef fish larvae increased under high pCO_2 rearing but not for an intermediate treatments. Whether increased otolith size negatively affects fish is unknown, but asymmetry between left and right otoliths can hamper auditory detection of suitable habitat by larval fish (Gagliano et al. 2008).

Hypoxia

Vaquer-Sunyer and Duarte (2008) reviewed experiments testing for minimum dissolved oxygen requirements of marine animals. For fish, mean ($\pm$ SE) dissolved oxygen concentration causing 50% mortality (LC_{50}) was 1.54 ± 0.07 mgL^{-1}. Mean concentration causing a sub-lethal response (SLC_{50}) was 4.41 ± 0.39 mgL^{-1}. Mean time to 50% mortality (LT_{50}) was 59.9 ($\pm$ 12.3) hours. Typical sub-lethal responses of fish were avoidance of hypoxic waters, reduced activity, and increased water flow over the gills.

Larvae are particularly sensitive to hypoxia (Ekau et al. 2010). Metamorphosis is physiologically demanding. Larvae do not feed during metamorphosis, yet oxygen demand can be twice that of normal. Larger fish, however, can be sensitive due to their lower surface area to volume ratio, other factors being equal (Ekau et al. 2010). Differences among taxa in sensitivity to hypoxia affect species composition and alter competitive and predator-prey interactions (Ekau et al. 2010). Biodiversity may decrease and be limited to hypoxia-tolerant species. Hypoxic areas may provide refuge from predation, for example for copepods that are less sensitive to hypoxia than their pelagic fish predators. Jellyfish are more tolerant of hypoxia than fish and may replace fish as the dominant predator in hypoxic areas (Ekau et al. 2010).

Since 2002, hypoxia has developed on the inner shelf of the central Oregon coast on multiple occasions (Keller et al. 2010). In 2007, bottom trawl surveys were conducted to assess benthic fish in the hypoxic area (Keller et al. 2010). Total (all species combined) biomass density and species richness at a station were positively correlated with dissolved oxygen concentration. Positive correlations between biomass density and dissolved oxygen were also found for 8 of the 16 species tested. Mean condition factor (an index representing the ratio of weight to length) of fish was lower at the stations with the lowest dissolved oxygen concentrations than at the rest of the stations for 5 of the 6 species tested. Dover sole was the only species for which neither biomass density nor condition factor differed across the hypoxia gradient. Dover sole are deep water fish that sometimes inhabit the oxygen minimum zone and are adapted to low oxygen conditions (Love 2011). The correlation between biomass density and dissolved oxygen suggested that some fish moved to areas with higher oxygen and (or) mortality was higher at the stations with the lowest dissolved oxygen (Keller et al. 2010). Between 2002 and 2007, hypoxia was most extreme in 2006. Based on data from annual coast-wide bottom trawl surveys during 2002-2006, biomass density within the central Oregon inner shelf hypoxic zone was lowest in 2006 when biomass density was only 18% of that measured in the more intensive 2007 survey (Keller et al. 2010).

Sea level rise

Surf smelt and sand lance require suitable intertidal beach spawning habitat that may be influenced by sea level rise. The factors governing spawning habitat suitability for these species are elevation in the intertidal zone and beach sediment grain size (Pentilla 2007). Surf smelt spawn in the upper one third of the intertidal zone from about +2.1 m (relative to mean lower low water) up to extreme high water. A study on Camano Island in Puget Sound found that surf smelt egg density was highest between +2.4 and +3.0 m (Krueger et al. 2009). Sand lance spawn at slightly lower elevations, from about +1.5 m up to mean higher high water (Pentilla 2007). The Camano Island study estimated that sea level rises of 13 cm and 69 cm would result in losses of 3.5% and 75% of the potential surf smelt eggs, respectively, assuming that surf smelt could not simply spawn higher on the beach as sea level rises.

Spawning sediment grain size for surf smelt is typically a sand-gravel mix with most of the material in the 1-7 mm diameter size range (Pentilla 2007). Surf smelt eggs are typically found 1-10 cm deep within the substrate. Sand lance spawn in finer grained sediment than surf smelt with most material ranging from 0.2-0.4 mm in diameter (Pentilla 2007). Sand lance also burrow into intertidal beach sediments and remain there for extended periods of time. At Clayton Beach, Washington, during winter, most buried sand lance occurred in sediments 0.36-0.50 in diameter at the lowest beach elevation sampled (-0.3 m) (Quinn 1999). Key questions for future availability of surf smelt and sand lance intertidal habitat are whether natural processes can keep pace with sea level rise to create suitable new habitat father up and along beaches.

Herring primarily spawn on nearshore aquatic vegetation including eelgrass and seaweeds. Depth increases from sea level rise will affect these plants (Mumford et al. 2007) and may affect herring abundance in the OCNMS. Herring migrate into the OCNMS from spawning grounds in nearby sheltered waters (Salish Sea, Barkley Sound, Grays Harbor, Willapa Bay) (Haegele and Schweigert 1985).

Increasing frequency and severity of storms

Increased storminess and attendant increased wave energy will have marked effects on nearshore habitats and biota (Section 3.3.1). Offshore habitats could also be affected, possibly through increased turbulence in surface waters. No information specific to fish was found.

Upwelling and Upwelling Favorable Winds

Large scale along-shore currents can affect migratory species. Pacific hake occupy the northward-flowing California undercurrent when migrating from Southern California to Pacific Northwest feeding grounds (Agostini et al. 2006). Greater spatial extent and stronger flow of this sub-surface current enhance northward migration by hake. Such conditions often occur during El Ninos (Agostini et al. 2008).

Altered hydrology

Altered hydrology will directly affect anadromous fish during the freshwater phase of their life cycle (Mantua et al. 2009). The implications of altered hydrology for salmonids for the major rivers draining directly into ONCMS are discussed in Section 2.8. Eulachon typically spawn in rivers with high spring flows. Spawning usually occurs well before peak flows, a strategy that often results in egg hatch coinciding with peak flows which facilitate downstream transport of larvae (Gustafson et al. 2010). Climate-driven alterations in peak flow timing may reduce eulachon spawning success if spawn timing remains the same and is mismatched to suitable river flows, or if eulachon adjust their time of spawning to match the new hydrologic pattern and larvae reach the estuary at a time when conditions are suboptimal (Gustafson et al. 2010).

Altered hydrology can also affect marine environments through changes in temperature, salinity, input of terrestrial nutrients, and effects on primary and secondary production. Besides discharge from western Olympic Peninsula rivers, the two main sources of freshwater entering the OCNMS are the Columbia River and the Juan de Fuca Strait (mostly Frasier River water). The Columbia River plume often extends as far north as the OCNMS (Emmett et al. 2006b). The spatial extent of the Columbia River plume offshore from Oregon and Washington varied among 1998-2002 and was restricted during a draught (2001), but the variation in extent did not affect juvenile salmon or coastal pelagic species distributions to any major degree (Brodeur et al. 2005; Emmett et al. 2006b). No information was found on fish response to variation in freshwater discharge from the Juan de Fuca Strait.

4.9 Seabirds

4.9.1 Summary

- Given their role as mid- to upper-trophic level predators, the susceptibility of seabirds to climate-mediated changes will depend in large part on the impacts that their prey species experience.

- Given the broad range in diet, foraging strategies and life history characteristics of seabirds, responses to climate change at the community level will not be uniform.

- In addition to the direct and indirect effects of climate change on seabird populations, it is important to consider that these impacts might interact synergistically with additional threats confronting seabirds both within the sanctuary and, for migratory species, on their migratory routes and wintering grounds.

4.9.2 Introduction

Given that seabirds utilize both terrestrial and marine habitats during their life cycles, depend on marine food webs throughout the year, and typically move across large spatial scales, they may be affected by multiple and potentially synergistic impacts of climate change. Making the assessment of the response of seabirds to climate change even more challenging is their broad role as mid- to upper-trophic level predators; as such, the susceptibility of seabirds to climate-mediated changes will depend in large part on the impacts that their prey species experience.

OCNMS is utilized by 12 species of breeding seabirds as well as approximately 90 additional species that use sanctuary waters during their non-breeding seasons. More than 10 families of seabirds are regularly represented in sanctuary waters. Such diversity suggests the possibility that responses by the seabird community to changes in climate will not be uniform.

There are a number of potential climate-mediated mechanisms that may impact seabirds, most of which are considered to be indirect, operating through changing the dynamics of currents, water columns and water masses (Yen et al. 2006; Ainley and Hyrenbach 2010) and/or by altering food web structure and relative prey abundance and availability (e.g. Kitaysky and Golubova 2000; Gaston et al. 2005; Dorresteijn et al. 2012). In the Pacific Northwest, multiple studies suggest that seabirds are regulated by bottom-up oceanographic and atmospheric forcing (Springer 1992; Parrish and Zador 2003), the effects of which are typically indirect.

However, direct impacts of climate change, although poorly studied to date, could exist. Such effects might include the flooding of breeding colonies due to sea level rise and increasing storm intensity, although this is more likely on lower-lying islands than most of those that occur within sanctuary waters. Coastal erosion may impact important seabird breeding islands and ultimately decrease available nesting habitat. In addition, thermal physiological stress of adults and chicks from overheating is possible, especially for surface-nesting species, although this has not yet been quantified.

4.9.3 Population-level responses

Population dynamics of seabirds can be affected by the impact of climate variability on adult survival and offspring production and recruitment. Given that seabirds are generally long-lived, there is frequently a time lag between the climate signal and the demographic response of the population, with the age at maturity being the most important variable explaining the length of the lag (Sandvik et al. 2012). Age to maturity for seabird species that use sanctuary waters varies approximately from 2-9 years of age, meaning that real changes to population demographics may not be perceived for a number of years following the initial change in conditions.

To date, most studies of seabirds have indicated generally negative associations between population parameters and changes in climate. These parameters include phenology of migration and reproduction, changing patterns of distribution, reproductive success, survival rates and general population dynamics (D'Alba et al. 2010). Seabird breeding parameters are commonly affected by both large-scale oceanographic phenomena, including the Pacific Decadal Oscillation (PDO, Jones et al. 2002), North Atlantic Oscillation (NAO, Wanless et al. 2009) and El Niño Southern Oscillation (ENSO, Ramos et al. 2006, Surman and Nicholson 2009a,b) and fine-scale conditions, including sea surface temperature, wind speed and local upwelling (Becker and Beissinger 2003, Frederiksen et al. 2004, Jaquemet et al. 2007). Thus, given the broad range in diet, foraging range and foraging strategies of seabirds, responses at the community level will not be uniform.

