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PORT GAMBLE S'KLALLAM TRIBE

March 2017

CLIMATE CHANGE IMPACT ASSESSMENT

PORT GAMBLE S'KLALLAM

NATURAL RESOURCES DEPARTMENT

ACKNOWLEDGMENTS

This assessment would not have been possible without the tremendous contributions of many individuals, listed below.

Project team

Paul McCollum, Natural Resources Director
Hans Daubenberger, Principal Habitat Biologist
Samuel Phillips, Environmental Scientist

Special thanks to the following Tribal staff and partners

Roma Call, Environmental Program Manager
Ahmis Loving, Loving Engineering & Consulting, P.S. Inc.
Laurie Mattson, Interim Health Director
Kerstin Powell, Health Services Manager
Joe Sparr, Planning Director
Sam White, Police Chief
Josh Wisniewski, Anthropologist
Tim Cullinan, Thom Johnson, Ryan Murphy, Cynthia Rossi, and Austin Paul from the Point No Point Treaty Council

We are also grateful for the contributions of our expert reviewers and interviewees

Tim Beechie
Tim Cullinan
Lisa Crozier
Joth Davis
Austin Paul
David Peterson

Thanks to the following for their regional coordination efforts around these issues

Eliza Ghitis, Northwest Indian Fisheries Commission
Kathy Lynn, Tribal Climate Change Project

Prepared for the Port Gamble S'Klallam Tribe by

Cascadia Consulting Group
University of Washington Climate Impacts Group

Recommended Citation Format

Port Gamble S'Klallam Tribe Natural Resources Department. 2016. Climate Change Impact Assessment. A collaboration of the Port Gamble S'Klallam Tribe, Cascadia Consulting Group, and the University of Washington Climate Impacts Group.

ACRONYMS

BC	British Columbia
BIA	Bureau of Indian Affairs (BIA)
CCVI	Climate Change Vulnerability Index
CHR	Community Health Representative
CIG	Climate Impacts Group
CMIP5	Coupled Model Intercomparison Project Phase 5
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DNR	Department of Natural Resources
ENSO	El Niño/Southern Oscillation
EPA	Environmental Protection Agency
ESA	Endangered Species Act
ESP	Environmental Sample Processor
GCM	General circulation model
GHG	Greenhouse gas
GRACE	Gravity Recovery and Climate Experiment
HAB	Harmful algal bloom
HPA	Hydraulic Project Approval
IPCC	Intergovernmental Panel on Climate Change
KFBP	Kitsap Forest & Bay Project
MHHW	Mean Higher High Water
MIROC	Model for Interdisciplinary Research on Climate
MPB	Mountain pine beetle
NGO	Non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
NRC	Natural Resources Commission
ORHAB	Olympic Region Harmful Algal Bloom partnership
PDO	Pacific Decadal Oscillation
PGST	Port Gamble S'Klallam Tribe
PNPTC	Point No Point Treaty Council
PNW	Pacific Northwest
PSE	Puget Sound Energy
PUD	Public Utility District
RCP	Representative Concentration Pathway
SRES	Special Report on Emissions Scenarios
USDA	United States Department of Agriculture
USFS	United States Forest Service
UW	University of Washington
WDFW	Washington Department of Fish and Wildlife
WCPP	Wetland Conservation Program Plan
WSDOT	Washington State Department of Transportation

CONTENTS

Tribal nations will likely be disproportionately impacted by climate change due to their intimate, long-standing relationship with the natural environment and its resources, as well as their reliance on a wide range of natural resources for subsistence and cultural traditions.

Executive Summary

The Port Gamble S'Klallam Tribe has been concerned about climate change and its actual and potential impacts for over a decade, with increasing focus in the last five years. This report, funded primarily by the Bureau of Indian Affairs (BIA) with initial start-up funding from the Environmental Protection Agency (EPA), uses a scientific literature review and interviews with Tribal staff to identify anticipated climate change impacts on local ecosystems, species, human health, cultural resources, and Tribal infrastructure.

The impact assessment focuses on the Port Gamble S'Klallam Tribe's primary traditional use area, which is the central part of their large Usual and Accustomed Area (U&A). The Tribe's primary traditional use area is comprised of the upper half of Hood Canal and all of Admiralty Inlet. Because this chapter draws from existing datasets and literature, the time periods, spatial scale, and scenarios used to generate the information varies. Where available, we have utilized studies that focus on Hood Canal and Admiralty Inlet or on the Puget Sound region. The Tribe's Natural Resources Department prefers to use the high emissions scenario results for its planning, considering this "business as usual" scenario seems to be the most likely given current greenhouse gas emissions trends.

OBSERVED AND PROJECTED CHANGES IN CLIMATE

Observed changes include:[1]

- *Temperature:* Air temperatures in the Puget Sound region increased by about +1.3°F between 1895 and 2014. All but six of the years from 1980 to 2014 were warmer than the 20th century average.
- *Precipitation:* There has been no discernible long-term trend in total *annual* precipitation for the Puget Sound region, though spring precipitation is increasing. Most studies find that both the frequency and intensity of heavy precipitation have increased to some degree in Western Washington.

[1] See the following chapters for source information.

- *Snowpack and glaciers*: Glaciers in the Olympic Mountains lost 34% of their area and 20% of their volume between 1980 and 2009. A decrease in spring snowpack has been observed at Hurricane Ridge.
- *Streamflow:* The spring peak in streamflow is occurring earlier in the year for many snowmelt-influenced rivers in the Puget Sound region.
- *Sea level rise:* Sea level at the Seattle tide gauge—which has a longer record than the gauge in Port Townsend—rose by 8.6 inches between 1900 and 2008.
- *Water temperature:* Average water temperatures in Hood Canal increased by approximately 1°F between 1950 and 2009.
- *Ocean acidification:* A combination of increased carbon dioxide in the atmosphere and nutrient runoff have lowered the pH of Hood Canal's deep waters thereby increasing its acidity.

Projected future changes include:

- *Temperature:* Under a high emissions scenario, the average annual temperature is projected to increase by 6°F by mid-century and 9°F by 2100. We expect more extreme heat events and fewer extreme cold events.
- *Precipitation:* Model projections for changes in annual and seasonal precipitation in the Puget Sound region vary. Overall, the region is expected to see wetter winters and drier summers. Extreme precipitation events are likely to become more frequent and more intense.
- *Snowpack and glaciers:* Spring snowpack will continue to decline as more winter precipitation falls as rain and snow melts earlier. We expect that the glaciers in the region will continue to recede.
- *Streamflow:* Not all of the watersheds in the Tribe's primary traditional use area have been modeled to date. Watersheds that currently receive a mix of rain and snow are likely to receive relatively less snow in the future as temperatures rise, resulting in higher winter streamflows and lower summer streamflows. Warmer summer water temperatures are expected.
- *Wildfires:* Climate change is projected to increase the frequency and severity of forest fires in Western Washington, although quantifying the change in fire risk is difficult due to the low frequency of large wildfires in Western Washington.
- *Sea level rise:* High emissions scenarios project a 56-inch increase in sea level in Seattle by 2100 (compared to 2000). Recently, scientists have noted that approaches used for sea level rise studies may have underestimated the contributions from melt in Greenland and Antarctica, suggesting that sea level rise could be higher.
- *Water temperature:* Sea surface temperatures in the region are projected to warm by just over 2°F by the 2040s under a moderate emissions scenario. Warming would be even higher under a high emissions scenario.
- *Ocean acidification:* The pH of Washington's coastal waters is projected to continue decreasing as the atmospheric concentration of carbon dioxide climbs. Specific projections are not available for Hood Canal.

These projected changes may impact the Tribe both directly and indirectly, through consequences to natural resources and human systems. Examples are described below, with more detailed descriptions in the following chapters.

NATURAL RESOURCES

Salmon: Warming stream temperatures can decrease growth rates, change migration timing, amplify vulnerability to disease and predation, and increase mortality. Lower summer streamflows can impede salmon migration. In the winter, heavier rainstorms and resulting high-flow events could cause more damage to deposits of salmon eggs in rivers and streams. As different salmon stocks and species have different life histories and habitats, specific impacts may differ, as described in the Salmon chapter of this report.

Forage fish and critical prey: Forage fish such as the Pacific herring, surf smelt, and Pacific sand lance form a critical link in the marine food web. They may be affected by increased water temperatures, lower dissolved oxygen levels in nearshore habitat, and reductions in suitable habitat due to sea level rise; however, the limited research on lifecycles of specific forage fish species makes it difficult to determine their relative vulnerability with great precision.

Shellfish: Shellfish like clams and oysters are being affected by ocean acidification, which makes calcium carbonate less available for young shellfish and larvae to form their shells. Toxins produced by harmful algal blooms may appear more often, making shellfish dangerous to eat. Higher sea levels can also inundate existing intertidal habitats and reduce the amount of time when Tribal members can access beaches for harvesting. New studies show potential impacts to Dungeness crab.

Forests: Climate change is expected to lead to changes in forest growth and productivity, wildfire risk, insect and disease outbreaks, and, eventually, the geographic distribution of tree species. With its relatively wetter climate, Western Washington has—and will continue to have—a lower wildfire risk than Eastern Washington, but there is likely to be a greater risk in our region than we have observed in the past. There are likely to be more outbreaks of the mountain pine beetle through mid-century as temperatures warm; however, outbreaks may decrease later in the century as climatically suitable habitat declines. As trees weaken in times of drought, they will become increasingly vulnerable to these and other pests and disease. Still, given the long lifespans of trees, forests will likely remain fairly stable for the next 20 to 50 years, despite ongoing changes in climate.

Wetlands: While development and pollution are likely to remain the lead degraders of local wetlands, climate change adds another layer of stress to these systems. The Point Julia salt marsh and wetland, for example, could be inundated by sea level rise. It may also be affected by increased erosion and damage from extreme coastal weather events. Tidal and intertidal wetlands and pocket estuaries play an important role as habitat for salmon and shellfish. As the climate changes, estuarine beaches and tidal swamps are expected to shrink, while some tidal flats and salt marshes may expand.

Birds: Birds' ability to travel easily and find new areas with climates suitable for their needs helps reduce their vulnerability. Species that live in specific thermal niches or have very specialized diets, however, will be less prepared for expected temperature variations or changes in the timing of food availability. The marbled murrelet, spotted owl, and western grebe have very specialized diets which can increase their vulnerability. Meanwhile, rising sea levels may reduce the extent of foraging habitat available for shorebirds like the brant.

Mammals: An increased wildfire risk in Western Washington's forested landscapes could damage areas that provide critical habitat for elk, deer, and bear. The potential for more frequent or intense drought, as well as changes in the types and prevalence of diseases, can also directly affect animal health and survival. On the other hand, milder winters could have some benefits, including potentially higher survival rates for juvenile elk.

HUMAN SYSTEMS

Infrastructure: The design and location of most Tribal facilities will likely make them able to withstand anticipated climate change impacts. At Point Julia, however, the lower elevation makes boat launches and other nearby facilities more vulnerable to sea level rise. Flooding would be exacerbated during storms or extreme high tides. Sea level rise and increased heavy rainfall events are also expected to speed up existing bluff erosion dynamics. New planned housing lots are all located safely away from low-lying areas and the bluff.

Health and safety: Like other communities in Washington State, the Tribe can expect longer and more frequent summertime heat waves, more wildfires with corresponding reduced air quality, and a longer pollen season. Climate change could also contribute in some places to the spread of some infectious diseases (e.g., fungal infections), contamination of wells, and more cases of shellfish poisoning. Depending on local landscapes, climate change could bring more floods, landslides, and other extreme events. While the Tribe has focused its emergency and safety preparations on earthquake preparedness, some of those measures could also help the community deal with weather-related events.

Cultural resources: Climate change impacts that reduce the abundance of salmon and shellfish could affect Tribal ceremonies and customs. Climate change—and non-climate stressors like development—could also reduce access to and the availability of other traditional foods and gathering materials. Most of the Tribe's archaeological sites are in coastal areas and are therefore exposed to sea level rise and erosion. Within the reservation, the Tribe can take steps to protect these sites; its ability to take action is more limited with regard to culturally significant sites in other parts of the Tribe's primary traditional use area. Climate change may impact the Tribe's cultural health and identity depending on the intensity and significance of climate change impacts. However, Tribal members are experts at resiliency and will adapt to the changing times ahead.

Additional details on each of these resources and systems can be found in the corresponding chapters of this report.

NEXT STEPS

The Tribe's Natural Resources Department will use this impact assessment as the foundation for a participatory vulnerability assessment and adaptation planning process in 2017, engaging a wide range of other Tribal departments to understand the risks and identify ways to proactively adapt. Many of the Tribe's existing programs already contribute to resilience, and these will be even more important in the context of a changing climate. It is likely the Tribe will need to take additional actions given the magnitude and scope of the projected changes. By looking ahead and engaging staff and community members in discussions about what the Tribe can expect and what steps we need and want to take, we can protect our traditions, our community, and our resources for many generations to come.

A dynamic interaction exists between people, ecosystems, and natural resources. Just as ecosystems and resources affect human populations, people drive changes in the natural world around them. In the case of climate change, these changes will be extraordinarily far-reaching, and are expected to include increased temperatures, changing weather patterns, more frequent and extreme weather events, rising sea levels, reduced mountain snowpack, and changing hydrology.

Background

INDIGENOUS PEOPLES AND CLIMATE CHANGE

Tribal nations will likely be disproportionately impacted by climate change due to several factors, including an intimate, long-standing relationship with the natural environment and its resources, limited and relatively non-diverse economies, limited energy security and transportation options, and the practice of subsistence activities in many communities. These characteristics make tribes more vulnerable to the impacts of climate change than most other North American communities. A broad range of tribal resources will be affected by climate change, including ecosystems, natural resources, human health, and energy production and use [1]. In addition to posing serious challenges in their own right, these vulnerabilities will also impact tribal cultures, traditions, and politics. "For indigenous peoples, the impacts of climate change extend beyond the physical environment to their responsibilities as governments and cultural continuity," writes Gary Morishima in *Climate Change and Indigenous Peoples: A Primer* [2].

The effects—both direct and indirect—of climate change are already being felt in many tribal communities. Tribes should hold central roles in shaping local and regional climate policies and programs.

FEDERAL RECOGNITION OF TRIBES' VULNERABILITY TO CLIMATE CHANGE

One of the twelve major findings of the federal government's 2014 National Climate Assessment is that "climate change poses particular threats to Indigenous Peoples' health, well-being, and ways of life." The Indigenous Peoples, Lands, and Resources chapter states that climate change impacts on many tribes "are projected to be especially severe," and that "adaptive responses to multiple social and ecological challenges arising from climate impacts on indigenous communities will occur against a complex backdrop of centuries-old cultures already stressed by historical events and contemporary conditions." This chapter also remarks that Native populations are particularly vulnerable to climate change impacts because their cultures and ways of life are so closely tied to specific geographic areas and natural resources.

The National Climate Assessment also details the five climate change impacts expected to have particularly severe effects on tribal communities:

1	Reduced access to traditional foods, due to factors such as warmer temperatures, more frequent droughts, and longer fire seasons
2	Decreasing water quality and quantity, and less predictable availability, due to factors such as reduced rainfall and snowfall, melting glaciers, and shifts in ocean currents
3	Declining sea ice, which has widespread impacts in Alaska
4	Thawing permafrost, which is damaging infrastructure and stressing cultural traditions in Alaska
5	Relocation, in Alaska and among other coastal tribal communities

The Climate Assessment lays the foundation for what could become a comprehensive program to deal with climate change. Other steps toward the development of such a program include President Obama's Climate Action Plan, issued in June 2013, and Executive Order 13653 on Preparing the United States for the Impacts of Climate Change, issued on November 1, 2013. The Executive Order recognizes that "[t]he impacts of climate change—including an increase in prolonged periods of excessively high temperatures, more heavy downpours, an increase in wildfires, more severe droughts, permafrost thawing, ocean acidification, and sea-level rise—are already affecting communities, natural resources, ecosystems, economics, and public health across the Nation."

The White House has set a mission for the federal government to pursue new strategies to improve the Nation's preparedness and resilience, in part through modernizing federal programs to support the efforts of states, regions, local communities, and tribes to invest in climate resilience; managing lands and waters for climate preparedness and resilience; and providing related information, data, and tools. When the President issued Executive Order 13653, he also created the State, Local, and Tribal Leaders Task Force on Climate Preparedness and Resilience, which was charged with providing recommendations to the President and federal agencies on how the federal government can do the following:

- Remove barriers, create incentives, and modernize federal programs to facilitate increased resilience to climate impacts, including those associated with extreme weather.
- Provide useful climate preparedness tools and actionable information for state, local communities, and tribes.
- Support state, local, and tribal preparedness for and resilience to climate change.

That Task Force presented recommendations to the President in November of 2014. The two tribal leaders on the Task Force—Chairwoman Karen Diver and Mayor Reggie Joule—received and compiled input from hundreds of tribal leaders nationwide. The Task Force recommendations aim to guide the federal government toward properly supporting tribes and other communities in building resilience.

GENESIS OF THIS PROJECT

The Port Gamble S'Klallam Tribe has been concerned about climate change and its actual and potential impacts for over a decade, with increasing focus in the last five years. The driving force behind this Climate Change Impact Assessment and anticipated follow-up work is the high probability of climate change driving major changes to the Tribe's important natural resources, beaches, shorelines, and animals that the Tribe has depended upon for many thousands of years. Future generations are likely to have to adapt their fishing, hunting and traditional practices and could experience changes in their way of life here on the reservation.

While the Tribe agrees with and fully supports the need to minimize and mitigate the sources and causes of climate change, this effort is primarily focused on developing future adaptation strategies and actions to counter the anticipated effects of climate change on the reservation and in the Tribal community. This is based in large part on the recognition that political will and potential for minimizing future climate change impacts is low, and in light of the amount of anthropogenic greenhouse gases that are already in the atmosphere. While society as a whole must play a part in reducing emissions—through a combination of policy, regulatory, and mitigation efforts—it primarily falls to each community and local tribal government to determine their own needs and actions for preparing and adapting to climate change impacts in ways that are locally relevant and appropriate.

The Tribe began this impact assessment with initial funding from the Environmental Protection Agency (EPA), and was able to do most of the work with grant funding from the Bureau of Indian Affairs (BIA). The Tribe is grateful for the significant funding from the BIA, which brought this report to completion. The Tribe established a climate change working group led by the Natural Resources Department, and brought in research and writing support from Cascadia Consulting Group.

FOCUS AREA: HOOD CANAL AND ADMIRALTY INLET

Area of interest

This report focuses on the Port Gamble S'Klallam Tribe's primary traditional use area, which is comprised of the upper half of Hood Canal and all of Admiralty Inlet. This is the central part of the Tribe's much larger Usual and Accustomed Area.

Hood Canal is a long and narrow fjord, with an average width of 1.5 miles (2.4 km) and average depth of 177 feet (53.8 meters). It has 212.9 miles (342.6 kilometers) of shoreline and 16.4 square miles (42.4 square kilometers) of tideland. Its surface area is 148.9 square miles (385.6 square kilometers) and it contains a volume of water totaling 17,000,000 acre-feet (21 cubic kilometers). Hood Canal extends for approximately 50 miles (80 km) southwest from the entrance between Foulweather Bluff and Tala Point to Union, where it turns sharply to the northeast—a stretch called The Great Bend. It runs northeast for about 15 miles (24 km) to Belfair, where it ends in a shallow tideland called Lynch Cove.

Along its entire length, Hood Canal separates the Kitsap Peninsula from the Olympic Peninsula. The U.S. Naval Base Kitsap, Bangor Annex, is located on the eastern shore of Hood Canal near the town of Bangor. Hood Canal has several internal bays, the largest of which is Dabob Bay. Most of Dabob Bay is a Naval Restricted Area, and is used by the submarines stationed at the Bangor Base. Quilcene Bay is an inlet extending northwest from Dabob Bay. Port Gamble Bay—and the town of the same name—sits near the north end of the canal.

Several rivers flow into the Hood Canal from the Olympic Peninsula, including the Skokomish, Hamma Hamma, Duckabush, Dosewallips, and Big Quilcene. Smaller rivers emptying into the canal from the Kitsap Peninsula include the Union, Tahuya, and Dewatto.

CLIMATE CHANGE MITIGATION AND REGULATION

This effort focuses on climate change impacts. We recognize that mitigation—taking action to reduce greenhouse gas emissions—is most important for reducing the severity of future impacts. However, given the present-day atmospheric concentration of greenhouse gases, climate impacts will occur, and we need to take steps to prepare for them.

Climate change mitigation represents a serious challenge. Lack of political will, complex global needs for collaboration and funding, economic constraints, and pushback from special interests make progress on large-scale mitigation and adaptation policies difficult. That said, Washington State has succeeded in moving forward on some crucial mitigation strategies locally. For example:

- On October 28, 2013, the governors of California, Oregon, and Washington and the British Columbia Premier, as well as members of the Pacific Coast Collaborative, signed the Pacific Coast Action Plan on Climate and Energy. The plan brings together each jurisdiction's 2050 targets for greenhouse gas reductions and identifies benchmarks toward these long-term goals.

- Governor Jay Inslee put forth a suite of legislative proposals in 2015 aimed at reducing carbon pollution, including the Carbon Pollution Accountability Act to create a market-based program to reduce greenhouse gas emissions, as well as funding and incentives for clean energy development and energy efficiency.

- A state carbon tax was proposed through a citizens' initiative in the November 2016 election. Although it was not approved by voters, it is seen as a significant first step in developing a future state-level carbon tax for Washington.

- Beginning in 2017, the Washington Clean Air Rule will require businesses and large polluters to cap their emissions at 100,000 metric tons of carbon pollution and progressively reduce their emissions over time. The 100,000 metric tons cap will be reduced by 5,000 metric tons every two years until it reaches 70,000 metric tons. The rule is enforced by the Department of Ecology.

- The Department of Ecology has created an Excel-based Greenhouse Gas Calculation Tool meant for use during the development of environmental impact statements required by the State Environmental Policy Act (SEPA).

The diversity of impacts on natural and human systems resulting from these climate changes, such as impacts on salmon and infrastructure, are summarized in subsequent chapters of this report.

Observed and Projected Climate Changes

INTRODUCTION

This chapter, prepared by Harriet Morgan, Lara Whitely Binder, and Ingrid Tohver at the University of Washington Climate Impacts Group, summarizes projected changes in regional climate (e.g., temperature, precipitation) and related factors (e.g., snowpack, streamflow) that will influence the Tribe's vulnerability to climate change. In particular, this document focuses on projected changes in air temperature, precipitation, snowpack, streamflow, stream temperature, landslides and sediment transport, fire risk, sea level rise, and ocean chemistry.

Because this chapter draws from existing datasets and literature, the time periods and spatial scale of the information vary. Where possible, information specific to the Tribe's primary traditional use area (see map in the Background chapter) is provided. Other frequently reported geographic scales in this report are the U.S. Pacific Northwest (covering the states of Washington, Oregon, and Idaho) and Puget Sound region (including the water bodies of Puget Sound and the Strait of Juan de Fuca, as well as any U.S. land areas that ultimately drain into these waters). Most projections are for mid-century (generally the 2050s) and end of century (2100).

OBSERVED CHANGES IN CLIMATE: PUGET SOUND REGION

Instrumental and observational data show that climate in the Puget Sound region and the greater Pacific Northwest is warming. While observed warming at the global scale can be conclusively attributed to rising greenhouse gas emissions, attribution at the regional scale (such as the Puget Sound region) is more difficult due to the strong influence of natural variability at smaller scales (see on page 20). Observed changes in regional temperature and precipitation include the following:

TEMPERATURE

- *Air temperatures are increasing in the Puget Sound region.* The lowland areas surrounding Puget Sound (Figure 1) warmed about +1.3°F (range: +0.7°F to +1.9°F) between 1895 and 2014, with statistically significant warming occurring in all seasons except for spring [3].[2,3,4] All but six of the years from 1980 to 2014 were warmer than the 20th century average [3]. This trend is consistent with the observed warming over the Pacific Northwest as a whole [4, 5].

- *The frost-free season has lengthened.* The frost-free season (and the associated growing season) in the Puget Sound region lengthened by +30 days (range: +18 to +41 days) from 1920 to 2014 [5, 6].

- *Nighttime air temperatures are rising faster than daytime air temperatures.* In the Puget Sound lowlands, daily minimum air temperatures (which generally occur at night) have increased by +1.8°F between 1895 and 2014, while daily maximum air temperatures (which generally occur in afternoon) warmed by +0.8°F over the same time period [3, 5].

- *Warm nights have become more frequent, but daytime heat waves have not changed.* Nighttime heat events have become more frequent west of the Cascade Mountains in Oregon and Washington (1901–2009) [7].[5,6] No statistically significant trend has been found for daytime heat events.

Observed trends in climate variability

While this project is focused on anticipating climate change impacts, it is important to note that natural climate variability will continue to influence Pacific Northwest climate—and through that, its communities and natural resources—even as human activities cause global warming.

Climate variability in the Pacific Northwest is largely governed by two large-scale oceanic and atmospheric oscillations: the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). ENSO cycles last up to a year, typically peaking between December and April; warm phases are referred to as "El Niño" and cool phases as "La Niña" [638]. The PDO is also characterized by warm and cool phases, but unlike ENSO the cool/warm phases of PDO typically persist for 10 to 30 years [639].

El Niño and warm-phase PDO tend to, but do not always, result in above-average annual temperatures and drier winters in the Pacific Northwest. El Niño and warm-phase PDO are also more likely to result in lower-than-average snowpack, lower flood risk, and higher forest fire risk. In contrast, La Niña and cool-phase PDO increase the odds for cooler-than-average annual temperatures and wetter winters, leading to higher winter snowpack, higher flood risk, and lower forest fire risk while in those phases. When the same phases of ENSO and PDO occur simultaneously (i.e., years characterized by both El Niño and warm-phase PDO or by La Niña and cool-phase PDO), the impact on Pacific Northwest climate is typically larger. If the ENSO and PDO patterns are in opposite phases in a given year, their effects on temperature and precipitation may offset each other to some degree.

How and whether ENSO and PDO will change in the future as a result of climate change remain open questions. Some studies suggest that climate change may cause a prolonged persistence of El Niño conditions in the equatorial Pacific, although the reasons remain uncertain [640, 641]. Despite this uncertainty, we expect ENSO and PDO to continue influencing Pacific Northwest climate in the coming decades, sometimes reinforcing or counteracting the effects of climate change.

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2 The range shows the 95% confidence limits for the trend estimate.

