Summary of Climate Change Effects on Major Habitat Types in Washington State

Marine And Coastal Habitats

Produced by the Washington Department of Fish and Wildlife,
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Climate Change Effects on Marine and Coastal Habitats in Washington State

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INTRODUCTION

This paper is intended as a reference document—a "science summary"— for the Ecosystems, Species, and Habitats Topic Advisory Group (TAG), which is one of four topic groups working with state agencies to prepare a statewide *Integrated Climate Change Response Strategy*. The climate change response strategy was initiated by the state legislature (SB 5560) to help the state adapt to climate change.

The purpose of this paper is to provide TAG members with information on climate change effects on fish, wildlife, habitats, and ecosystems in marine environments so as to inform the assessment of priorities and the development of recommendations about adaptation responses. The paper is intended to summarize relevant literature regarding historical baselines, observed trends, future projections, knowledge gaps, and implications for biological communities. The paper focuses primarily at the ecosystem level due to limited availability of studies regarding climate change effects on habitats and species.

This document draws from synthesis reports, government publications, non-profit publications, and peer-reviewed studies. These include the two primary reference documents for the *Integrated Climate Change Response Strategy*, which are the Climate Impacts Group's *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate* (WACCIA) (CIG, 2009); and *Leading the Way: Preparing for the Impacts of Climate Change in Washington. Recommendations of the Preparation and Adaptation Working Groups* (Preparation and Adaptation Working Groups (PAWG), 2008).

This document attempts to summarize and organize relevant scientific findings to provide TAG members with a starting point as they prioritize climate impacts and recommend response strategies. In many cases, this document uses language taken directly from the cited sources. This document is for discussion purposes only and is not intended to be published or cited. Readers should cite the primary sources of information.

Please note that we accepted information as it was presented in synthesis reports. Readers may wish to return to the primary sources utilized in those synthesis reports for more information. In cases where we accepted the interpretation of primary information as it was stated in a secondary source, we have provided the following note in the footnote: "Information as cited in [secondary source]."

As with most summary or synthesis efforts, this document reports the central findings from published literature and typically does not address the inherent complexity and uncertainty that may be present. This is especially true of future projections, which are often based on multi-model ensembles that do not perfectly capture the complexity of Washington's unique climate systems and geographic variability. These projections are valuable primarily to identify a directional trend and a sense of magnitude. As an example of the inherent uncertainty of future projections, the WACCIA notes that multi-model ensembles of global climate projections may under-represent the local severity of climate change.[1] For more information on climate models used in the WACCIA, see Appendix 1.

[1] Salathé, et al. (2009) Regional climate model projections for the State of Washington. In: *WACCIA*

This document discusses climate change effects on marine systems, but does not specifically address climate change effects on salmon. As anadromous species, salmon are affected by climate impacts to both marine and freshwater ecosystems. A starting point for information on climate impacts to salmon can be found in chapter 6 of the Climate Impact Group's Washington Climate Change Impacts Assessment (WACCIA):

> Mantua, N.J., I. Tohver, and A.F. Hamlet. 2009. Impacts of climate change on key aspects of freshwater salmon habitat in Washington State. Chapter 6 in *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*, Climate Impacts Group, University of Washington, Seattle, WA.

This document was produced by National Wildlife Federation and reviewed by WDFW staff (led by Ken Warheit, Ph.D., Chief Scientist, Fish Program) and Scott Redman from Puget Sound Partnership and Nate Mantua from University of Washington Climate Impacts Group (CIG). Significant efforts have been made to accurately characterize the information presented. However, we must emphasize that this document is neither comprehensive nor complete. In this complex and rapidly evolving field, we do not expect that we have identified all of the most up-to-date data or presented the complexity of climate projections. In addition, there are many gaps in knowledge, especially regarding climate change effects on specific habitats or locations. Still, we hope that this provides a starting point for discussion, and that readers will augment this with additional data to advance our understanding of climate impacts and responses.

GLOBAL AND REGIONAL CLIMATE TRENDS

CO_2 Concentrations – *global trends*

Today's atmospheric carbon dioxide (CO_2) concentrations are approximately 385 parts per million (ppm).[2] Over the past 800,000 years, atmospheric CO_2 concentrations have varied between about 170 and 300 ppm.[3] Today's concentrations are approximately 30 percent higher than the earth's highest level of CO_2 over that time period.[4]

Temperature – *global and regional trends and projections*

Global average temperature has risen approximately 1.5°F since 1900, and is projected to rise another 2°F to 11.5°F by 2100.[5] In the Climate Impact Group's *Washington Climate Change Impacts Assessment* (WACCIA, 2009), Mote and Salathe project that annual temperatures in the Pacific Northwest will increase 2.2°F on average by the 2020s and 5.9°F by the 2080s; these projections are compared to 1970 to 1999 and averaged across all climate models. [6] Rates of warming range from 0.2° to 1.0°F per decade.[7]

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[2] Karl et al. (eds) (2009). *Global Climate Change Impacts in the United States.* (U.S. government report)
[3] Ibid.
[4] Ibid.
[5] Karl et al. (eds) (2009). *Global Climate Change Impacts in the United States.* (U.S. government report)
[6] Mote and Salathe. (2009). Future Climate in the Pacific Northwest. In: *WACCIA* (CIG, 2009).
[7] Ibid.

Precipitation – *regional projections*

In WACCIA, Mote and Salathe (2009) state that projected changes in annual precipitation for the Pacific Northwest (averaged across all climate models) are small: +1 to +2%.[8] However, some of the models used projected an enhanced seasonal cycle in precipitation, with changes toward wetter autumns and drier summers.[9] For summer months, a majority of models projected decreases in precipitation, with the weighted average declining 16% by the 2080s.[10] Some models predicted reductions of as much as 20-40% in summer precipitation; these percentages translate to 3- 6 cm over the season.[11]

In winter, a majority of models projected increases in precipitation, with a weighted average value reaching +9% (about 3 cm) by the 2080s under their higher-emissions modeling scenario (A1B); this value is small relative to interannual variability.[12] Although some of the models predicted modest reductions in fall or winter precipitation, others showed very large increases (up to 42%).[13]

CLIMATE EFFECTS ON MARINE AND COASTAL ECOSYSTEMS

Washington's coastline stretches through 3,100 miles of diverse terrain along the shores of the Pacific Ocean and Puget Sound.[14] This area encompasses a variety of habitats including bays and estuaries, coastal dunes and beaches, rocky shores, and the continental shelf.

Major climate-driven effects on coastal and marine habitats described in this document are:

- **Rising sea surface temperature (SST)**
- **Sea level rise (SLR)**
- **Altered hydrology**
- **Coastal erosion**
- **Coastal hypoxia**
- **Decreasing ocean pH ("ocean acidification")**

These effects are highlighted based on information in Huppert et al. (WACCIA Ch. 8 - CIG, 2009), Snover et al. (2005), the recommendations presented by the Preparation and Adaptation Working Groups (PAWG, 2008), and additional research cited within each section. For each effect, this paper employs the following structure:

- **Background information** – description of physical characteristics
- **Observed changes** – changes in physical variables
- **Future projections** – direction and/or magnitude of physical change, if available
- **Biological communities** – *examples* of observations and changes in habitats or species
- **Information gaps** – if any have been specifically identified

[8] Ibid.
[9] Mote and Salathe. (2009). Future Climate in the Pacific Northwest. In: *WACCIA* (CIG, 2009).
[10] Ibid.
[11] Ibid.
[12] Ibid.
[13] Ibid.
[14] Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA* (CIG, 2009).

- **Suggestions for further information** – as provided by individuals that have reviewed this paper

At its conclusion, this document also presents possible adaptation actions for consideration that are drawn from Huppert et al. (WACCIA Ch.8 - CIG, 2009), Glick et al. (2007, 2008), the *California Climate Change Adaptation Strategy* (2009) and the recommendations of the Coastal Preparation and Adaptation Working Group (PAWG, 2008).