Within the California Current System (CCS), multiple studies have linked low breeding propensity and/or reproductive success in seabirds with high sea surface temperatures and associated low productivity (Abraham and Sydeman 2004, Sydeman et al. 2006, Lee et al. 2007, Jahncke et al. 2008). El Niño events, predicted to become more frequent in many climate change scenarios, have particularly dramatic negative impacts on seabird reproduction within the CCS and have also been linked to short-term declines in adult survival (Lynn et al. 1998, Chavez et al. 2002, Lee et al. 2007). At least for the species that breed within OCNMS, population-level declines are predicted if diminished productivity were to become a chronic stressor in the surrounding marine ecosystem.

Climate change can also produce more favorable environments for certain species (e.g., Gaston et al. 2005). At least in the short- to medium term, milder climatic conditions during the winter months might enhance overwinter survival for some species. For example, earlier ice break-up resulted in better nestling survival, body condition and nestling growth for four Arctic-breeding species, including thick-billed murres (*Uria lomvia*) and northern fulmars (*Fulmarus glacialis*) (Gaston et al. 2005). In addition, an extension of favorable climatic conditions might allow for range expansions into higher latitudes, meaning that species whose range limits currently lie to the south of sanctuary waters may be able to access them successfully in the future. Results from the TOPP (Tagging of Pacific Predators) project suggest that potential core habitat for seabirds in the North Pacific may increase significantly under a variety of climate change models, although distributions of both prey and seabird predators may be shifted northward (Hazen et al. 2012). However, changes in dominant wind regimes and, thus, migration corridors may render some potential habitat inaccessible (Hazen et al. 2012). Furthermore, responses are likely to be species-specific due to difference in phenotypic plasticity and dietary breadth (Hazen et al. 2012).

Phenological changes in the timing of breeding may alter dynamics in seabird colonies that support multiple species, such as the breeding seabird community on Tatoosh Island that is comprised of nine species from four different families. Phenological plasticity varies between seabird species, with the result that more phenologically labile species may shift the timing of breeding in response to changing oceanographic conditions. This shift could result in greater interspecific competition for nesting space in colonies and for food (Lynch et al. 2012).

At the community level, changes in climate can be expected to produce, at times, opposite trends among the component species. For example, in a northern Pacific community of four alcid species (auklets and puffins), there was a negative correlation between sea surface temperature and reproductive success of the two planktivorous auklet species, while the two piscivorous puffin species showed a positive correlation (Kitaysky and Golubova 2000). The macrozooplankton which serves as the dietary basis for the planktivorous auklets is more abundant during cold oceanographic regimes whereas meso-zooplankton, the potential prey of juvenile pelagic fish upon which piscivorous alcids depend, is typically more abundant during warmer regimes (Kitaysky and Golubova 2000). Given that the community of breeding seabird species in sanctuary waters is comprised of multiple functional groups (planktivorous, piscivorous and opportunistic species), population trends may diverge.

Even within a species, the response to climate variability may not be uniform but, rather, may vary regionally. For species with wide breeding or wintering distributions, such as rhinoceros auklets (*Cerorhinca monocerata*) and common murres (*Uria aalge*), changes in climate may not be uniform throughout their range. As such, some populations may benefit or be unaffected while populations in other regions may decline (Satterthwaite et al. 2012).

Another important consideration is the significant community of seabird species that do not breed within the sanctuary but use it during migration and/or during the non-breeding season. For this seasonal community, which includes two albatross species from the subtropical Pacific, Southern Hemisphere shearwaters, and Arctic- and Mexican-breeding species, distant climate change impacts in other parts of their range confound our interpretation of climate change impacts operating at a local level on these populations.

Upwelling and Upwelling Favorable Winds

Projections related to changes in upwelling patterns in OCNMS are mixed (Section 2.6). Seabird reproductive success in the CCS is positively related to upwelling strength due to the increased productivity that results from this physical forcing mechanism (Ainley et al. 1995, Sydeman et al. 2006, Barth et al. 2007, Jahncke et al. 2008). Delays in the timing of upwelling and/or declines in upwelling magnitude have led to well-documented breeding failures in California Current seabirds (Sydeman et al. 2006, Barth et al. 2007, Ronconi and Burger 2008).

In contrast, the consequences of increased upwelling magnitude are unknown. An increase in the intensity of upwelling may result in enhanced productivity in the system through the input of additional nutrients. The increased movement of deep, colder water to the surface may also counteract regional sea surface temperature increases. However, there is also evidence to suggest that stronger upwelling conditions could actually result in decreased food availability for seabirds as plankton may be driven deeper (Pringle 2007), thereby forcing planktivorous fish and crustaceans deeper in the water column and making them less accessible to avian predators.

Food availability and abundance

Primary production influences higher trophic level organisms in complex processes (McGowan 1998). Changes in primary production can produce an ecological cascade, with seabirds, as mid- to upper-trophic level predators, impacted indirectly but significantly through changes in prey availability. Oceanographic features that produce or contribute to high primary productivity, including mesoscale features such as fronts and eddies, may change with changing climate (Surman et al. 2012). As they change, productivity may be spatially and/or temporally displaced, which may impact the ability of seabirds to forage successfully. A long-term multi-trophic level study in the North Sea documented trophic mismatching for five seabird species breeding in the region, with phenological changes in the chick-rearing period resulting from changing productivity patterns (Burthe et al. 2012). In the Canadian Arctic, a long-term study of alcid diet has indicated a general decline in prey diversity, with a corresponding decrease in cold-water species (Provencher et al. 2012). Models of predicted habitat shifts in the eastern Pacific suggest that mismatches between predators, including seabirds, and prey could enhance climate change impacts (Hazen et al. 2012).

In some situations, changes in climate can also produce enhanced foraging conditions for marine birds. Generally milder conditions and extended upwelling periods may produce a possible lengthening of the growing season for phytoplankton with a consequent increase in seabird prey biomass. In the Alaska Gyre, a delay in migration dates has been documented for multiple seabird species, presumably in response to extended availability of forage nekton in the region (Thompson et al. 2012).

The response of seabird species to changing food availability also depends on the plasticity of their foraging behavior, with some species able to accommodate changing sea surface temperatures and associated changes in productivity by shifting diet and/or foraging regions (Gremillet et al. 2012, Hazen et al. 2012). It is difficult to predict *a priori* the extent to which focal species have the capacity to adaptively respond to changes in climate via foraging plasticity, by shifting diet, expending more effort foraging, or by foraging farther from colonies during the breeding season.

Ocean acidification

No studies to date have considered the effects of ocean acidification on seabirds. Such effects, if any, are likely to be indirect as a result of impacts on prey species.

Synergistic interactions

In addition to the direct and indirect effects of climate change, it is important to consider that these impacts might interact synergistically with additional threats confronting seabird populations both within the sanctuary and, for migratory species, on their migratory routes and wintering grounds. Such current threats include predation by invasive species, especially on breeding colonies; degradation and loss of breeding habitat; acute and chronic marine pollution; fisheries bycatch; and competition with fisheries.

4.10 Sea Otters and Pinnipeds

4.10.1 Summary

- Cumulative climate stressors (ocean temperatures, ocean acidification, storm events and hypoxia) could reduce the sea otter population along the Olympic coast or force them to move out of the area due to changes in prey availability. This could lead to trophic cascades within the kelp ecosystem since kelp grazers would no longer be kept in balance by otter predation.
- Climate change may cause fish to shift their distributional range and thus reduce their availability as pinniped prey. However pinnipeds have some ability to switch to other prey sources, so the net impact is unknown.

4.10.2 Introduction

Within the OCNMS there are 29 species of marine mammals that are either residents or migrate through the area (National Oceanic and Atmospheric Administration 2011). This section highlights four species, which includes one mustelid , the sea otter (*Enhydra lutris*) and three of the five pinniped species common to the area (harbor seal (*Phoca vitulina*), California sea lion (*Zalophus californianus*), and Steller sea lion (*Eumetopias jubatus*)). All of these marine mammals will be affected by changes in climate to varying degrees as previously summarized by Largier et. al. (Largier et al. 2010) and Learmonth et al. (Learmonth et al. 2006). The projected climate conditions that likely will have the most affects on marine mammals include increased sea temperature, ocean acidification, sea level rise and alternations of oceanic processes. Each of these 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, changing trophic and community structure, timing of breeding, reproductive success, changes in behavior, stress on body health and susceptibility to disease (Learmonth et al. 2006; Laidre et al. 2008).

Sea otters are of particular importance due to their role as keystone species since their presence/absence can have marked influences on nearshore community structure and biodiversity (Estes and Palmisan.Jf 1974; Estes et al. 1989), including their role in ecosystem carbon budgets (Wilmers et al. 2012). Their population in OCNMS has been rising slowly with a peak of 1,125 animals in 2007 (Jameson and Jeffries 2010). The population is still considered to be below the estimated carrying capacity based on historical and regional habitat use, which includes rocky, sandy and mixed substrates (Laidre et al. 2002) and they are listed as endangered by the state of Washington (Lance et al. 2004).

Among pinnipeds, harbor seals are year-round residents and pup along the Olympic coast. Their populations have been increasing for some period of time (Jeffries et al. 2003; Carretta et al. 2011) and they are adaptable to varying conditions. Thus they are less likely to show dramatic impact to climate change.

The two otariid species, California sea lions and Steller sea lions, migrate into OCNMS waters primarily for foraging opportunities in the nutrient-rich upwelled waters. To current day, their populations have showed increased use of the area (Carretta et al. 2011).

4.10.3 Responses to Climate Change

Increasing ocean temperature

Increased ocean temperatures will likely cause changes in availability of some macroinvertebrate species that are preferred prey of sea otters. This could include possible range shifts and/or depth profiles, though otters may adapt to other prey species. Increased sea temperatures will also likely contribute to increased risks of exposure to biotoxins from harmful algal blooms (Van Dolah 2005) and pathogens (Brancato et al. 2009; Bossart 2011), adding to environmental stressors and likelihood of increased mortalities.

Harbor seals may be forced to switch prey sources due to increasing sea temperatures causing range shifts in their major fish prey, which may also contribute in increased exposures to biotoxins and pathogens (Van Dolah 2005; Brancato et al. 2009).

Increasing sea temperatures and vertical stratification in the water column may impact California sea lions and Steller sea lions due to the alteration of the trophic structure of their major fish prey (Van Dolah 2005). As with harbor seals, increasing temperatures may cause additional impacts from biotoxins and pathogens (Gulland 2000; Van Dolah 2005; Brancato et al. 2009; Largier et al. 2010; Bossart 2011).

Ocean acidification

Ocean acidification, will likely have negative impacts on sea otter populations since their main prey, calcifying shellfish (including molluscs, crustaceans and echinoderms) will be severely impacted (Riedman and Estes 1990; Laidre and Jameson 2006).