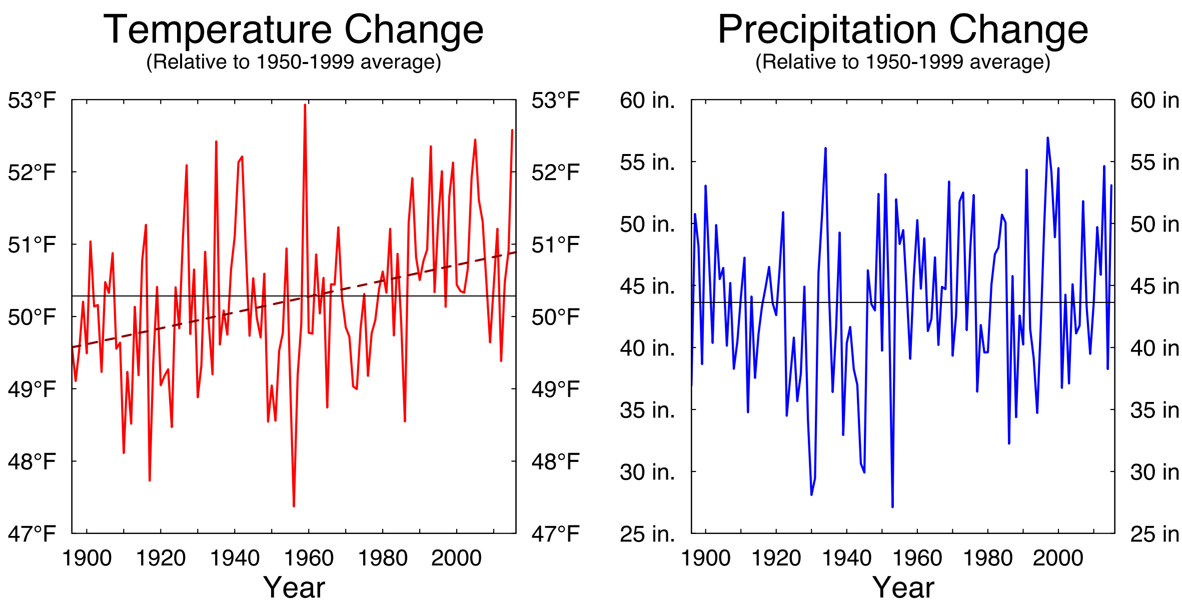
3 Temperature trends are only reported if they are statistically significant at or above the 95% confidence level. All trends are reported for the full length of the available observed record.

4 These trends were determined using data from the U.S. Climate Divisional Dataset, developed by the National Centers for Environmental Information (NCEI). NCEI provides long-term climate summaries for each of the country's 344 climate divisions. Results for the "Puget Sound Lowlands" climate division were used in the present analysis, which includes all of the low-lying land areas surrounding Puget Sound, where most of the historical weather observations are concentrated. For more information, see www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php.

5 Heat events are defined as 3 or more consecutive days above the 99th percentile for the minimum [8.3°F (4.6°C)] temperature anomalies between 1901 and 2009.

6 Many characteristics of Puget Sound's climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region. Results for Puget Sound are expected to generally align with those for western Oregon and Washington, and in some instances the greater Pacific Northwest, with potential for some variation at any specific location.

Figure 1. Temperature is rising in the Puget Sound lowlands, but there is no long-term trend in annual precipitation. Average annual air temperature (left, red, in °F) and total annual precipitation (right, blue, in inches) for the Puget Sound Lowlands climate division, shown relative to the average for 1950-1999 (black horizontal line in both graphs, corresponding to 50.3°F for annual average temperature and 43.6 inches for annual total precipitation). The dashed line in the temperature plot is the fitted trend, indicating a warming of +1.3°F (range: +0.7°F to +1.9°F) from 1895 to 2014. The trend for precipitation is not statistically significant and therefore is not shown. Figure source: Climate Impacts Group, Data source: Vose et al. 2014 [3].



PRECIPITATION, STORMS, AND WINDS

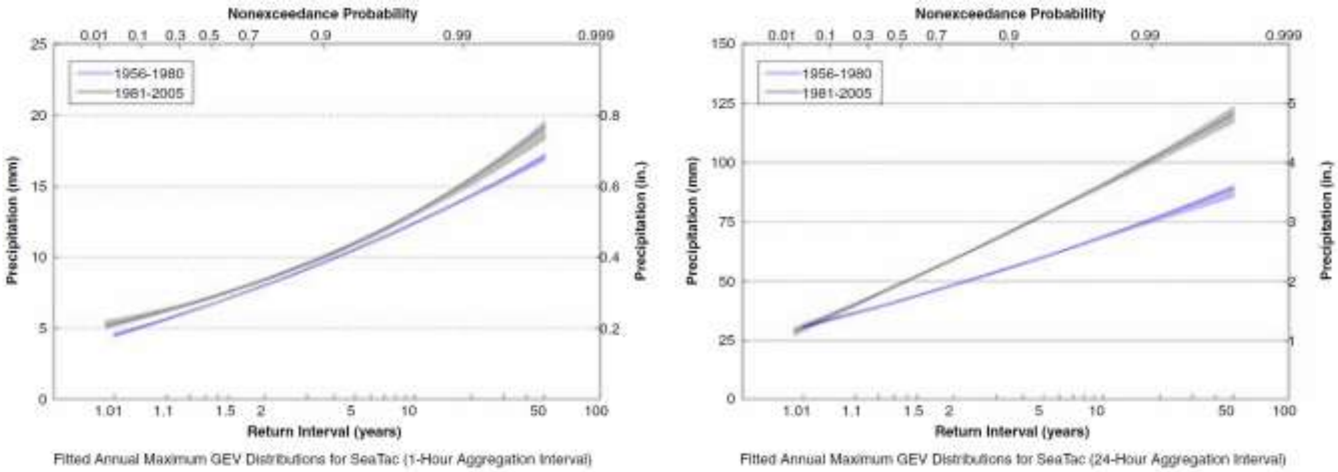
- *There has been no discernible long-term trend in annual precipitation for the Puget Sound region (Figure 1).* Natural variability has a large influence on precipitation in the Puget Sound region, causing ongoing fluctuations between wet years and dry years and wet decades and dry decades. This large range of variability makes it difficult to discern any statistically significant trends in regional precipitation.

- *Spring precipitation is increasing, but no other trends are statistically significant.* Seasonal and annual precipitation trends are generally not statistically significant, and in most cases are smaller than natural year-to-year variations. The one exception is spring (March–May) precipitation, which increased by +27% in the Puget Sound lowlands from 1895 to 2014 [3]. The changes in other seasons are not statistically significant.

- *Modest increases in heavy rainfall have been documented in Western Washington.* Most studies find increases in both the frequency and intensity of heavy precipitation in Western Washington [8, 9, 10]. For example, Rosenberg et al. 2010 found a statistically significant +23% increase in the annual-maximum 2-day event for the Puget Sound region (1981–2005 relative to 1956–1980) (see Figure 2) [10]. Not all trends are statistically significant, however. Results depend on the dates and methods of the analysis [10, 11, 12, 13].

- *Observed trends in wind speed are ambiguous.* Some studies find increases, others find decreases, and others conclude that there is no significant trend in winds for the Pacific Northwest region. Results depend on the data and methods used for the analysis.

Figure 2. Changes in fitted 1-hour (left) and 24-hour (right) annual maximum precipitation distributions for Sea-Tac Airport from 1956–1980 (purple line) to 1981–2005 (gray line). GEV stands for Generalized Extreme Value. Uncertainty bounds are indicated by the shaded areas. Both figures show an increase in the 1-hour and 24-hour rain events, although none of the changes was found to be statistically significant at the 95% confidence interval (the 24-hour distributions at Sea-Tac were statistically significant at the 90% interval). Figures and caption adapted from Rosenberg et al. 2010, Figure 2 [10].



Temperature and Precipitation—Port Gamble S'Klallam Tribe

In the absence of long-term temperature and precipitation monitoring stations on the Port Gamble S'Klallam Tribe reservation, trends are reported for several stations near to the Tribe's reservation and primary use area:

- Forks (Station 452914)
- Port Angeles (Station 456624)
- Port Townsend (Station 456678)
- Cushman Powerhouse 2 (Station 451939; located several miles below Cushman Dam on the North Fork of the Skokomish River, near Hood Canal)
- Everett (Station 452675)

Observed trends (1895–2014) in average annual and seasonal temperature and precipitation for these stations are provided in Table 1. With the exception of Port Angeles, which showed a slight cooling trend, the areas covered by these stations saw modest increases in average annual temperature ranging from 0.35°F (Cushman Powerhouse 2) to 1.19°F (Forks) for the period from 1895 to 2014. All stations except Port Angeles showed modest to large increases in average annual precipitation. Seasonal temperature and precipitation trends varied by station (see Figure 3).

Table 1. Observed temperature and precipitation trends (1895–2014) for Forks, Port Angeles, Port Townsend, Cushman Dam Powerhouse #2, and Everett, Washington. Note that trends at individual stations are not necessarily representative of regional or sub-regional trends, due to the effects of topography, land cover, and other factors. (Data source: Office of the Washington State Climatologist, www.climate.washington.edu.)

FORKS	Change in Temperature (˚F)			Change in Precipitation (inches)				
	Annual Mean	Annual Max	Annual Min	Annual Average	Winter *(Dec-Feb)*	Spring *(Mar-May)*	Summer *(June-Aug)*	Fall *(Sept-Nov)*
Trend, 1895–2014	+1.19 (±1.08)	+1.9 (±1.29)	+0.48 (±1.0)	+3.09 (±18.27)	−3.21 (±13.2)	+5.95 (±7.09)	+1.55 (±3.49)	−0.6 (±9.73)
Trend, 1895–1950	+0.24 (±0.99)	+1.31 (±1.12)	−0.83 (±1.01)	−24.16 (±17.93)	−11.54 (±13.01)	+3.45 (±6.89)	2.86 (±3.31)	−16.78 (±10.34)
Trend, 1951–2014	+3.69 (±1.12)	+4.76 (±1.34)	+2.74 (±1.0)	+5.71 (±18.44)	−14.99 (±13.36)	+14.88 (±7.1)	+1.31 (±3.6)	+4.05 (±9.17)

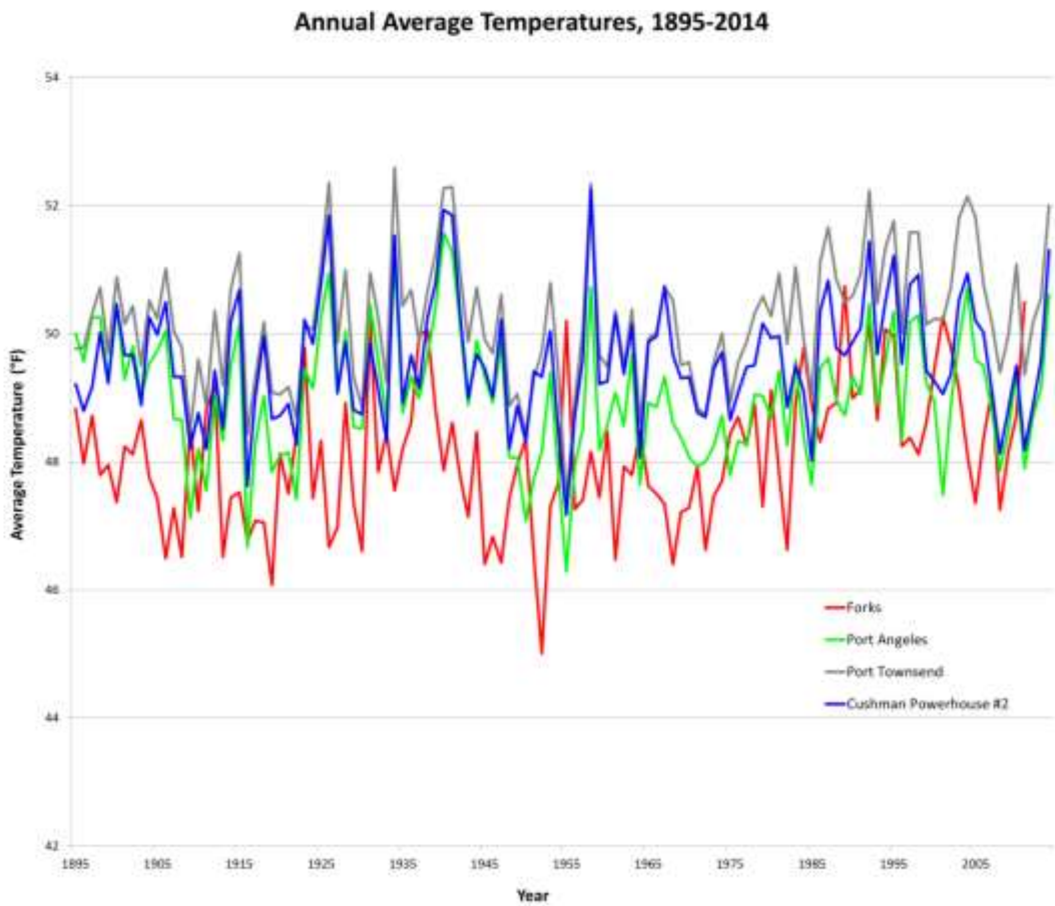
PORT ANGELES	Change in Temperature (˚F)			Change in Precipitation (inches)				
	Annual Mean	Annual Max	Annual Min	Annual Average	Winter *(Dec-Feb)*	Spring *(Mar-May)*	Summer *(June-Aug)*	Fall *(Sept-Nov)*
Trend, 1895–2014	−0.24 (±0.99)	+0.36 (±1.01)	−0.71 (±1.1)	−10.23 (±7.62)	−5.83 (±4.18)	−0.83 (±1.77)	−0.24 (±1.08)	−3.1 (±3.73)
Trend, 1895–1950	+0.12 (±1.07)	+1.9 (±1.11)	−1.67 (±1.16)	−43.08 (±9.51)	−17.37 (±4.58)	−7.85 (±2.16)	−1.31 (±1.14)	−15.11 (±4.43)
Trend, 1951–2014	+2.02 (±0.87)	+1.19 (±0.91)	+2.98 (±0.93)	−2.26 (±4.81)	−4.17 (±3.46)	+1.79 (±1.34)	−0.95 (±1.02)	+1.31 (±2.88)

PORT TOWNSEND	Change in Temperature (˚F)			Change in Precipitation (inches)				
	Annual Mean	Annual Max	Annual Min	Annual Average	Winter *(Dec-Feb)*	Spring *(Mar-May)*	Summer *(June-Aug)*	Fall *(Sept-Nov)*
Trend, 1895–2014	+0.83 (±0.99)	+0.71 (±1.15)	+0.83 (±0.94)	+1.31 (±3.21)	−0.6 (±1.78)	+1.43 (±1.32)	+0.12 (±1.21)	+0.36 (±1.53)
Trend, 1895–1950	+0.71 (±0.98)	+1.79 (±1.12)	−0.36 (±0.93)	−3.81 (±3.19)	−2.74 (±1.69)	−1.79 (±1.17)	+0.48 (±1.27)	+0.36 (±1.58)
Trend, 1951–2014	+2.86 (±0.98)	+3.33 (±1.17)	+2.5 (±0.91)	+1.07 (±3.15)	−1.07 (±1.85)	+2.98 (±1.33)	−1.31 (±1.16)	+0.6 (±1.49)

CUSHMAN	Change in Temperature (˚F)			Change in Precipitation (inches)				
	Annual Mean	Annual Max	Annual Min	Annual Average	Winter *(Dec-Feb)*	Spring *(Mar-May)*	Summer *(June-Aug)*	Fall *(Sept-Nov)*
Trend, 1895–2014	+0.36 (±0.93)	−0.36 (±1.09)	+1.07 (±0.95)	+28.08 (±17.97)	+10.59 (±9.88)	+7.5 (±5.17)	+1.19 (±1.76)	+8.93 (±7.66)
Trend, 1895–1950	+0.71 (±0.97)	+0.48 (±1.14)	+0.95 (±0.92)	−14.4 (±9.7)	−4.4 (±6.48)	−0.6 (±3.32)	−0.6 (±1.61)	−8.33 (±5.48)
Trend, 1951–2014	+0.83 (±0.9)	+0.71 (±1.01)	+0.95 (±0.9)	+86.16 (±21.57)	+31.77 (±11.76)	+22.97 (±6.09)	+1.55 (±1.83)	+29.75 (±8.81)

EVERETT	Change in Temperature (˚F)			Change in Precipitation (inches)				
	Annual Mean	Annual Max	Annual Min	Annual Average	Winter *(Dec-Feb)*	Spring *(Mar-May)*	Summer *(June-Aug)*	Fall *(Sept-Nov)*
Trend, 1895–2014	+0.71 (±1.05)	+0.83 (±1.17)	+0.60 (±1.1)	+3.21 (±5.55)	−1.19 (±2.93)	+2.14 (±2.08)	+1.31 (±1.86)	+0.95 (±2.71)
Trend, 1895–1950	+0.60 (±1.07)	+0.60 (±1.17)	−0.36 (±0.93)	−5.36 (±5.23)	−4.88 (±2.68)	−1.31 (±2.04)	+0.48 (±1.56)	+0.6 (±2.7)
Trend, 1951–2014	+2.5 (±1.01)	+0.95 (±1.13)	+3.93 (±1.12)	+1.79 (5.59)	−4.64 (±3.13)	+5.71 (±2.02)	−0.71 (±2.0)	+1.19 (±2.7)

Figure 3. Average annual temperatures at weather stations on the Olympic Peninsula. Data recorded from 1895 to 2014. Data source: Office of the Washington State Climatologist, www.climate.washington.edu.



SNOWPACK, GLACIERS, AND STREAMFLOW

Warming temperatures and changes in precipitation over the last century have contributed to declining spring snowpack, receding glaciers, and earlier peak streamflows in Washington's watersheds. These trends reflect the influence of both natural variability and long-term regional warming [14, 15]. Over shorter time scales, however, natural variability can dominate, resulting in short-term trends that may differ from long-term trends.

- *Long-term declines in spring snowpack.* Spring snowpack in the Washington Cascades declined by about −25% (or about −4% per decade) from the mid-20th century to 2006 [16, 17, 18]. Spring snowpack also declined at Hurricane Ridge in the northern Olympic Mountains between 1949 (when snow surveying began) through the late 1990s [19]. More recently (1976 to 2007), there was an apparent (though not statistically significant) increase in spring snow accumulation in the Cascades [16].[7]

- *Declining glacier area.* Trends in glacier area and volume can vary substantially from decade to decade but are declining overall.[8] Observed decreases in glacier area range from a −56% (±3%) loss in the North Cascades (1900–2009) [20] to a −34% decline in area in the Olympic Mountains (1980–2009) (Figure 4, left) [21]. Observations also show consistent decreases in glacier volume and the total number of glaciers remaining [21, 22]. Riedel et al. 2015 found that glacier loss in the Olympics was greatest in the drier northeastern part of the peninsula and for south-facing glaciers. For example, Anderson Glacier (Figure 4, right; Table 2) lost 77% of its area between 1980 and 2009, while the nearby north-facing Eel Glacier lost 23% of its area **[21].** The total decline in glacier volume for glaciers in the Olympic Peninsula was 20% **[21].**

- *Changes in streamflow timing.* In addition to observed changes in temperature and precipitation, several Puget Sound region rivers have experienced shifts in seasonal streamflow timing and volume due to long-term changes in temperature, snowpack accumulation, glacial melt, and sedimentation. The spring peak in streamflow is occurring earlier in the year for many snowmelt-influenced rivers in the Puget Sound region (observed over the period 1948–2002) as a result of decreased snow accumulation and earlier spring melt. The shift ranges from no change to about 20 days earlier depending on location (relative to 1948–2002) [23].

[7] Hydrologic trends are reported if they are statistically significant at the 90% confidence level or more.

[8] For example, total glacier area in the North Cascades declined rapidly for the first half of the 20th century, followed by a period of little change, then an additional decline since the 1990s [20, 651].

Figure 4. Comparison photographs show thinning and retreat of the Blue Glacier on Mount Olympus (left) and Anderson Glacier (right). Photo credits: Blue Glacier – 1899: Olympic National Park archives, 2008: Jim Patterson, Olympic National Park. Anderson Glacier – 1936: Asahel Curtis, 2004: Matt Hoffman, Portland State University. From www.nps.gov/olym/learn/nature/glaciers.htm.

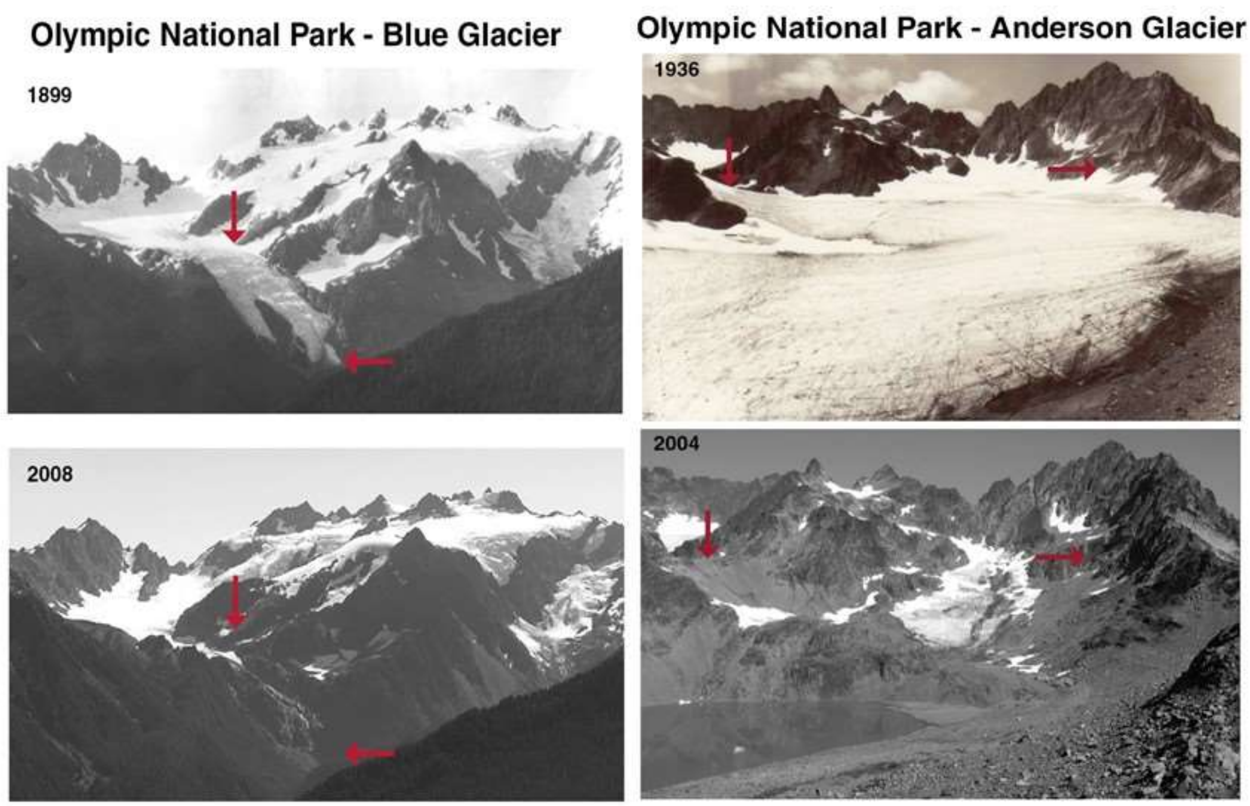


Table 2. Changes in area, in square kilometers, for five Olympic Peninsula glaciers located east of the Elwha Valley. Adapted from Table 1 in Reidel et al. 2015.

Glacier (Mountain-Aspect)	1980 Area (km^2)*	2009 Area (km^2) (± error)	% Change
Christie (Christie–North)	0.2	0.099 (±0.003)	−51%
Lillian (McCartney–North)	0.14	0.029 (±0.001)	−21%
Cameron (Cameron)	0.16	0.103 (±0.003)	−36%
Anderson (Anderson–South)	0.61	0.14 (±0.003)	−77%
Eel (Anderson–North)	1.11	0.85 (±0.008)	−23%

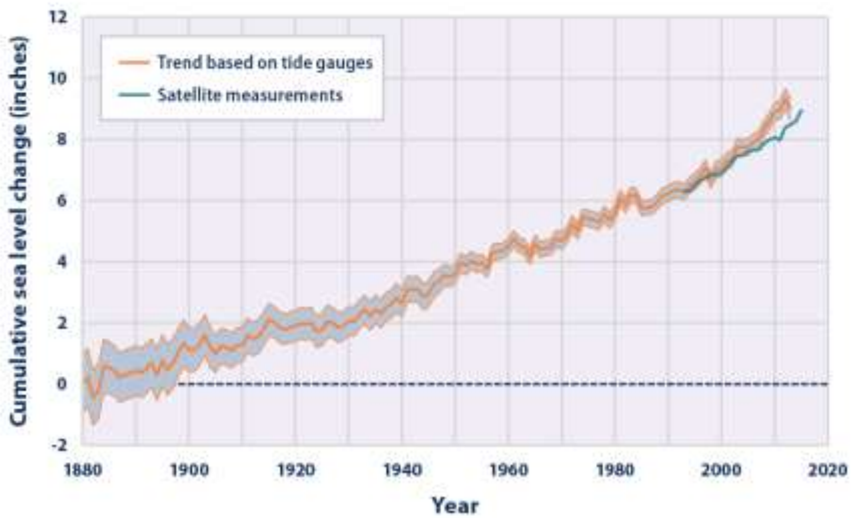
*Based on aerial photographs taken between 1976 and 1982.

SEA LEVEL RISE

Observed changes in local sea level ("relative sea level") reflect changes in global sea level as well as changes in local factors that affect the amount of sea level change observed at a particular location.

Globally, sea level has risen approximately 8 inches (averaged across all oceans) since 1880 (Figure 5) [24, 25]. While the total amount of sea level rise is notable, a more significant aspect of this rise is the rate of change. The average annual rate of sea level rise since the mid-1800s is larger than any similar period in the past 2,700 years [26, 27]. It is *very likely* that the rate of global mean sea level rise was +1.7 millimeters per year (range: +1.5 to +1.9 mm/year) between 1901 and 2000 [28].[9] Between 1993—the point when satellite altimetry data became available—and 2010, the rate was *very likely* higher at +3.2 (+2.8 to +3.6) millimeters per year [28, 29]. Similarly high rates occurred between 1920 and 1950 [28].[10,11]

Figure 5. Observed change in global sea level, 1880–2015. The figure shows the change in average absolute sea level change, which refers to the height of the ocean surface regardless of whether nearby land is rising or falling. Since 1880, global sea level has risen over 8 inches. The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used. Figure source: U.S. Environmental Protection Agency, based on data from CSIRO 2015 and NOAA 2016 [30, 31, 32].