We have attempted to assemble and summarize the best information available, often using language directly from the cited sources. However, climate science is a rapidly evolving field. Readers are encouraged to read the cited sources and other reports on these issues for a fuller understanding of the state of the science.

Rising Sea Surface Temperature

Ocean water temperatures are expected to rise as global air temperatures rise,[15] since the world's oceans are the main storage reservoir for excess heat energy initially retained within Earth's atmosphere.[16] Since 1961, the oceans have been absorbing more than 80% of the heat added to the climate system.[17] For example, from 1969 to 2008 the global oceans showed a linear average increase in heat content of 0.40×10^{22} Joules per year in the top 700 meters of the water column.[18]

It is important to note that increases in SST as a result of global climate change occur simultaneously with natural cycles in ocean temperature, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). For example, the PDO naturally shifts heat across regions of the Pacific Ocean and may be responsible for perhaps a third of the warming trend observed in the Pacific between 1900 and 2000.[19] Natural increases in ocean temperature account for part of the overall warming trend observed in the Pacific; this makes it is difficult to distinguish the precise contributions of natural variation and climate change.[20]

Observed Changes

Globally, sea surface temperatures (SST) have risen between 0.36°F and 1.8°F from 1970 to 2004, with an average rise of 1.08°F.[21] In several regions of the United States, coastal water temperatures have

[15] California Natural Resources Agency (2009), *California Climate Adaptation Strategy.*
[16] Information as cited in Hansen et al. (2005), *Earth's energy imbalance: confirmation and implications*. (primary literature)
[17] Information as cited in USAID (2009), *Adapting to coastal climate change: A guidebook for development planners*. (agency report)
[18] Levitus et al. (2009), *Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems*. (primary literature)
[19] Information as cited in Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)
[20] Ibid.
[21] Information as cited in USAID (2009), *Adapting to coastal climate change: A guidebook for development planners*. (agency report)

risen by about 2°F.[22] Long-term SST records do not exist for Puget Sound.[23] However, data from Race Rocks lighthouse in the Strait of Juan de Fuca near Victoria, B.C. show an increase in SST of 1.7°F between 1921 and the early 2000s.[24]

Future Projections

According to the IPCC 2007 report (Parry et al., 2007), global sea surface temperatures are projected to rise by 1.8 – 5.4°F in the next century.[25] Temperatures in Puget Sound are also predicted to rise. Although ocean models employ relatively coarse resolution and nearshore circulation is complex, modeled change in SST around Washington and Puget Sound is about 2.2°F by the period 2030-2059, which is significantly outside the 20th century variability.[26]

Climate change is also likely to increase the interannual variability of winds that modify ocean temperatures, as a result of changes in winter storm tracks and storm intensity.[27] Ultimately, we may observe alternating years of warmer and cooler ocean temperatures with slow background warming.[28]

Examples of how the physical marine environment may change in response to rising SST include:

- **Altered water quality**: Warmer water holds less oxygen, which may alter current coastal water quality.[29]
- **Altered upwelling and nutrient cycling**: Changes in land and sea temperature may contribute to changing wind patterns that can alter upwelling and nutrient cycling along the coast. [30]

Biological Communities – Observations & Change

Increases in water temperature can affect species' metabolism, growth, and reproduction, thereby altering their geographic distribution.[31] Warming temperatures are expected to have a direct effect first in coastal ecosystems, since shallower waters such as bays, estuaries, and wetlands warm more quickly than deeper ocean waters.[32] For example, eelgrass beds typically grow in shallow subtidal or intertidal areas,[33] and warmer periods can cause drying that concentrates mineral salts to levels that are stressful

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[22] Information as cited in Karl et al. (eds) (2009), *Global Climate Change Impacts in the United States*. (U.S. government report)
[23] Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)
[24] Ibid.
[25] Information as cited in Parry et al. (2007), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.
[26] Mote and Salathe (2009), *Future Climate in the Pacific Northwest*, In *WACCIA* (CIG, 2009).
[27] Living Oceans Society (2009), *Climate and Oceans Think Tank – Proceedings, Day 1.*
[28] Ibid.
[29] California Natural Resources Agency (2009), *California Climate Adaptation Strategy.*
[30] Information as cited in California Natural Resources Agency (2009), *California Climate Adaptation Strategy.*
[31] Ibid.
[32] California Natural Resources Agency (2009), *California Climate Adaptation Strategy.*
[33] Mumford (2007), *Kelp and eelgrass in Puget Sound*. (Puget Sound Nearshore Partnership Report)

or toxic.[34] Thom et al. (2005) state that eelgrass variation may be related to sea level and temperature changes such that eelgrass would be expected to decline under warmer, dryer conditions in the Northwest. [35]

Other effects that rising SST may have on biological communities include:

- **Regional declines in abundance of some fish and seabird species**: Warmer ocean temperatures together with changed nutrient availability may result in a decrease in fish populations or a shift in their geographic distribution.[36] The implications of rising SST on fish and seabirds may be foreshadowed by observed changes during natural warming periods such as El Niño events. For example, historical natural periods of warmer ocean temperatures have corresponded with relatively low salmon abundances.[37] During the 1997-1998 El Niño, California's commercial squid catch declined from 110,000 metric tons the previous year to 1,000 metric tons during the El Niño.[38] Temperature fluctuations have been associated with population booms or crashes of Pacific sardines, whose spawning habitats expand and shift north in warm years.[39] Seabird populations have also been observed to decline in warm years, when prey and nutrients are not as close to the ocean surface.[40] Hence, seabird productivity might also be expected to decline in future warm years.[41]

- **Altered distribution of some fish species**: Due to warming and changes in species' geographic distributions, some fish species may migrate northward[42], while others may move out of the areas where they currently occur.[43] For example, under a doubling of CO_2, models predict that Pacific salmon would experience a range decline as they move northward into the Bering Sea and the Arctic.[44] Impacts to fish may be complex, considering that southern species of zooplankton may also move northward; these prey species may have less of the rich oils needed by our native fish, reducing the quality of their food supply.[45]

- **Physiological changes**: Warmer temperatures could lead to higher growth rates for some cold-blooded marine organisms.[46] However, temperatures that are too high can stress an organism.[47]

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[34] Thom et al. (2001), *The influence of climate variation and change on structure and processes in nearshore vegetated communities of Puget Sound and other northwest estuaries*. (primary literature)

[35] Thom et al. (2001), *The influence of climate variation and change on structure and processes in nearshore vegetated communities of Puget Sound and other northwest estuaries*. (primary literature).

[36] Information as cited in California Natural Resources Agency (2009), *California Climate Adaptation Strategy.*

[37] Information as cited in Karl et al. (eds.) (2009), *Global Climate Change Impacts in the United States* (See Regional Climate Impacts:Northwest). (U.S. government report)

[38] Information as cited in California Natural Resources Agency (2009), *California Climate Adaptation Strategy.*

[39] Living Oceans Society (2009), *Climate and Oceans Think Tank – Proceedings, Day 1.*

[40] Living Oceans Society (2009), *Climate and Oceans Think Tank – Proceedings, Day 1.*

[41] Ibid.

[42] Information as cited in California Natural Resources Agency (2009), *California Climate Adaptation Strategy.*.

[43] Living Oceans Society (2009), *Climate and Oceans Think Tank – Proceedings, Day 1.*

[44] Ibid.

[45] Ibid.

[46] Information as cited in Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)

The consequence of these changes will depend in part on the resources available to support growth and fish health. Some species may benefit from increased SST, while others may not.