The availability of fish prey species for pinnipeds may be negatively affected by ocean acidification (Largier et al. 2010).

Sea level rise

Sea level rise is unlikely to affect sea otters. However if sea levels rose sufficiently to cover low-lying reefs, the haul-out patterns of harbor seals would be impacted, contributing to physiological stress. The greater dexterity of sea lions to climb steeper offshore rocks for their haul-outs would not be impacted.

Increasing frequency and severity of storms

Increased frequency and severity of major storm events would limit otter foraging bouts which are highly critical due to their metabolic need to consume roughly 25% of their body weight per day (Riedman and Estes 1990) and could lead to separation of mother-pup pairs.

Major storm events could have negative impacts on harbor seal pupping sites along low-lying rocky reefs, which has been documented as mortalities in elephant seal pups (Pettee 1999; Sydeman and Allen 1999).

Upwelling and Upwelling Favorable Winds

While there are no clear projections regarding upwelling or upwelling-driven productivity in OCNMS (Section 2.6), if upwelling events are altered, the timing or avoidance of the area by

California and Steller sea lions may be adversely influenced since they are attracted to the area when prey are abundant during these events (Sydeman and Allen 1999; Largier et al. 2010).

Increasing occurrence of coastal hypoxia and anoxia

Increased nearshore hypoxia events would negatively impact the availability of macroinvertebrate prey for sea otters. And depending on the temporal and spatial extent of low oxygen events, this may similarly negatively impact availability of fish prey sources for pinnipeds.

Altered hydrologic patterns

If changes in climatic patterns lead to increase river flows in the watersheds, the resulting increased sediment plumes fanning out in the nearshore will likely have negative impacts on benthic macroinvertebrates and kelps due to the smothering affects. This would result in negative impacts on sea otter prey availability and sea otter resting sites amidst the kelp canopy.

4.11 Cetaceans

4.11.1 Introduction

Twenty three species of cetaceans have been documented to occur in OCNMS (National Oceanic and Atmospheric Administration 2011) (seven of them, humpback whales, gray whales, killer whales, Risso's dolphins, Dall's porpoise, Pacific white side dolphins, and harbor porpoise) occurring regularly (Green et al. 1992; Osmek et al. 1996; Shelden et al. 2000; Calambokidis et al. 2004b; Forney 2007). Cetacean species which are found in OCNMS, with the likely exception of harbor porpoises, display seasonal trends in their residency patterns. In general, the seasonal occurrence of these species in the OCNMS is likely tied to prey availability for these highly mobile predators.

Humpback whales are one of the more numerous whales in OCNMS (Calambokidis et al. 2004b; Forney 2007), occurring from early summer well in to winter (Sheldon et al. 2000, NWFSC unpublished data), after which they undertake a southern migration to breeding grounds. During the time the whales are in the OCNMS they have been observed feeding on schooling fish (Shelden et al. 2000), although the species are unknown. Humpbacks are known to feed on several prey species in the north Pacific Ocean including both euphausids and schooling fish which include mackerel, sand lance, capelin, and herring (Winn and Reichley 1985).

Gray whales in the eastern north Pacific undertake a coastal seasonal migration between the breeding lagoons in Baja Mexico and the Bering Sea, Alaska. A small fraction of the gray whale population, termed the "Pacific Coast Feeding Aggregation" (Calambokidis et al. 2004a) remains in the nearshore waters of the OCNMS and adjacent coastal areas during the summer to feed. The prey of this population has been documented in adjacent coastal waters of British Columbia to consist of primarily invertebrates, including Porcelain crab larvae, mysids, benthic amphipods, and benthic ghost shrimp, as well as herring eggs (Darling et al. 1998).

All three ecotypes of killer whales (resident, transient, offshore) commonly inhabit the OCNMS, occurring in all seasons (Calambokidis et al. 2004b; Hanson et al. 2008; Hanson et al. In Press) but with some seasonal variability in occurrence. Each ecotype is defined by its dietary specialization, i.e., resident: salmon (Ford et al. 1998; Hanson et al. 2010b), transients: marine mammals (Baird and Dill 1995; Ford et al. 1998) and offshore: sharks and fish (Dahlheim and White 2010). Resident type killer whales are known to be Chinook specialists in the summer (Ford et al. 1998; Hanson et al. 2010b) and there is evidence that this preference may persist in coastal waters (Hanson et al. 2010a).

Dall's porpoise were the most frequently sighted small cetacean in the OCNMS and estimated to be the most numerous (Calambokidis et al. 2004b; Forney 2007). However, they appear to be resident primarily in the summer as there are very few sightings of them in the winter months (Hanson et al. 2008; Hanson et al. 2009; Hanson et al. 2010a). Data for a satellite tagged Dall's porpoise showed that the porpoise inhabited the Juan de Fuca eddy region during the summer months before moving into the central Strait of Juan de Fuca in the fall (Hanson 2007). The diet of Dall's porpoise occurring in the OCMNS is unknown but diet studies in the north Pacific Ocean indicate that Dall's porpoise eat small fish and squid (Scheffer 1953; Crawford 1981; Ohizumi et al. 2003). Limited information from stranded animals from inland waters of Washington State indicates that diet is consistent with findings for porpoise diet in the pelagic environment (W. Walker, pers comm.).

Pacific white-sided dolphins, although occurring intermittently in the OCMNS, are primarily observed in the offshore waters, and can occur in large groups (Green et al. 1992; Green et al. 1993; Calambokidis et al. 2004b; Forney 2007). This species has been observed well into late fall and early winter (Shelden et al. 2000). No information on the diet of this species in OCNMS exists, however this species was observed to be in close proximity to humpback whales feeding on schools of fish off the Washington coast (Shelden et al. 2000).

Harbor porpoise commonly occur in the nearshore waters of the OCNMS (Green et al. 1992; Osmek et al. 1996; Calambokidis et al. 2004b). Harbor porpoise likely maintain year round residency, as exhibited by late fall sightings (Shelden et al. 2000), genetic differences between the several West Coast US stocks (Chivers et al. 2007) and limited movements of radio-tagged animals (Hanson 2007). Harbor porpoise diet was assessed from the stomach contents animals collected during the summer as bycatch in a tribal fishery in coastal waters near Neah Bay which showed that they consumed primary herring, squid, smelt and gadids (Gearin et al. 1994).

Risso's dolphins occur along the U.S. West Coast., and appear to shift their range from California to off the coast of Washington in the OCNMS during the spring and summer months (Green et al. 1992; Green et al. 1993). They are typically observed seaward of the continental shelf (Green et al. 1993; Calambokidis et al. 2004b). Their diet in the OCNMS is unknown but studies from various areas of their range indicate that forage on a variety of cephalopods (Kruse et al. 1999).

4.11.2 Potential response of cetaceans to climate change in OCNMS

The changes in the environment due to alteration of the climate may have direct or indirect effects on cetaceans in the OCNMS (Learmonth et al. 2006). Two studies investigated the potential impacts of climate change on marine mammals in the California Current System (CCS). Although Ainsworth et al. (2011) projected up to a 20% reduction in some marine mammals overall, in the northern California Current it was predicted that marine mammals may increase slightly in abundance. King et al. (2011) suggested that, in general, marine mammals would switch to alternative prey and undertake movements to follow prey and specifically predicted a northward movement for cetaceans such as common dolphins and a "decline in cool temperate species, such as Dall's porpoise."

Ocean Temperature

Many of the cetacean species occurring in OCNMS are not at the southern end their range, so it is unlikely that increasing ocean temperature alone will affect the suitability of their habitat. There is the potential for northerly shifts in these species overall range, though, which may influence abundance. Conversely, for those species that occur seasonally, (i.e., humpback and gray whales, Dall's porpoise, Pacific white-sided and Risso's dolphins) these species may increase the duration of their residency, assuming that prey base is suitable. In addition, other species with warm water distributions, such as common dolphins which now occur there rarely, may become more frequent.

Upwelling and Upwelling Favorable Winds

Marine mammals are found in association with bathymetric features such as the continental slope (Azzellino et al. 2008) and oceanic features such as fronts or eddys (Woodworth et al. 2012), which promote mixing and productivity. Spring upwelling on the continental slope in OCNMS (Pirhalla et al. 2009) likely results in the aggregation of cetacean species. A major oceanic feature of the OCNMS is the Juan de Fuca eddy which several cetacean species are likely to exploit during its occurrence in the summer. Dall's porpoise have been the only cetacean species noted to take advantage of this feature (Hanson 2007) but the summer distribution of species such as humpback whales and Pacific white-side dolphins (Calambokidis et al. 2004b) suggests that these species may also associate with this feature. Changes in ocean currents and productivity from climate change may resemble a positive ENSO event (i.e., decreased productivity will likely affect prey abundance possibly resulting in changes in the distribution of some species. Dall's porpoise were less common in Monterey Bay during an El Nino event (Benson et al. 2002); short finned pilot whales were replace by Risso's dolphins (Shane 1994; Shane 1995) and bottlenose dolphins expanded their coastal range (Wells et al. 1990).

Indirect and Synergistic Effects

It is possible that climate change in the OCNMS could cause changes in prey abundance. In particular the forage fish community is projected to change due to climate (Section 4.8.4), and declines in forage fish abundance are possible (Ainsworth et al. 2011), whereas increases of some other cetacean prey species (i.e. squid) may increase. Zooplankton abundance or community structure is also projected to change (Section 4.2), which could influence cetaceans indirectly.

The degree to which cetacean species currently found in the OCNMS may be impacted will be based on the breadth of their diet and residency patterns. The diverse diet of most species that consume one or more class of prey (e.g., humpback, Dall's, harbor porpoise, Pacific white sided dolphins) may allow them to switch to different prey with little to no impact to populations. Additionally, seasonally occurring species may shift their distribution north. Resident species, harbor porpoise for example, may only have prey switching as an option to adapt to an altered prey base. The predicted increase in squid (Ainsworth et al. 2011) may result in an increase of those species that eat squid (Risso's and Pacific white-sided dolphins, Dall's and harbor porpoise).

The variety of adaptations available to cetaceans suggests that transient killer whale occurrence will remain unchanged. However, projected reductions in pelagic fish, and specifically Chinook salmon (Section 4.8), may stress resident killer whales. The general lack of information on the diet of offshore killer whales in the OCNMS makes it difficult to project the potential effects of climate change on their occurrence.

The extent to which various species compete for prey resources in the OCNMS is unknown due to the paucity of diet data. However, it is possible that range expansion by warmer water species could result in new competition from more sub-tropical species, as has occurred in the north Atlantic with common and white-beaked dolphins (MacLeod et al. 2005). Consequently changes in community structure are possible.