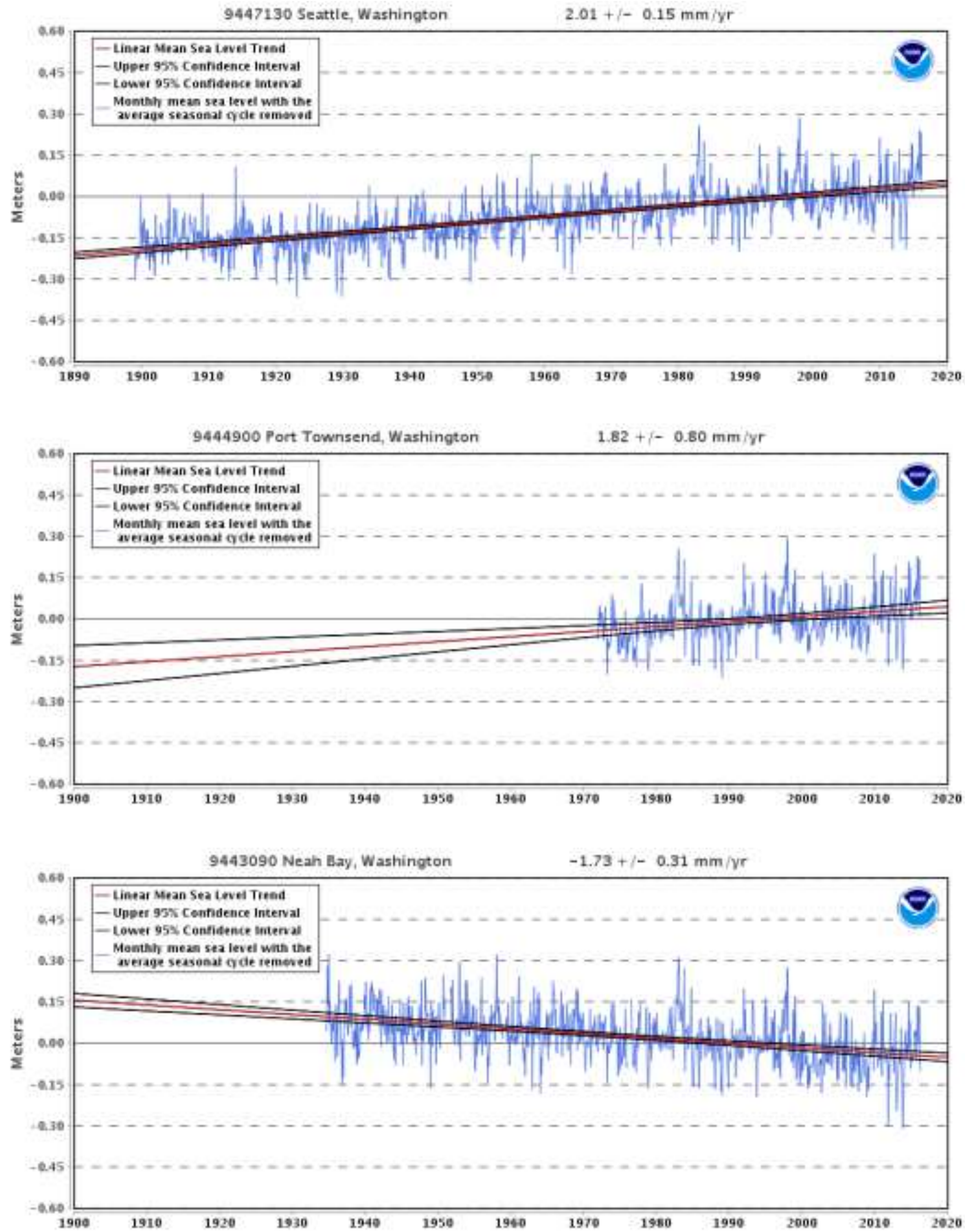
Locally, sea level is rising at most locations in or near the Puget Sound. Sea level at the Seattle tide gauge, the longest running tide gauge in the Puget Sound region, rose +8.6 inches between 1900 and 2008 (+0.8 inches or +20 mm/decade) (Figure 6, top) [33]. The average rate of change in sea level at Port Townsend is comparable to Seattle (+0.7 inch or +17.78 mm/decade), although the total amount of rise for the period of record (+3.2 inches or +81 mm) is lower because of the shorter record length (1972–2015) (Figure 6, middle). In contrast, records show a decline in sea level for the northwest Olympic peninsula, a region experiencing uplift as a result of tectonic processes (Figure 6, bottom). For example, at the Neah Bay tide gauge, relative sea level dropped by −5.5 inches from 1934 to 2015 (−0.7 inch or -17.78 mm/decade) [33].

[9] Likelihood of the outcome is 90 to 100%.

[10] Likelihood of the outcome is 90 to 100%.

[11] A recent (2003–2011) slowing in the annual rate of sea level rise (average of +2.4 mm/year versus +3.5 mm/year) has been attributed to natural variability, in particular a succession of La Niña years since the 1997–1999 El Niño [652]. However, even at that slower rate, the annual rate of sea level rise remained well above the average annual rate observed between 1901 and 2010.

Figure 6. Monthly mean sea level trends for the Seattle (top), Port Townsend (middle), and Neah Bay (bottom) tide gauges. Each plot shows the linear trend (red line), the 95% confidence interval (black lines), and the monthly mean value. The mean sea level trend for Seattle (1899–2015) is +2.01 millimeters per year with a 95% confidence interval of ±0.15 mm/year (equivalent to a change of 0.66 feet in 100 years). The mean sea level trend for Port Townsend (1972–2015) is +1.82 mm/year with a 95% confidence interval of ±0.80 mm/year (equivalent to a change of 0.60 feet in 100 years). The mean sea level trend for Neah Bay (1934–2015) is −1.73 mm/year with a 95% confidence interval of ±0.31 mm/year (equivalent to a change of −0.57 feet in 100 years). Trends exclude the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. Figure and trends source: NOAA Tides and Currents, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html.



OCEAN TEMPERATURE

Surface and subsurface water temperatures in Puget Sound and the northeast Pacific Ocean have warmed over the long term. Water temperature for stations located at Admiralty Inlet, Point Jefferson, and in Hood Canal increased +0.8 to +1.6°F, depending on location, from 1950 to 2009 [34]. A similar range of warming has been observed along the coast and at depth; northeast Pacific coastal sea surface temperature increased about +0.9 to +1.8°F over the past century (1900–2012) [35]. Northeast Pacific subsurface temperatures (~300 to 1,300 feet deep) increased +0.45 to +1.1°F (1956–2006) [35].

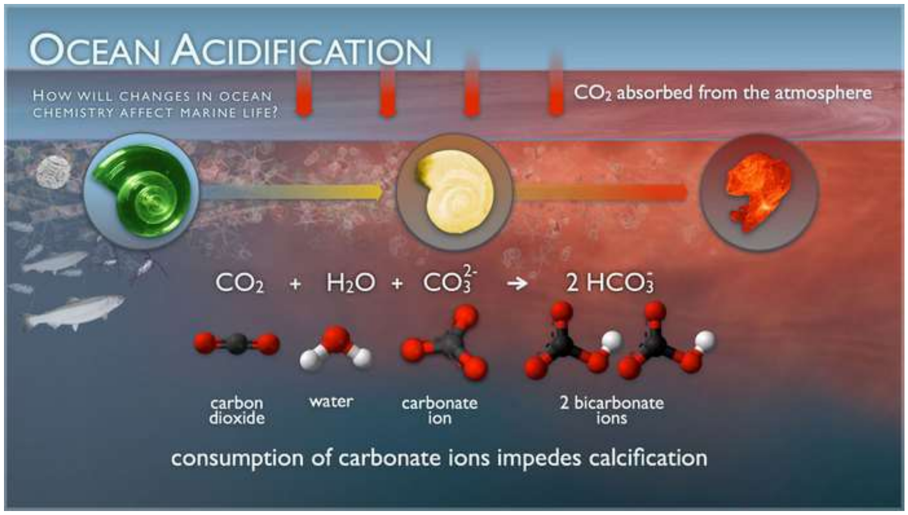
Natural variability can influence sea surface trends over shorter time periods, especially along the U.S. West Coast. For example, while most (71%) of the world's coastlines warmed between 1982 and 2010, sea surface temperatures along the U.S. West Coast decreased up to 2°F (or 0.72°F per decade) during that period [36]. The strong influence of El Niño and the Pacific Decadal Oscillation, as well as intensification of upwelling along the coast, are believed to have contributed to this trend (similar cooling was also observed along the west coast of South America, a region that is also strongly affected by the El Niño/Southern Oscillation and coastal upwelling). More recently, sea surface temperatures in the northeast Pacific were dominated by an unusually warm (2°F to 7°F above normal), expansive (1,000 miles wide and 300 feet deep), and persistent (2014–2015) patch commonly referred to as "the blob" [37]. The pattern of sea surface temperatures that have characterized "the blob" has largely diminished, however, as of July 2016.

OCEAN ACIDIFICATION

Ocean acidification, like climate change, is generated by increasing levels of carbon dioxide in the atmosphere. Ocean acidification is not, however, caused by the warming and alteration of climate systems and patterns [38].

Oceans naturally absorb carbon dioxide from the atmosphere (Figure 7). As more carbon dioxide is introduced to the atmosphere (i.e., greenhouse gas emissions), the oceans absorb the carbon dioxide (Figure 8). Worldwide, the oceans have absorbed about 30% of the carbon dioxide associated with human activities since the start of the industrial age (about 1750) [27]. The added carbon dioxide has changed the ocean's chemistry by increasing its acidity and reducing the availability of carbonate ions [39]. More specifically, the pH of the northeast Pacific Ocean surface waters decreased by −0.1, corresponding to a +26% increase in the hydrogen ion concentration, since the pre-industrial era (~1750) and by −0.027 from 1991 to 2006 [27]. The increase in the hydrogen ion concentration reduces the amount of calcium carbonate—a critical mineral used by many marine organisms to form hard body parts such as shells and skeletons—in marine water, affecting the ability of those organisms to build and maintain body parts dependent on calcium carbonate.

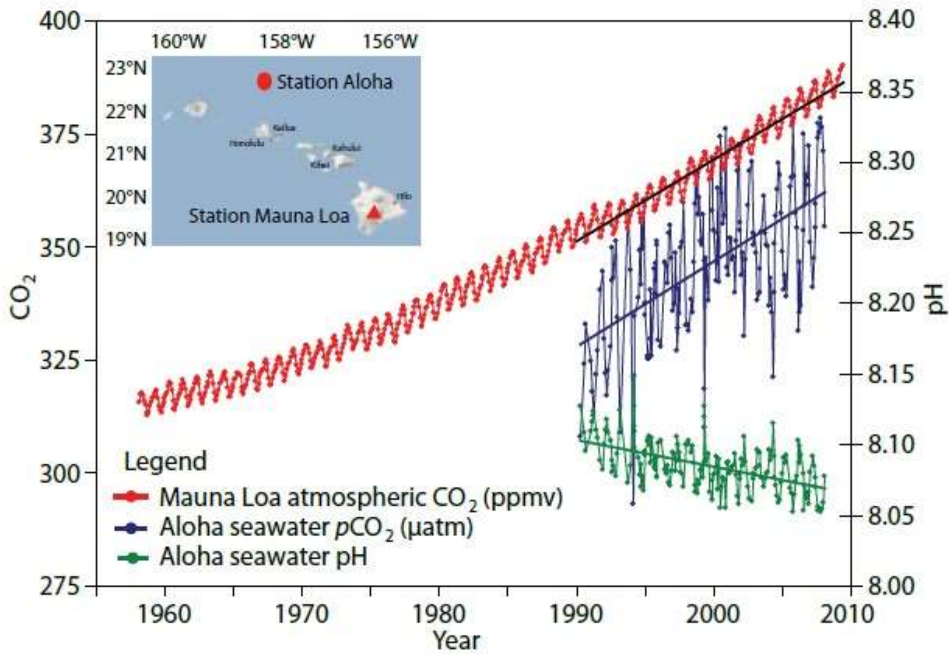
Figure 7. Ocean acidification occurs when carbon dioxide, which is being released at increasingly higher levels as a result of human activities, is absorbed by the ocean. When mixed with seawater, carbon dioxide chemically changes into carbonic acid. Carbonic acid lowers the ocean's pH level, nudging it toward acidity. Carbonic acid also increases the water's hydrogen ion concentration, ultimately limiting the availability of carbonate ions (a key component of calcium carbonate) for building and maintaining hard body parts, such as shells. Figure source: NOAA PMEL.



Washington's marine waters are particularly susceptible to ocean acidification because of the influence of regional upwelling, which transports offshore, carbon-rich water to the continental shelf [40]. In urbanized estuaries and restricted inlets of Puget Sound (such as Hood Canal), runoff containing nutrients and organic carbon from land sources also influences pH levels. Added nutrients and organic carbon stimulate algal growth, ultimately increasing acidity as the algae and other associated organic matter decompose [39, 41].

The lack of high-quality, long-term, carbon time-series measurements in Puget Sound makes it hard to directly determine the effects of locally emitted carbon dioxide on pH changes in the region [41]. Feely et al. 2010 estimated that ocean acidification has already caused a decrease in pH of 0.05 to 0.15 units in Puget Sound. That study also estimated that ocean acidification accounted for 24 to 49% of the decrease in pH in the deep waters of Hood Canal, relative to estimated pre-industrial values.

Figure 8. Time series of atmospheric CO_2 at Mauna Loa (in parts per million volume, ppmv; red), surface ocean pCO_2 (µatm; blue) and surface ocean pH (green) at Ocean Station ALOHA in the subtropical north Pacific Ocean. Note that the increase in oceanic CO_2 over the past 17 years is consistent with the atmospheric increase within the statistical limits of the measurements. Figure and caption source: Doney et al. 2009 [42]. As of the time of this writing (March 2017), CO_2 at Mauna Loa is now over 400 ppm (www.co2.earth/daily-co2).



PROJECTING CHANGES IN CLIMATE USING GREENHOUSE GAS SCENARIOS

Projecting changes in 21st century climate requires the use of global climate models and scenarios of future greenhouse gas emissions, which incorporate assumptions about future changes in global population, technological advances, and other factors that influence the amount of carbon dioxide and other greenhouse gases emitted into the atmosphere as a result of human activities. Greenhouse gas scenarios are developed by international climate modeling centers for use by the scientific community globally to study climate change and climate change impacts.

The projections summarized in this chapter are based on two generations of greenhouse gas scenarios: the current generation of greenhouse gas scenarios (the Representative Concentration Pathway (RCP) scenarios) and the previous generation of scenarios used primarily from 2001 to 2013 (the SRES scenarios). Characteristics for these greenhouse gas scenarios are summarized in Table 3. Where possible, the greenhouse gas scenario(s) associated with specific findings reported in this chapter are noted to help the reader know the relative level of greenhouse gas "forcing" associated with a finding (i.e., if the reported change is reflective of a low versus high level of greenhouse gases).

Table 3. Greenhouse gas scenarios used in global and regional climate studies. The scenarios most commonly used in Pacific Northwest climate change studies are noted with an asterisk (*). Greenhouse gas scenarios are typically updated every 5 to 10 years for use in Intergovernmental Panel on Climate Change (IPCC) global assessment reports. Table modified from Snover et al. 2013, Table 3-1 [43].

Representative Concentration Pathway (RCP) scenarios (IPCC 2013) [27].	Scenario characteristics	Amount of carbon dioxide in the atmosphere, 2100 [44]	Comparable SRES scenarios (IPCC 2001, 2007; replaced by RCPs starting in ~2012)	Qualitative description
RCP 4.5*	A low scenario in which greenhouse gas emissions stabilize by mid-century and fall sharply thereafter	538 parts per million (ppm)	Very close to B1 by 2100, but higher emissions at mid-century	Low
RCP 6.0	A medium scenario in which greenhouse gas emissions increase gradually until stabilizing in the final decades of the 21st century	670 ppm	Similar to A1B by 2100, but closer to B1 at mid-century	Medium
RCP 8.5*	A high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century	936 ppm	Nearly identical to A1FI	High

PERSPECTIVE ON RECENT AND PROJECTED GREENHOUSE GAS TRENDS

As shown in Table 3, the concentration of greenhouse gases in the atmosphere is projected to increase dramatically in the 21st century absent substantial reductions in greenhouse gas emissions. Prior to the start of the Industrial Revolution, the concentration of carbon dioxide in the atmosphere was 280 parts per million (ppm). By the end of 2014, the annual average concentration of carbon dioxide in the atmosphere as measured at Hawaii's Mauna Loa Observatory was 398.61 ppm, and three individual months in 2014 (April, May, and June) exceeded 400 ppm for the first time since observations at Mauna Loa began in 1958.[12] The annual average for 2015 was 400.83 ppm. The high greenhouse gas emissions scenario (RCP 8.5), often referred to as a "business as usual" scenario, has an atmospheric concentration of carbon dioxide of 936 ppm in 2100 and levels out at 1,962 ppm by the year 2250 [44]. Annual greenhouse gas emissions will vary from year to year but are generally tracking with RCP 8.5.

[12] Monthly average concentrations in carbon dioxide will vary due to seasonal and monthly variations in carbon dioxide emissions (and uptake) from human and natural sources (e.g., plant respiration). For example, monthly values in 2015 ranged between 397.63 ppm (September 2015) and 403.94 ppm (May 2015). The highest monthly mean value reported to date since measurements began at Mauna Loa in March 1958 is 404.02 ppm (February 2016).

PROJECTED CHANGES IN THE TERRESTRIAL ENVIRONMENT

TEMPERATURE

By mid-century, the Puget Sound region is likely to regularly experience average annual air temperatures that exceed what was observed in the 20th century [45].

Annual and seasonal air temperatures in the Puget Sound region are projected to increase rapidly during the 21st century as a result of rising greenhouse gases (Figure 9, left panel; Table 4). By mid-century, average annual temperature is projected to increase by 4 to 6°F, on average, for a low and high greenhouse gas scenario; the warming projected for the end of the century is even larger (5 to 9°F, on average). Warming is projected in all seasons with the largest increases, relative to other seasons, occurring during the summer (Figure 10). Models also project that extreme heat events will become more frequent, while extreme cold events are projected to become less frequent in the region.

As shown in Figure 9 and Table 4, the range of warming produced by the different greenhouse gas scenarios prior to 2050 is relatively small compared to the range of warming that occurs later in the century. This difference reflects the fact that warming prior to the 2050s is largely driven by past (i.e., 20th century) and early 21st century greenhouse gas emissions. After about 2050, differences in the underlying assumptions of future conditions that inform the greenhouse gas scenarios (e.g., later 21st century global population levels, reliance on fossil fuels) start to have a larger role in determining the range and rate of projected warming and the impacts that result from that warming [4, 45].

Figure 9. All scenarios project warming in the Puget Sound region for the 21st century; projected changes in annual precipitation are small compared to year-to-year variability. The graphs show average yearly air temperature and precipitation for the Puget Sound region, relative to the average for 1950–1999 (horizontal gray line, corresponding to an annual average temperature of 44°F and an annual total precipitation of 78 inches). The black line shows the average simulated air temperature or precipitation for 1950–2005, based on the individual model results indicated by the thin gray lines. The thick colored lines show the average among model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5; see Section 1), while the thin colored lines show individual model projections for each scenario. Figure source: Climate Impacts Group, using downscaled climate projections developed by Abatzoglou and Brown (2011) [27, 45].

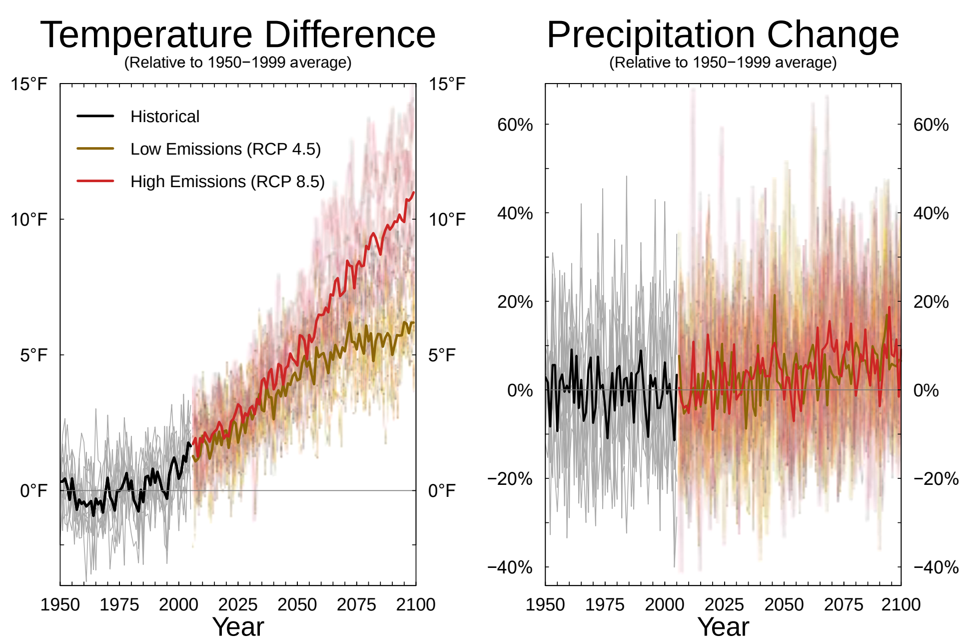


Table 4. Projected changes in average annual and seasonal temperature and extreme heat and cold events for the Puget Sound region for the 2050s and 2080s [46].

		2050s (2040–2069, relative to 1970–1999)		2080s (2070–2099, relative to 1970–1999)	
Change in…*	Greenhouse gas scenario**	Mean	Range	Mean	Range
Average annual air temperature	Low (RCP 4.5)	+4.2°F	+2.9 to +5.4°F	+5.5°F	+4.1 to +7.3°F
	High (RCP 8.5)	+5.5°F	+4.3 to +7.1°F	+9.1°F	+7.4 to +12°F
Average winter air temperature	Low (RCP 4.5)	+3.9°F	+2.8 to +5.0°F	+5.0°F	+4.3 to +6.3°F
	High (RCP 8.5)	+4.9°F	+3.2 to +6.5°F	+8.3°F	+6.0 to +10°F
Average spring air temperature	Low (RCP 4.5)	+3.9°F	+2.4 to +5.3°F	+5.3°F	+3.8 to +8.2°F
	High (RCP 8.5)	+4.8°F	+3.0 to +7.6°F	+7.9°F	+5.2 to +11°F
Average summer air temperature	Low (RCP 4.5)	+5.1°F	+3.3 to +7.5°F	+6.4°F	+4.6 to 9.1°F
	High (RCP 8.5)	+6.8°F	+4.8 to +9.7°F	+11°F	+8.8 to +15°F
Average fall air temperature	Low (RCP 4.5)	+4.1°F	+2.6 to +5.6°F	+5.2°F	+3.7 to +7.1°F
	High (RCP 8.5)	+5.6°F	+3.9 to +7.2°F	+9.0°F	+6.5 to +11°F
Temperature of hottest days[13]	Average of RCP 4.5 and 8.5	+6.5°F	+4.0 to +10.2°F	+9.8°F	+5.3 to +15.3°F
Temperature of coolest nights[14]	Average of RCP 4.5 and 8.5	+5.4°F	+1.3 to +10.4°F	+8.3°F	+3.7 to +14.6°F

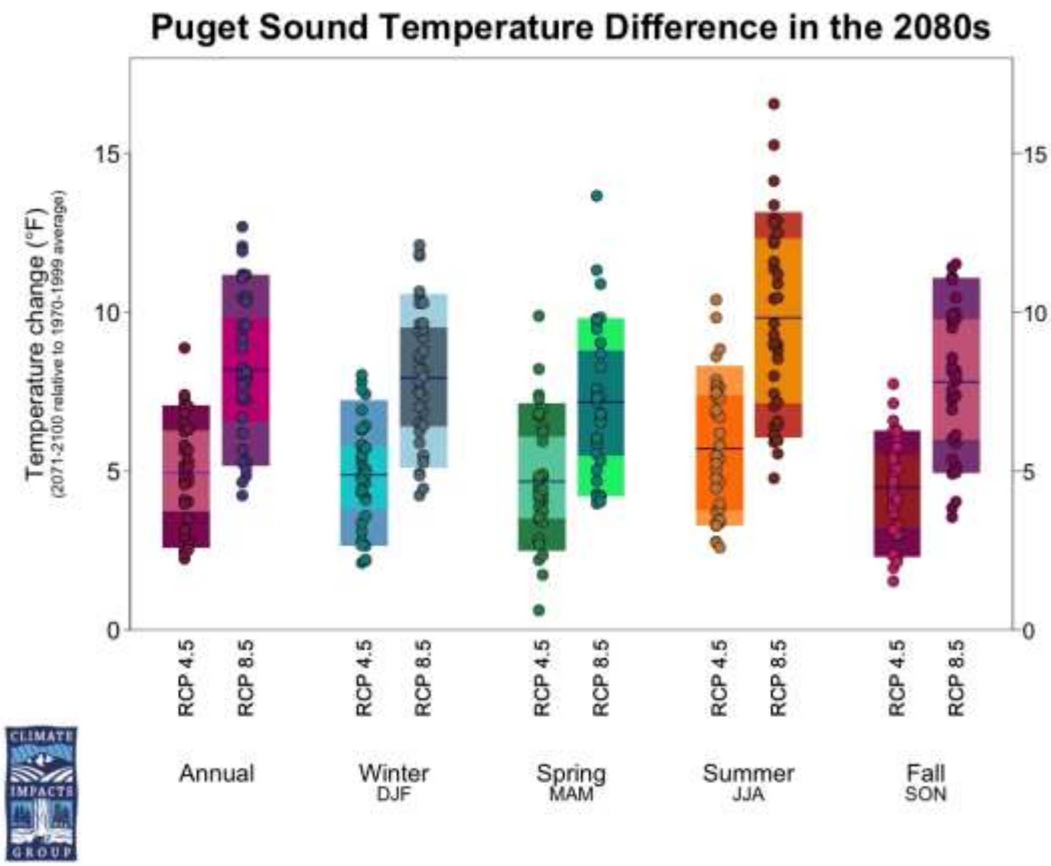
* Winter = Dec–Feb, Spring = Mar–May, Summer = June–Aug, Fall = Sept–Nov

** Under the low greenhouse gas scenario (RCP 4.5), global greenhouse gas emissions stabilize by mid-century and fall sharply thereafter. Under the high greenhouse gas scenario (RCP 8.5), emissions continue to increase through 2100 and beyond. RCP 8.5 is considered a "business as usual" scenario; global emissions are currently following this trajectory (footnote adapted from Raymond 2016) [47].