- **Increased susceptibility to disease**: Extremely high temperatures are stressful and can reduce an organism's resistance to disease.[48] Increased temperatures reportedly correspond to disease epidemics among sea urchins, seabirds, and some marine mammals; they could also lead to a decline in shellfish growth, reproduction, distribution, and health.[49,50]

Information Gaps

- Reviewers noted that some models predict that ocean generated fog may increase as a result of rising SST. Further research on this topic and its implications may be warranted.
- We have presented general information on potential alterations in the distribution of fish species. Reviewers noted that there may also be effects on other taxa such as birds and mammals. This may be another area of additional research.
- Reviewers noted that biological communities south of Washington may shift northward wholesale, or may become disaggregated (i.e., only some species move north). Further information on the degree to which either of these will occur would be helpful.
- Reviewers requested further information on how increasing SST may contribute to dead zones and trophic effects. In addition, readers may wish to explore the literature on changes in species' distribution, diet, and reproductive success; studies showing negative effects of warm-water El Niño events on piscivorous birds and mammals; articles on the effects of SST, PDO, and El Niño on seabirds; and the genetic consequences of rising SST or climate change.

Suggestions for further information

- Reviewers suggested that Russell Rogers at WDFW Point Whitney Lab is an outstanding source of information and references regarding marine species invasions and diseases affecting shellfish (Russell.Rogers@dfw.wa.gov).
- NOAA provides a brief and informative summary of the effects of El Niño on the Pacific salmon catch. See <http://www.elnino.noaa.gov/enso4.html>.

Sea-Level Rise (SLR)

Atmospheric warming causes global sea levels to rise due to a combination of thermal expansion of the earth's oceans and melting glaciers and polar ice sheets, a phenomenon known as "eustatic" sea-level

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[47] Ibid.

[48] Information as cited in Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report).

[49] Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report).

[50] Information as cited in Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA*(CIG, 2009).

rise (SLR). This is distinguished from local, or "relative" sea-level rise, which is also influenced by factors such as vertical land movements.

Because of local uplift or subsidence, the observed relative SLR in a region may differ from globally predicted averages. For example, the Juan de Fuca oceanic plate is subducting under the North American continental plate in western Washington. This causes uplift in northwestern Washington – hence, the Olympic Peninsula has been rising at a rate of about 2 mm/yr while south Puget Sound is subsiding at about the same rate.[51] If these trends continue, relative SLR will be greatest in south Puget Sound and least on the northwest tip of the Olympic peninsula. [52]

Observed Changes

In the last 100 years, average global sea levels have risen about 6.7 inches, which is about 10 times faster than the rate of sea-level rise over the last 3000 years.[53] From 1961 to 2003, global sea levels rose at an average rate of approximately 0.07 in/yr, while in the past decade that rate has accelerated to 0.12 in/yr.[54] About 57% of sea level rise observed since 1993 is due to thermal expansion.[55]

On the coast of Washington, sea levels rose 0.04 in/yr to 0.11 in/yr between 1898-2000 (4.08 inches – 11.2 inches over 102 years).[56] From 1973-2000, sea levels rose approximately 0.11 in/yr (2.97 inches over 27 years) at Toke Point in Willapa Bay on the southern coast, and 0.05 in/yr (1.35 inches over 27 years) at Cherry Point, near Bellingham.[57]

Future Projections

Global projections vary, but the most recent estimates from the Intergovernmental Panel on Climate Change (IPCC) cite an additional 7-23 inch rise in global average sea level by 2090-2099 relative to 1980-1999.[58] A recent study suggests that this projection may significantly underestimate the rate of sea level rise; a feasible range by 2100 might be 20-56 inches above 1990 levels.[59]

In Puget Sound, the WACCIA's "medium" estimate of SLR in the next century is 7-23 inches relative to 1980-1999.[60] In contrast, the northwest Olympic Peninsula may experience relatively little SLR, as the rate of tectonic uplift currently outpaces predicted SLR rates.[61] Uplift may also be occurring along the central and southern Washington Coast; however, there is a lack of available data for this region and it is difficult to predict SLR in the coming century.[62]

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[51] Mote et al. (2008), *Sea level rise in the coastal waters of Washington State*. (CIG report)
[52] Information as cited in Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA* (CIG, 2009).
[53] Information as cited in IPCC (2007), *Climate Change 2007: Synthesis Report*.
[54] Information as cited in USAID (2009), *Adapting to coastal climate change: A guidebook for development planners*. (agency report)
[55] Information as cited in IPCC (2007), *Climate Change 2007: Synthesis Report*.
[56] Mote et al. (2008), *Sea level rise in the coastal waters of Washington State*. (CIG report)
[57] Ibid.
[58] Information as cited in IPCC (2007), *Climate Change 2007: Synthesis Report*.
[59] Rahmstorf, S. (2007), *A Semi-empirical approach to projecting future sea-level rise*. (primary literature)
[60] Mote and Salathe (2009), *Future Climate in the Pacific Northwest*. In: *WACCIA* (CIG, 2009).
[61] Ibid.
[62] Ibid.

However, the WACCIA notes that the application of SLR estimates in decision making will depend on location, time frame, and risk tolerance.[63] For decisions with long timelines and low risk tolerance (such as coastal development and public infrastructure) users should consider low-probability high-impact estimates that take into account, among other things, the potential for higher rates of SLR driven by recent observations of rapid ice loss in Greenland and Antarctica, which though observed were not factored into the IPCC's latest global SLR estimates.[64] Combining the IPCC high emissions scenario with 1) higher estimates of ice loss from Greenland and Antarctica, 2) seasonal changes in atmospheric circulation in the Pacific, and 3) vertical land deformation, a low-probability high-impact estimate of local SLR for the Puget Sound Basin is 22" by 2050 and 50" by 2100.[65] Low-probability, high impact estimates are smaller for the central and southern Washington coast (18" by 2050 and 43" by 2100), and even lower for the NW Olympic Peninsula (14" by 2050 and 35" by 2100) due to tectonic uplift.[66]

Biological communities – Observations & Change

Sea-level rise could inundate coastal habitats such as marshes, beaches, and tidal flats if ecosystems cannot shift upland quickly enough, or if habitats are prevented from doing so because of development or coastal armoring (e.g., bulkheads).[67] Vulnerable habitats might include beach and dune systems, coastal saltmarshes, and marine riparian habitats, among others.[68] Coastal habitats provide important refuge and spawning areas for finfish, shellfish, and wildlife, maintain a biodiverse landscape, and provide services such as water quality improvement. Currently, many coastal habitats have minimal opportunity for inland migration because of barriers such as dikes, seawalls, and other armoring structures; dams and levees have also altered the natural patterns of sedimentation that nourish deltas, beaches, and marshes.[69] The Coastal Preparation and Adaptation Working Group (PAWG, 2008) recognized that rates of sea level rise, the ability of habitats to migrate landward, and the availability of sediment (i.e., changes in tidal dynamics and sedimentation) will be important considerations in nearshore habitat adaptation.[70]

A 2007 report by the National Wildlife Federation entitled *Sea Level Rise and Coastal Habitats in the Pacific Northwest* published several SLR modeling scenarios for a wide range of coastal areas across Washington State. Based on those models, the report found that a 27 inch rise in sea level would have the following broad consequences on Washington's marine habitats by 2100:[71]

- 65% loss of estuarine beaches due to erosion and inundation

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[63] Ibid.
[64] Mote and Salathe (2009), *Future Climate in the Pacific Northwest*. In: *WACCIA* (CIG, 2009)..
[65] Ibid.
[66] Ibid.
[67] Glick et al. (2007), *Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, southwestern Washington, and northwestern Oregon*. (NWF report)
[68] Ibid.
[69] Ibid.
[70] Preparation and Adaptation Working Groups (PAWG). 2008. *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*.
[71] Glick et al. (2007), *Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, southwestern Washington, and northwestern Oregon*. (NWF report)

- 6 % loss of ocean beaches
- 61% loss of tidal swamps
- 44% loss of tidal flats
- 52% conversion of brackish marshes to tidal flats, transitional marsh, and saltmarsh
- Expansion of transitional marsh