For those species dependent on projected declines in prey resources there exists the possibility of reduced reproductive success. For example, reduced prey availability is thought to be associated with decreased fecundity in southern resident type killer whales in the Pacific Northwest (Ward et al. 2009). For many cetacean species the OCNMS is an important summer foraging area and decreases in prey may adversely impact reproductive output.

An additional impact of diminished prey resources is an increased susceptibility to disease (Gulland and Hall 2005). Increased water temperature may allow diseases to expand their range (Danovaro et al. 2011), either due to more favorable temperatures allowing pathogen survival or through increased range of carrier species. The recent mortalities caused by *Cryptococcus gattii* in small cetaceans in the Pacific Northwest were interesting - this fungi has previously only been found only in tropical and subtropical environments (Kidd et al. 2004). Additionally, reduced prey availability may lead to the need to burn fat reserves, which may mobilize accumulated contaminants and reduce immune-competence. The possibility of an increase in toxic algal blooms (Section 4.1) also suggests another source of stress for cetaceans. Mortality in humpback whales has been attributed to such an occurrence in the North Atlantic (Geraci et al. 1989).

As previously noted, climate change is likely to resemble the periodic El Nino conditions that are currently experienced, with resulting potential changes in cetacean prey and ultimately these species distribution and abundance. However, it is unclear the extent to which frequency, duration, and amplitude of these events will occur and the degree to which these longer term or more extreme changes will potentially affect OCNMS cetacean populations.

5 Key Considerations for Moving Forward With Adaptation in OCNMS

5.1 Introduction

OCNMS borders one of the few undeveloped coastlines remaining in North America, enhanced by the protection provided by the Olympic National Park, Washington Maritime National Wildlife Refuge Complex, and Hoh, Makah, Quileute, and Quinault tribal lands. While the relative isolation of OCNMS protects the sanctuary from many of the pressures associated with proximate human development, the sanctuary is not immune to the consequences of climate change, as described in the preceding chapters.

The OCNMS Climate Change Action Plan (National Oceanic and Atmospheric Administration 2011) calls for addressing the impacts of climate change on the sanctuary. This chapter introduces some of the fundamental questions and concepts that arise when adapting natural resources to climate change, and summarizes how climate change affects existing management priorities and stressors in OCNMS. The chapter does *not* tell OCNMS how it should adapt to climate change and what actions specifically should be taken. Those questions will be answered by OCNMS staff and collaborators via the climate change working group called for in the Climate Change Action Plan (Strategy CLIM3, Activity A).

Box 5-1. Factors influencing decisions about management priorities, risk priorities, and adaptation actions for adaptation planning [modified from US Environmental Protection Agency (2009)]:

1. Timing of projected impacts (e.g., short-term, mid-term, long-term) relative to the timing of management decisions and actions.
2. Severity of projected impacts (e.g., catastrophic, severe, major, minor, insignificant), and geographic scale (e.g., localized, sanctuary-wide, west-coast wide).
3. Probability of occurrence of different impacts.
4. Ecological, economic, or social significance/value of endpoints of concern (e.g., ecosystem services that are being protected).
5. Capacity of the responding entity (e.g., a community, organization, etc.) to undertake the action. Capacity to act can be shaped by: a) the availability of information to support adaptive decision making; b) the availability of adaptation options suitable for addressing risks; c) implementation costs; d) timing and time horizon for decision making and implementation; e) linkages to other decisions; f)

5.2 Adapting Natural Resources to Climate Change

Broadly speaking, adapting to climate change requires a continuous set of adjustments made to reduce the negative consequences of climate change and, where relevant, take advantage of new opportunities (Neil Adger et al. 2005). The specifics of how this is done at any given location or scale will vary depending on the nature of the climate change impacts and vulnerabilities that need to be addressed, the risk tolerance of the individuals and institutions involved in adaptation, available resources, and other factors (Box 5-1). The adjustments can be both proactive (i.e., in anticipation of projected impacts) and reactive (i.e., in response to impacts), and often involve a mix of regulatory and non-regulatory approaches.

A central issue in adaptation planning is understanding what is being adapted to and for what purpose (e.g. Smith et al. 2000). The scientific synthesis provided in this report provides a solid foundation for answering the first question: what does OCNMS need to adapt to? The second question – for what purpose – may prove far more difficult to answer both conceptually and in practice.

Part of the challenge is deciding if, when, and where adaptation should be directed at helping species and ecosystems increase their *resistance* (i.e., their ability to avoid, prevent, or otherwise minimize climate impacts), *resilience* (i.e., their ability to recover to a prior condition quickly after a disturbance), or *ability to respond* (i.e., their ability to accommodate change and transition to a new state) to climate change (Millar et al. 2007; Millar 2008). Because the level of intervention required to make species and ecosystems resistant or resilient to climate change is likely to increase over time as climate change progresses, (Millar et al. 2007) suggest that actions promoting resistance and resilience are most suitable for relatively short-term projects focused on high-value[2] or high-priority species or ecosystems. Practices that facilitate gradual adaptation and transition to change include assisted species migration; increasing redundancy and buffers (e.g., by introducing species over a range of environments rather than within its historical distribution); expanding genetic diversity; promoting connected landscapes; and "realigning" a landscape after disturbance with current and projected future conditions rather than historical pre-disturbance conditions (Millar et al. 2007).

In the case of OCNMS, adaptation decisions will be shaped in part by the sanctuary's existing mission, goals, and objectives, as well as the stated purposes and policies of the National Marine Sanctuaries Act and in consultation with affected tribes whose "Usual and Accustomed" areas are overlapped by Sanctuary boundaries. Some of these decisions are already taking shape, as evidenced by the sanctuary's 2011 Management Plan (National Oceanic and Atmospheric Administration 2011). Section 5.2-D2 (Climate Change Action Plan) links a set of selected climate change strategies to current OCNMS goals and objectives. However, climate change is raising fundamental questions that could affect current and future interpretation of some of these goals and objectives. One issue is the use of certain words or phrases that may take on different meaning in a changing climate, potentially creating new levels of obligation or changes in scope without any specific change in language. For example, Goal E of the 2011 Management Plan requires that OCNMS (emphasis added):

> "E. *Maintain* the sanctuary's natural biological diversity and *protect*, and where appropriate, *restore* and enhance sanctuary ecosystems."

Given projected changes in climate, do "maintaining" and "protecting" require preserving the assemblage of species, ecosystems, and natural processes of today's sanctuary or some other preferred benchmark? Similarly, what are appropriate restoration objectives in a changing climate? Restoration has traditionally been undertaken to return ecosystems or locations to desired (often undisturbed) conditions following a natural or man-made disturbance or alteration. However, as noted previously, reaching and maintaining a desired state that is linked to today's

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[2] Although "high value" can be used describe economic value, as done Millar et al. 2007 (for forest harvest value), the term can also be used to describe non-economic values. For example, Higgason and Brown 2009 note that the Gulf of Farallones defines "high value habitat" as "habitat that supports either high species diversity or abundance or both".

climate may require more intensive efforts going forward in time. Examples of other words or phrases that raise similar questions in OCNMS guiding documents are listed in Table 1.

Table 6. Examples of words or phrases from OCNMS guidance documents that could be interpreted differently because of climate change.

Goal, Objective, or Other Related Statement	Comment
OCNMS mission statement: "To *protect* the Olympic Coast's natural and cultural resources through responsible stewardship, to conduct and apply research to *preserve the area's ecological integrity* and maritime heritage, and to promote understanding through public outreach and education."	Climate change is projected to impact natural and cultural resources. Does protecting those resources mean protecting them as they exist today? How is ecological integrity defined and how is that definition tied to a specific climate? Does preserving ecological integrity require maintaining the integrity as it stands currently?
Objective C2. Monitor *key resources* within the sanctuary to identify significant changes over time (National Oceanic and Atmospheric Administration 2011) (Table 1, pg 5).	Climate change may affect what is considered a "key resource." Are there resources not currently considered "key" that would be in future scenarios?
Objective E1. Work collaboratively with strategic partners to *conserve natural habitats, populations, and ecological processes* by *preventing*, *minimizing* and/or *mitigating* stressors on resources in the sanctuary (National Oceanic and Atmospheric Administration 2011) (Table 1, pg 6).	Climate change is expected to cause habitats and species to shift. What does it mean to conserve, prevent, minimize, and/or mitigate in a changing climate?

OCNMS staff, the Sanctuary Advisory Council, and the Olympic Coast Intergovernmental Policy Council will be central to determining how to interpret these and other words or phrases for the sanctuary. NOAA and its federal and state partners and tribal co-managers, as well as the courts and U.S. Congress, are also expected to play a role.

Numerous documents provide guidance on the process of adapting to climate change (e.g., Snover et al. 2007; NOAA Office of Ocean and Coastal Resource Management 2010; Glick et al. 2011). Basic elements of a structured adaptation planning process involve 1) identifying important climate change impacts and vulnerabilities, 2) developing, prioritizing, and selecting adaptation actions, 3) implementing selected adaptation actions, 4) monitoring, evaluating, and updating adaptation actions as needed, and 5) communicating with stakeholders and decision makers about adaptation goals, objectives, and planned activities. Ideally the process brings staff from different departments or programs together to ensure that linkages, barriers, and opportunities across programs are identified; participation by neighboring communities or other entities that affect or are affected by an organization's adaptation planning effort may also be sought (e.g. Swinomish Tribe Office of Planning and Community Development 2010)

Preparing for climate change is not predicated on the use of a structured, formal planning process, however. Many entities have deliberately forgone formal adaptation planning efforts (due in some cases to a lack of funding or authority) and have instead opted to adopt a more basic framework for considering and enacting adaptive actions that simply asks "How does climate change affect what we do?" and "What would we do differently on the basis of that information?". These questions can be asked at a broad organizational level, at the level of an individual program, or for a single decision. Answers to these basic questions may alter how projects are prioritized and what strategies are chosen to achieve desired outcomes.

Box 5-2. Suggested guiding principles for "climate-smart" conservation (adapted from Hansen et al. 2010)

1. Protect adequate and appropriate space.
2. Manage for uncertainty. Expect surprises.
3. Reduce non-climate stresses.
4. Mainstream climate adaptation.
5. Plan for both climate variability and climate change.
6. Reduce the rate and extent of climate change.

5.3 Guidelines for Adaptation Planning

Regardless of whether adaptation is undertaken through formal or informal processes, there are several tenets or guiding principles related to "climate-smart conservation" that can be used to frame adaptation thinking (Snover et al. 2007; Hansen et al. 2010; Watson et al. 2012). Some of the more common tenets are summarized here (Box 5-2).