[13] Projected change in the top 1% of daily maximum temperature. Projections are based on 10 global models and two greenhouse gas scenarios (RCP 4.5 and 8.5).

[14] Projected change in bottom 1% of daily minimum temperature for climate scenarios described in Footnote 13.

Figure 10. Projected change in annual and seasonal Puget Sound temperature, in °F, for the 2080s (2070–2099), relative to 1970–1999. Projections are based on statistical downscaling of 10 global climate models and 2 greenhouse gas scenarios: a low (RCP 4.5) and a high (RCP 8.5) scenario. Individual climate model projections for each scenario are shown using colored dots. Boxes show the average projected change along with the 10th, 25th, 75th, and 90th percentile values among all climate model projections. The horizontal "0" line denotes zero change. Figure source: Climate Impacts Group, based on figures 2.5b and 2.6 in Dalton et al., 2013.



PRECIPITATION

Annual and Seasonal Precipitation

There is limited model agreement in how annual and seasonal precipitation in the Puget Sound region will change as a result of rising greenhouse gases, suggesting that natural variability will continue to dominate 21st century precipitation trends. This stands in contrast to temperature, where strong model agreement supports the conclusion that rising greenhouse gases will likely force average annual and seasonal temperatures beyond the range of 20th century natural variability after mid-century.

Climate scenarios currently show modest increases in average annual precipitation (about +7%, on average for the 2080s, relative to 1970–1999), although these changes are small relative to historical variability (Figure 9, right panel).[15] Changes in annual precipitation also vary widely in size and direction depending on models; most models show increasing annual precipitation while some models show a decrease (Table 5).

[15] Year-to-year variation in precipitation are about ±10 to 15%, on average.

Projected changes in fall, winter, and spring precipitation for the Puget Sound region are mixed (Table 5; Figure 11). While some models project decreases in cool-season precipitation, the majority of models project increasing fall, winter, and spring precipitation. In contrast, all scenarios project up to a −27% decline, on average, in summer precipitation (June-August) for the Puget Sound region by the 2080s, relative to 1970–1999.[16] It is important to note that because only 10% of annual precipitation falls during summer, the projected decline in summer precipitation would not lead to large changes in the amount of summer rainfall. Nevertheless, even small reductions are important given the importance of summer rain in lessening municipal and agricultural water demand on already limited summer water supplies.

Table 5. Projected changes in average annual and seasonal precipitation for the Puget Sound region for the 2050s and 2080s [46].

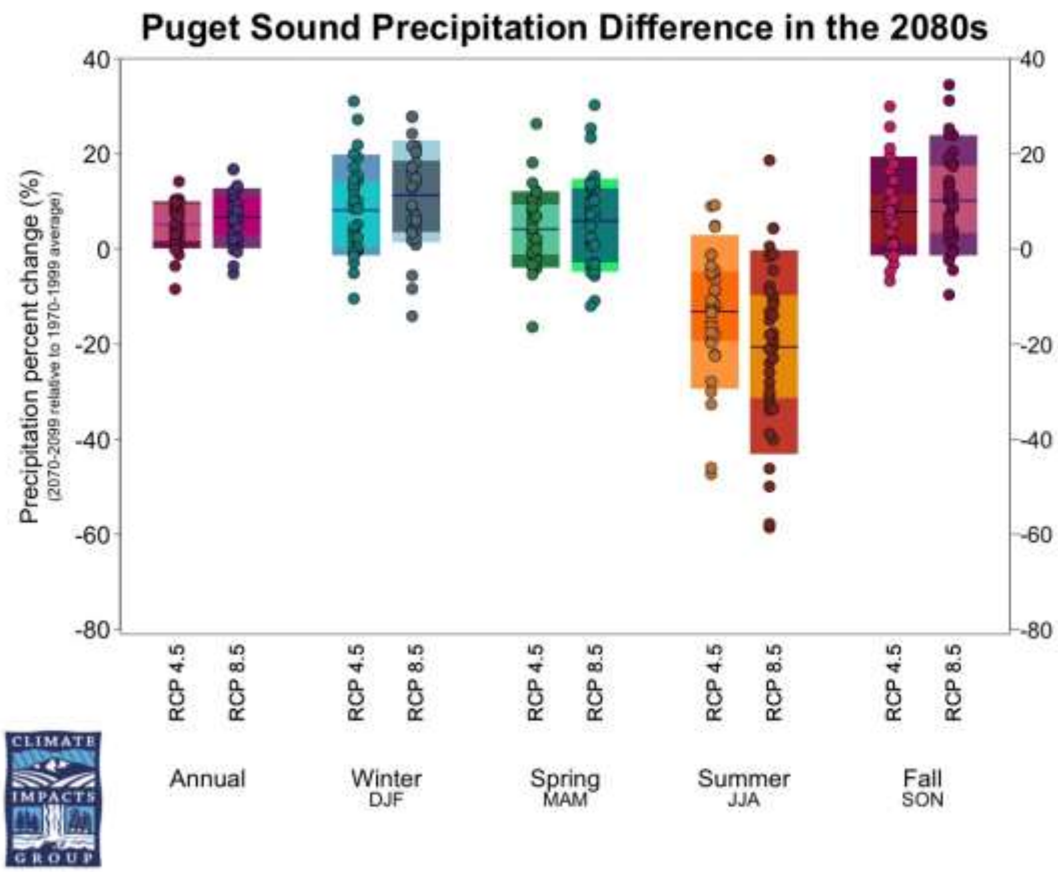
		2050s (2040–2069, relative to 1970–1999)		2080s (2070–2099, relative to 1970–1999)	
Change in…*	**Greenhouse gas scenario****	Mean	Range	Mean	Range
Average annual **precipitation**	Low (RCP 4.5)	+4.2%	+0.6 to +12%	+6.4%	−0.2 to +10%
	High (RCP 8.5)	+5.0%	−1.9 to +13%	+6.9%	+1.0 to +9.4%
Average winter **precipitation**	Low (RCP 4.5)	+9.9%	−1.6 to+21%	+11%	+1.3 to +16%
	High (RCP 8.5)	+11%	+1.8 to +19%	+15%	+6.2 to +23%
Average spring **precipitation**	Low (RCP 4.5)	+2.4%	−9.4 to +13%	+1.6%	−3.2 to +9.3%
	High (RCP 8.5)	+3.8%	−7.7 to +13%	+2.5%	−6.7 to +11%
Average summer **precipitation**	Low (RCP 4.5)	−22%	−45 to −6.1%	−20%	−37 to −10%
	High (RCP 8.5)	−22%	−50 to −1.6%	−27%	−53 to +10%
Average fall **precipitation**	Low (RCP 4.5)	+5.5%	−5.7 to +13%	+12%	+1.6 to −21%
	High (RCP 8.5)	+6.3%	−2.4 to +19%	+10%	+1.9 to +15%

* Winter = Dec–Feb, Spring = Mar–May, Summer = June–Aug, Fall = Sept–Nov

** Under the low greenhouse gas scenario (RCP 4.5), global greenhouse gas emissions stabilize by mid-century and fall sharply thereafter. Under the high greenhouse gas scenario (RCP 8.5), emissions continue to increase through 2100 and beyond. RCP 8.5 is considered a "business as usual" scenario; global emissions are currently following this trajectory (footnote adapted from Raymond 2016)

[16] Projections stem from 10 global climate model projections, based on both a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario. The 10 global climate models were selected for their ability to accurately represent the climate of the Pacific Northwest [96].

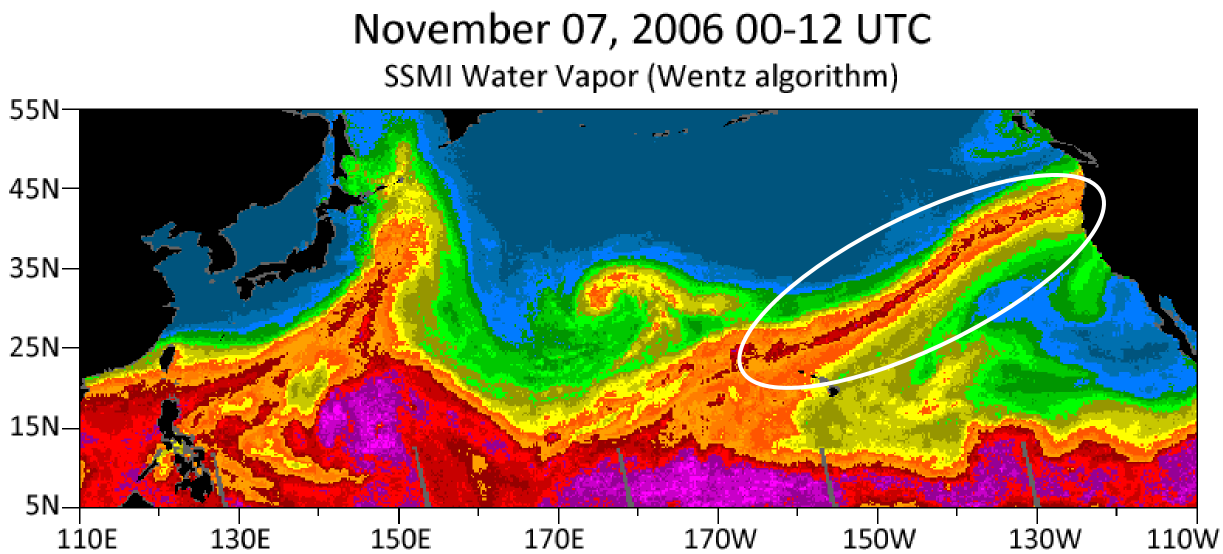
Figure 11. Projected change in annual and seasonal Puget Sound precipitation, in percent, for the 2080s (2070–2099), relative to 1970–1999. Projections are based on statistical downscaling of 10 global climate models and two greenhouse gas scenarios: a low (RCP 4.5) and a high (RCP 8.5) scenario. Individual climate model projections for each scenario are shown using colored dots. Boxes show the average projected change along with the 10th, 25th, 75th, and 90th percentile values among all climate model projections. The horizontal line denotes zero change. Figure source: Climate Impacts Group, based on Figures 2.5b and 2.6 in Dalton et al., 2013 [48].



Extreme Precipitation

Extreme precipitation events, frequently caused by atmospheric rivers, are expected to increase in both frequency and intensity. Atmospheric rivers are narrow ribbons of water vapor transport extending from the tropics to the west coast of North America during the winter months (Figure 12). An atmospheric river event that forms in the tropics near Hawaii is often referred to as a "Pineapple Express" [49].

Figure 12. Satellite view of the Pacific region showing an atmospheric river (circled in white) originating in the tropical Pacific Ocean on November 7, 2006. Brighter colors indicate areas where the atmosphere is holding more moisture. Figure source: NOAA.



An in-depth examination of precipitation projected by climate models shows that atmospheric river events will increase in frequency and intensity during winter along the U.S. West Coast [17]. For the 2080s (2070–2099, relative to 1970–1999), the heaviest 24-hour rain events in western Oregon and Washington are projected to intensify, on average, by +22%, for a high (RCP 8.5) greenhouse gas scenario. In addition, atmospheric river events are projected to occur 7 days per year by the 2080s in comparison to 2 days per year historically, under a high (RCP 8.5) greenhouse gas scenario [50].[17]

Similar increases in frequency and intensity are reported by Hagos et al. 2016 for the west coast of North America. Hagos et al. found that the number of days meeting the definition of an atmospheric river ("landfalling atmospheric river days") increased 35% (+8%) in the period 2080–2099, relative to 1980–1999, for a high (RCP 8.5) emissions scenario [51].[18] The intensity of atmospheric river events, defined as events with daily precipitation values higher than the 97.8 percentile, increased 28% (+7%) for the same period [51].

The location and intensity of the Puget Sound convergence zone is an important component of extreme precipitation events in the central Puget Sound region. The impact of climate change on the convergence zone is unknown, however [52, 53].

[17] The study evaluated precipitation totals on days with the top 1% (99th percentile) in daily water vapor transport, the principal driver of heavy rain events in the Pacific Northwest. Projections are based on an analysis of 10 global climate model projections and a high greenhouse gas scenario (RCP 8.5). Projected changes in intensity were evaluated for latitudes ranging from 40 to 49°N. Although global models are coarse in spatial scale, previous research has shown that they can adequately capture the dynamics that govern west coast storms and heavy precipitation events.

[18] For the purposes of the study, a landfalling atmospheric river day is counted when at least one model grid point over the west coast of North America meets the study's definition of an atmospheric river. See Hagos et al. 2016 for more detail.

WIND

Preliminary analysis of projected changes in winds finds that wind patterns and the strength of low pressure systems in the Puget Sound region are not projected to change as a result of climate change.[19] Although some studies suggest that warming will result in a "wavier" (i.e., more variable) storm track, this is considered highly speculative [54, 55, 56].

The behavior of the jet stream is governed by many factors; understanding how these combine to drive changes in its behavior is still an active area of research [57, 58]. In addition, it is unclear how such changes might affect the Puget Sound region [59].

SNOWPACK, GLACIERS, AND STREAMFLOW

Snowpack and Glaciers

Projected changes in temperature and precipitation result in less snow accumulation and a shorter snow season as more precipitation falls as rain instead of snow and as snow melts earlier in spring (Figure 13, Figure 14). Average spring snowpack in the Puget Sound region is projected to decline by −42% to −55% by the 2080s (2070–2099, relative to 1970–1999), on average, for a low

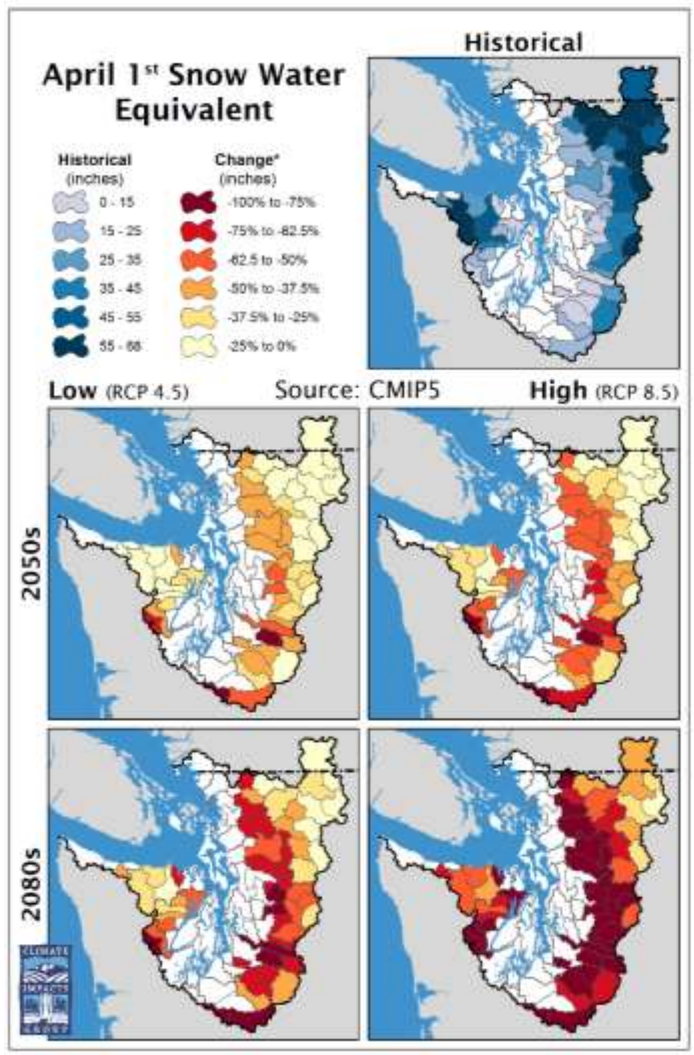


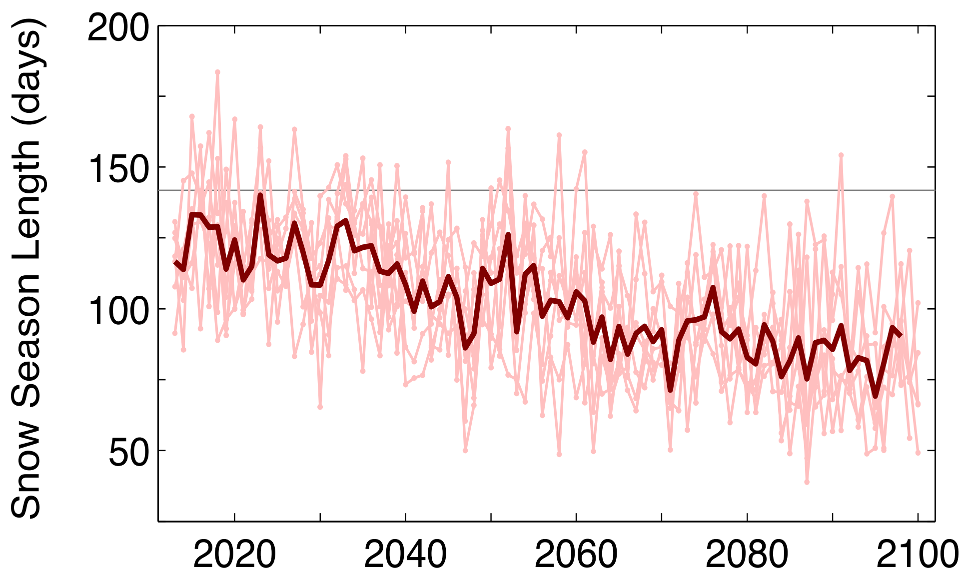
Figure 13 (at right) Projected changes in April 1st Snow Water Equivalent (SWE) for the HUC-10 scale. Maps show the historical and projected April 1st SWE, a measure of the total amount of water contained in the snowpack. The figure compares watershed averages for historical conditions (1970–1999, in inches) and the projected change (in percent) for 10 global models. Two time periods are considered: the 2050s (2040–2069) and the 2080s (2070–2099), based on a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario. Results are only shown for watersheds with an average historical April 1st SWE of at least 0.4 inch. White to dark blue shading on the historical map indicates areas which received highest levels of April 1st SWE in Puget Sound. Projected decreases in SWE are depicted by the yellow to red shading. Figure created by Robert Norheim, Climate Impacts Group, based on CMIP5 projections used in the IPCC 2013 report [27]. Data source: Mote et al. 2015 [45].

[19] While scientists expect more extreme precipitation, this does not mean that winds will intensify; research shows that storms would carry more moisture but not necessarily stronger winds.

(B1) and moderate (A1B) greenhouse gas scenario [60].[20,21,22]

Continued declines in glacial area are also expected. To date, only two studies have evaluated the projected effects of climate change on Puget Sound glaciers, and both studies suggest that continued glacial recession in the region is likely. One study found that only two (Easton Glacier and Rainbow Glacier) of the 12 North Cascades glaciers with annual measurements are expected to persist under current climate conditions, regardless of projected warming [61]. An additional study modeled glacier response in three Puget Sound tributaries (Thunder Creek, Cascade River, and Nisqually River). All scenarios showed that the glaciers persisted through 2100, but glacier area decreased substantially, especially after the 2050s [62].[23]

Figure 14. Shorter snow season with warming; large year-to-year variability. Projected length of the snow season, in days, for middle elevations (4,000 to 5,000 feet) for the Cascade Mountains in Oregon and Washington. The plot shows projected snow season length from seven individual climate models (thick pink lines) and the average among all models (thick red line) for a medium greenhouse gas scenario (A1B). For comparison, the average snow season length for 1950-1999 was 142 days (shown as the gray horizontal line). Although the length of the snow season is clearly expected to decrease significantly over this century, individual years with substantially longer or shorter snow seasons than the general declining trend are also expected to occur. [20] Data source: Hamlet et al. 2013 [60].



Streamflow Timing and Volume

Climate change impacts on the hydrology of Puget Sound watersheds will vary by watershed depending on the balance of wintertime rain and snow accumulation within a watershed, among other factors. Changes for two watersheds that bracket the north and south ends of the Port Gamble S'Klallam Tribe's primary

[20] Specifically, changes in April 1st Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1st is the approximate current timing of peak annual snowpack in the mountains of the Pacific Northwest. Changes are only calculated for locations that regularly accumulate snow (historical April 1st SWE of at least 10 mm, or about 0.4 inch, on average).

[21] Projected change for 10 global climate models, averaged over Puget Sound. Range spans from a low (B1) to a moderate (A1B) greenhouse gas scenario.

[22] Two principal datasets are often used to evaluate hydrologic projections for Puget Sound and the greater Pacific Northwest: (1) the latest set of projections, developed by Mote et al. in 2015 [45], which stem from the newer 2013 IPCC report [27], and (2) the previous set of projections, developed by Hamlet et al. in 2013 [60] based on the climate projections used in the IPCC's 2007 report [99]. Although newer, the more recent projections appear to have temperatures that are too cold in mountainous areas. For this reason, most of the results presented in this section stem from the 2010 dataset.

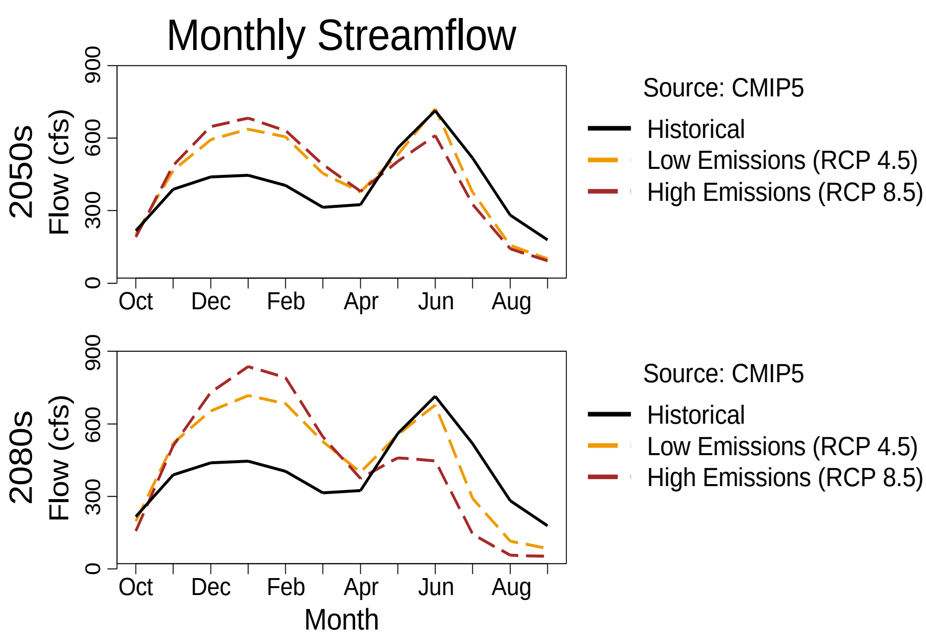
[23] See footnote 21.

traditional use area—the Dungeness and the Skokomish watersheds—and the Puget Sound region are summarized here.[24] Note that the hydrologic changes reported in this section do not take into account the effects of dams, which can mitigate the impacts of climate change by reducing peak flows or holding water for release during low-flow periods.

Dungeness River Watershed. The Dungeness River watershed is a moderate elevation, mixed rain-and-snow watershed that empties into the Strait of Juan de Fuca on the northwest side of the Olympic Peninsula. Streamflows in the Dungeness are characterized by two periods of relatively high streamflows. The first peak is during fall, coinciding with the return of the fall rains. Streamflows drop during winter when temperatures are cold enough for snow to accumulate at higher elevations. A second peak in streamflows occurs in early spring as a result of snowmelt (Figure 15).

Mixed rain-and-snow watersheds are projected to experience the greatest changes in streamflow volume and timing relative to other watershed types. In these basins, warmer winter temperatures cause more winter precipitation to fall as rain rather than snow, contributing to higher winter streamflows and lower spring (April 1) snowpack. Warmer spring temperatures and lower snowpack also lead to lower, and in some cases earlier, spring runoff. Summer streamflows are reduced both as a function of lower spring snowpack/runoff and higher summer temperatures, which can increase losses due to evapotranspiration. These changes in seasonal runoff become more pronounced over time as warming increases, collectively transforming the Dungeness watershed from a mixed rain-and-snow watershed to a rain-dominant watershed.

Figure 15. Monthly graph of streamflow for the Dungeness River. Estimates of the monthly average flow are based on the water year, starting in October and ending in September. Changes are shown for two time periods: the 2050s (top) and the 2080s (bottom), for both a low (RCP 4.5, yellow line) and a high (RCP 8.5, red line) emissions scenario. All changes are relative to average historical flows (black). Figure source: Climate Impacts Group.



[24] Changes in streamflows have not been evaluated as yet for the Dosewallips or Big Quilcene watersheds.

Specific changes for the **Dungeness River** include the following:

- The average summer (June, July, and August) streamflow in the Dungeness River is projected to decrease −35% (range: −60 to −19%) by the 2040s (2030–2059; relative to the 1970–1999), and −56% (range: −76 to −32%) by the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B).

- The average winter (December, January, and February) streamflow in the Dungeness River is projected to increase +41% (range: +22 to +77%) by the 2040s (2030–2059; relative to the 1970–1999), and +66% (range: +20 to +118%) by the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B).

- The center timing for annual streamflow is projected to occur 15 days (−35 to −6 days) earlier by the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B) [60].[25]

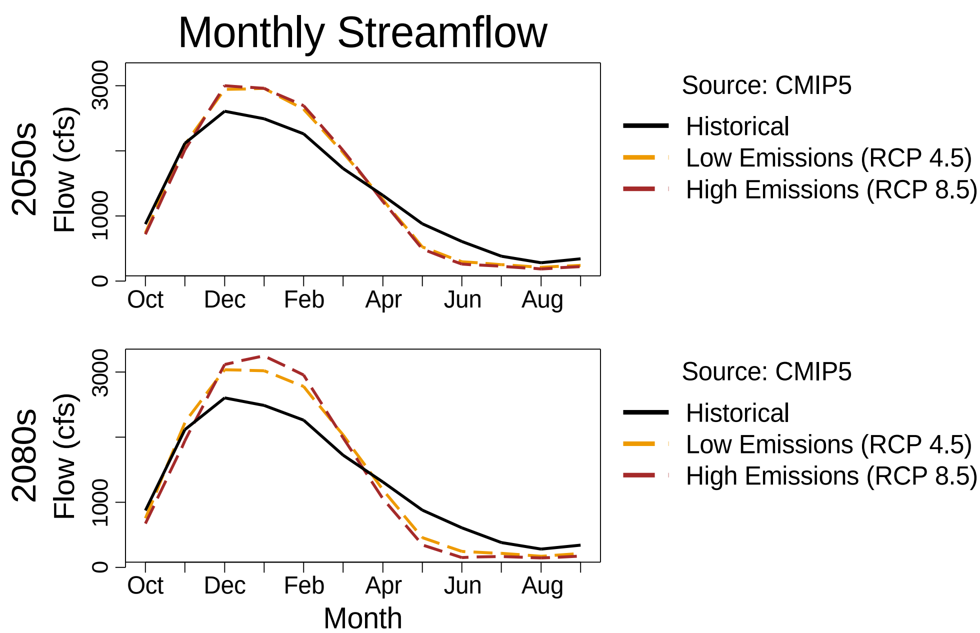
- Summer minimum streamflow (7Q10, or the lowest 7-day average flow that occurs on average once every 10 years) is projected to decrease −35% (range: −45 to −27%) for the 2080s (relative to 1970–1999) for a moderate greenhouse gas scenario (A1B) [60].