There was considerable variability in modeled habitat changes between different locations. Glick et al. (2007) summarized the report results by stating that many freshwater marshes and swamps may be converted to saltmarshes or to transitional marshes that experience frequent saltwater inundation. A reduction in estuarine beaches, tidal flats, and ocean beaches was expected across a variety of sea-level rise scenarios.[72] Effects on one coastal habitat type may also influence other natural communities that are biologically, chemically, or physically linked to it.[73] For example, marshes provide food and habitat resources that would be lost or redistributed as the habitat shifts. Thousands of shorebirds also rely on resources from tidal flats during their winter migration.[74]

A report by the Coastal Preparation and Adaptation Working Group (PAWG, 2008) highlights several sea-level rise impacts on marine areas in Washington. For example, the report states that spits and barrier beaches may experience more frequent and severe flooding, increased erosion and potential for breaching, and loss of associated beach, wetland, and estuarine habitat.[75] Depending on whether dikes are maintained, some low-lying deltas may be inundated and the habitats shoreward of the dikes could be lost.[76] Increased flooding, soil saturation, and salt water intrusion into the estuary may also occur.[77]

Information Gaps

- Reviewers questioned whether there is any research available that has modeled the interactive effects between SLR, erosion, and accretion. Such information may be helpful; we do not know if it exists.
- Reviewers questioned whether new habitats may be created as a result of SLR, and if that process might partially compensate for habitat losses. This would be worthy of further study.

Suggestions for further information

- Reviewers stated that good potential sources of information regarding the impacts of SLR on shellfish aquaculture include Brady Blake at WDFW Point Whitney Lab (Brady.Blake@dfw.wa.gov) and Dan Cheney at the Pacific Shellfish Institute

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[72] Glick et al. (2007), *Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, southwestern Washington, and northwestern Oregon*. (NWF report).
[73] Information as cited in Glick et al. (2007), *Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, southwestern Washington, and northwestern Oregon*. (NWF report)
[74] Glick et al. (2007), *Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, southwestern Washington, and northwestern Oregon*. (NWF report)
[75] Preparation and Adaptation Working Groups (PAWG). 2008. *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*.
[76] Ibid.
[77] Ibid.

(http://www.pacschell.org/staff.htm). This topic is also discussed in Huppert et al. (WACCIA Ch.8 - CIG, 2009).

Altered Hydrology

"Hydrology" refers to the movement of water through the landscape and its cycles throughout the globe. In Washington State, climate change may lead to reduced spring snowpack, earlier spring snowmelt, increased winter flows, and decreased summer flows.[78] Although these hydrologic alterations deal primarily with fresh water, they have important implications for Washington's marine systems – particularly Puget Sound. Freshwater inflow from the basin's major rivers influences physical characteristics such as water temperature, salinity, and circulation patterns in the Sound.[79]

Observed Changes

Key scientific studies provide divergent results regarding Cascade mountain snowpack. Snover et al. (2005) cites information that April 1 snowpack (measured as snow water equivalent , or SWE) has declined markedly almost everywhere in the Cascades since 1950.[80] These declines exceeded 25 percent at most study locations, and tended to be largest at lower elevations.[81] In contrast, Stoelinga et al. (in press) examined snowpack data over a longer time period (1930-2007)and concluded that snowpack loss occurred at a rate of approximately 2.0% per decade, yielding a 16% loss.[82]

Snover et al. (2005) cite that freshwater inflow to Puget Sound has changed over the period 1948-2003 in the following ways:[83]

- A 13% decline in total inflow due to changes in precipitation
- A 12 day shift toward earlier onset of snowmelt
- An 18% decline in the portion of annual river flow entering Puget Sound during the summer
- An increase in the likelihood of both low and unusually high daily flow events

Stoelinga et al. (in press) found that the dates of maximum snowpack and 90% melt-out have shifted 5 days earlier since 1930. Karl et al. (2009) claim that the peak of spring runoff shifted from a few days to as many as 30 days earlier in the second half of the 20th century. [84] While factors such as land use

[78] Snover et al. 2005. *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)
[79] Ibid.
[80] Information as cited in Snover et al. 2005. *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)
[81] Ibid.
[82] Stoelinga, M.T. et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains.* (primary literature)
[83] Information as cited in Snover et al. 2005. *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report).
[84] Information as cited in Karl et al. (eds) (2009), *Global Climate Change Impacts in the United States* (See Regional Climate Impacts:Northwest). (U.S. government report)

practices and natural cycles of ocean-atmospheric change may drive recent observations, these changes are also generally consistent with expected consequences of global climate change.[85]

Future Projections

- **Snow water equivalent (SWE)**: Relative to late 20th century averages (1971-2000), April 1 SWE is projected to decrease by 27-29% across the state by the 2020's, 37-44% by the 2040's, and 53-65% by the 2080's.[86] Note that a recent study by Stoelinga et al. (in press) presents the contrasting prediction that cumulative loss of Cascade spring snowpack from 1985-2025 will be only 9%.[87]

- **Freshwater inflows (e.g., streamflow)**: Earlier snowmelt is expected to contribute to higher runoff and freshwater inflows in the winter and reduced streamflows in the summer.[88] In Puget Sound, reductions in freshwater inflow may affect water circulation, salinity, and stratification.[89] Precise implications and quantitative predictions of change are unavailable, as the subject of alterations in circulation and mixing is generally unstudied.[90]

Biological Communities – Observations & Change

Precipitation patterns in Washington State are expected to change as a result of global climate change, and this could lead to an increase in the amount or frequency of nutrients entering coastal waters.[91] For example, winter rainfall is expected to increase as a result of climate change, leading to more winter flooding west of the Cascade Mountains;[92] if the timing of high flows corresponds with human releases of pollutants, this could mean consequent increases in inputs of polluted or nutrient-rich runoff into the environment. Changes in the quantity and timing of freshwater inflow could also alter overall patterns in salinity, resulting in shifts in the distribution, type, and abundance of organisms (e.g., salt marsh plants, eelgrass) living in estuarine regions of Puget Sound.[93]

Coastal Erosion

Coastal erosion involves the wearing away of land due to processes such as wave action, tidal currents, or runoff. Erosion from these processes deposits sediment to shorelines that shapes and nourishes habitats such as coastal beaches and nearshore marshes. The vulnerability of a particular area to erosion

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[85] Information as cited in Snover et al. (2005). *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)

[86] Elsner, M.M. et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*. In: *WACCIA* (CIG, 2009).

[87] Stoelinga, M.T. et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains.* (primary literature)

[88] Elsner, M.M. et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*. In: *WACCIA.*

[89] Snover et al. (2005). *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)

[90] Ibid.

[91] Ibid.

[92] Information as cited in Karl et al. (eds) (2009), *Global Climate Change Impacts in the United States* (See Regional Climate Impacts:Northwest). (U.S. government report)

[93] Snover et al. 2005. *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG report)

may depend on factors such as the type of rock or sediment, the slope of the land, degree of exposure to wind and waves, and anthropogenic influences such as clearing or building.

Observed Changes

Natural rates of erosion vary widely among locations in Washington State. In Island County, 51% of the shoreline is classified as "unstable", as opposed to 20% of Bainbridge Island and only 3% of San Juan County.[94] A few examples of erosion rates from different areas of Washington are described below. These examples are presented by Huppert et al. (WACCIA Ch.8 - CIG, 2009); here, they are used to illustrate the variability in erosion that can be observed through space and time.

- In Island County, erosion rates have been measured from a centimeter to more than two feet per year.
- On Whidbey Island, erosion contributes to landslides experienced on the western shore. Typical erosion rates are approximately 3 cm/year, although high waves observed more recently have caused larger amounts of erosion.
- On Bainbridge Island, bluff erosion rates are generally between two and six inches per year, despite this island's protection from strong waves.