The first tenet is **protect adequate and appropriate space** to accommodate changing conditions, thereby providing species and ecosystems the ability to move to more optimal locations as climate change progresses(Hansen et al. 2010). This may require expanding reserves, including inward expansion of coastal reserves, or adding buffers (Lawler 2009). Other adaptation activities in this category may include identifying and protecting climate refugia; supporting habitat connectivity along climatically suitable corridors; protecting a diversity of habitats, communities, and species; and protecting more resilient populations.

A second tenet is **manage for uncertainty and expect surprises** (Peterson et al. 1997; Baron et al. 2009; Camacho 2009; Peterson et al. 2011). Adapting to climate change inherently requires making decisions in the face of uncertainty. While this is not unique (few decisions are made with perfect information) the rapid pace of projected change and the complexity of the problem (both in terms of geographic scale and range of impacts) can amplify decision uncertainties. Climate change also undermines traditional implicit and explicit assumptions that past climatic conditions are an adequate guide for today's management and planning decisions. This does not mean that the past is irrelevant when planning for climate change; to the contrary, the past can be helpful in pointing out existing vulnerabilities to future impacts.

Approaches for managing uncertainty and surprises vary. Three frequently suggested approaches are adaptive management, scenario planning, and the use of no/low regrets adaptation options (De Loë et al. 2001; Peterson et al. 2003; Willows 2003; Luers and Moser 2006; Snover et al. 2007; Baron et al. 2009; Lawler 2009; Hansen et al. 2010). Adaptive management, as originally defined and discussed in the published literature, is a framework that uses controlled experimentation, monitoring, assessment, and adjustment as the basis for management and institutional learning (Holling 1978; Walters 1986; Lee 1994). This is sometimes referred to as "active adaptive management" (Allen and Gunderson 2011). However, climate change literature has tended to embrace a broader interpretation of the approach, using the term to describe a more general process of iterative decision making, evaluation, and adjustment without deliberate management experimentation (also known as "passive adaptive management") (Gregory et al. 2006; Williams 2011).

In either case, adaptive management is well suited *conceptually* for adapting to climate change since the framework allows for regular re-evaluation and adjustment of decisions based on evolving climate change science and what is learned over time about the effectiveness of adaptive actions. In practice, active adaptive management programs have rarely been successfully implemented (Allen and Gunderson 2011) and even passive adaptive management approaches face challenges in a changing climate. Notable issues are the long time scales over which some climate change impacts may unfold and uncertainty about how exactly those impacts will unfold; these issues can create challenges for sustained monitoring and make it more difficult to interpret outcomes, particularly in complex biological systems where there is an already incomplete understanding of the system even without climate change. (Doremus 2010) suggests that adaptive management is most suitable where 1) there is an information gap that is important to management choices, 2) it seems possible to fill that gap on a management-relevant time scale, and 3) it seems possible to adjust the initial decision over time in response to new information.

Scenario planning, in the context of climate change[3], uses climate model projections or other information on climate impacts to produce a range of possible futures that can then be used to guide discussion and selection of robust adaptation options. The approach has been used increasingly by the National Park Service as a tool for managing for climate change (Weeks et al. 2011). In most cases, adaptation planning efforts will integrate consideration of available climate change scenarios as the basis of decision making without necessarily employing a formal scenario planning approach. See Box 5-3 for more on choosing and using climate change scenarios.

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[3] More broadly, scenario planning uses different story lines about how the future might unfold as a tool for decision making. The approach was first developed by the military in the 1940s. For more on the general practice of scenario planning, see "Scenario Planning" (*The Economist*, 2008) at http://www.economist.com/node/12000755 and the FHWA Scenario Planning Guidebook (2010), available at http://www.fhwa.dot.gov/planning/scenario_and_visualization/scenario_planning/index.cfm.

Box 5-3. Choosing and using climate change scenarios in ecological impacts assessment and adaptation planning

Scientists and resource managers charged with identifying and preparing for climate risks often struggle with the uncertainty associated with climate change projections. For some locations, even the direction of change in primary climate variables like annual precipitation is unknown (e.g., (Deser et al. 2012)). The “cascade of uncertainty” resulting from the necessity of linking multiple models to translate projected climate changes into biological impacts can create a frustratingly wide range of projected future conditions. A common response is to try to narrow this range by attempting to identify which emissions scenario(s), climate model(s), and/or downscaling method(s) are “best”. However, continued advances in climate science show that this is impossible. There is no ‘best’ scenario at any scale, rather ‘best’ scenario(s) for each individual application.

Determining appropriate climate change scenario(s) for biological impacts assessment and management depends on (1) the specific impact pathways and climate drivers that determine the climate response of the local species or system of interest and (2) the risk tolerance and time horizon characteristics of the related management decision (Snover in review).This means that the most appropriate scenarios for a particular analysis will not necessarily be the “best” for any other because of likely differences in local climate drivers, climate impact pathways, and decision characteristics.

No or low regrets adaptation options are actions that provide benefits under a wide range of climate change scenarios at relatively little cost or risk. Examples include increasing organizational capacity to adapt to climate change (e.g., Table 2) and public education about climate impacts and how it affects the sanctuary. Other no/low regret actions may include reducing non-climate stressors such as pollution and invasive species (see next tenet) and protecting a diversity of habitat types in order to support migration of species as climate changes. Whether these later examples actually qualify as no/low regrets options depends on the degree of technical, financial, or political costs associated with implementing the actions.

Table 2. Examples of strategies and tactics for building adaptive capacity

(from (Binder et al. 2010); based on (West and Gawith 2005); (Luers and Moser 2006);(Snover et al. 2007)

Strategies	*Tactics*
Increase staff access to information about climate and climate impacts so staff can stay current on research relevant to the decisions they make	• Increase staff access to science experts and peer-reviewed science and policy publications • Host brown bag seminars, department meetings, and scientific briefings for staff • Include climate impacts/adaptation information in websites, newsletters, fact sheets, utility inserts, brochures • Include information on climate impacts and adaptive planning activities in public meetings

Increase technical capacity of staff to incorporate information on climate impacts into decisions	• Address key information gaps, where relevant, though improved monitoring and data collection; by conducting research; and by partnering with organizations to fund needed research on climate impacts • Increase training opportunities and access to technologies that support adaptation needs • Increase partnerships with organizations that can support adaptation needs • Hire expertise in areas that support adaptation needs • Dedicate new or existing staff time to overseeing adaptation activities
Increase legal and administrative capacity to adapt to climate change	• Develop an adaptation planning strategy to guide adaptation activities • Assess regulatory, institutional, and cultural barriers to implementing adaptation actions • Modify regulations, policies, administrative procedures, etc. to remove or minimize identified barriers • Improve guidance/best management practices to incorporate adaptive planning objectives • Provide the necessary financial and staff resources to support adaptive planning

A third tenet is **reduce non-climate stresses**. This recommendation, which is frequently cited in adaptation literature (e.g. Gilman et al. 2008; Palmer and Peterson 2008; Baron et al. 2009; Higgason and Brown 2009; Lawler 2009; Secretariat of the Convention on Biological Diversity 2009), recognizes that climate change is one of many stressors affecting natural systems and that reducing non-climate stressors (such as invasive species, habitat loss, pollution, and overharvesting) can increase resilience to climate change. Although the benefits of reducing non-climate stressors are generally well established, the degree to which reducing non-climate stresses increases system resilience may depend on the specific nature of the climate impact(s). For example, reducing the impact of fishing on corals may do little to increase the resilience of corals to thermally-induced coral bleaching given the dominant impact of coral bleaching on coral health (Côté and Darling 2010). Reducing fishing stress may have significant climate resilience benefits for other aspects of the same marine ecosystem, however.

A fourth tenet is to **mainstream climate adaptation** into operational and planning processes (Snover et al. 2007; Baron et al. 2009; Olhoff and Schaer 2010; Jackson 2011). Climate change impacts are diverse and have the potential to affect a wide range of programs and management activities within an organization, including emergency management, asset maintenance and management, and planning. Mainstreaming climate change adaptation requires recognizing how climate change may affect decisions being made within and across individual program areas and institutionalizing methods for regular integration of that information into decision-making processes. In doing so, the intended outcomes of those decisions become more likely to occur in a changing climate.

Two other common tenets of climate adaptation are **plan for both climate variability *and* climate change** and **reduce the rate and extent of climate change** by reducing greenhouse gas emissions (Smith et al. 2000; Hansen et al. 2010; Watson et al. 2012). Naturally occurring phenomena like El Niño and La Niña affect global and regional climate on an annual basis (see, for example, (Ropelewski and Halpert 1986; Grimm et al. 2000). In the Pacific Northwest, El Niño events increase the odds for warmer and drier winter conditions, higher average winter sea level, lower winter snowpack, and less favorable coastal ocean and streamflow conditions for salmon (Miles et al. 2000; Mote et al. 2003). La Niña events can increase the odds for the opposite. While we do not know at this time if and how climate change will alter the frequency or intensity of natural climate variations like El Niño and La Niña, we know that natural variability will continue to occur in a changing climate. This means the region will continue to see warmer than average years (and decades) and cooler than average years (and decades) even as "average" is redefined by climate change.

The goal to reduce the rate and extent of climate change stems from the recognition that absent meaningful and sustained cuts in greenhouse gas emissions, the rate and magnitude of projected climate change could overwhelm adaptation efforts. The OCNMS Climate Action Plan institutes greenhouse gas reduction objectives by directing OCNMS to become a "climate-smart sanctuary" under the Office of National Marine Sanctuaries' Climate-Smart Sanctuaries Initiative.[4] Listed activities include conducting a greenhouse gas emissions inventory to determine where emission reductions can be made to meet green operating standards established in the Climate-Smart Sanctuaries program.

5.4 Climate Change Impacts on OCNMS Priority Management Areas

OCNMS has a stated mission "to protect the Olympic Coast's natural and cultural resources through responsible stewardship, to conduct and apply research to preserve the area's ecological integrity and maritime heritage, and to promote understanding through public outreach and education." The 2011 Management Plan and OCNMS Terms of Designation (the original terms under which OCNMS was established) identify four management focal points which are common among marine ecosystems and give the sanctuary particular value: water, habitats, living resources, and maritime archaeological resources. The impacts of climate change on each of these four areas are summarized in the following sections, along with relevant related stressors. Examples of relevant adaptation strategies, based in part on existing OCNMS activities (especially research and monitoring), are also noted. These should not be considered the only activities relevant to the sanctuary, however.