Skokomish Watershed. The Skokomish River watershed is a rain-dominant watershed emptying into Hood Canal south of the Tribe's primary use area. Rain-dominant watersheds are characterized by a single period of high streamflow during the late fall and winter. Because of their low elevation, rain-dominant watersheds accumulate little to no snow (Figure 16).

Rain-dominant watersheds like the Skokomish are not expected to experience significant changes in streamflow, although hydrologic modeling for rain-dominant systems does not take into account changes in extreme precipitation, which can drive flooding in those basins. For the Skokomish, projected increases in winter precipitation contribute to higher winter streamflows, while warmer summer temperatures and projected declines in summer precipitation are expected to increase the severity of low flow extremes.

[25] "Center timing" is defined as the day of the water year (starting on October 1st) when cumulative streamflow reaches half of its total annual volume. An earlier shift in that midpoint indicates that more runoff is occurring earlier relative to the historical period.

Figure 16. Monthly graph of streamflow for the Skokomish River. Estimates of the monthly average flow are based on the water year, starting in October and ending in September. Changes are shown for two time periods: the 2050s (top) and the 2080s (bottom). Figure source: Climate Impacts Group.



Specific changes for the **Skokomish River** include the following:

- The average summer (June through August) streamflow in the Dungeness River is projected to decrease −35% (range: −60 to −19%) by the 2040s (2030–2059; relative to the 1970–1999) and −56% (range: −76 to −32%) by the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B).

- The average winter (December through February) streamflow in the Skokomish River is projected to increase +13% (range: +3 to +31%) by the 2040s (2030–2059; relative to the 1970–1999) and +19% (range: −1 to +45%) by the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B).

- The center timing for annual streamflow is projected to occur –46 days earlier (range: −56 to −38 days), on average, by the 2080s (2070–2099, relative to 1970–1999) for a moderate emissions scenario (A1B) [60].

- Summer minimum streamflow (7Q10) is projected to decrease −18% (range: −22 to −8%) for the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B) [60].[26]

[26] Projected change for 10 global climate models for a moderate (A1B) greenhouse gas scenario.

Puget Sound Region. By the 2080s (2070–2099), watersheds in the Puget Sound region are projected to be primarily rain-dominant as a result of warming temperatures (Figure 17). For the 12 major watersheds in the Puget Sound region:[27]

- Total annual streamflow is projected to increase +6% to +7%, on average, by the 2080s (2070–2099, relative to 1970–1999) for a low (B1) and moderate (A1B) greenhouse gas scenario [60].[28]
- Total winter streamflow is projected to increase by +28% to +34% on average by the 2080s (2070–2099, relative to 1970–1999) for a low (B1) and moderate (A1B) greenhouse gas scenario [60].
- Total summer streamflow is projected to decrease by −24% to −31% on average by the 2080s (2070–2099, relative to 1970–1999) for a low (B1) and moderate (A1B) greenhouse gas scenario.
- Minimum summer streamflow is projected to decline between −16% and −51%, on average, by the 2080s (2070–2099, relative to 1970–1999) for a moderate (A1B) greenhouse gas scenario.

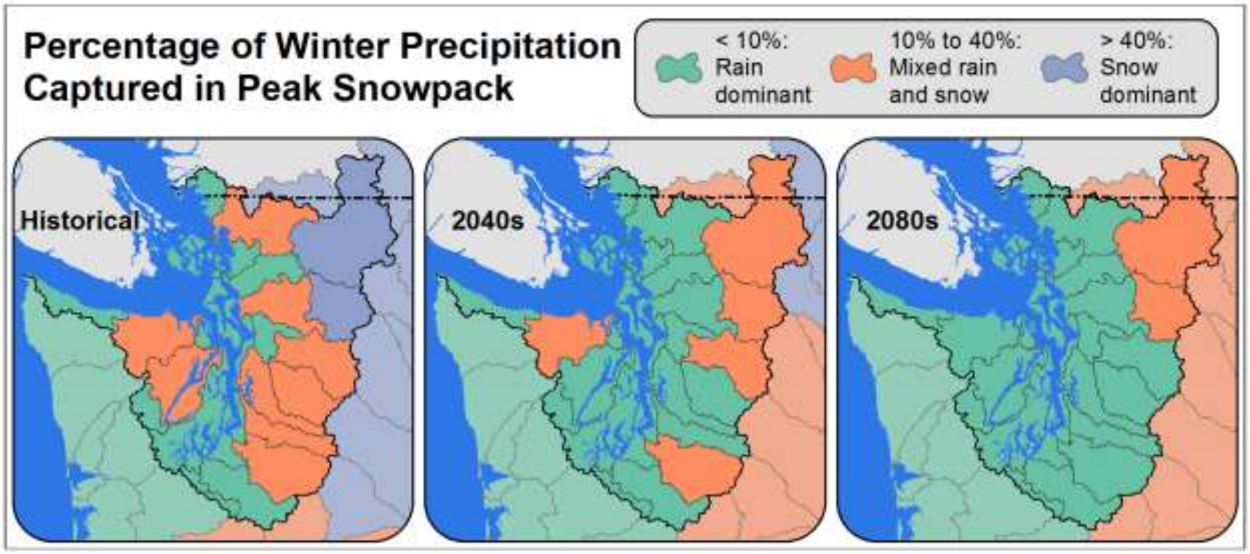
As noted previously, the effects of reservoir operations are not included in these projections. The projected changes in summer streamflows also do not account for contributions from (and eventual losses of) glacier melt. The degree to which this matters will vary by watershed. For example, Riedel et al. 2015 estimate that glacial ice, snow, and firn (glacial snow) contributions to summer (May 1–September 30) streamflows in the Hoh River range from 8.9% to 15.4%. Contributions to late summer flows (August and September) in the Hoh are higher (18-30%) [21].[29] Contributions to May 1–September 30 summer flows for the Elwha and Dungeness rivers are estimated to be 2.5 to 4% and 3.0 to 3.8%, respectively [21].

[27] Projected changes in streamflow were calculated for 12 Puget Sound watersheds. Listed in clockwise order, starting at the U.S.–Canadian border, they are the Nooksack River at Ferndale (USGS #12213100), Samish R. near Burlington (USGS #12201500), Skagit R. near Mt. Vernon (USGS #12200500), Stillaguamish R. (Flows were obtained for the NF Stillaguamish R. near Arlington, USGS #12167000, then scaled to the river mouth based on the ratio of basin area and total precipitation), Snohomish R. at Snohomish (USGS #12155500), Cedar R. at Renton (USGS #12119000), Green R. at Tukwila (USGS #12113350), Nisqually R. at McKenna (USGS #12089500), Puyallup R. at Puyallup (USGS #12101500), Skokomish R. near Potlach (USGS #12061500), Dungeness R. at Dungeness (USGS #12049000), and Elwha R. at McDonald Bridge near Port Angeles (USGS #12045500).

[28] Projected change for ten global climate models, averaged over Puget Sound. Range spans from a low (B1) to a moderate (A1B) greenhouse gas scenario.

[29] Based on August–September discharge in the Hoh River 1987 and 2010 with positive degree-day (PDD) model results.

Figure 17. Current and future watershed classifications, based on the proportion of winter precipitation stored in peak annual snowpack. Map compares average historical conditions (1970–1999) and average projected future conditions for 10 global models, 2 time periods: the 2040s (2030–2059) and the 2080s (2070–2099) and a moderate greenhouse gas scenario (A1B). By the end of the 21st century, Puget Sound will no longer have any snow-dominant watersheds, and only a few remaining that can be classified as mixed rain-and-snow. Data source: Hamlet et al., 2013 [60].



Similar variance is found in other areas. In the North Cascades, for example, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed [63]. In the near term, increasing melt from glaciers may help offset lower summer streamflows. However, over the longer term, glacier contributions will decline and ultimately be eliminated.

Flooding

Shifts in seasonal streamflow volumes, coupled with increases in extreme precipitation events, rising seas, and increasing sediment loads are all key factors expected to increase flood risk in the Puget Sound region. The projected increase in flood risk is greatest for mixed rain-and-snow basins (due to the shift to more winter precipitation falling as rain rather than snow) and rain-dominant basins (due to more extreme precipitation events). More specifically:

- Peak streamflow volume is projected to increase by +18% to +55%, on average, for 12 Puget Sound watersheds by the 2080s (2070–2099, relative to 1970–1999), based on a moderate (A1B) emissions scenario [60].

- For the Dungeness River, the projected change in streamflow associated with the 100-year (1% annual probability) flood event increases +55% (+20 to +116%) for the 2080s (2070–2099, relative to 1970–1999) for a moderate (A1B) greenhouse gas scenario.

- For the Skokomish River, the projected change in streamflow associated with the 100-year (1% annual probability) flood event increases +23% (+4 to +59%) for the 2080s (2070–2099, relative to 1970–1999) for a moderate (A1B) greenhouse gas scenario.

The Elwha, Dungeness, Quilcene, Dosewallips, and Duckabush rivers are also expected to experience more severe winter peak flows and increased flooding, although specific projections are not available at this time [64].

In addition to increasing the peak flows in the region, floods are also expected to become more frequent. For example, by the 2040s, the volume of flows associated with the historical 100-year flood event in the Skagit River become a 32-year event; the historical 30-year flood event becomes a 10-year event [65].[30] Similarly, by the 2040s, the historical 100-year flood event in the Snohomish River becomes a 30-year event, and the historical 10-year event becomes a 5-year event [66].

STREAM TEMPERATURES

Water temperatures are projected to increase. Stream temperatures are doubly affected by climate change: both by warmer air temperatures and declining summer flows. River and stream temperatures generally track air temperatures, but they do not change as rapidly. River and stream temperatures throughout the Puget Sound region are projected to increase as a result of increasing air temperatures and declining summer streamflow. Stream temperatures in the Puget Sound region are projected to increase by +4.0°F to +4.5°F by the 2080s (2070–2099, relative to 1970–1999), in response to both increasing air temperatures and decreasing summer streamflows [67].[31]

Puget Sound rivers are projected to exceed thermal tolerances more frequently for cold-water fish species. Stream temperatures are an important determinant in the quality of Puget Sound aquatic habitat and salmon health. When exposed to warm water temperatures, salmon (>64°F)[32] and char (>54°F)[32] become more susceptible to pathogens, suffer higher mortality, and stop or slow their migration (see the Salmon chapter for more detail on these impacts). The Tribe experienced a "sneak preview" of these impacts during the summer of 2015, when unusually low streamflows and unusually warm spring and summer temperatures pushed river and stream temperatures above maximum Department of Ecology water quality temperature thresholds for long periods of time. By the 2080s (2070–2099, relative to present), 12 out of 37 Puget Sound stream monitoring sites are expected to experience weekly average stream temperatures which exceed thermal tolerances for salmon (64°F) for as much as 7.5 weeks longer. For the Dungeness and Skokomish rivers:

- By 2080s (2070–2099, relative to present), the Dungeness and Skokomish rivers are expected to experience an increase of +0 and +3 river miles, respectively, with August stream temperatures that exceed the thermal tolerances for salmon (>64°F).
- By 2080s (2070–2099, relative to present), the Dungeness and Skokomish rivers are expected to experience an increase of +32 and +120 river miles, respectively, with August stream temperatures that exceed the thermal tolerances for char (>54°F).

LANDSLIDES AND SEDIMENT TRANSPORT IN RIVERS AND STREAMS

Continued declines in snowpack and projected increases in the frequency and intensity of heavy rain events in the Puget Sound region are expected to increase landslide frequency and the rate of erosion and sediment transport in rivers and streams in winter and spring. These changes can affect aquatic habitat quality and river flood risk. Sediment transport to coastal areas can also affect coastal and estuarine habitats, coastal flooding, and relative sea level rise in the Puget Sound region.

[30] Results based on running the Echam 5 global climate model with a moderate warming scenario (the A1B emissions scenario).
[31] Based on a composite of 10 global climate model projections for a moderate (A1B) greenhouse gas scenario.
[32] In this report we use regulatory thresholds listed in EPA (2007) [73], which defines 12°C (54°F) and 17.5°C (64°F) as the criteria for protecting adult char and salmon, respectively. Note that some analyses consider the average monthly temperature for August, which will likely result in an underestimate of the implications for maximum August temperatures.

Landslides

The topography and geography of the Port Gamble S'Klallam Tribe's primary traditional use area make the area prone to landslide events. The location and size of landslides depend on several factors, including precipitation duration and intensity, antecedent soil moisture, soil types, slope gradients, runoff patterns, land cover, and land use [68]. Most landslides in the Pacific Northwest occur on the west side of the Cascades during the rainy season (October–May). They are predominantly initiated by intense rain events or by lower intensity, but persistent rainfall over a prolonged period (precipitating high soil moisture content), rapid snow or ice melt, or low evaporative demand that allow soil moisture to persist [53].

While there are currently no published projections for changing landslide hazards in the Puget Sound region, studies in nearby areas [69] and expected shifts in the mechanisms linking climate with landslides suggest an increase in the likelihood of landslides in winter and early spring and a decreased likelihood in summer. One study in the Queets Basin on the west slope of the Olympic Peninsula projected a +7 to +11% increase in areas with high landslide susceptibility[33] by 2045, relative to 1970–1999 [69].[34] Another study focused on Howe Sound, British Columbia, projected a 28% increase in debris flow currents into Howe Sound between 2075 and 2100 [70].[35] The authors note, however, that the projected increase is significantly lower than past changes in landslide activity associated with logging practices and roadbuilding, underscoring the role that changes in land use have on landslide risk [70]. More information on the projected seasonal shifts relevant to the Puget Sound region are noted below.

Increasing landslide risk in winter. Higher winter temperatures, declining snowpack levels, and increasing heavy rain events are expected to increase landslide risk during winter in the Puget Sound region. Warmer winter temperatures can reduce slope stability by affecting the rate and type of weathering that occurs on slopes [71, 72, 73], decreasing the viscosity of groundwater (i.e., more lubricating), and thawing frozen ground, which enables increased infiltration through the soil [74, 75]. Lower snowpack also allows for increased infiltration and exposes more area to erosion during heavy rain events [76]. Finally, heavy rain events reduce slope stability by rapidly raising the water table and by enhancing water drainage through the soil to lower layers [72]. Each of these factors plays a role in increasing winter soil water content west of the Cascades, and with that, the potential for landslides. For example, December 1st soil moisture is projected to increase by up to +35% by the 2040s (2030–2059) relative to 1970–1999 along the slopes of the Cascade Mountains, under a moderate emissions scenario (A1B) [77].

Decreasing landslide risk in summer. In contrast to winter, landslide risk in summer is expected to decrease due to projected increases in temperature and subsequent declines in spring snowpack, summer streamflow, and summer soil water content. Rising temperatures can also increase evaporation, resulting in drier summer soils and more stable conditions in deeper soils. The earlier onset of snowmelt is expected to decrease soil water content, which could increase slope stability in summer. These findings do not take into account the increased risk of landslides associated with forest fires, which are more likely west of the

[33] This study categorized landslide susceptibility by using a set of weights calculated by Van Westen (1997) for specific landslide controlling factors (e.g., slope, land cover, elevation). Weights receive negative values when landslide susceptibility is low and positive values when susceptibility is high. A landslide susceptibility map was developed by summing the weights over each pixel of the Queets Basin. The range of susceptibility values for the Queets Basin spanned −3.24 to 2.21 and was divided into three susceptibility classes using thresholds of 33% and 67% of the cumulative susceptibility. This resulted in three susceptibility classes: low (<0.05), medium (0.06 to 0.79), and high (>0.79).

[34] Estimates were obtained using the Distributed Hydrology Soil Vegetation Model (DHSVM) with a landslide ("mass wasting") algorithm. Projections were obtained from two global climate models (CGCM_3.1t47 and CNRM-CM3), each based on a low (B1) and a moderate (A1B) greenhouse gas scenario, respectively.

[35] Study results based on examining monthly mean simulations of precipitation from 19 climate models and 3 greenhouse gas scenarios: a low (B1), moderate (A1B), and high (A2) scenario. Results assume the degree of forest cover, land use, type and distribution of tree cover, and forest fire frequency remain constant.

Cascades as a result of climate change (discussed later), and changes in land use such as logging or road construction that can increase the risk of landslides in areas affected by these activities.

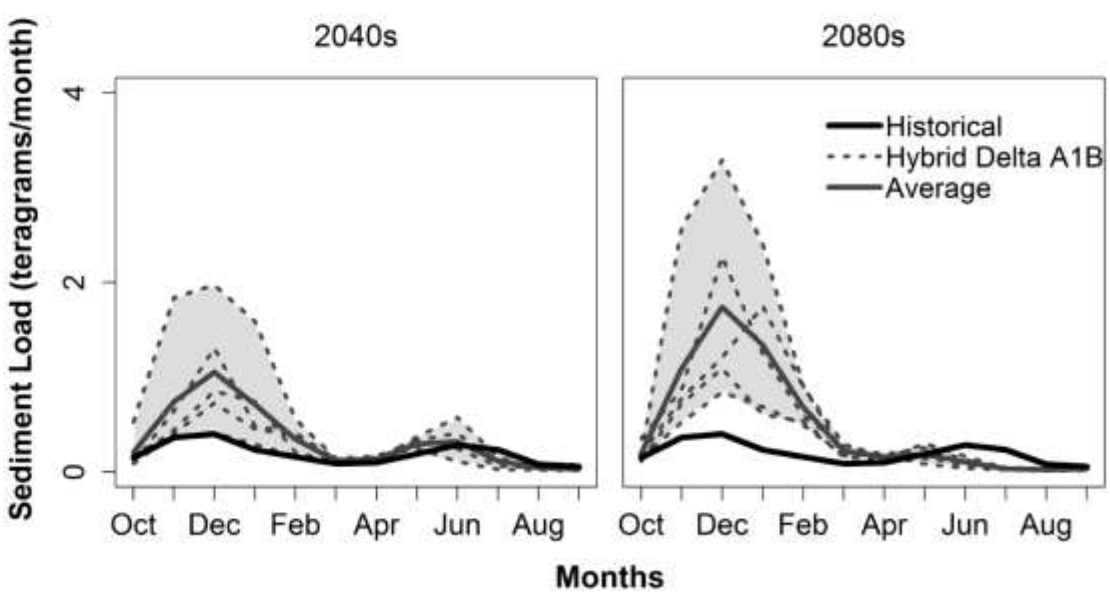
Sediment Transport

Annually, Puget Sound rivers carry 6.5 million tons of sediment into Puget Sound and its surrounding waters. The amount and size of sediment particles in a river or stream is largely driven by discharge volume and river slope. Steep, fast-flowing rivers carry gravel, rocks, and boulders, while smaller rivers transport clay and silt [78]. While sediment particle size is largely dependent on river discharge and slope, overall river sediment load is not. The Skagit, Nooksack, and Puyallup rivers have the largest sediment loads draining into Puget Sound [78].

Projections of climate change-induced changes to sedimentation in Puget Sound are not available for most Puget Sound river systems and remain a complicated dynamic to capture in modeling studies. However, sediment transport in Puget Sound rivers is expected to decrease in summer and increase in winter and spring as declining snowpack and glacial recession expose more unconsolidated soils to rain and as extreme precipitation events become more frequent and severe [79, 80].

A recent assessment for the Skagit River illustrates how sediment transport could be affected within Puget Sound rivers. Lee et al. 2016 found that peak sediment delivery in the Skagit River is projected to increase during winter and decrease during summer [65]. Specifically, by the 2080s, peak sediment delivery is projected to increase by +376% (range: +140% to +730%) between December and February and to decrease by −76% (range: −60% to −90%) between July and September relative to historical conditions using a moderate greenhouse gas scenario (A1B) (Figure 18). Considering a 5 GCM ensemble average, researchers project that the Skagit River's annual average sediment load will reach 4.1 teragrams or 4.1 million metric tons per year (1 teragram = 1 trillion grams) by the 2040s and 5.8 teragrams per year by the 2080s, relative to 2.3 teragrams per year historically [65]. This projected increase in sediment loading in the Skagit River could be both advantageous and hazardous to surrounding ecosystems and human populations. For example, an increased sediment load could facilitate marsh accretion but may simultaneously reduce the river's carrying capacity, increasing the risk of overtopping and flooding [65].

Figure 18. Simulated monthly average sediment loading for the Skagit River near Mount Vernon for the 2040s (left) and 2080s (right). Figure source: Lee et al. 2016 [65].



Riverbed aggradation due to sediment transport has recently been observed in the Puyallup River [81]. Between 1984 and 2009, the average elevation change of the Puyallup River channel rose by as much as 7.5 feet. Conveyance capacity, or the discharge conveyed through a given channel reach for a given stage, is frequently used to assess the susceptibility of specific river reaches to flooding [81]. Certain sections of the Puyallup River have experienced a decrease in conveyance capacity between 1984 and 2009 as a result of riverbed aggradation. Specifically, between 1984 and 2009 the conveyance capacity of the upper Puyallup (between river mile 21.5 and 19.5) decreased by as much as 9,000 cubic feet per second [81]. This decrease in conveyance capacity could potentially lead to increased risk of flooding in these specific reaches. The Puyallup can give us an idea of what might occur in other rivers important to the Port Gamble S'Klallam, where measurements of this type have not yet been made.

FOREST FIRE, INSECT, AND DISEASE RISK

Climate change will affect forests in multiple ways, including changes in growth and productivity, species distribution and forest composition, phenology, and changes in disturbance agents such as wildfire, insect infestations, and disease. While each of these will play a role in determining how forests respond to a changing climate, changes in disturbance agents are expected to have a greater impact on forests relative to other changes [82, 83].

Forest Fire

Climate change is projected to increase the risk of forest fires in Western Washington, although quantifying the change in fire risk is difficult due to the low frequency of large wildfires in western Washington. Fire history west of the Cascades is defined by infrequent, large, stand-replacing fires (where most of the forest is killed) occurring every 200 to 500 years [84, 85, 86]. There were three major burning episodes on the Olympic Peninsula during the Little Ice Age (1300–1750), the last of which occurred between 313 and 346 years ago. This fire (or multiple fires) burned more than 1 million acres on the Olympic Peninsula and between 3 and 10 million acres in western Washington [87].

Climate change impacts on fire risk are frequently described in terms of changes in frequency, severity, intensity, and area burned (see box at right.) [88]. In general, Western Washington is expected to see more frequent and more severe wildfires, resulting in an increase in annual area burned by forest fire over the coming century (Figure 19). Two studies project that the annual area burned west of the Cascades could more than double, on average, by 2070–2099 compared to 1971–2000 [83, 89]. Multiple factors contribute to this expected increase in area burned, including the following:

- Increased summer soil moisture stress (due to warmer spring/summer temperatures, increased evaporation, reduced summer precipitation, and declining snowpack).
- Earlier onset of the growing season, which increases fuel loads (due to warmer spring temperatures, increasing cool-season precipitation, and reduced snowpack).
- Lengthening of the fire season (due to increasing spring and fall temperatures).

Key Forest Fire Risk Metrics

Fire frequency: The number of fires in a particular area in a particular period.

Fire intensity: The amount of energy released by a fire (i.e. how hot it burns). Fire intensity is often discussed in correlation with fire severity, which refers to the overall effects of fire on vegetation (e.g., tree mortality), forest structure, and other issues such as human infrastructure.

Area burned: The total amount of area burned by fire.

(Peterson and Littell 2012)

- Earlier drying of fuel moisture (due to warmer spring/summer temperatures and reduced summer precipitation).
- Changes in insects and diseases that may lead to more tree stress or mortality (see next section).

Human uses of forested areas and the legacy of past and current forest management practices, such as clear-cutting, monoculture tree planting, and fire suppression, will also exacerbate future fire risk.

Additional information can be found in the Forest Resources chapter.

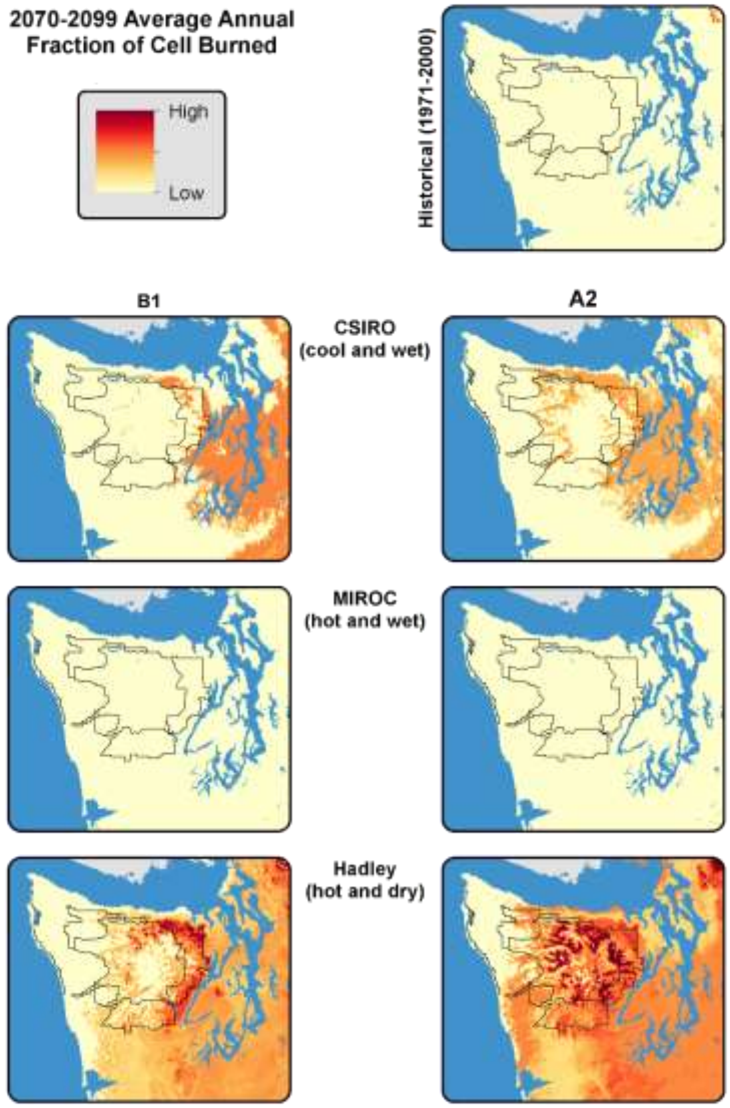


Figure 19 (at right). Projected average annual fraction of cell burned on the Olympic Peninsula for the 2070–2099 time period compared to modeled historical fire activity. This output is derived by averaging the area of a cell that is burned over the period of interest. Numbers are not shown in the legend because they are not intuitive. However, darker colors indicate more fire. Projections are from the MC1 model for three global climate models (GCMs) (rows) and two Intergovernmental Panel on Climate Change carbon dioxide emissions scenarios (columns). The B1 emissions scenario is characterized by relatively low future emissions, and the A2 scenario is characterized by relatively high future emissions. Olympic National Park and Olympic National Forest are outlined in black. CSIRO = Commonwealth Scientific and Industrial Research Organization; MIROC = Model for Interdisciplinary Research on Climate. (Data from R. Neilson and the MAPSS Team, USDA Forest Service and Oregon State University, Corvallis, Oregon.) Figure and caption source: Halofsky et al. 2011 [90].