Global climate change may accelerate coastal erosion due to sea-level rise and increased wave height .[95] Shifts in storm tracks as a result of climate change may alter wind patterns, such that waves hit the beach with more force or from new directions (resulting in new patterns of erosion). [96,97] Global climate changes may also be influencing coastal erosion rates, particularly in southwestern Washington. Researchers have observed that storm waves off the coast are up to eight feet higher than they were only 25 years ago, delivering 65% more force when they hit the beach.[98] (Increased storm wave data are specific to Washington coast. Data are not reported for interior Puget Sound, which experiences different conditions).

Although the severity of coastal erosion is expected to increase as a result of sea-level rise and intensification of storm activity,[99] we have found no quantitative projections on the extent of this increase for different locations within Washington State.

Biological Communities – Observations & Change

Changes in sediment erosion, transport, and accretion could affect the ability of certain habitats to adapt to climate change. For example, if river deltas experience erosion but are deprived of sediment

[94] Information as cited in Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA* (CIG, 2009).
[95] Ibid.
[96] Carter, L. (2003), *US National Assessment of the Potential Consequences of Climate Variability and Change. Educational Resources Regional Paper: Pacific Northwest*. US Global Change Research Program. (website)
[97] Information as cited in Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA* (CIG, 2009).
[98] Information as cited in Washington Economic Steering Committee and the Climate Leadership Initiative Institute for a Sustainable Environment, University of Oregon. 2006. *Impacts of climate change on Washington's economy: A preliminary assessment of risks and opportunities*.
[99] Ibid.

inputs, these habitats may not be able to accrete quickly enough to offset inundation from sea level rise.[100] A major factor that reduces sediment inputs in nearshore areas is the construction of seawalls and bulkheads; these structures sequester sand in one place but accelerate erosion in others.[101] If coastal erosion increases as a result of climate change, property owners may react by building more bulkheads, thereby depriving other coastal habitats of needed sediment.[102]

Sea-level rise is expected to increase erosion rates and coastal flooding of Washington's beaches and bluffs, by causing the shoreline to migrate landward as waves break higher on the beach profile.[103] The Coastal Preparation and Adaptation Working Group (PAWG, 2008) notes that climate change may induce forested bluffs to shift to unstable, bare slopes, that beaches could be "squeezed" between sea-level rise and coastal armoring, and that changes in bluff erosion could affect beach nourishment.[104] These are only a few examples of habitat changes that may occur in conjunction with climate change and alterations in sediment dynamics.

Information gap

- We could find no information on specific locations or types of habitats that might be most vulnerable to accelerated erosion rates or changing sediment dynamics.

Suggestion for further information

- To address the gap mentioned above, reviewers suggested focusing on the need to model the temporal and spatial patterns of erosion. The Dept. of Ecology has done some of this modeling in southwestern Washington: http://www.ecy.wa.gov/programs/sea/swces/index.htm.

Coastal Hypoxia

"Hypoxia" describes the condition of a water column that is largely deficient of dissolved oxygen – generally, a body of water is considered hypoxic when there is less than 2.0 mg/L of oxygen dissolved within it.[105] "Anoxia" is used to describe a water body that is totally devoid of dissolved oxygen.

Global climate change could increase the likelihood of hypoxia in the oceans and coastal environments by altering the physical environment in at least two ways:

- **Increased water temperature:** As a result of increasing SST, less oxygen will be able to dissolve into the warmer waters[106] - potentially increasing the likelihood of hypoxic events.

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[100] Glick et al. (2007), *Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, southwestern Washington, and northwestern Oregon*. (NWF report)
[101] Johannessen and MacLennan (2007), *Beaches and Bluffs of Puget Sound*. (Puget Sound Nearshore Partnership Report)
[102] Johannessen and MacLennan (2007), *Beaches and Bluffs of Puget Sound*. (Puget Sound Nearshore Partnership Report).
[103] Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA* (CIG, 2009).
[104] Preparation and Adaptation Working Groups (PAWG) (2008). *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*.
[105] Information as cited in Grantham et al. (2004), *Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific*. (primary literature)
[106] California Natural Resources Agency (2009), *California Climate Adaptation Strategy*.

- **Altered upwelling patterns**: There is evidence that climate change could alter coastal upwelling patterns and boost the delivery of deep, hypoxic waters into productive nearshore zones.[107,108] Hypoxic “oxygen minimum zones” can naturally occur in deep waters, where respiration removes oxygen that is not replenished by contact with the sea surface.[109] Upwelling processes can bring these deeper water masses nearer the surface, resulting in increasingly hypoxic conditions in coastal areas.[110] The wind patterns that cause upwelling are due in part to temperature differences between the land and ocean surface, and it is thought that global climate change will promote heating over the land, thereby resulting in more intense upwelling events.[111]

Observed Changes

Along the Pacific Northwest coast, hypoxic waters are becoming more common and are occurring in new locations. In 2006, researchers documented anoxia on the inner shelf in Oregon, where it had never before been recorded (although hypoxic waters have historically been upwelled onto the continental shelf, these waters have generally remained on the deeper, outer portions of the shelf).[112] As Chan et al. (2008) stated, “Five decades of available records show little evidence of shelf hypoxia and no evidence of severe inner-shelf hypoxia before 2000”.[113] More specifically, hypoxic water in depths less than 165 feet in this region is considered unusual, and was not reported before 2002 although measurements were made along the Oregon coast for over 50 years.[114] Along Washington’s outer coast, oxygen concentrations over much of the inner shelf dropped below 0.5 mL/L in 2006, causing a significant hypoxic event.[115] Such events have been recorded in historical archives between 1949-1983 as occurring throughout the period of record. [116]

Scientists hypothesize that these hypoxic events are due to anomalous upwelling driven by unusual changes in wind patterns.[117] These wind patterns are what might be expected to result from increased differences between land and sea surface temperatures due to global climate change. Specifically, temperature gradients across the shore support more intense alongshore winds, which drive surface

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[107] Grantham et al. (2004), *Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific*. (primary literature)
[108] Levin et al. (2009) *Effects of hypoxia on coastal benthos.* (primary literature)
[109] Grantham et al. (2004), *Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific*. (primary literature)
[110] Information as cited in Chan et al. (2008), *Emergence of anoxia in the California Current large marine ecosystem*. (primary literature)
[111] Bakun, A. 1990. *Global climate change and intensification of coastal ocean upwelling*. (primary literature)
[112] Chan et al. (2008), *Emergence of anoxia in the California Current large marine ecosystem*. (primary literature)
[113] Ibid.
[114] PISCO (2009), *Hypoxia off the Pacific Northwest Coast*. (educational outreach publication)
[115] Connolly et al. (2008), *Seasonal and event-scale processes contributing to hypoxia on the continental shelf of Washington*. (abstract)
[116] Ibid.
[117] Grantham et al. (2004), *Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific*. (primary literature)

water off the coast and result in the upwelling of deeper waters.[118] The changes in oceanic and atmospheric conditions that have produced the anomalous hypoxic events are consistent with expectations of how these systems might be altered due to climate change; however, it has not been proven that climate change is the cause.[119]

Future Projections

Global climate change could reduce the solubility of oxygen in ocean waters and alter wind patterns that affect how oxygen is transported and mixed in the sea.[120] Associated changes in upwelling may result not only in more intense episodes of nearshore hypoxia, but also in alterations of the timing and delivery of nutrients into coastal zones. [121]

Biological Characteristics – Observations & Changes

More intense upwelling events could be problematic for nearshore organisms that are not adapted to frequent, upwelling-associated hypoxic events and cannot tolerate extended periods of low oxygen.[122] Mobile organisms (such as fish) may be able to respond to the onset of a hypoxic event (depending upon its rapidity), while sessile or sluggish organisms may not be able to move from hypoxic zones. Severe, inner-shelf hypoxia has resulted in massive die-offs of fish and invertebrates.[123] Survival of species such as rockfish and Dungeness crab has been observed to decline during hypoxic events.[124] In general, hypoxic conditions tend to lead to reductions in diversity and in body size of organisms, and can specifically alter an organism's behavior, growth, reproductive success, and survival for species that are not adapted to such conditions.[125]

Information gap

- We could find no quantitative projections describing how the frequency, location, or extent of coastal hypoxia will change in the U.S., Pacific Northwest, or Washington state as a result of climate change.