5.4.1 Water

As a marine sanctuary, water is one of the most central characteristics of OCNMS, and maintaining healthy waters is important to sustaining the integrity of ecological, oceanographic, and economic processes that shape the sanctuary. Water quality in OCNMS is not notably compromised, in part because there have been few point sources of pollution in the area and no

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[4] NOAA's Climate-Smart Sanctuary Program was created in 2010 to help sanctuaries plan, adapt, manage, and mitigate for climate change. For more on the program, see http://www.climate.noaa.gov/news/2011/CPO_ONMSonepager9_12_11.pdf

large industrial developments or population centers adjacent to the sanctuary (Office of National Marine Sanctuaries 2008). However, linkages between climate change and other oceanic stressors could reduce marine water quality, via increased hypoxic events (see Section 2.7), increased water temperature (see Section 2.2), and ocean acidification (see Section 2.3). Over time, these changes will likely alter the composition, structure, and interaction of current biological communities within the sanctuary (see Section 3). For example, possible alterations to patterns of ocean productivity, increasing temperature, and sediment/nutrient distribution may increase the occurrence and intensity of toxic algal blooms, which are detrimental to human health as well as a number of tribal, commercial, and recreational fisheries (see Section 4.1). Other stressors such as sediment loading from land based sources, due to more intensified precipitation, glacial retreat, and reduced winter and spring snowpack in the Olympics (Elsner et al. 2010), could also affect water quality.

Related current activities. Since 2000, nearshore oceanographic moorings along the Olympic Coast have been deployed to measure water temperature, salinity, dissolved oxygen, currents, plankton density, and other standard environmental parameters. OCNMS has partnered with other agencies, organizations and academic institutions, such as the University of Washington and Northwest Association of Networked Ocean Observing Systems (NANOOS), to build and deploy a number of these oceanographic monitoring devices. Data from these buoys and devices are currently used to gain a better understanding of linkages between the physical, chemical, and biological processes between nearshore and deep offshore waters. However, these devices can be further utilized to characterize the temporal and spatial nature of changing conditions. These data can also be coupled with other biological studies and monitoring efforts to inform both long-term and short-term observed changes in the biological community.

Possible actions. Examples of relevant actions related to managing water quality in a changing climate:

1. Evaluate the suitability of current water quality monitoring parameters for supporting climate change adaptation. Develop a long-term monitoring plan to collect and analyze water quality data likely to be affected by climate change. These data should be added to a long-term model that allows for temporal and spatial analysis.

2. Begin to analyze historical water quality data sets [adapted from Gulf of the Farallones National Marine Sanctuary Ocean Climate Summit Report (Largier et al. 2010)[5]].

3. Continue to support and collaborate with agencies and institutions on the deployment of oceanographic monitoring devices with a focus on long-term collection and analysis that can be used to inform climate adaptation [adapted from OCNMS Management Plan (National Oceanic and Atmospheric Administration 2011)].

5.4.2 Habitats

The Olympic Coast has a broad diversity of habitats including rocky shores, sandy beaches, kelp forests, sea stack and islands, open-ocean or pelagic habitats, the continental shelf seafloor, and

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[5] Available at: http://farallones.noaa.gov/manage/climate/pdf/OCSummitReport_060310.pdf

submarine canyons. These areas provide essential habitat to many species, including a number of endangered and threatened species that live in or migrate through the sanctuary. For example, the islands and pinnacles, or sea stacks, along the coast provide critical nesting and resting sites for the California and Stellar sea lions, harbor and elephant seals, and numerous seabirds. The high biological productivity of the coastal and offshore waters sustains valuable fisheries that contribute significantly to the State and tribal economies. In the 2008 Condition Report, OCNMS reported that the majority of habitats of the sanctuary were relatively unaltered or degraded with the possible exception of the deep-water seafloor where bottom-contact fisheries have been conducted for decades (Office of National Marine Sanctuaries 2008).

Each habitat in OCNMS plays a unique role in supporting the coastal ecosystem, and climate related impacts on these habitats will be complex. Changes in oceanographic characteristics such as the timing and magnitude of waves, currents, and sediment supply (see Sections 2.5 and 3.3.1) will have consequences for beaches and coastal structures. Although climate change may alter some physical characteristics of these habitats over time, climate change may also affect the basic functionality of the habitat through alterations of species abundance, community composition, and ecological interactions (see Section 3). Table 3 summarizes the importance of each habitat to OCNMS and highlights pre-existing and climate-related stressors that are most likely to have a significant effect on habitat functionality.

Related current activities. To date OCNMS has established priority management areas and collaborated with partners on numerous projects that include the protection of essential fish habitat for groundfish, negotiating the reburial of exposed fiber optic cable, and removal of marine debris. Since 2000, OCNMS has also been involved in habitat mapping efforts to characterize the seafloor habitats within the sanctuary. Continued efforts to map and characterize species-habitat associations are critical to inform management decisions, especially in a changing climate. These mapping activities will aid in the establishment of a baseline that can be used to assess potential changes in habitat structure and species associations.

Possible actions. Examples of relevant actions related to managing sanctuary habitat in a changing climate:

1. Create an inventory of baseline habitat status [adapted from Office of National Marine Sanctuaries (2008)].

2. Complete habitat mapping and characterization efforts for the entire sanctuary area to establish a comprehensive and informative baseline [adapted from OCNMS Management Plan (National Oceanic and Atmospheric Administration 2011)].

3. Evaluate how the location and function of different habitat types may be affected by climate change.

4. Where relevant, reduce non-climate stressors that may limit the ability of habitats to adapt to a changing climate.

Table 3. Summary of Habitats and Potential Impacts of Climate Change in the OCNMS (Office of National Marine Sanctuaries 2008)

Habitat	Importance to OCNMS	Key Taxa Referenced in Biological Chapter	Current Status	Key Physical Elements of Climate Change	Key Threats of Climate Change	Existing Pressures besides climate change
Intertidal/ Shallow Water	Among the highest biodiversity of all marine invertebrates and macroalgae of all eastern Pacific coastal sites	Phytoplankton, zooplankton, macroalgae and seagrasses, mussels, urchins, fish	Relatively undisturbed; Few locations allow shoreline armoring or human visitation; Few non-native species	Anoxia/Hypoxia, OA, Sea level rise, Storms, Temperature	Erosion and sedimentation, direct impact of increased wave energy and sea level, reduced habitat through thermal stress and increased predator activity	Marine Debris, Oil spill concern
Nearshore	Kelp: provides structure & protective environment Sea Stacks: havens and resting sites for marine mammals and seabirds	Phytoplankton, zooplankton, kelp, urchins, Dungeness crab, fish, marine mammals and seabirds	Kelp beds considered stable; Few non-native species	Anoxia/Hypoxia, OA, Sea level rise, Storms, Temperature	Direct impact of increased wave energy and sea level, restructuring of soft sediment sub-tidal habitats	Hypoxic occurrences not related to climate change
Pelagic (most extensive habitat of sanctuary)	Supports a number of endangered and threatened marine mammals, fish and seabirds	Phytoplankton, zooplankton, marine mammals and seabirds	Unknown	Temperature, OA, Hypoxia/ Anoxia, Storms. Upwelling	Productivity is impacted, OA may reduce survivorship of some zooplankton species.	Oil spill concern
Deep-Sea Benthic	Hard-bottom substrates that support rich invertebrate assemblages including deepwater coral and sponges.	Deep sea corals and sponges, Pacific cod, halibut, rockfish	Sediment contaminant levels are low; Poor mapping and characterization (no baseline)	Temperature, OA, Hypoxia/ Anoxia, Upwelling	Changes in temperature and OA could reduce suitability for deep sea corals	Fishing and marine debris (i.e. bottom trawling and derelict fishing gear); Military activities

5.4.3 Living Resources

The sanctuary provides an essential habitat for a wide variety of marine mammals and birds, and is of particular interest due to the presence of endangered and threatened species that live or migrate through the region. Twenty-seven species of marine mammals are reported to breed, rest within, or migrate through the sanctuary, including the California gray whale, the threatened northern sea lion, and the occasional humpback whale (an endangered species). The seabird colonies of Washington's outer coast are among the largest in the continental United States and also include species listed as endangered or threatened. The living resources of the coast are also important to the cultures and vitality of the coastal tribes. Fishing is one of the mainstays of tribal economies as well as being central to their cultures and way of life – so much so that the right to fish was expressly reserved in treaties with the United States. Timber and tourism are also important to tribal economies. The high biological productivity of coastal and offshore waters in the sanctuary support valuable fisheries, including Dungeness crab, groundfish, salmon and steelhead, blackcod (sablefish) and razor clams, all of which are expected to be affected either directly or indirectly by climate change (see Section 4).

Climate change on the outer coast of Washington will likely have a significant impact on the living resources of the sanctuary (see Section 4). OCNMS should expect both short-term and long-term changes in population abundances and community composition as well as fundamental changes in ecological interactions; identifying and drawing conclusions from these changes will be complicated by the highly variable nature of the coastal environment. As new species migrate in and familiar species migrate out of the sanctuary (as a consequence of generally expected poleward range-shifts), we can expect significant alterations to the present biological community (see Section 3).

Related current activities. OCNMS currently works with partners (e.g., Olympic National Park) to monitor populations of seabirds and marine mammals, detect non-indigenous species, conduct regular intertidal monitoring, and evaluate the need for wide area closures by fisheries management authorities to allow populations to recover and support sustainable fisheries. OCNMS has also led and collaborated on several projects that establish population trends and baseline information for invertebrates and sea otters, against which future data can be compared.

Possible actions. Examples of relevant actions related to managing living resources in a changing climate:

1. Use findings from this report to establish and prioritize key management areas and/or species that are likely to be significantly affected by climate change [Strategy CLIM3, OCNMS Climate Change Action Plan (National Oceanic and Atmospheric Administration 2011)].

2. Continue partnerships to monitor changes in the biological community over time. Identify key "indicator species", those species likely to display the first signs of climate change effects, and focus monitoring efforts on these species [adapted

from OCNMS Management Plan (National Oceanic and Atmospheric Administration 2011)].

3. Develop or partner in the development of long-term management plans for key ecological and economically important species that incorporate climate-related information as needed.

5.4.4 Archaeology

In addition to the sanctuary's biological resources, the region also encompasses significant historical resources including Native American village sites, ancient canoe runs, petroglyphs, artifacts, and shipwrecks. Adjacent to sanctuary waters are a number of Native American tribes including the Hoh, Makah, and Quileute Tribes and the Quinault Indian Nation. The shores of the Olympic Peninsula contain dozens of known late prehistoric archaeological sites that are rich in materials that document tribal heritage. Other sites in the nearshore coastal forests adjacent to the sanctuary also contain mid-Holocene shorelines and other prehistoric archaeological sites. The sanctuary also has one of the most significant and unique maritime cultural landscapes in the United States. Within sanctuary boundaries, there are more than 180 shipwrecks dating from 1808 to 1972.