Insects and Disease

Climate change is expected to affect the frequency, location, and duration of insect and disease outbreaks in the Puget Sound region. These changes will result from impacts on the life cycles of insects and diseases as well as impacts on the host species that increase forest susceptibility. Changes in frequency, location, and duration will vary by insect and disease and can also vary over different time scales. More information about specific insects, including mountain pine beetle and spruce beetle, can be found in the Forest Resources chapter.

In addition to insects, forest disease prevalence is expected to change as a result of climate change. Location, changes in host species, and disease sensitivity to changes in seasonal precipitation, temperature, and moisture stress are some of the key factors influencing how diseases may be affected by climate change. For example, wetter and warmer winter and spring conditions (which are consistent with current climate projections) with may increase the severity and distribution of Swiss needle cast [91]. If conditions are warmer and drier, however, the effect of Swiss needle cast may be reduced [92].

Increasing air temperatures and declining summer water availability are also expected to increase the impact of *Armillaria* root disease and some canker pathogens on conifer and hardwood forest communities in the Puget Sound region [89, 92].

PROJECTED CHANGES IN THE NEARSHORE AND MARINE ENVIRONMENT

SEA LEVEL RISE

Coastal areas in Washington State and the Puget Sound region will experience a variety of impacts associated with sea level rise.[36] Key impacts include inundation of low-lying areas, increased exposure to storm surge, increased coastal flooding and erosion, and shifting or loss of habitat types. The amount of sea level rise at any specific location will reflect projected global rates of rise as well as regional factors that influence local sea levels, including seasonal wind patterns, vertical land movement resulting from plate tectonics, glacial rebound or isostatic rebound, thermal expansion, and sedimentation.

Projected Changes in Global Sea Level Rise

Global sea level is projected to increase by +11 to +38 inches by 2100 (relative to 1986–2005), depending on the amount of 21st century greenhouse gas emissions [27].[37,38] All studies project an increase in global sea level for emissions scenarios, although different approaches result in different estimates of the exact amount of sea level rise projected.

Recent studies suggest that the likely range of global sea level rise reported by the Intergovernmental Panel on Climate Change could underestimate how much sea level rise may occur during (and after) the 21st century. This is primarily because of concerns that the approaches underestimate the contributions from melt on Greenland and Antarctica. For example, Rietbroek et al. 2016 found that the amount of thermal expansion in the ocean, which occurs as a result of warming ocean temperatures and is a major component of global sea level rise, was almost double the amount previously assumed for the period 2002–2014 [93]. The new calculation was based on Gravity Recovery and Climate Experiment (GRACE) satellite data, which became available starting in 2002.

Joughin et al. 2014 concluded that collapse of Thwaites Glacier in Antarctica may already be underway, although at a relatively moderate rate [94]. The key cause is an increased presence of warm water circulating at depth around Antarctica. A full collapse of the ice sheet is expected to be triggered when melt rates exceed 1 millimeter per year (0.4 inches) sea level equivalent. According to most model scenarios,

---

[36] Sea level in the northwest Olympic Peninsula is currently expected to fall, relative to land, through the mid- to late 21st century as a result of tectonic uplift that is causing Neah Bay to rise at a rate faster than the rate of global sea level rise.

[37] Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "moderate" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI; descriptors are based on cumulative emissions by 2100 for each scenario. See Section 1 for details.

[38] Sea level rise projections vary with greenhouse gas scenarios. The average and associated ranges reported in IPCC 2013 are +17 in. (range: +11 to +24 in.) for the very low (RCP 2.6) greenhouse gas scenario to +29 in. (range: +21 to +38 in.) for the very high (RCP 8.5) scenario. See Section 1 for more details on greenhouse gas scenarios.

this threshold could be reached within 200 to 900 years. A full collapse of the ice sheet is projected to lead to a long-term increase in global sea level of +10 feet.

Most recently, DeConto and Pollard 2016 reported that sea level rise contributions from Antarctica could exceed 3 feet by 2100 as a result of the destabilizing effects of warm ocean currents on ice sheets in Antarctica, ultimately resulting in 5 to 6 feet of global sea level rise when accounting for other contributions [95]. While these studies all point to the potential for higher amounts of global sea level rise, a new consensus estimate is not currently available.

Projected Changes in Puget Sound Sea Level Rise

Sea level in the Puget Sound region is projected to continue rising through the 21st century. The relative rise in sea level projected for Seattle is +24 inches, on average (range: +4 to +56 inches) by 2100 (relative to 2000) [33]. Local amounts of sea level rise in other locations could be higher or lower than this range, depending on local rates of vertical land motion Table 6).

Emerging efforts to provide probabilistic estimates of sea level rise show the potential for higher amounts of sea level, although at a relatively low level of probability. For example, Petersen et al. 2015 found a 1% probability that sea level rise in Port Townsend will reach or exceed +62 inches (5.4 feet) by 2100 [37]. The 50% probability threshold is +28 inches (2.4 feet). Projections are lower for Port Angeles and Neah Bay due to uplift along the north Olympic Coast (Table 7).

Table 6. Regional absolute sea level rise projections for Puget Sound are roughly similar among different studies, but there are important differences. Projections are for "eustatic" sea level, which is independent of changes in land elevation. Results are shown in inches for 2030, 2050, and 2100 (relative to 2000), from three regionally specific studies: Petersen et al. 2015 [37] (based on Kopp et al. 2014, NRC 2012, and Mote et al. 2008 [96, 33, 97]). Values shown are the central (for NRC 2012), medium (for Mote et al. 2008), or median (for Petersen et al. 2015) projections, with the projected range included for each (for Petersen et al. 2015, the range corresponds to the 99% confidence limits). For simplicity only the results for the high (RCP 8.5) scenario from Petersen et al. 2015 are included in the table [37].

Domain	2030	2050	2100
Strait of Juan de Fuca (Petersen et al. 2015)	+4 inches *(+1 to +6 in.)*	+7 inches *(+1 to +14 in.)*	+23 inches *(+6 to +55 in.)*
Washington State (NRC 2012)	+4 inches *(+1 to +8 in.)*	+9 inches *(+4 to +18 in.)*	+28 inches *(+14 to +54 in.)*
Puget Sound (Mote et al. 2008)	---	+ 6 inches *(+3 to +22 in.)*	+13 inches *(+6 to +50 in.)*
Port Gamble	Not available at this time		

Table 7. Relative sea level (third column) and annual extreme coastal flood projections (right column, which includes sea level rise) for the coastal communities of the Strait of Juan de Fuca relative to the contemporary Mean Higher High Water (MHHW) tidal datum. The third column of the table provides the probability (in percent) that mean sea level will be at or above a certain elevation (in feet) above contemporary MHHW by 2030, 2050 or 2100. The right column of the table provides the probability in a given year that the largest single coastal flooding event will reach a given elevation (in feet) above the contemporary MHHW. This column reflects how storm surge amounts vary at locations across the peninsula. Table and caption from Petersen et al. 2015 [37].

Location	Probability	… that mean sea level will reach or exceed ___ feet relative to current MHHW…			… and that the annual extreme coastal flood will reach ____ feet relative to current MHHW			
		2030	*2050*	*2100*	*Current*	*2030*	*2050*	*2100*
Neah Bay and Clallam Bay-Sekiu	99%	-0.1	-0.2	-0.1	2.0	2.1	2.2	2.6
	95%	-0.1	-0.0	0.3	2.4	2.4	2.6	3.1
	83%	0.0	0.1	0.7	2.7	2.9	3.0	3.7
	75%	0.0	0.2	0.9	2.8	2.9	3.1	3.9
	50%	0.1	0.3	1.3	3.2	3.3	3.5	4.5
	25%	0.1	0.5	1.8	3.6	3.6	3.9	5.1
	17%	0.2	0.5	2.0	3.7	3.8	4.0	5.4
	5%	0.2	0.7	2.7	4.1	4.1	4.4	6.2
	1%	0.3	0.9	4.0	4.3	4.4	4.8	7.5
Port Angeles	99%	0.1	0.1	0.5	1.1	1.4	1.6	2.2
	95%	0.1	0.2	0.9	1.4	1.6	1.9	2.7
	83%	0.2	0.4	1.2	1.6	1.9	2.2	3.2
	75%	0.2	0.4	1.4	1.8	2.0	2.3	3.4
	50%	0.3	0.6	1.9	2.1	2.3	2.6	3.9
	25%	0.3	0.7	2.3	2.4	2.6	3.0	4.5
	17%	0.3	0.8	2.6	2.5	2.8	3.2	4.8
	5%	0.4	0.9	3.3	2.8	3.1	3.5	5.5
	1%	0.5	1.2	4.6	3.1	3.4	3.9	6.8
Port Townsend	99%	0.2	0.4	1.0	1.1	1.5	1.9	2.8
	95%	0.3	0.5	1.4	1.3	1.8	2.2	3.3
	83%	0.3	0.7	1.8	1.6	2.1	2.5	3.8
	75%	0.4	0.7	2.0	1.8	2.2	2.6	4.0
	50%	0.4	0.9	2.4	2.1	2.5	2.9	4.5
	25%	0.5	1.0	2.9	2.4	2.8	3.3	5.1
	17%	0.5	1.1	3.1	2.5	2.9	3.5	5.3
	5%	0.6	1.2	3.9	2.8	3.3	3.8	6.1
	1%	0.6	1.5	5.2	3.1	3.6	4.1	7.3

Coastal Flooding, Storm Surge, and Erosion

Coastal Flooding. Coastal flooding is a frequent problem in the Puget Sound region. One cause of high-impact coastal flood events is atmospheric low pressure systems. Intense low pressure systems in the Puget Sound region can result in up to two feet of additional sea level, increasing the potential for coastal flooding, storm surge and erosion.

Sea level rise will exacerbate coastal flooding, including flooding in coastal river deltas, including flooding associated with atmospheric low pressure systems. In coastal river deltas, higher sea level can increase the extent, depth, and duration of flooding by delaying flood waters in rivers and streams to draining into Puget Sound. In the Skagit River floodplain, for example, the area flooded during a 100-year event is projected to increase by +74% on average by the 2080s (2070–2099, relative to 1970–1999), when accounting for the combined effects of sea level rise and increasing peak river flows (see Section 3) [98, 99]. In Olympia, +6 inches of sea level rise shifts the probability of occurrence for the 1-in-100-year flood event from a 1% annual chance to 5.5% annual chance (1-in-18-year) event [100].[39] With +24 inches of sea level rise, the 1-in-100-year flood event would become an annual event.[40]

Storm Surge. Climate change is not projected to change the overall behavior of storms that produce damaging surge events in the Pacific Northwest, higher sea level and increased extreme storm events will amplify the inland reach and impact of high tides and storm surge, increasing the likelihood of major flood events.

Coastal Erosion, Bluff Erosion, and Sediment Transport. Shoreline erosion along the Puget Sound coast is a major sediment source [78]. One study estimated that shoreline erosion contributes 9.1 million tons of sediment per year [101]; it should be noted that the uncertainty surrounding this estimate is considered high [78]. Increased erosion is expected in many coastal areas as sea levels rise, although the effects depend on the geology and exposure of each location. Coastal bluffs are expected to be particularly sensitive to sea level rise. One study projects that coastal bluffs in San Juan County could recede by −75 to −100 feet by 2100 (relative to 2000) as a result of sea level rise [102].[41] This amount corresponds to a doubling, on average, of the current rate of recession [3]. Another study focused on the Dungeness and Elwha drift cells (areas for which distinct sediment sources and sinks can be identified) projected that sea level rise would increase average annual bluff erosion rates by approximately 4 inches per year by 2050. Heavy precipitation, nonpoint source runoff, groundwater saturation, development near bluffs, and the presence (or absence) of shoreline protection can also affect to erosion rates [103, 104].

Sediment inputs from coastal erosion are necessary for the persistence of beaches and coastal areas, which provide food and habitat for estuarine and nearshore plant and animal species in the Puget Sound region. However, while insufficient sediment transport can lead to beach and habitat erosion, excess sediment loads can fragment or bury important habitat types, such as eelgrass beds [78]. It remains uncertain if bluff erosion will mitigate sea level rise in nearshore areas or if sediment will be transported offshore by increased wave exposure due to higher water levels [105].

The Port Gamble S'Klallam Tribe is doing a new study on bluff erosion in the reservation area. Additional information about local bluff erosion can be found in the Infrastructure chapter.

Additional information on sea level rise can also be found in the special section following this chapter.

[39] A +6-inch increase in regional sea level is currently near the median value projected in Petersen et al. (2015) [60] for Seattle for 2030.

[40] A +24-inch increase in sea level is currently within the range (+14 to +63 inches) projected in Petersen et al. (2015) [60] for Seattle for 2100, relative to 2000.

[41] Projections are based on an empirical model that assumes that the equilibrium rate of shoreline erosion is proportional to the rate of sea level rise. Projections are based on the NRC (2012) [57] report and a moderate (A1B) and high (A1FI) greenhouse gas scenario.

OCEAN TEMPERATURE

Sea surface temperatures in the northeast Pacific Ocean are projected to warm by about +2.2°F by the 2040s (2030–2059, relative to 1970–1999), although short-term (up to several decades) variability resulting from coastal upwelling, ENSO, and PDO could affect this projected change [106]. These results are consistent with the +2°F warming projected for the Northwest coastal ocean by mid-century (2040–2049) under a moderate (A1B) warming scenario [107].

It is important to recall that sea level rise is significantly connected to thermal expansion (see Sea Level Rise Special Section following this chapter). For this reason, rising temperatures in the ocean water column will directly increase sea level rise.

OCEAN ACIDIFICATION

The pH of Washington's coastal waters is projected to continue to decrease as the atmospheric concentration of carbon dioxide climbs. Based on current carbon dioxide emissions scenarios, ocean acidity is projected to increase by 100 to 150% globally by 2100 (a decline in pH of −0.06 to −0.32), relative to pre-industrial levels [27].[42] According to NOAA's Pacific Marine Environmental Laboratory, the pH level projected for the end of the 21st century is a level "that the oceans haven't experienced for more than 20 million years" [108].

As noted previously, research on Hood Canal finds that ocean acidification currently accounts for 24 to 49% of the decrease in pH in the deep waters of Hood Canal relative to estimated pre-industrial values. This contribution increases to 49 to 82% with a doubling of atmospheric carbon dioxide, relative to pre-industrial levels [41]. Under greenhouse gas current scenarios, atmospheric carbon dioxide could double by about 2050 for a high emissions scenario (RCP 8.5) or after 2100 for a low scenario (RCP 4.5).

[42] Range for end of the 21st century for the very low (RCP 2.6) to the high (RCP 8.5) greenhouse gas emissions scenarios.

Special Section

SEA LEVEL RISE

INTRODUCTION

The Port Gamble S'Klallam Tribe is particularly concerned about how sea level rise will impact its land, resources, infrastructure, and community, and this section therefore dives more deeply into projected changes.

Warming temperatures are causing increased rates of ice melt and thermal expansion of water all over the world [109]. For many coastal regions, these changes have led to rising sea levels that have contributed to increased coastal flooding and changes in habitat structure.

According to the University of Washington Climate Impacts Group, sea level rise in the Puget Sound region is expected to continue throughout the 21st century and will permanently inundate some low-lying coastal areas [46]. Sea level rise will also increase the frequency, magnitude, and duration of flood events and accelerate coastal erosion [46]. These changes will affect coastal habitat and could damage coastal infrastructure that includes, among other assets, fisheries and shellfish-harvesting equipment and operations. As a result of regional differences in vertical land movement (caused by tectonic uplift, isostatic rebound, and/or excessive groundwater withdrawal), sea level rise will not be uniform throughout Puget Sound or the Olympic Peninsula.

SEA LEVEL RISE PROJECTIONS

Data records from tide gauges as far back as the 1880s have made reliable global projections of sea level rise possible [109]. More recently, technological advances (e.g., satellite measurements, sophisticated climate models) have allowed for more accurate sea level rise observations and projections at global and local scales [109]. Most of these projections forecast conditions up to 2100, but researchers believe sea level rise will continue for at least several centuries [109].

Sea level rise projections reflect the statistical relationship between historical sea level, temperature data, and probable future climatic conditions under various greenhouse gas emissions scenarios [110]. However, climate models are not useful for predicting major state shifts of the Earth's physical processes, including shifts in ice sheet dynamics on Greenland and Antarctica that may lead to faster rates of sea level rise (now generally accepted as a possibility within the 21st century) [110]. Accordingly, projected rates of future sea level rise beyond 2100 are uncertain at best and are potentially underestimated [110].

GLOBAL SEA LEVEL RISE

Globally, the annual rate of sea level rise has accelerated in recent decades. Since the mid-1800s, the rate of sea level rise has been larger than in the past two millennia [27]. It is *very likely* that the rate of global mean sea level rise was +1.7 millimeters per year (range: +1.5 to +1.9 mm/year) between 1901 and 2000 [28].[43] Satellite altimetry data became available starting in 1993; those measurements show that between 1993 and 2010, the mean rate was *very likely* higher at +3.2 (range: +2.8 to +3.6) millimeters per year [28].

Antarctic Ice-melt

New concerns have arisen within the climate science community that global sea level rise estimates could be underestimated, mostly due to uncertainty around the contributions from melt on Greenland and Antarctica. For example, research from Joughin et al. published in 2014 showed that the collapse of Antarctic glaciers may already be taking place as a result of warm water circulating around Antarctica [94].

[43] Likelihood of the outcome is 90 to 100%.

This destabilization effect of warm ocean currents on Antarctic ice sheets has been echoed in a 2016 study by DeConto and Pollard [95]. When considering this potential for more drastic Antarctic ice melt, global sea level rise projections nearly double previous estimates, suggesting that 6 feet of sea level rise by 2100 is possible [95].

Greenland Ice-melt

Greenland's contribution to global sea level rise is in the form of melt-water runoff and ice discharge from calving glaciers [111]. Future projections based on multiple RCP scenarios predict that Greenland will continue to contribute to global sea level rise beyond 2100, with the high emissions scenario (RCP 8.5) showing significant increases of Greenland ice-melt and corresponding sea level rise throughout the next century [111]. Kopp et al. concluded that global sea level could rise up to 4 feet by 2100 based on the RCP 8.5 scenario; this estimate includes ice-melt from Greenland and Antarctica as well as thermal expansion of water [112].

For more detail on the science behind what is causing additional ice-melt on Greenland and Antarctica, please refer to the chapter on Nonlinear Changes in Climate.

LOCAL SEA LEVEL RISE

Sea level rise projections vary within Washington State due to regional differences in tectonic activity, isostatic rebound, and subsidence rates. Estimates for Port Townsend and Seattle are among those most useful to understand local sea level rise for the Tribe, given the proximity and the long record of observed data from these stations. See Table 8 for projected ranges of sea level rise for years 2050 and 2100.

Table 8. Projected ranges of sea level rise at Port Townsend and Seattle by 2050 and 2100. Ranges reflect modeling based on various emissions scenarios, including a "business as usual" scenario.

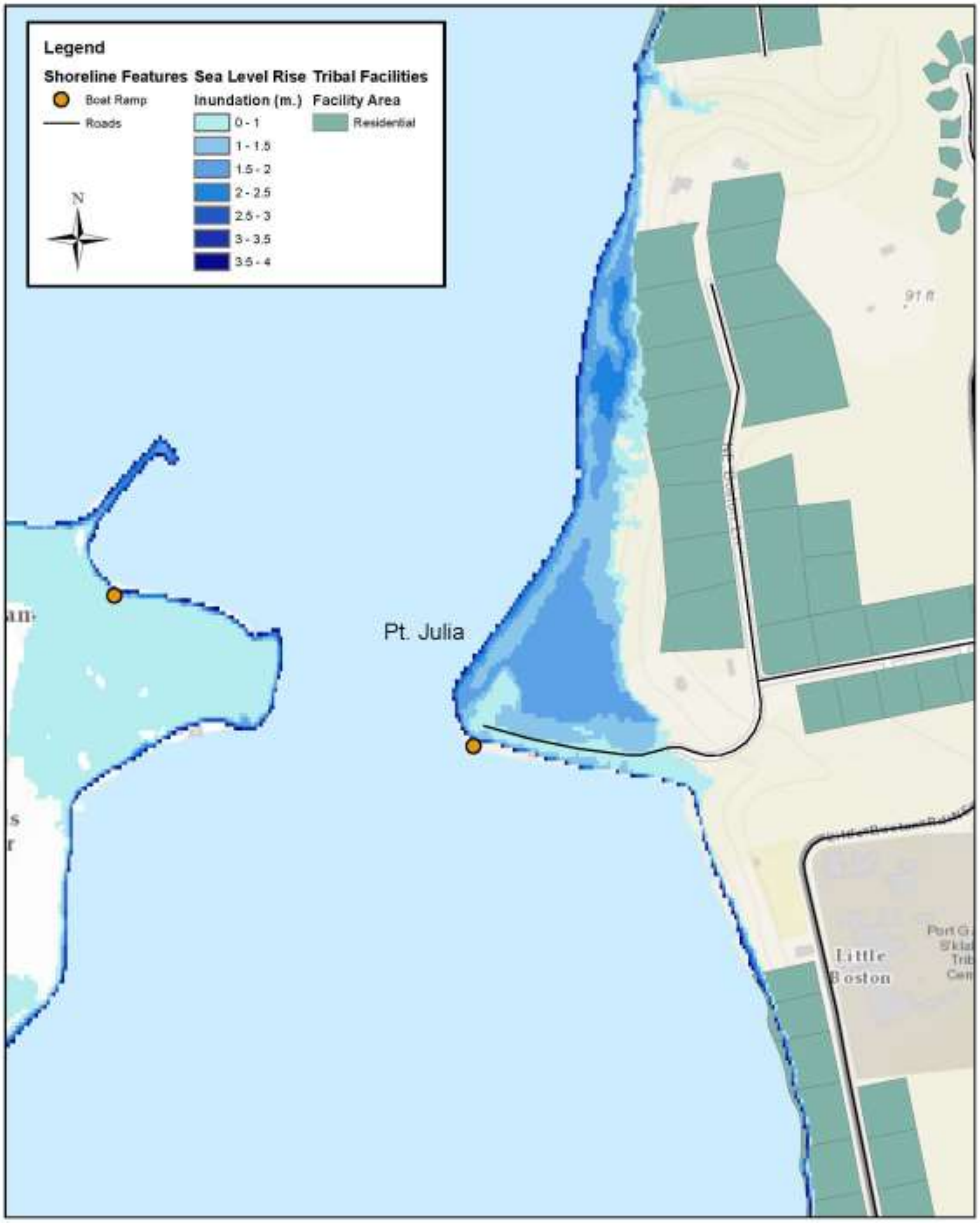
Location	Projected sea level rise by year
Port Townsend [37]	2050: 5 to 18 inches 2100: 12 to 62.5 inches
Seattle [113][44]	2050: 7 to 19 inches 2100: 24 to 56 inches

Changes in local sea level ("relative sea level") reflect changes in global sea level as well as changes in local factors that determine the amount of sea level change at a particular location. King tides and storm surge help to simulate what can be expected in the future. A king tide in the winter of 2015 inundated nearly all of the Point Julia boat launching area (see Figure 20). In addition to inundation, these temporary events give scientists and resource managers a chance to observe what other effects sea level rise may have on bluffs, wetlands, shellfish-harvesting areas, and other important coastal resources [114]. Figure 21 shows expected areas of inundation along the Port Gamble coast with 6 feet of sea level rise.

[44] In Seattle, sea level rose by approximately +9 inches between 1900 and 2008 [46].

Figure 20. Point Julia boat launch inundated during a king tide event in December 2015.
Photo: Hans Daubenberger, Port Gamble S'Klallam Tribe.

Figure 21. Projected inundation of Point Julia and adjacent areas in a scenario with 6 feet (1.83 meters) of sea level rise. The darker blue patch just off the immediate shoreline includes the low-lying wetland area that is directly north of Point Julia Road. This area was flooded during the king tide event in December 2015 (as pictured in Figure 20).



Data Sources: Point No Point Treaty Council and National Oceanic and Atmospheric Administration

The Tribe is currently working with the University of Washington to forecast local relative sea level through 2160, combining regional projections with data from tide gauges and continuous GPS stations in or near Tribal lands. This section will be updated when the new data are available in 2017.

Impacts of Sea Level Rise

Because of variations in the coastal geography of Western Washington, the effects of sea level rise will differ from place to place as well. At many sites, the impacts could include the following:

- **Changes in tidal and intertidal zone habitats:** More than half of beach land in the upper Hood Canal and Kitsap Peninsula is predicted to be lost and converted to tidal flats by 2050 because of sea level rise [115]. Additional detail can be found in the Wetlands chapter. The Tribe is currently working with the University of Washington to better understand potential impacts on local estuaries and the resulting consequences for shellfish habitat.

- **Risk of damage to infrastructure and drainage:** Higher groundwater levels and changing hydraulic gradients in stormwater drainage outfalls can affect coastal aquifers and make it more difficult to drain stormwater and wastewater effluent.