Suggestions for further information

- Reviewers noted that further investigation of how climate change might affect hypoxic events specifically within estuaries (i.e., Hood Canal) would be worthwhile.

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[118] Bakun, A. (1990), *Global climate change and intensification of coastal ocean upwelling*. Also cited in Bakun, A. and SJ Weeks (2004), *Greenhouse gas buildup, sardines, submarine eruptions and the possibility of abrupt degradation of intense marine upwelling ecosystems*. (primary literature)
[119] PISCO (2009), *Hypoxia off the Pacific Northwest Coast*. (educational outreach publication)
[120] Middleburg, J.J. and L.A. Levin (2009), *Coastal hypoxia and sediment biogeochemistry*. (primary literature)
[121] Grantham et al. (2004), *Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific*. (primary literature)
[122] Chan et al. (2008), *Emergence of anoxia in the California Current large marine ecosystem*. (primary literature)
[123] Grantham et al. (2004), *Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific*. (primary literature)
[124] Ibid.
[125] Levin et al. (2009), *Effects of natural and human-induced hypoxia on coastal benthos*. (primary literature)

- Reviewers suggested contacting Jan Newton (Univ. of Washington) for more information regarding hypoxia in Hood Canal. http://www.hoodcanal.washington.edu/observations/hypoxia.jsp
- Literature reviews of the impacts of hypoxia on marine invertebrates are available. Note that the sensitivity of marine species to hypoxic events may depend upon the rapidity of the event's onset. Please contact Dan Siemann at NWF (siemannd@nwf.org) for access to this information, which was suggested and provided by individuals who reviewed this document.

Ocean Acidification

"Ocean acidification" is the term used to describe the observed decline in average ocean pH since the Industrial Revolution (~ 1800). The pH scale ranges from 0-14 and is a measure of a substance's acidity or alkalinity, based on the concentration of hydrogen ions in the solution. More acidic substances have higher concentrations of hydrogen ions. A "neutral" substance (e.g. pure water) has a pH of 7, while acidic substances have a lower pH and alkaline substances a higher pH. The scale itself is logarithmic, such that a substance with a pH of 6 is ten times more acidic than a substance with a pH of 7. Hence, pH changes that appear to be small may actually represent a significant alteration in ocean chemistry.

Global ocean pH declines as increasing levels of atmospheric carbon dioxide are absorbed by the ocean; this results in an increase in the amount of carbon dioxide dissolved in the water.[126] Dissolved carbon dioxide reacts with water to form carbonic acid, which breaks apart into hydrogen, bicarbonate, and carbonate ions. The concentration of hydrogen ions in the ocean therefore increases, reducing ocean pH. Other than equilibration with the atmosphere, declines in ocean pH also occur via processes such as respiration by marine organisms, which adds carbon dioxide to ocean waters.[127]

Observed Changes

At the end of the Pleistocene (~10,000 years ago), ocean pH was basically stable at 8.2 - a value that persisted until the beginning of the Industrial Revolution.[128] Since that time, the oceans have absorbed about 120 billion metric tons of carbon dioxide from the atmosphere – this is 22 million metric tons per day, or about 33% of anthropogenic carbon emissions.[129] As a result, global ocean pH has declined 0.1 unit relative to its pre-industrial value.[130]

Researchers at Tattoosh Island on the northwestern tip of Washington State (near Neah Bay) have reported multi-year pH measurements available for this region. They reported that daily and even annual pH measurements can fluctuate as much as 0.24 units in a typical day at their study site due to

[126] Guinotte, J.M. and V.J. Fabry (2008), *Ocean acidification and its potential effects on marine ecosystems*. (primary literature)
[127] Byrne et al. (2010), *Direct observations of basin-wide acidification of the North Pacific Ocean*. (primary literature)
[128] Fierstein, D. 2007. *Illustration of the ecosystem effects of ocean acidification*. (website)
[129] Information as cited in Feely, R.A. et al. (2008), *Evidence for upwelling of corrosive "acidified" water onto the continental shelf*. (primary literature)
[130] Orr, J.C. et al. (2005), *Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms*. (primary literature)

factors such as photosynthesis and respiration.[131] However, the researchers detected a decrease in average pH between 2000 and 2008, associated with increases in atmospheric carbon dioxide. [132] This decline occurred at a faster rate than both what has been observed on a global scale and what is predicted by models.[133]

In addition to alterations in surface ocean pH, studies have also been conducted on changes in the characteristics of deeper waters and their circulation. More acidic water naturally develops in the deeper ocean due to respiration by marine organisms.[134] Upwelling events, such as those off the Pacific Coast, can bring this deeper, more acidic water closer to the surface.[135] Recently, however, this more acidic water has been observed penetrating closer to the surface and the coast than previously recorded. According to a study by Feely et al. (2008), water masses acidic enough to be detrimental to shell-making have risen 50-100m since preindustrial times, due to oceanic uptake of anthropogenic carbon dioxide. As the authors state, "…the upwelling process caused the entire water column shoreward of the 50-m bottom contour to become undersaturated [with respect to aragonite]…a condition that was not predicted to occur in open ocean surface waters until 2050" (p. 1491).

Another recent study by Byrne et al. (2010) characterized changes in direct pH measurements in the North Pacific over 34° of latitude, in both surface and deep waters of up to 6000m. This study confirmed that pH was declining in the upper ocean at rates that mirrored the rise in atmospheric carbon dioxide.[136] The researchers estimated how much of the observed pH change was attributable to naturally-created as opposed to human-generated CO_2 inputs, and found the human "signal" extending to depths of 150-500m, depending upon location.[137] Although the signal varied spatially over different latitudes, a study section from 22-38°N showed an average change in pH as a result of anthropogenic influences to be -0.011 (+-0.001), or 48% (+-10%) of the total pH change between 800m and the mixed layer.[138] The authors expect that on a timescale of several decades, pH changes that are attributable to human CO_2 emissions will eventually dominate the overall signal – in other words, distinctions between total pH change and pH change attributable to humans will become increasingly subtle.[139]

Future Projections

Globally, average surface ocean pH is predicted to decrease 0.14-0.35 pH units by 2100,[140] largely as a result of continued absorption of atmospheric carbon dioxide. For example, if the concentration of

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[131] Wootton et al. (2008), *Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset.* (primary literature)
[132] Ibid.
[133] Ibid.
[134] Feely, R.A. et al. (2008), *Evidence for upwelling of corrosive "acidified" water onto the continental shelf*. (primary literature)
[135] Ibid.
[136] Byrne et al. (2010), *Direct observations of basin-wide acidification of the North Pacific Ocean*. (primary literature)
[137] Ibid.
[138] Ibid.
[139] Ibid.
[140] Cao et al. (2007), *Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation*. (primary literature)

carbon dioxide reaches 500 ppm by 2050 and 800 ppm by 2100, this increase will result in a decline of approximately 0.4 pH units.[141]