As identified in the 2011 OCNMS Management Plan, there is a need to conduct inventories and monitoring, and to assess possible impacts of sea level rise on coastal archaeological resources. Coastal archaeological resources may be negatively impacted by rising sea levels and other factors associated with climate change. Many of these historical sites and a few shipwrecks are located near the coastline and could be flooded under sea level rise scenarios.

Related current activities. Under the National Historic Preservation Act, federal agencies such as OCNMS are required to inventory and assess resources (e.g. shipwrecks, historical archaeological sites) to determine what, if any, management actions could be taken to preserve critical sites and material against currently identified threats.

Possible actions. Examples of relevant actions related to managing historic sites in a changing climate:

1. Establish priority areas most likely to be compromised by rising sea levels [adapted from OCNMS Management Plan (National Oceanic and Atmospheric Administration 2011)].

2. Partner with local tribes to continue to inventory resources and to develop appropriate preservation efforts with a focusing on areas likely to be most compromised by sea level rise [adapted from OCNMS Management Plan (National Oceanic and Atmospheric Administration 2011)].

3. Establish education and volunteer programs that will allow for a more "rapid" inventory of resources most threatened by climate change (adapted from Channel

Islands National Marine Sanctuary Management Plan (National Oceanic and Atmospheric Administaration 2009)).

5.5 Climate Change Impacts on Existing Pressures

OCNMS has also identified a number of other existing pressures on the resources of the sanctuary (Office of National Marine Sanctuaries 2008). Some of these pressures such as fishing, invasive species, and underwater noise pollution are likely to be worsened or compounded by the effects of climate change. Other identified pressures such as commercial development, oil spills, vessel discharge, increased human use, and military activities may also be affected by climate change but the influence is not as clear.

Commercial and recreational fisheries are major components of the coastal economy and provide valuable food resources both regionally and globally. Tribal fisheries were reserved through treaties signed with the United States and continue to be central to tribal cultures and the broader regional economy. The tribal and non-tribal commercial fishing industries in Washington State are co-managed by the tribal, state, and federal governments and are structured around a multi-species fishery, which includes groundfish, halibut, albacore, salmon, and shellfish. Recreational fisheries inside the sanctuary, which are managed primarily by the Washington Department of Fish and Wildlife and Olympic National Park, include shore-based (surf casting, razor clamming, and intertidal collection) and vessel-based activities. Most, if not all, harvested species are expected to be both directly and indirectly affected by climate change (see Section 4). Fishing trends are expected to change as fish species distribution and abundance changes. Northward range shifts will affect present community compositions (potential increase in southern species), and the cumulative effects of climate change will likely lead to declines in current benthic and pelagic fish populations (see Section 4.8). In the long-term, these climate related changes in species abundance and distribution may necessitate changes in the type and amount of species that we target in both commercial and recreational fisheries.

The number of non-native species including those arriving due to range-shifts is expected to increase (see Section 3.2.3). This influx of non-native species, which have the potential to become invasive species, could alter present biological communities causing long term changes in ecological functioning. Currently, OCNMS, the State, and tribes have implemented regulations and monitoring efforts to minimize the spread and impact of invasive species. However, management actions in response to invasive species should reflect considerations of a changing climate especially in the marine environment where spatial connectivity often makes containment of invasive species a challenge.

Some recent studies have suggested that the increased absorption of CO_2 in the ocean could have an impact of the propagation of sound in the water, decreasing sound absorption for frequencies lower than 10kHz and essentially amplifying noise made by shipping (Hester et al. 2008; Potty 2009). This change in aquatic sound propagation could affect the communication abilities of the many marine mammals that use the sanctuary.

In a long-term scenario, this inability to communicate could reduce the reproductive success and survivability of these marine mammals.

Increased interest in commercial development such as ocean wave energy projects and open-ocean aquaculture may arise due to the desire to develop alternative energy sources or replace/replenish fisheries affected by climate change. Such scenarios are hypothetical and subject to a number of other social, economic, and ecological factors.

The sanctuary also lies at the entrance to the Strait of Juan de Fuca, which is one of the busiest waterways in the world, providing a route for approximately 10,000 large commercial vessels transits per year. Therefore, oil spills are generally considered one of the most serious threats to resources in the sanctuary. Although the probability of a large oil spill occurring is low, the potential impact to sanctuary resources is high. An oil spill within sanctuary waters has the potential to cause both rapid and sustained damage to the integrity of habitats within the OCNMS that could last for years. Oil contamination of marine species including marine mammals and seabirds can have long-term lethal and sub-lethal effects. While there is no direct linkage between climate change and the potential for oil spills, the increasing intensity and frequency of storms could increase risk to shipping traffic and indirectly increase the potential for oil spills. Changes in the volume of shipping traffic through the sanctuary could increase or decrease this risk as well.

Another source of pollutants that can have negative effects on ecosystem functioning and integrity is the intentional discharge from vessels (e.g., sewage, graywater, ballast, and bilge water). Currently these intentional discharges are controlled by both state and federal regulations. Although there are currently little to no observable impacts of intentional vessel discharges on sanctuary resources, the sanctuary could see more on-shore delivery of pollutants discharged at sea *if* climate change causes changes in ocean circulation that bring those pollutants into the sanctuary, thereby generating a need for re-evaluation of regulations. However, this is a hypothetical situation that should be assessed through circulation models appropriate for climate change scenario evaluation.

Human use, including sport fishing, kayaking, surfing, wildlife viewing, clamming, and beachcombing, is at a relatively low intensity in the sanctuary due to the low population density along the coast, and climate change is unlikely to have a direct effect on human usage of the environment. However, climate change could indirectly affect some patterns of usage. For example, climate change is expected to increase the frequency of harmful algal blooms, which can infect shellfish, such as razor clams, and make them toxic and unsuitable for human consumption (see Section 4.1). Other pressures such as military activities (Department of the Navy 2013) within the Northwest Training Range Complex are also unlikely to be directly impacted by climate change.

5.6 Conclusions

Adapting to climate change is a process that will evolve over time through an ongoing set of actions and decisions that reflect the changing nature of the resource being managed; our increasing understanding of climate change impacts; and the evolving regulatory requirements, social objectives, and other decision parameters that guide how we manage resources (Neil Adger et al. 2005). As such, adaptation requires instituting approaches that promote ongoing learning, assessment, and adjustment.

OCNMS is well positioned to play a valuable role in adapting West Coast marine resources to climate change. The sanctuary's relatively undisturbed condition provides research and monitoring opportunities that will help further the region's understanding of climate change trends and impacts on the marine and nearshore environment. The sanctuary's size and diversity of habitats and species may also provide unique opportunities for facilitating resistance, resilience, and response to climate change. OCNMS should identify where it has the ability to directly manage climate change impacts and build on the strong partnerships it has within and outside the region to address the impacts it cannot directly manage.

6 Appendices

6.1 Greenhouse Gas Emissions Scenarios

To support efforts from around the world to project future changes in climate, the Intergovernmental Panel on Climate Change (IPCC; http://www.ipcc.ch/) has developed different scenarios of greenhouse gas emissions for use in global climate modeling efforts. One of the primary reasons for developing emissions scenarios is to enable coordinated studies of climate change, climate impacts, and mitigation options and strategies. These scenarios are often referenced in climate-change research and investigations, including throughout this report. We provide a short summary here to assist the reader with the interpretation of projections of change discussed in this report. Unless otherwise noted, information and figures in this section are from the IPCC's Special Report on Emission Scenarios (http://www.grida.no/publications/other/ipcc_sr/).

Scenarios are designed to "cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. The scenarios encompass different future developments that might influence greenhouse gas (GHG) sources and sinks, such as alternative structures of energy systems and land-use changes." Global population, for example, is one of the many factors incorporated into emissions scenarios, and a variety of different population scenarios are plausible in the next 100 years (Figure 6-1). None of the scenarios "includes any future policies that explicitly address additional climate change initiatives." The range of emissions scenarios are NOT intended to express a probability of occurrence.

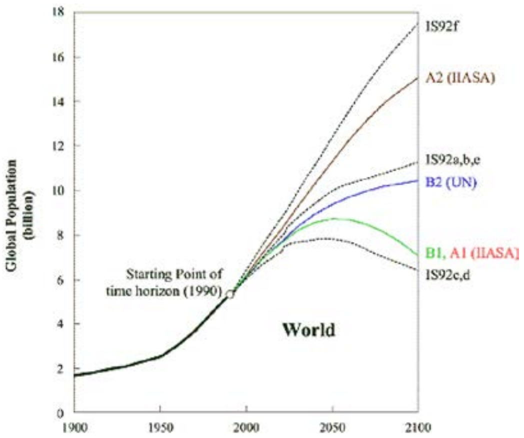

Figure 6-1. Various population scenarios used as a basis for SRES and IS92 emissions scenarios. Figure: IPCC

The IPCC developed a set of widely used and referenced global greenhouse gas emissions in 1992. This so-called "IS92" scenario family included 6 scenario groups, a-f, that were intended to capture a range of potential future scenarios. In particular, the IS92a scenario, which is frequently referred to as a "business-as-usual" scenario, was often used as a stand-alone emissions scenario in climate impact studies (Figure 6-2). In 1996 the IPCC decided, based on a variety of shortcomings with the IS92 scenarios, to develop a new set of scenarios, released in 2000 and known as the "SRES" scenarios. These scenarios are grouped in four families, or storylines (A1, A2, B1 and B2), based on different assumptions about demographic, social, economic, technological, and environmental change. The A1 family is further divided into three subsets (A1B, A1T and A1Fl) reflecting various levels of fossil-fuel consumption in the future. As an example, the B1 scenario family lies near the lower limit of projected changes in greenhouse gas emissions (Figure 6-2). The B1 scenarios assume global population growth peaks by mid-century and then declines, a rapid economic shift towards service and information economies, and the introduction of clean and resource-efficient technologies.