- **Shoreline and bluff erosion:** Storm surges on top of sea level rise will contribute to increased erosion of shorelines. While storm surge is not projected to change, storm surge will reach higher as a result of rising sea levels. Additional information about bluff erosion on and near the reservation can be found in the Infrastructure chapter.

Responses to Sea Level Rise

- **Shoreline armoring:** Some communities and property owners are increasingly armoring shorelines (that is, using physical structures to reduce coastal erosion) to protect infrastructure and development close to the water. Regrettably, this armoring can further degrade habitats and exacerbate beach erosion in areas without armoring, as it disrupts natural coastal processes that sustain beaches and it prevents beaches from moving inland over time.

  Shoreline armoring projects in Washington are permitted through the Washington Department of Fish and Wildlife's (DFW) Hydraulic Project Approval (HPA) process [116]. Immediately preceding a coastal storm event, the DFW can issue emergency HPAs to homeowners that apply for them [116]. To expedite permitting before an event, these emergency HPAs are exempt from the SEPA process (including public comment) [116]. With the potential for more frequent or rapid coastal erosion expected with sea level rise and storm surges, it is possible that the SEPA-exempt emergency HPAs will become more widely used. More research is needed to determine the impacts to coastal habitat that the increased use of emergency HPAs would have.

- **Retreat:** For communities experiencing recurrent flooding and bluff erosion, managed retreat away from hazardous areas is perhaps the only way to completely avoid all risk associated with sea level rise [117]. On Washington's outer coast, the Quinault Tribe has begun the planning phase to relocate its Taholah village to higher ground away from the coast after repeated seawall breaches, intense flooding, and culvert failures from storms in 2014 and 2015 [118].

- **Accommodation:** Accommodating sea level rise includes actions that avoid retreating from the coast but do not change the characteristics of the shoreline and allow sea level rise to occur [119]. In some coastal communities, accommodation can be in the form of elevating structures located in flood zones [119]. The floating bridges, docks, and homes found throughout the Puget Sound region could also be considered a way to accommodate sea level rise [120].

This chapter describes the current understanding of nonlinear responses based on the latest scientific studies. Due to the potential severity of these impacts, and the fact that new, cutting-edge scientific research continues to be underway, it will be important to review the state of the science as often as possible going forward to make sure that we can anticipate and prepare robustly to protect our community, our natural resources, and our livelihoods in the face of these potentially dramatic changes.

Nonlinear Changes in Climate

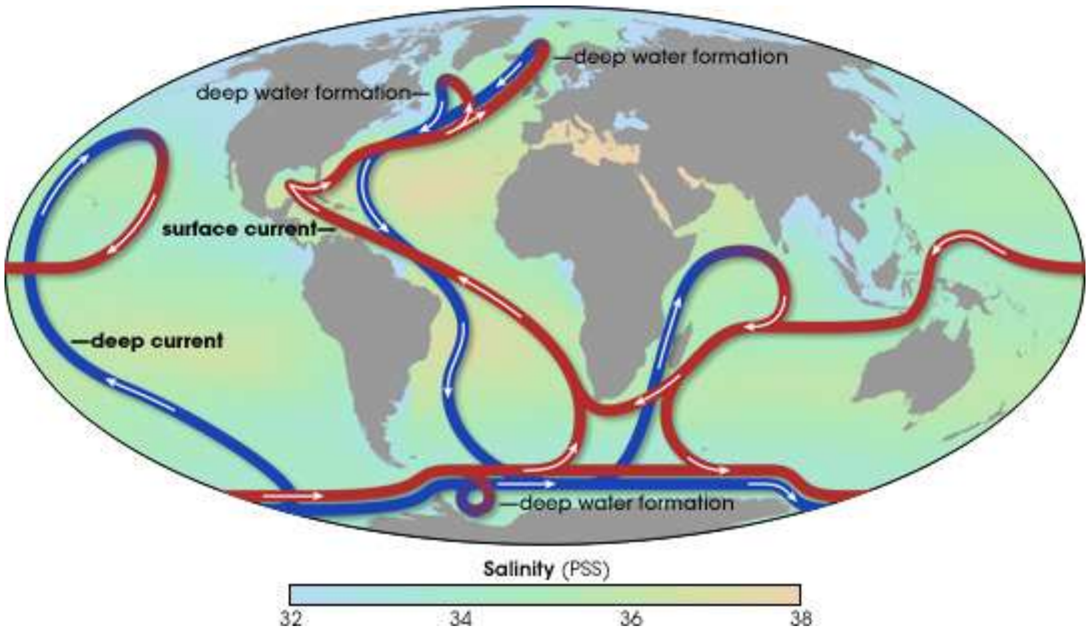
INTRODUCTION

Compounding climate change effects from interdependent subsystems, in addition to the projected impacts from greenhouse gas emissions, may lead to new and difficult-to-predict consequences. Nonlinear system responses could cause abrupt and severe impacts, some of which could cause serious disruptions to human and natural systems [121]. Possible impacts include weakening or collapse of global circulation systems, extreme sea level rise, and gas releases from melting permafrost and warming ocean sediments [121].

CHANGES TO GLOBAL OCEAN CIRCULATION

Deep ocean circulation and currents are driven by differences in water temperature and salinity in the deep ocean and at the ocean surface. In certain areas of the ocean (e.g., near Greenland and Iceland), these differences pull warmer, less dense water into a region as colder, saltier water sinks and gets picked up by deep ocean currents. This circulation, referred to as the thermohaline circulation, shapes global weather patterns by redistributing heat in the global ocean (Figure 22) [121]. The Atlantic Meridional Overturning Circulation (AMOC), which occurs in the North Atlantic, is part of the Atlantic Thermohaline Circulation. The AMOC depends on warm salt water from the mid-latitudes and tropics releasing its heat to the atmosphere in the northern latitudes, which becomes colder and denser and sinks beneath less saline waters [121, 122]. The cold water is replaced by warmer surface water circulating northward from the tropics, and the cycle continues [121].

Figure 22. Thermohaline circulation, the global conveyor belt of ocean currents that influence the Earth's climate [123].



Thermohaline Circulation Slowdown

Slowdowns of deep-sea circulations can have implications for global temperature by interfering with the ability of the oceans to transport heat to northern latitudes. This is a case where the effects of rising temperatures on ice sheets like Greenland and Antarctica can trigger changes in ocean circulation that actually cause a rapid decrease in global temperatures that could disrupt plant productivity and food production in ways that have significant consequences for human communities.

Freshwater Input

The strength of ocean circulation is tied to the rate of freshwater input, which suggests that any major change in the influx of freshwater could significantly alter the functionality of AMOC, in particular by slowing the circulation [124, 125]. Researchers have come to this conclusion after modeling simulations in which increased freshwater input from melting ice sheets around the North Atlantic resulted in a disruption of thermohaline circulation [125]. These simulations could also explain the paleoclimatological evidence of millennial-scale climate variability in the North Atlantic, wherein periods of increased freshwater flow to the North Atlantic caused decreases in ocean circulation [125]. Thermohaline circulation, therefore, seems to be highly sensitive to even small changes in the hydrologic cycle [125]. Increased rainfall in the North Atlantic and the melting of glaciers and sea ice projected by climate models could lower sea surface salinities, possibly halting the sinking of cold, salty water and again altering the functionality of thermohaline circulation by causing it to weaken [126]. It is possible that the weakening of thermohaline circulation has already begun. River discharge into the Arctic Ocean increased by 7% between 1936 and 1999, and the Atlantic Ocean has experienced significant freshening over the past 40 years [127]. Arctic sea ice is melting faster than expected [128], and the influx of this fresh meltwater poses what is arguably the largest threat for disrupting thermohaline circulation.

Observations over the past decade have shown that AMOC has weakened, essentially slowing down, but more analysis is needed to definitively say if this weakening is caused by natural changes in overturning (as suggested by historical models and the paleoclimate record mentioned previously) or is driven by anthropogenic climate change [124]. Research has shown that levels of atmospheric carbon dioxide four times pre-industrial levels (which were approximately 280 ppm) could lead to a near-complete shutdown of circulation [129]. Reaching such high levels of atmospheric carbon dioxide is possible if humans continue emitting greenhouse gases at our current rate [130], which reached 400 ppm for the first time in Earth's history in 2013 [131]. Under a high emissions scenario (RCP 8.5), greenhouse gas emissions will increase three-fold compared to levels in 2000 [132].

Past Disruptions of Ocean Circulation

Previous disturbances in thermohaline circulation were abrupt and dramatic [122, 125]. Melting glaciers approximately 10,000 years ago led to a short-term disruption of the Atlantic thermohaline circulation and subsequent cooling in the North Atlantic region that lasted between 50 and 150 years [133]. Average summer temperatures in that region are thought to have been about 3°F (1.6°C) cooler than before the circulation disruption as a result of these changes [133]. In subtropical areas, the paleoclimate record shows temperatures during a circulation slowdown more than 10,000 years ago were as much as 7°F (4°C) cooler than before the slowdown [134]. Ice cores from Antarctica have shown clearly that previous weakening and breakdowns of these currents have happened but over climate change transitions of tens of thousands of years; the current quick changes over the last hundred years or so are very likely anthropogenic.

Long-term cooling events like those described here present clear evidence of the undeniable relationship between ocean currents and climate and the role of currents as heat-energy distributors around the globe. But more research is needed to determine if changes in the ocean currents-climate dynamic could also result in short-term changes in weather, specifically extreme weather. We know that ocean currents go through natural cycles that alter the sea's surface temperature and lead to mostly predictable climatic variations, such as El Niño and La Niña periods [135]. Therefore, it remains theoretically possible that when disruption of ocean circulation results in changes in heat transfer between the ocean and atmosphere, one consequence could be extreme weather events [135]. A better understanding of ocean physics would allow researchers to answer this question with more confidence.

Another consequence of changes in ocean circulation could be an increase in sea level of up to 31 inches (80 cm), in addition to the sea level rise associated with warming from greenhouse gases [121]. This is caused by a redistribution of mass in the ocean when currents are altered, often resulting in regional sea level changes when only certain parts of circulation are disturbed

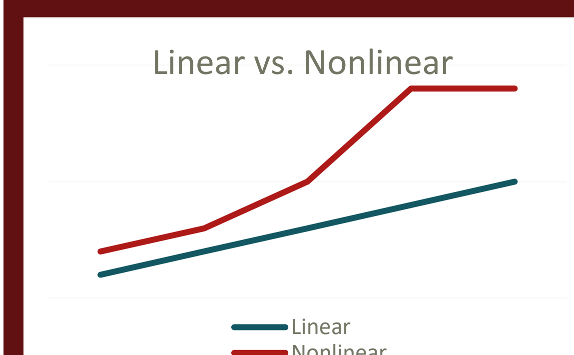
What does "nonlinear" really mean?

Climate models show us what we can expect from incremental increases in atmospheric greenhouse gases and allow us to forecast the impacts of gradual changes in environmental conditions as a result of those greenhouse gases. When represented visually (as in a graph), these gradual changes form a simple linear position (see

Figure 23). However, our climate doesn't always act in a simple, linear fashion. Research shows that certain oceanic and atmospheric systems are quite sensitive to the effects of climate change, in particular global warming, such that dramatic responses to changing conditions can occur rather abruptly once a certain threshold is surpassed. On a graph, these abrupt changes distort a simple linear trend into something nonlinear – as shown in Figure 23.

Therefore, when it comes to climatic change, the term "nonlinear" refers to abrupt, and potentially severe, changes in our climate. These events are often difficult to predict and evidence of their occurrence in the paleoclimate record can sometimes be ambiguous, which in turn makes them difficult to incorporate in modern-day modelling scenarios.

Figure 23. Visual representation of linear and nonlinear data.



[127]. Modeling performed by Knutti and Stocker (2000) found the potential for an additional 19 inches of global average sea level rise during a complete circulation shutdown simulation [136].

Uncertainties

It should be noted that response of thermohaline circulation to the effects of global warming, even with current modeling technology, is relatively unknown [125]. More efforts in simulating the consequences of an abrupt slowdown or complete shutdown of thermohaline circulation are needed [125]. Additionally, a realistic timeframe for a future shutdown of thermohaline circulation has yet to find consensus among researchers. While AMOC has undeniably weakened, some scientists believe a future shutdown would only occur after decades of global warming (while admitting a partial collapse within the next 100 years cannot be ruled out) [137]. Others are more leery of citing a specific timeframe due to the inability of climate models to accurately and confidently simulate past abrupt collapse [138].

If a shutdown occurs, we can expect large-scale cooling to take place in the Northern Hemisphere as was experienced in previous events; however, depending on how much warming was experienced prior to the shutdown, it is possible any such cooling event might simply revert surface air temperatures to levels more in line with pre-industrial levels [137, 139]. Modeling performed by Vellinga and Wood (2008) showed that a thermohaline circulation shutdown in the year 2050 would indeed result in a global temperature decrease for the Northern Hemisphere, but summer temperatures would still remain above pre-industrial levels [137]. Additionally, any such shutdown would likely only be temporary [137, 140]. Modeling simulations show that average temperatures in Northern Hemisphere would cool approximately 14°F (8°C) in some places for the first 50 years after the shutdown, along with reduced precipitation and diminished plant growth (a decrease of 5% world-wide) [140]. Circulation would mostly recover within 100 years, and climatic anomalies would start to disappear [140].

EXTREME SEA LEVEL RISE

Rising seas threaten coastal communities, economies, and ecosystems. A recent study by Hansen et al. (2016) has shown that succeeding in the Paris Agreement's goal of limiting global warming to no more than 2°C (about 4°F) above pre-industrial levels may not be enough to mitigate sea level rise and avoid deleterious ecosystem changes [141]. This conclusion is supported by events in prior interglacial periods, where evidence shows sea level rise of 20 to 30 feet (6 to 9 meters) and extreme storms occurred when Earth was only a little bit warmer than it is today-- less than 1°C (about 2°F) warmer [141]. The Sea Level Rise chapter of this report describes the most recent climate change projections based on linear changes in thermal expansion and ice melt; below we elaborate on those with additional information about nonlinear changes from significant changes to mountain glaciers and the ice sheets in Antarctica and Greenland.

Mountain Glaciers

Ice loss from glaciers and ice caps (ice masses less than 50,000 square kilometers of land area, or roughly the size of Costa Rica) account for 60% of sea level rise unattributed to thermal expansion [142]. This is equal to 0.07 inches (1.8 mm) per year of global sea level rise just from glaciers, and this contribution has accelerated over the past decade [142]. Between 1994 and 2013, Alaska alone lost 75 billion metric tons of ice per year; about 94% of that mass loss came from glaciers located on land and by lakes [143]. Because land-based glacier melt is so closely linked with air temperature, warmer summers will mean those glaciers will melt faster as the climate continues to change.

Given the contributions of glaciers and ice caps to global sea level rise, it has been argued that understanding their changing dynamics and instability as a result of continued warming is perhaps most important for preparing for sea level rise [142].

Antarctica

Ice melting can lead to a variety of cascading consequences for the dynamics of ice sheets (defined as an ice mass greater than 50,000 square kilometers and therefore larger than ice caps), including disintegration [141]. The Antarctic ice sheets produce tens of thousands of icebergs each year, many of which break off from ice shelves—huge masses of floating ice attached to land and created by glacier runoff [144]. In more typical conditions, when an iceberg calves from a shelf, the shelf is pushed seaward by its associated glacier until they can reconnect with the iceberg [145]. Accelerated melting of the icebergs can prevent reconnection from happening though, causing glaciers to increase velocity and bring more ice into the warming sea [146], which would contribute to sea level rise [147]. Recent research shows that parts of the Antarctic ice shelves are experiencing more rapid and frequent calving as a result of melting of the bottom layers of the ice, in and of itself becoming the primary driver of mass loss [148]. Bottom-layer melting accounted for approximately 1,300 gigatons of ice loss from melting per year on the Antarctic ice shelves between 2003 and 2008 [148].

Large Antarctic ice shelves named Larsen A and Larsen B collapsed in 1995 and 2002 respectively [146]. Studies of Larsen B found that the flow of glaciers feeding Larsen B accelerated following the collapse [146, 149]. Researchers are now monitoring a rift in Larsen C that has grown rapidly in recent years and could result in the most significant calving event of the last 30 years (Figure 24) [150]. The collapse of Larsen C would not significantly contribute to global sea level rise, but it is likely that the glaciers behind Larsen C will increase their velocity after the collapse (as seen in prior ice shelf collapses) and make contact with open ocean [147]. As those glaciers melt, they will contribute to sea level rise [147]. Figure 25 shows a photograph of the rift in Larsen C taken in November 2016.

Figure 24. Graphic showing the growing rift in the Larsen C ice shelf with a to-scale size comparison with the country of Wales [151].

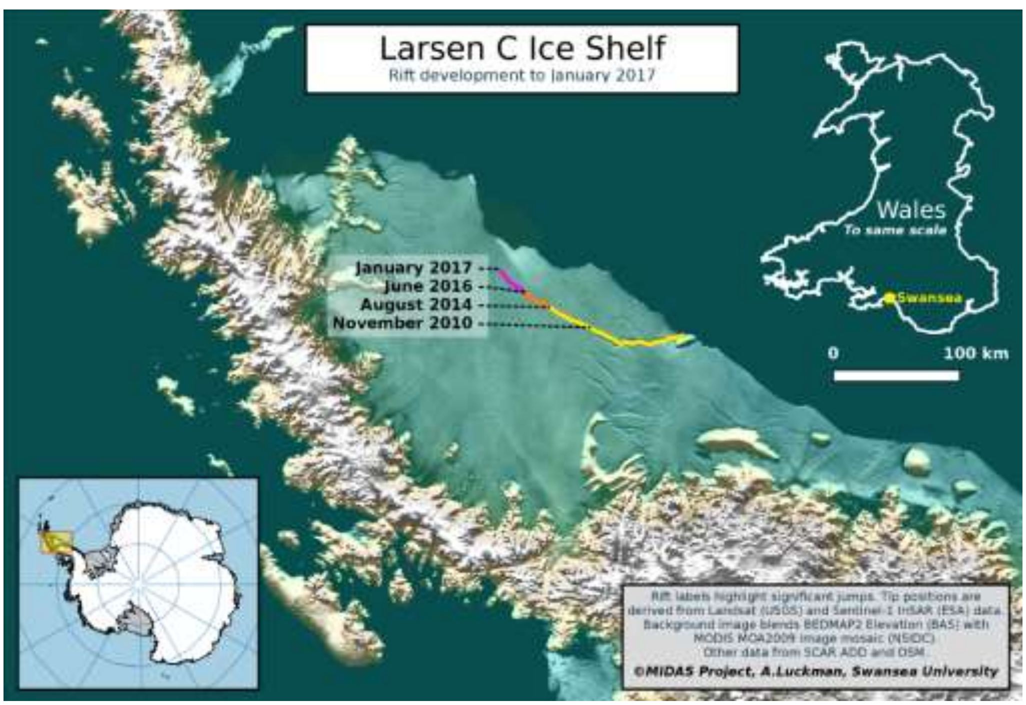


Figure 25. Photograph taken in November 2016 of the Larsen C rift [152].

Advances in satellite altimetry have allowed researchers to better understand the growing instability of West Antarctica, where McMillan et al. found ice losses have increased 31% since 2010 [153]. Global sea level rise resulting from a complete collapse of the West Antarctic Ice Sheet is estimated to be 11 feet (3.3 meters), with slightly higher levels along both the Pacific and Atlantic seaboards of the United States [154].

Greenland

Multiple studies have examined the instability of the Greenland Ice Sheet and its present and potential future contributions to sea level rise [155, 156, 157]. If melted completely, the Greenland Ice Sheet would cause nearly 23 feet of global sea level rise, but a complete melting would likely take thousands of years and reflect no change in our current rate of greenhouse gas emissions [155]. That being said, the Greenland Ice Sheet has recently experienced more surface melting than at any time since 1979 (when monitoring via satellite began), and several of its largest glaciers have doubled their velocities, meaning they will likely drain the Ice Sheet more rapidly [155]. Currently, mass loss from the Greenland Ice Sheet is projected to increase sea level by 1.5 feet by 2100, but this could be underestimated considering the increases in surface melt and glacier velocity [155].

Recent *in situ* observations of Greenland's firn (the layer of snow being compacted into new glacier ice) by Machguth et al. (2016) add to the body of literature explaining how Greenland Ice Sheet instability contributes to sea level rise. Previous studies reported that the porous firn could act as a sponge for melting ice and limit its flow to the sea; however, new evidence shows that ice layers near the surface of the firn prohibit the percolation of water and instead force water to flow seaward [158]. This means that the firn may not help minimize loss of mass as much as previously thought and that the Greenland Ice Sheet's potential future contributions to sea level rise may again be underestimated [158].

Other research using remote sensing has shown that Greenland's glaciers have begun flowing more quickly in the past decade, as mentioned previously [155, 159]. Approximately half of the freshwater discharge from the Greenland Ice Sheet comes through 12 quickly flowing "outlet" glaciers that are fed by the interior ice sheet. Ice shelves attached to the outlet glaciers, often hundreds of feet thick, have started to break apart and may be what has allowed the increased velocity of Greenland's glaciers. It is thought that this increased velocity and the associated discharge of ice may be the result of a longer summer melting season in southern Greenland as a result of global warming [155]. Regardless of what has caused the glaciers to pick up speed, the result has been a net decrease in the amount of ice on Greenland [155].

Ice melt on a the relatively small portion of Greenland below the 70th parallel was responsible for 1 centimeter of sea level rise throughout the entire globe between 1997 and 2003 [155]. Melting of the Greenland Ice Sheet has continued, and, in 2012, a ridge of warm air remained unusually stagnant over Greenland, resulting in melt occurring on more than 98% of the ice sheet's surface—the most extensive melt event on the Greenland Ice Sheet in more than a century [160].

GREENHOUSE GAS RELEASE

Greenhouse gas emissions from anthropogenic sources are well understood, but natural sources (also known as biogenic sources) emit greenhouse gases as well. It is possible that with increased warming, we may see increases in emissions from these biogenic sources, including from permafrost, wetlands, and ocean sediment, which would further contribute to global climate change.

Melting Permafrost

As warmer air causes permafrost to thaw, areas of the poles that have been frozen for millennia will become subject to microbial decomposition, which releases carbon dioxide emissions [161]. Models simulating the thawing of permafrost beginning at the surface predict a net increase in atmospheric carbon levels over the course of several decades [162]. In other words, these models predict that thawing permafrost will release more carbon than can be captured by vegetation elsewhere [162]. Permafrost would no longer help to sequester carbon and mitigate climate change at this point and would instead become a source of carbon dioxide—a dramatic reversal. This shift is likely to take place by the year 2100 for areas north of the 60th parallel (such as the northern territories of Canada, much of Alaska, and virtually all of Greenland and Siberia) [161].

Melting of land ice may result in localized surface collapse in a process called thermokarst, which changes the hydrology of the affected area by allowing surface water to collect in collapsed areas and expedite localized thawing [162]. Permafrost thaw as a result of thermokarst happens much more rapidly (only a few years in some cases) than thawing from warming air temperature alone [162]. Large-scale models that do not consider the influence of thermokarst on permafrost dynamics may be underestimating how quickly thawing will occur [162]. It will also be important to determine the likely extent of areas susceptible to thermokarst. Grosse et al. (2013) found that vast areas of Siberian permafrost are vulnerable to such events [163]. One such area, the Yamal Peninsula, has had at least one major crater formed from the thawing of permafrost—now known as the Yamal Crater, discovered in 2014 (Figure 26) [164].

Figure 26. Scientists descend into the Yamal Crater [165].

Von Deimling et al. (2015) modeled permafrost degradation and carbon dioxide and methane release [166]. Their model included processes such as soil-hydrologic conditions, various warming scenarios controlling the amount of organic matter stored in wetlands and sediments, rates of aerobic and anaerobic carbon release, and a simplified climate carbon model [166]. With increasing warming, the active layer of thaw and carbon release will deepen [166]. Snow cover is an important insulation factor that can protect the permafrost to some degree and keep the thaw layer from deepening as quickly [167], but a lack of snow-cover mapping in the Arctic and the difficulty in predicting future snowfall have precluded it from the model [166].

In any case, the high emissions scenario (RCP 8.5) predicts a sharp increase in permafrost thawing in the second half of the 21st century [166]. It is still largely unclear, however, if any increase in permafrost thawing will be sustained long-term; furthermore, the amount of greenhouse gas emitted from thawing will depend on the decomposability of organic carbon at the thawed area, which can vary from place to place [162]. According to Schuur et al (2015), emissions from permafrost thaw are not expected to outstrip emissions from fossil fuels but could become similar in magnitude. As such, emissions from thawing permafrost are not likely to singularly cause abrupt climate change [162].

Emissions from Wetlands

Historically, wetlands have been considered important in sequestering atmospheric carbon dioxide through the formation of peat (partially decomposed plant material) [168]. Wetlands remove carbon dioxide from the atmosphere and store it in water-logged conditions, but these ecosystems can be susceptible to climate change, such as extensive drought, which jeopardizes their ability to be carbon sinks. [169]. However, it is wetlands' methane contributions that are thought to be most damaging to the climate [170].

Wetlands account for nearly one-third of the world's total methane emissions [171], mainly because moist environments with low oxygen levels are ideal for methane production. As a result, thawing of northern latitude wetlands will increase methane contribution to the atmosphere [161, 170]. However, despite being sources of methane emissions, the ecosystem services provided by wetlands—including being heat sinks in addition to carbon sinks—are thought to outweigh their contributions to atmospheric greenhouse gas over the long-term [172].

Ocean Sediment

Marine sediments in the Arctic Ocean store large quantities of methane, and it is possible that changes in the amount of sea ice or stratification of the water column may affect the long-term storage of that methane [173]. For example, if less sea ice (which tends to inhibit wind speeds over bodies of water) results in higher wind speeds, an increase of sea-air exchange of methane would likely follow [173]. This means that methane trapped underwater from the decomposition of microbial material would have a greater chance of escaping into the atmosphere if winds were allowed to exert more energy on the water surface [173].

Additional research on this topic has found that sediment in some shallow, nearshore areas emits more methane than previously thought [174]. Shallow, well-mixed continental shelves make up approximately one-third of the total continental shelf area, which suggests that methane emissions from marine sediment could be underestimated [174]. As with the other sources, increased methane emissions from ocean sediment would contribute to an acceleration of global climate change.

CONCLUSION

Nonlinear climate change, while still developing as a specialization within the climate science field, allows us to begin to foresee the effects of drastic, abrupt climate change. These effects will likely be in the form of various consequences of disrupted global ocean circulation, extreme sea level rise, and increased greenhouse gas emissions from biogenic sources.