Biological Communities – Observations & Changes

Decreasing ocean pH is recognized as problematic for marine organisms that make shells; these organisms need the compound carbonate to build shell, which becomes less available in more acidic waters.[142] Shellfish, corals, and some types of plankton are examples of organisms that require carbonate to build their shells. There is great concern that ocean acidification will result in the decline of these species and others that provide habitat, support biodiversity, supply fisheries, and represent an important food base in oceanic food webs.[143]Calcareous marine species may decline due to ocean acidification, and be replaced by non-calcareous counterparts.[144] On the Great Barrier reef, researchers have observed a rapid, 14% decline in calcification in *Porites* corals since the 1990s.[145] Declines in calcification have also been observed in laboratory experiments with coccolithophores, foraminifera, pteropods, and shellfish species.[146] Shifts in species dominance and community composition, as well as a loss of important prey bases, could alter food web structures. For example, pteropods are one of the major prey items for juvenile salmon.[147] In addition, a number of studies have shown that more acidic water reduces the survival of larval marine species, including shellfish such as mussels, clams, and oysters.[148]

Some species, such as eelgrass, have been projected to possibly benefit from acidification - in this case due to an enhancement of photosynthesis from an increased abundance of dissolved carbon dioxide.[149] However, these benefits may be species specific and ultimately offset by water quality decline. For example, increased water temperatures, increased amounts of sediment and nutrient runoff, and increased occurrences of hypoxic conditions are all likely to contribute to seagrass decline in Chesapeake Bay.[150]

Information gap

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[141] Information as cited in Feely et al. (2008). *Evidence for upwelling of corrosive "acidified" water onto the continental shelf*. (primary literature)

[142] Byrne et al. (2010), *Direct observations of basin-wide acidification of the North Pacific Ocean.* (primary literature)

[143] Feely, R.A. et al. (2008), *Evidence for upwelling of corrosive "acidified" water onto the continental shelf*. (primary literature)

[144] Wootton et al. (2008), *Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset*. (primary literature)

[145] Living Oceans Society (2009), *Climate and Oceans Think Tank – Proceedings, Day 1.*

[146] Living Oceans Society (2009), *Climate and Oceans Think Tank – Proceedings, Day 1.*

[147] Feely et al. (2008), *Evidence for upwelling of corrosive "acidified" water onto the continental shelf*. (primary literature)

[148] Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA* (CIG, 2009). Also in Feely, et al. (2008), *Evidence for upwelling of corrosive "acidified" water onto the continental shelf*. (primary literature)

[149] Guinotte and Fabry (2008), *Ocean acidification and its potential effects on marine ecosystems.* (primary literature)

[150] Moore and Jarvis (2008), *Environmental factors affecting recent summertime eelgrass diebacks in the lower Chesapeake Bay: Implications for long-term persistence*. (primary literature)

- We found no specific predictions of the extent of pH decline expected in U.S. coastal waters or specific locations within Washington state, and do not know how this will compare to predicted global averages.

SOME POSSIBLE RESPONSES FOR CONSIDERATION

***NOTE**: The issues and potential responses listed in this section represent ideas from the surveyed literature. This list presents examples of adaptation responses suggested by others. It is not exhaustive, and we encourage readers to critically consider the applicability of each response in Washington state. The choice of response strategy may be influenced by a range of factors, including degree of impact, irreversibility, risk, vision for the future, and goals. Readers are encouraged to add further suggestions for issues or responses.

Responses presented in the Preparation and Adaptation Working Group's report (PAWG, 2008) are highlighted here in **gray** for ease of reference.

RISING SEA SURFACE TEMPERATURE	
Effects/Impacts	**Possible Response(s)**
Rising sea surface temperature	
Sea level rise	
Water quality decline	
Habitats further stressed by addition of climate impacts to non-climate stressors (e.g. pollution, erosion)	• Research impacts of non-climate stressors in specific locations and their interaction with climate change impacts[151]
Changes in coastal upwelling and nutrient supply	
Shifts in species' distribution	
Changes in predator-prey dynamics	
Increased susceptibility of organisms to disease	
Increased physiological stress	• Emphasize ecosystem-based management approaches for fisheries, to help stocks cope with existing stressors[152] • Manage fisheries to rebuild depleted wild populations[153]

[151] California Natural Resources Agency (2009), *California Climate Adaptation Strategy.*

[152] Glick, P. and the Florida Coastal and Ocean Coalition (2008), *Preparing for a sea change in Florida: A strategy to cope with the impacts of global warming on the State's coastal and marine systems*. (NWF report)

[153] Ibid.

SEA LEVEL RISE (SLR)	
Effects/Impacts	**Possible Response(s)**
Sea level rise	
Increasing coastal erosion	• Conduct beach nourishment only where ecologically appropriate.[154] • Remove hard structures that prevent the movement of sand alongshore. [155] • Pursue pilot projects to examine alternatives to armoring that would preserve shoreline processes in entire drift cells.[156]
Inland habitat migration	• Determine areas of wetland migration corridors[157] • Purchase coastal property[158] • Remove coastal armoring (e.g. bulkheads)/ replace with "softer", natural alternatives[159] • Designate natural buffers in coastal areas.[160] • Incorporate SLR into conservation and restoration priorities and strategies. [161]
Loss or transition of coastal habitats	
Loss of ecosystem functions and services	
Inputs of toxins	• Incorporate future sea level rise in prioritization, design, and post-project maintenance of toxic cleanup sites in shoreline areas.[162]
Inundation of property and habitat	• Improve mapping and characterization of SLR vulnerability for all Washington coasts.[163] • Notify property purchasers of any potential SLR risks.[164] • Utilize Flood Control Assistance Account Program planning to address SLR.[165] • Purchase vulnerable coastal properties. [166] • Provide rolling easements for coastal landowners.[167] • Incorporate expected SLR into flood zone designations,[168] and comprehensive development plans.

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[154] Glick, P. and the Florida Coastal and Ocean Coalition (2008), *Preparing for a sea change in Florida: A strategy to cope with the impacts of global warming on the State's coastal and marine systems*. (NWF report)
[155] Ibid.
[156] Preparation and Adaptation Working Groups (PAWG) (2008), *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*.
[157] Glick, P. and the Florida Coastal and Ocean Coalition (2008), *Preparing for a sea change in Florida: A strategy to cope with the impacts of global warming on the State's coastal and marine systems*. (NWF report)
[158] Ibid.
[159] Ibid.
[160] Preparation and Adaptation Working Groups (PAWG) (2008), *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*.
[161] Ibid.
[162] Ibid.
[163] Ibid.
[164] Ibid.
[165] Ibid.

Siting new construction	• Include best available data on SLR in design of coastal facilities, construction, and major repair projects. [169] • Incorporate SLR into state infrastructure funding programs.[170] • Address climate change impacts in state land use and shoreline planning statutes and regulations. [171]

ALTERED HYDROLOGY	
Effects/Impacts	**Possible Response(s)**
Reduced spring snowpack & freshwater storage	
Earlier spring snowmelt	
Seasonality of freshwater flows: increased in winter, decreased in summer	
Change in water temperature	
Change in water salinity	
Change in circulation patterns in Puget Sound	
Change in water stratification in Puget Sound	
Change in the distribution, abundance, and type of estuarine organisms	
Inadequate infrastructure for increased rainfall events	• Evaluate capacity for stormwater and sewage retention and upgrade as necessary[172] • Use natural buffers to help store water.[173] • Upgrade stormwater regulations to account for the likelihood of more frequent heavy rainfall events. [174] • Determine strategies for increasing use of reclaimed water. [175]
Water quality (e.g. Timing or amount of toxic or nutrient-rich runoff)	• Protect and restore wetlands and riparian floodplains to act as filters for removing nutrients and toxins in runoff. [176]

[166] Glick, P. and the Florida Coastal and Ocean Coalition (2008), *Preparing for a sea change in Florida: A strategy to cope with the impacts of global warming on the State's coastal and marine systems*. (NWF report)
[167] Glick et al. (2007), *Sea-level rise and coastal habitats in the Pacific Northwest: An analysis for Puget Sound, southwestern Washington, and northwestern Oregon*. (NWF report)
[168] Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA* (CIG, 2009).
[169] Preparation and Adaptation Working Groups (PAWG) (2008), *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*.
[170] Ibid.
[171] Ibid.
[172] Glick and the Florida Coastal and Ocean Coalition (2008), *Preparing for a sea change in Florida: A strategy to cope with the impacts of global warming on the State's coastal and marine systems*. (NWF report)
[173] Ibid.
[174] Ibid.
[175] Ibid.
[176] Ibid.