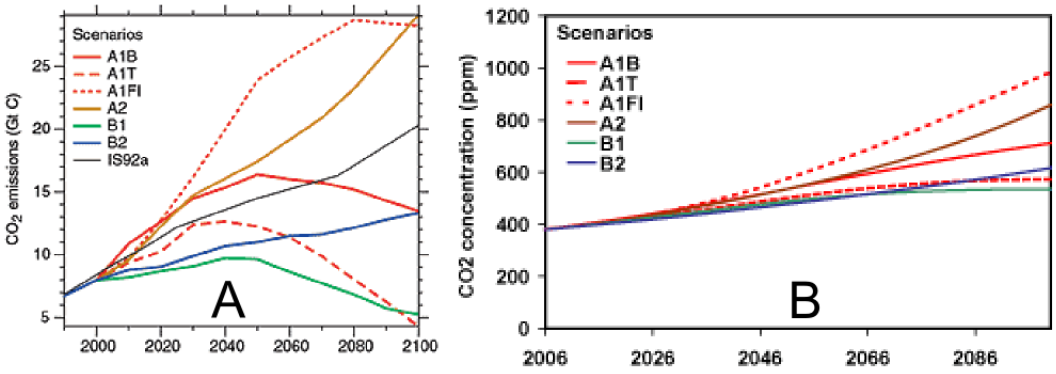

Figure 6-2. Projected changes over the 21st century in annual emissions (A) and the atmospheric concentration of CO2 under the six SRES and one IS92 scenario family. Image: IPCC (A) and US EPA (B)

The IPCC develops a range of scenarios in order to provide reasonable future projections of greenhouse gas emissions under a variety of possible demographic, technological and political futures. For climate model and impact studies, all scenarios are intended to be used together. In practice, though, a subset of the scenarios, or sometimes just one, is used as input for a particular modeling investigation or climate impact study, or chosen as a de facto most probable future scenario. However, no probability is assigned to these emission scenarios by the IPCC. In fact, present CO_2 emissions exceed all of the SRES emission scenario families (Figure 6-3), and only time will reveal which, if any of these scenarios, will mirror actual future emissions.

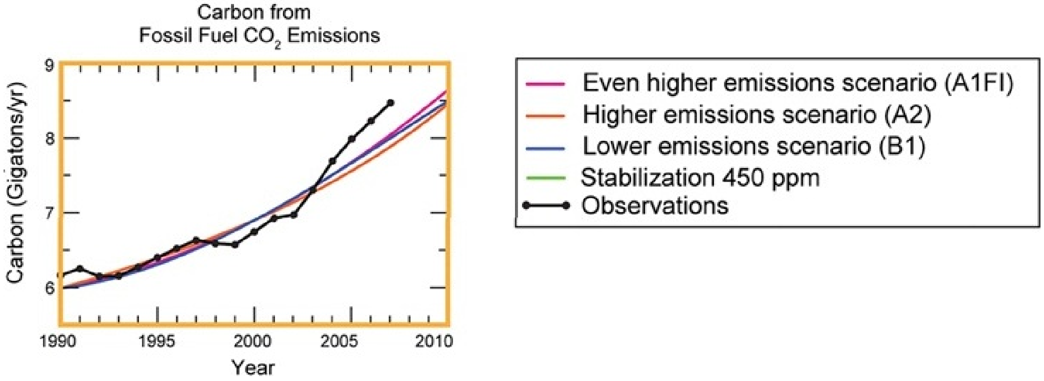

Figure 6-3. Three SRES emission scenario families compared against observations of emissions since 1990. Figure: US EPA

6.2 A Note on Statistical Significance

Throughout this report the concept of significance will be used in a formal, statistical sense. Statistical significance describes a quantitative pattern that is unlikely to have occurred by chance. A statistically significant difference, trend or pattern is one that, given the variability in the data, is probably "real." By contrast, some data sets may show a pattern, trend or difference, but are not statistically significant, suggesting that it is prudent to assign less confidence to the suggested trend, pattern or difference.

A test of significance may occur at various levels. A test that suggests that a pattern is statistically significant at the 95% level indicates that there is a 95% chance given the variability in the data that the pattern didn't occur by chance alone. Alternatively, it can be stated that there is only a 5% chance that a statistically significant difference, or trend, identified in the data, is misidentified as "real" due to variability in the data under consideration. Tests of significance can occur at any "level," but 90%, 95% or 99% are frequently encountered. The 95% level will be considered the default level in this report unless otherwise stated.

The reader will also encounter confidence intervals referred to throughout this report, also typically associated with a level (i.e. 95%). Confidence intervals are calculated from observations and therefore incorporate the variability in the data. They are always associated with a parameter (typically a mean value) and provide some sense of the likelihood that, if the data were collected repeatedly, the mean value would again fall within the stated interval. They therefore are designed to provide the degree of confidence that a particular calculated parameter falls within a certain range. A 95% confidence interval is considered standard for the purposes of this report, and suggests that if the observations were made again that the mean value would still fall within the stated interval 95% of the time. Like significance levels, confidence intervals can be calculated at other levels, but the 95% level will be viewed as the default in this report unless otherwise specified.

6.3 Climate Variability in the NE Pacific Ocean (Including OCNMS)

OCNMS is subject to considerable variability in a variety of physical and ecological parameters (temperature, sea level, oxygen, chlorophyll, etc.) at seasonal, annual and decadal time-scales due to large-scale climate patterns manifested throughout the northeast Pacific Ocean. While seasonal variability is well-characterized (Figure 1-1-5 , for example), variability due to “climate cycles” at annual to decadal time-scales is often characterized in terms of three patterns or modes, specifically the El Nino-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO). There appears to be no consensus regarding any chance in the frequency or intensity of these modes of variability related to long-term climate change (Vecchi and Wittenberg 2010). For the timeline considered by this document (to 2100), these modes of variability are viewed as overlays on a changing mean climate condition.

The attributes of these modes, and the linkages between them, are briefly summarized here.

6.3.1 El Nino-Southern Oscillation

By a variety of measures, the El Nino-Southern Oscillation (ENSO) represents the leading mode of climate variability for the globe and for the northeast Pacific Ocean. It involves strong interactions between the atmosphere and ocean in the equatorial Pacific that are manifested by changes in the east-west pattern of surface temperature and deep cumulus convection in the Pacific Ocean. During the warm or positive phase of ENSO (also referred to in this report and elsewhere as “El Nino”), the central and eastern portions of the tropical Pacific feature positive upper ocean temperature and westerly wind anomalies and enhanced convection. The cold or negative phase of ENSO (often referred to as “La Nina”) has ocean and atmospheric anomalies in the opposite direction. The perturbations in the location and intensity of convection in association with ENSO have remote effects on global atmospheric circulation. The northeast Pacific and OCNMS have a predictable response to ENSO. Coastal areas of the northeast Pacific tend to experience anomalously warm upper ocean temperatures, down-welling favorable winds, reduced primary productivity, the anomalous appearance of southern marine species and elevated average water level during El Nino (such as the anomalous elevated sea level associated with the 1998 ENSO event in Figure 2-12), with the opposite occurring during La Nina. The physical manifestations of ENSO events tend to last for approximately a year.

6.3.2 Pacific Decadal Oscillation

The PDO is defined as the leading mode of variability in sea surface temperature (SST) in the Pacific Ocean north of 20°N (approximately the latitude of Mexico City, Mexico). While the PDO is not independent of ENSO, and positive phases of ENSO tend to be associated with positive phases of the PDO (Newman et al. 2003), the longer periods associated with the PDO (years to decades) distinguish it from individual ENSO events. The spatial pattern of the PDO consists of anomalies of one sign in the western North Pacific in tandem with anomalies of opposite sign in a horseshoe shape extending from off the coast of western North America through the Gulf of Alaska and into the southern Bering Sea. In OCNMS the PDO's positive phases is associated with warm temperature anomalies, positive sea level pressure (SLP) and higher-than-average sea surface height (SSH). The SLP anomalies are correlated with ENSO, with the result that the positive phase of the PDO tends to occur during periods of more frequent El Nino events. The driving factors that cause the PDO aren't entirely clear (Kwon et al. 2010), but regardless of its cause(s), the PDO is important to the northeast Pacific through its modulation of lower-trophic level productivity and community structure (see Section 4.2, for example), with implications for the entire marine food web.

6.3.3 North Pacific Gyre Oscillation

There is increasing appreciation of the importance of the NPGO to physics and biology of the northeast Pacific. The NPGO is defined as the second leading mode of sea surface height (SSH) variability in the north Pacific (DiLorenzo et al. 2008); the leading mode in SSH is associated with the PDO. The NPGO constitutes an index for the strength of the subtropical and subpolar gyres of the north Pacific, and tends to coincide with a north-south oriented dipole in SLP. In its positive phase, both gyres are relatively strong, meaning enhanced equatorward flow in the California Current and poleward flow in the Alaska Current. These flow variations tend to be accompanied by anomalies in salinity and nutrient concentrations. The NPGO appears to represent a means for the north Pacific to influence ENSO through the seasonal footprinting mechanism (Vimont et al. 2003). Through this or a related linkage the NPGO may be an important element of north Pacific decadal variability, but the dynamics are unclear. The potential predictability of the north Pacific involving the physical interactions between these modes, and their likely response to climate change, is an area of focus for on-going research (e.g., Furtado et al. 2011).

6.4 Glossary of terms and acronyms

$\Omega_{\text{aragonite}}$: Saturation state of aragonite, a mineral form of calcium carbonate. This describes the amount of aragonite available in solution (in seawater in the context of this report) based on the physical characteristics of the water (temperature/density) and the solubility characteristics of the carbonate mineral.

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

Aleutian Low: A persistent low pressure center that forms near Alaska's Aleutian Islands in the Northern Hemisphere winter.

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

CCS: The California Current System. The marine region adjacent to the west coast of North America (stretching, approximately, from southern British Columbia to southern Baja California) defined by seasonal upwelling. The CCS has been described as a single ecosystem unit.

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

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.

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

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).

Global Climate Model: Global Climate Models link General Circulations Models, which are mathematical models of the general circulation of the atmosphere and/or ocean for the Earth, with energy terms included, with sea ice and land-surface simulation (or other) components. Used for weather forecasting, climate investigations, and projecting climate change.

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.

Hypercapnia: Condition of excess carbon dioxide in the blood or circulatory system.

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

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

IPCC: Intergovernmental Panel on Climate Change. An intergovernmental scientific body set up to advise governments on global climate change trajectories, consequences, and adaptation options. More at www.ipcc.ch.

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

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

OCNMS: Olympic Coast National Marine Sanctuary

OMZ: Oxygen Minimum Zone. The part of the open ocean water column at which oxygen saturation is seawater is at its lowest. In general this occurs between 200 and 1000 m.

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

pCO_2: In general, the partial pressure of a gas is a measure of the gas molecules' activity at a certain temperature. The partial pressure of CO_2, or “pCO_2”, is reported in the context of ocean acidification because gases dissolve, diffuse, and react according to their partial pressures, not their concentrations in the atmosphere and ocean. Scientists often measure the concentration of CO_2, then calculate pCO_2.

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

Saturation depth (horizon): Surface ocean waters are supersaturated with respect to CaCO3 (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 CaCO3 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 (Hs): the average height of the one third highest waves.

Specific Heat: The heat required to raise the temperature of a unit mass of a substance by 1 C. The specific heat of water is amongst the highest of common substances, thus water acts as a thermal buffer.

Stratification: the building up of layers

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

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

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.

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