COASTAL EROSION	
Effects/Impacts	**Possible Response(s)**
Changing and accelerating patterns of erosion	
Increased susceptibility of bluff and beach property and infrastructure to damage or loss	• Encourage landward siting and relocation of structures using tools such as acquisition, rolling easements, transfer of development rights, stronger setbacks, and/or tax incentives[177] • Research alternatives to beach armoring.[178] • Avoid development on bluffs. [179]
Loss of beach habitat	• Artificially nourish beaches only in ecologically appropriate locations.[180] • Protect and conserve functioning areas & adjacent nearshore areas.[181] • Include habitat reclamation opportunities in long-term management of armored and diked shorelines. [182]
Changes in sediment dynamics (rates of erosion vs. accretion)	
Lack of public awareness	• Public outreach and education programs[183]
Anthropogenic responses (e.g. increased beach armoring) and ecological consequences	

COASTAL HYPOXIA	
Effects/Impacts	**Possible Response(s)**
Reduced oxygen solubility	
Shift in location & extent of upwelled hypoxic waters onto inner continental shelf	
Species mortality	
Shifts in upwelling, changes in timing and delivery of nutrients to coastal zone	

[177] Glick and the Florida Coastal and Ocean Coalition (2008), *Preparing for a sea change in Florida: A strategy to cope with the impacts of global warming on the State's coastal and marine systems*. (NWF report)
[178] Preparation and Adaptation Working Groups (PAWG) (2008), *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*.
[179] Huppert et al. (2009), *Impacts of climate change on the coasts of Washington State*. In: *WACCIA* (CIG, 2009).
[180] Glick and the Florida Coastal and Ocean Coalition (2008), *Preparing for a sea change in Florida: A strategy to cope with the impacts of global warming on the State's coastal and marine systems*. (NWF report)
[181] Preparation and Adaptation Working Groups (PAWG) (2008), *Leading the way - preparing for the impacts of climate change in Washington: Recommendations of the Preparation and Adaptation Working Groups*.
[182] Ibid.
[183] Ibid.

Reduction in species diversity	
Reduction in organism body size	
Change in organisms' reproductive success	

OCEAN ACIDIFICATION	
Effects/Impacts	**Possible Response(s)**
Decline in average ocean pH	• Reduce the amount of CO_2 entering Earth's atmosphere [184]
More acidic waters upwelled into shallower depths	
Reduced survival of some marine species	
Alterations in food webs	
Shifts in marine community composition from calcareous to non-calcareous species	
Water quality	
Enhancement of photosynthesis for marine primary producers	

[184] Glick, P. and the Florida Coastal and Ocean Coalition (2008), *Preparing for a sea change in Florida: A strategy to cope with the impacts of global warming on the State's coastal and marine systems*.

APPENDIX 1: A NOTE ON CLIMATE MODELS

This text is excerpted from Climate Impacts Group's 2009 *Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate* (WACCIA).

Global Models

Envisioning global climate in a future with much higher greenhouse gases requires the use of physically based numerical models of the ocean, atmosphere, land, and ice, often called global climate models (GCMs) or climate system models.[185] A common set of simulations using 21 GCMs was coordinated through the Intergovernmental Panel on Climate Change (IPCC).[186] These models typically resolve the atmosphere with between 6,000 and 15,000 grid squares horizontally, and with between 12 and 56 atmospheric layers.[187]

Simulations of 21st century climate require projections of future greenhouse gases and sulfate aerosols (which reflect sunlight and also promote cloud formation, thereby offsetting greenhouse gases locally), more than 40 of which were produced under the auspices of the IPCC.[188] [For the WACCIA,] three of these scenarios were commonly chosen for forcing the GCMs: B1, A1B, and A2.[189]

A2 produces the highest climate forcing by the end of the century, but before mid-century, none of the scenarios is consistently the highest.[190] Because more modeling groups ran A1B than A2, and since our focus for this study was on mid-century change, we chose A1B as the higher emissions scenario and B1 as the low emissions scenario for our analysis of 21st Century PNW climate.[191] Though B1 is the lowest of the IPCC illustrative scenarios, it still produces changes in climate that many scientists call "dangerous" (Schellnhuber et al., 2006) — a threshold that a growing number of political leaders have stated their intention to avoid.[192] At the high end, scenario A1FI (not shown) results in even higher climate forcing by 2100 than A2 or A1B.[193] Recent global emissions of CO2 have been exceeding even the A1FI scenario (Raupach et al., 2007).[194]

Regional Models

Global climate models do not account for the atmospheric processes that determine the unique spatially heterogeneous climatic features of Washington.[195] Statistical downscaling is based on fine-scale data derived using assumptions about how temperature and precipitation vary over complex terrain in order

[185] Mote and Salathe. (2009). Future Climate in the Pacific Northwest. In: *WACCIA*(CIG, 2009).
[186] Ibid.
[187] Ibid.
[188] Ibid.
[189] Ibid.
[190] Ibid.
[191] Ibid.
[192] Ibid.
[193] Ibid.
[194] Information as cited in Mote and Salathe. (2009). Future Climate in the Pacific Northwest. In: *WACCIA* (CIG, 2009).
[195] Salathé, et al. (2009) Regional climate model projections for the State of Washington. In: *WACCIA* (CIG, 2009).

to interpolate the sparse station network (about 50-km spacing) to a 6-km grid.[196] Information simulated by the coarse-resolution global models (with output on a 100-to-300 km grid) is then used to project the future climate.[197] This approach represents the mean climate and local regimes quite well but does not take into account how the terrain influences individual weather systems.[198]

Our results show that, with increased spatial resolution relative to global models, regional climate models can represent the local forcing from the complex terrain to produce more realistic spatial and temporal variability of temperature, precipitation, and snowpack in the State of Washington.[199] With the ability to resolve topographic effects, more robust changes in mountain snowpack and extreme precipitation emerge.[200] These changes are consistent between the two regional simulations despite differences in seasonal precipitation and temperature changes in the global and regional model results.[201] It is clear that changes in the seasonal climate and the frequency of extreme events may be locally much more intense than can be inferred from statistical methods.[202] The implication is that, while a valuable tool for regional climate impacts assessment, multi-model ensembles of global climate projections and statistical methods may under represent the local severity of climate change.[203]

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[196] Ibid.
[197] Salathé, et al. (2009) Regional climate model projections for the State of Washington. In: *WACCIA* (CIG, 2009)..
[198] Ibid.
[199] Ibid.
[200] Ibid.
[201] Ibid.
[202] Ibid.
[203] Ibid.

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Marine systems and likely climate change effects:

- See <http://www.pugetsoundnearshore.org/technical_reports.htm> for a number of technical reports that may help quantify likely effects of climate change. Examples of reports that are available include:
    - *Orcas in Puget Sound*
    - *Marine Forage Fishes in Puget Sound*
    - *Kelp and Eelgrass in Puget Sound*
    - *Great Blue Herons in Puget Sound*
    - *Nearshore Birds in Puget Sound*
    - *Native Shellfish in Nearshore Ecosystems of Washington State*
    - *Juvenile Pacific Salmon and the Nearshore Ecosystem of Puget Sound*

- *Marine Riparian Vegetation Communities of Puget Sound*
- *Beaches and Bluffs of Puget Sound and the Northern Straights*
- *Guidance for Protection and Restoration of the Nearshore Ecosystems of Puget Sound*
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