As a result, it is becoming clearer that we need to have a better understanding of nonlinear climate change if we expect to be resilient to such abrupt changes. This concept is especially made apparent in light of the paleoclimate data that show that similar nonlinear changes in the Earth's climate have happened before, with dramatic results. With huge areas of Antarctic ice shelves calving, the weakening of the Atlantic Meridional Overturning Circulation, and the increasing prevalence of thermokarst in Arctic and sub-Arctic permafrost, we seem to be experiencing the beginning phases of a near-future, drastic shift in our climate.

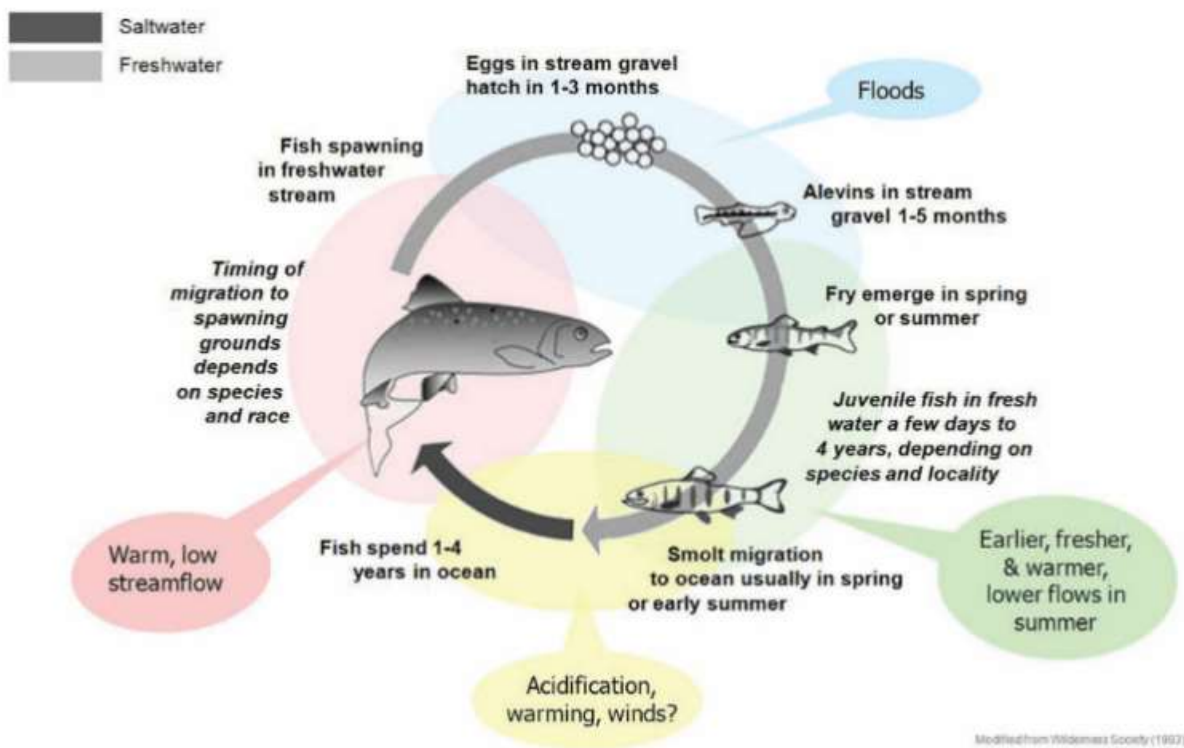
Impacts on Natural Systems

SALMON

INTRODUCTION

Fishing represents a way of life in the Port Gamble S'Klallam Tribe, and the Tribal community depends on salmon for sustenance, income, and cultural identity. Puget Sound salmon stocks are extremely vulnerable to a number of stressors, including shoreline development and armoring, flood control measures, hydropower, deforestation, habitat degradation, hydrologic changes, and overfishing. Climate is an important factor for anadromous fish and their habitats at every stage of their lifecycle (see Figure 27).

Figure 27. Climate change impacts on salmon across the life cycle. Source: University of Washington Climate Impacts Group; modified from Wilderness Society 1993 [175].



As the climate continues to change, drivers that are likely to adversely affect our local salmon populations include warmer water temperatures, lower oxygen levels, increased marine hypoxic events, and changes in streamflow volume and timing. The timing of a selection of climate impacts on life history stages of Chinook and coho salmon are shown in Figure 28. Direct biological effects on salmon include physiological stress, depletion of energy resources, changing prey base, increased susceptibility to predation, competition with invasive species, increases in diseases and pathogens, changes in habitat availability, and barriers to spawning efforts.

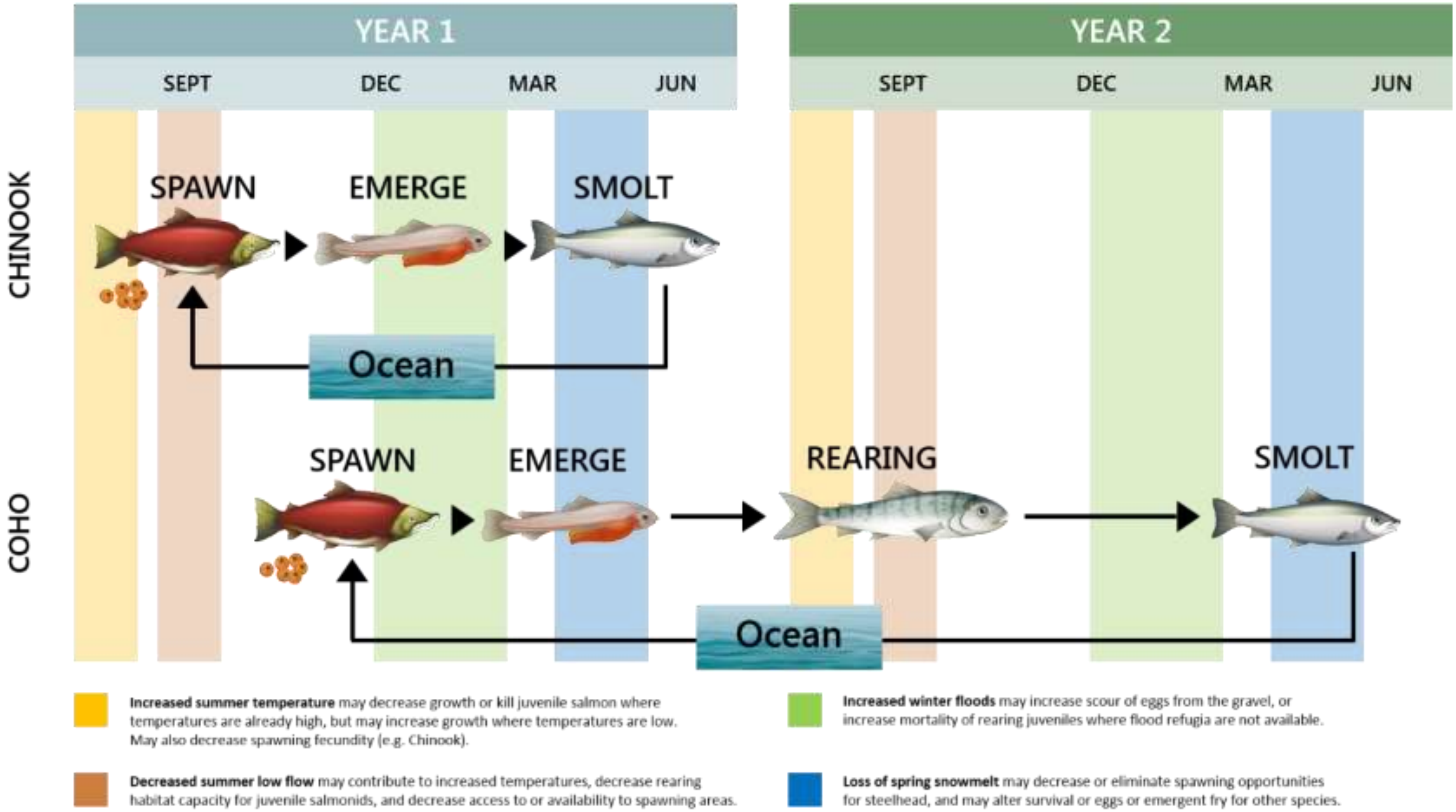
Because of differences in life history and habitat among the different stocks and species of salmon, steelhead, and trout, the same climate events can seem to affect different stocks and species in varying ways, as shown in Table 9.

Table 9. Potential biological vulnerabilities of salmon to changes in water flows and temperatures. Source: Adapted from Nelitz et al. 2007 [176].

Life Stage	Chinook, Coho, Sockeye	Chum, Pink
Eggs	Scouring Stranding Change in hatch timing	Scouring Stranding Change in hatch timing
Fry	Change in growth rates Thermal stress and mortality Oxygen stress Change in prey density Change in competition	Change in growth rates Thermal stress and mortality Oxygen stress Change in prey density Change in competition
Parr	Change in growth rates Thermal stress and mortality Oxygen stress Change in prey density Change in competition	
Smolts	Increased predation and competition Change in growth rates Oxygen stress Delayed outmigration Change in age at outmigration Change in physiological function	
Spawners	Change in run timing Increased disease susceptibility Thermal stress and mortality Reduced food conversion efficiency Increased predation	Change in run timing Increased disease susceptibility Thermal stress and mortality Reduced food conversion efficiency Increased predation

This chapter explores these issues in more detail.

Figure 28. Timing of climate change effects on stream flow and temperature by life history stages of ocean-type Chinook salmon and coho salmon. Source: Adapted from Beechie et al. (2012) with author permission [177].



Threshold Values

Several aspects of water quantity and quality are vital for salmon at all life stages, as they can affect fitness, susceptibility to disease, mortality risk, and other factors [178]. For adult salmon, the seven-day average of the daily maximum temperature is considered lethal around 73°F; meanwhile, migration is reportedly inhibited around 75°F, and the risk of disease increases around 57°F [178].

The following tables show known thresholds and ranges for environmental factors: Table 10 and Table 11 show maximum thermal tolerances for different salmonid life stages and species; Table 12 shows dissolved oxygen thresholds; and Table 13 shows salinity tolerances for salmonids.

Climate change is expected to increase water temperatures, bringing them nearer to—or in some cases over—established threshold levels [178]. For more information on how climate change is expected to affect water temperatures, see the Ocean Temperature section of this chapter. Climate change is also expected to affect sedimentation and dissolved oxygen levels in salmon habitat [178]. For more information on these thresholds, see the Water Quantity and Flow section and the Water Quality section of this chapter. Tolerance levels for pH are not provided here due to a lack of data and because physiological effects of ocean acidification are expected to be minor for most adult salmon. Adult marine fish are effective acid-base regulators due to evolved ion regulation mechanisms in the gills [179], but more research is needed to fully understand the impacts ocean acidification may have on juveniles. See the Ocean Acidification section in this chapter for more information.

Table 10. Water temperature threshold ranges for salmon [180].

Temperature Range	Impact
55.4 – 58.1°F	Optimal range for spawning, rearing, and migrating
59.9 – 67.1°F	Range for increased disease risk in adults
68.9 – 70.7°F	Threshold for adult mortality
>70.7°F	Threshold for juvenile mortality

Table 11. Maximum weekly temperature upper thermal tolerances for salmonids [181].

Species	Upper thermal tolerance
Cutthroat trout (*O. clarki*)	73.9 °F
Rainbow trout (steelhead) (*O. mykiss*)	75.2 °F
Chum salmon (*O. keta*)	67.6 °F
Pink salmon (*O. gorbuscha*)	69.8 °F
Coho salmon (*O. kisutch*)	74.1 °F
Chinook salmon (*O. tshawytscha*)	75.2°F

Table 12. Dissolved oxygen concentration limits for salmonid life stages (mg O2/L) [182].

Effect Level	Embryonic and Larval Life Stages[45]	Other Life Stages
No Impairment	11	8
Slight Impairment	9	6
Moderate Impairment	8	5
Severe Impairment	7	4
Acute Mortality Limit	6	3

Table 13. Salinity tolerances for smolting salmonids [183].

Species	Salinity[46]
Chinook	20 %
Chum	Not available
Sockeye	20 %
Coho	20 %
Pink	Not available

FRESHWATER ISSUES

WATER QUANTITY AND FLOW

Climate change-driven variations in rainfall, decreased snowpack, and increased warming will combine to cause more frequent and more severe extreme flow events in the Northwest's streams and rivers [184]. Changes in flow overall are largely driven by a shift from watersheds dominated by snowmelt and rain/snow mix to watersheds dominated by rainfall and by increased variability of precipitation [184]. Lower summer low-flow events and larger winter floods are projected to become more common in a warming climate; both types of extreme events threaten salmon populations. As summer flow levels drop, water temperatures will increase even further; together, these changes will reduce habitat for salmon [185]. In the winter, other pressures arise: increased streamflow can scour river beds and potentially harm eggs and juveniles (e.g., pushing juveniles out to marine waters too early) [185].

Low-flow Events

Summer low-flow events are predicted to become more widespread and more severe in river basins throughout the Pacific Northwest as summers become drier and hotter [178]. During the summer of 2015, several of the hatcheries operated by the Washington Department of Fish and Wildlife (WDFW) experienced low water levels and high water temperatures, causing a loss of approximately 1.5 million

[45] Assumed 3 mg/L difference between water column concentration and intragravel concentration where eggs and larvae occur.

[46] Under experimental rearing temperature conditions of 50-59°F (10-15°C). Salmon reared at this salinity experienced no reduction in growth rate [183].

juvenile fish [186]. Sockeye salmon in the Columbia River basin encountered lethal temperatures of 76°F in some rivers and streams as they tried to migrate upstream. Thousands of fish died, and many were observed to have signs of bacterial infections [187].

Low streamflows are predicted to have substantial impacts on salmon populations during their freshwater lifecycles [105]. Increased frequency and severity of low-flow events will limit both juvenile salmon attempting to travel downstream to the ocean and adult salmon traveling upstream to spawn [105]. For example, ocean-type Chinook, which use freshwater for spawning during summer months (when streamflow is expected to be lowest), could confront more barriers to spawning with more frequent low-flow events [105]. In some extreme cases, low flows will prevent fish from reaching their spawning grounds [188]. Extreme low flows may also compound the effects of increased water temperatures on salmon that were discussed in the previous section [185].

The increase in low-flow events is attributed to a variety of factors related to climate change, including increased evaporation, reduced springtime snowpack, and reduced summer precipitation [178]. With rising winter temperatures, more winter precipitation will fall as rain rather than snow, which will greatly influence flows in historically snow-dominated watersheds [178]. Warmer spring temperatures will also trigger earlier spring snow melt [185].

Higher summer air temperatures will also directly reduce streamflows by increasing evaporation, especially in wider, shallower channels [189]. It is important to note the feedback loop that exists between evaporation and low streamflows: as evaporation reduces water flows, the water will warm further, making increased evaporation likely [185]. As a result, summer base flows are projected to be lower, and fish will be forced into smaller channels and less diverse habitats [189]. Projected declines in summer precipitation will only exacerbate these conditions. Groundwater contributions and reservoir operations, where relevant, may help offset some of the projected streamflow decline. Further study is needed to quantify the impacts of these potential buffers as well as their reliability as a solution to low-flow events, given that a warmer climate also creates a higher water demand for human uses.

Floods, Washout, and Scouring

A 2015 study by Ward et al. found that over the last half century, river flows in the Pacific Northwest have become more variable [184]. In low-lying areas, this variability may be caused in part by stormwater runoff from developed areas, but variability observed at higher altitudes—in areas with relatively low human impacts—indicates that this change is also driven by larger shifts in weather patterns [184]. Overall, Ward et al. found that while flow variability had a significant negative effect on Chinook population growth, high flows themselves had mixed positive and negative effects [184]. Other studies, however, indicate that high flows during incubation correlate with decreased Chinook salmon return rates, possibly due to scouring or egg suffocation from increased sedimentation [105].

The danger of high-flow events is especially acute for fall- and winter-spawning salmon species [189]. As severe floods start to happen more frequently, gravel scour will increase, leading to greater egg and alevin mortality for fall- and winter-spawning species [189]. Lower flows in summer and autumn will require these species—including Chinook, coho, chum, sockeye, and bull trout—to deposit eggs in the deeper, more central areas of a channel; when high-flow events occur in the winter, incubating eggs and overwintering juvenile fish will be exposed to higher risk of scouring [184]. Increased scouring directly limits population growth by reducing the number of viable eggs that are able to grow into new generations of salmon [184].

While higher winter streamflows are expected to present a number of risks for salmon populations in the Pacific Northwest, there may be some minor benefits. Ward et al. estimated a slight positive relationship between mean winter flow and salmon productivity [184]. The study cited reduced predation on juveniles as a benefit and a possible contributing factor to the increase in productivity [184]. These benefits, however, do not necessarily outweigh the harms of high winter flows.

Sediment Loading and Transport

While human-caused runoff plays an important role in sedimentation of streams and rivers, the projected increase in extreme precipitation due to climate change—and the high-flow or flooding events often caused by extreme precipitation—will also lead to more sedimentation in river and stream beds [185]. The presence of fine sediment in spawning streams can cause salmon eggs or alevins to suffocate by reducing available oxygen [185]. Sedimentation is also likely to reduce the amount of gravel substrate available for spawning [185]. Together, these effects could have a significant effect on the survival of salmon spawn.

A 2009 meta-analysis of sedimentation studies found a linear negative relationship between sediment concentrations and egg-to-fry survival in 34 of 39 studies analyzed [190]. The study found that all sizes of sediment studied had a significant negative impact and that fine sediment is much more detrimental to salmon survival than larger sediment particles [190]. On average, a 1% increase in fine sediment (less than 0.85 mm diameter) decreased survival rates among Chinook, coho, and chum salmon by nearly 17% [190]. The study also found evidence of a threshold effect in Chinook and steelhead survival, in which survival rates dropped to less than 10% when fine sediment concentrations were greater than 25% [190].

WATER QUALITY

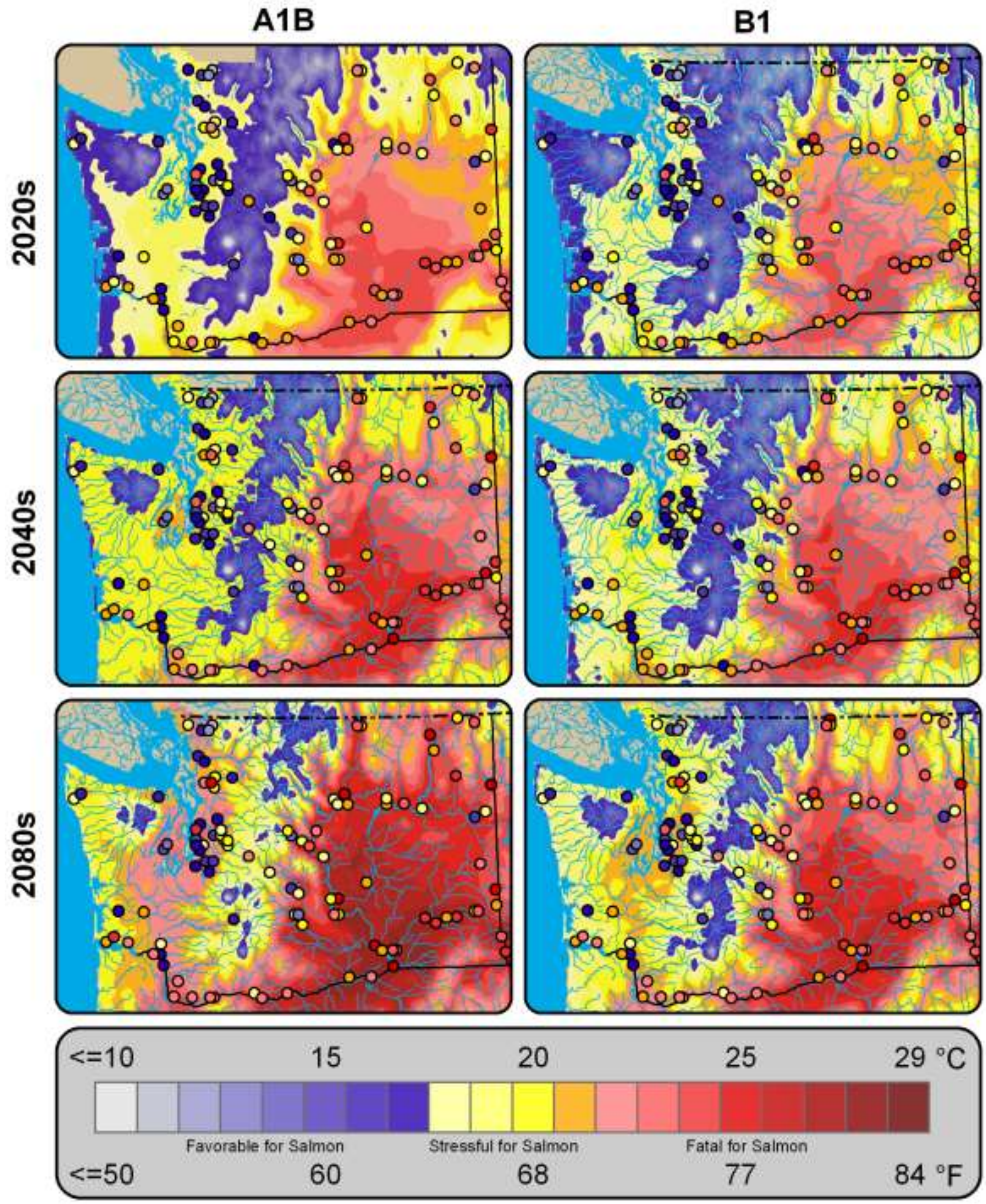
Stream Temperature

The projected rise in stream temperature will likely reduce the reproductive success for some salmon species—particularly stream-type salmon with long freshwater rearing periods [178]. According to Mantua, Tohver, and Hamlet, annual maximum stream temperatures throughout Washington are projected to increase by 3.6 to 9°F by the 2080s [191].[47] By the 2040s, temperature stress is expected to be one of the most dangerous climate-driven pressures on salmon [192]. The danger of rising water temperatures is particularly acute for some salmonid species in the Northwest (e.g., sockeye) that already live in conditions near the upper range of their thermal tolerance [48]. An increase of even a few degrees above optimal range can affect salmon in many ways, including by reducing available oxygen; decreasing growth rates; increasing susceptibility to predators, toxins, and disease; and changing migration timing [188]. Average water temperatures as low as 59°F have been shown to cause increased predation of salmonids and put them at a competitive disadvantage with warm-water fish [178]. Figure 29 shows the increasing August air and water temperatures projected throughout Washington State [191].[48]

[47] Under both A1B and B1 emissions scenarios.

[48] Under both A1B and B1 emissions scenarios.

Figure 29. August mean surface air temperature (colored patches) and maximum stream temperature (dots) in Washington State. Source: University of Washington Climate Impacts Group.



Pacific Northwest salmon with stream-type life histories will be at risk of a range of impacts stemming from increased thermal stress [178]. Higher temperatures can cause physiological stress, depletion of energy reserves, and disruptions to breeding [185]. Summer temperatures could reach, or even exceed, the incipient lethal temperature for salmon; furthermore, rising temperatures will favor non-salmonid species better adapted to warm waters, such as bass, American shad, brook trout, and brown trout—potentially increasing predation and competition in habitats where salmon are already strained by temperature and flow changes [189, 105]. A host of secondary impacts are also likely, including changes in habitat, migration, and in the growth and development of embryos and fry [189].

Impacts on Growth and Juvenile Development

The growth and development of juvenile salmon is most influenced by food supply and water temperature [105]. Embryos and juvenile fish are expected to develop more quickly due to rising winter and spring temperatures [105]. Increases in water temperature have been shown to harm survival through changes in incubation duration of eggs, time of emergence, and migration behavior of juveniles [105].

In winter, warmer water temperatures accelerate embryo development and can cause earlier emergence of fry [189]. Juveniles will continue developing rapidly, possibly resulting in their migrating downstream and entering the ocean earlier in the season, before the plankton they subsist on has reached sufficient levels [185]. Warmer waters will also increase metabolic demands, requiring fry to consume more food to develop properly. Growth rates will suffer if warmer streams cannot provide additional food resources to offset the fry's faster metabolism [189].

Before salmon can safely migrate to the ocean, they must undergo smoltification: changes necessary to allow them to survive in marine waters. Increased temperatures during this phase can block or change the timing of seaward migration, cause premature smoltification, or even reverse the smoltification process to make salmon unable to tolerate saltwater [193]. Temperatures above 53.6 to 59°F have been shown to impair smoltification [193].

Impacts on Spawning

Mature salmon returning to fresh water to spawn are also expected to face challenges due to rising temperatures (marine temperature is discussed in the Marine Issues section of this chapter). In warmer streams, cold-water salmon species experience increased metabolic rates and a decrease in available energy for swimming; the consequences may include delays in upstream migration or a complete failure to spawn. Areas of particularly warm water can create a thermal barrier that migrating salmon must swim around. In some cases, the thermal barrier can prevent migrating salmon from spawning [185]. Mass mortality due to predation, increased disease transmission, or lack of oxygen can occur when these barriers cause salmon to group together in a single area [185].

A 2006 study by Goniea et al. found that average migration rates for fall Chinook salmon in the lower Columbia River tended to slow when water temperatures reached about 68°F; fish were finding refuge in cooler tributaries and waiting until temperatures dropped [188]. Fall Chinook and summer steelhead, which initiate upstream migration in the summer and are listed under the Endangered Species Act (ESA), are vulnerable to higher temperatures and lower streamflows. They will often take refuge in cooler tributaries until temperatures become more tolerable [188]. Similarly, ESA-listed summer chum in Hood Canal are vulnerable because they rely on low-elevation streams that will be altered through warmer temperatures and reduced streamflow [178].

Rising temperatures have also been demonstrated to reduce the quality and viability of gametes (mature sexual reproductive cells, i.e., sperm or eggs) in various fish species, although more research is needed to thoroughly explore these effects in salmonids [194]. The optimal thermal range for salmon spawning falls between 42 and 55°F, and various studies have shown that exposure to temperatures above 55.4°F just prior to or during spawning can harm salmonid gametes, resulting in reduced fertilization rates and lower embryo survival [193].

Rising temperatures are predicted to result in substantial loss of Washington's headwater habitat.

Worst case projections indicate a 22% loss by 2090 under a high emissions scenario [189]. Still, rising temperatures could have a less severe impact in Washington than in Oregon and Idaho, where potential loss of headwater habitat could exceed 40% by 2090 [189].

Impacts from Viral and Bacterial Diseases and Parasites

Salmon are susceptible to several bacterial and viral diseases and to parasites, many of which (though not all) become more virulent as temperatures increase [195]. Higher temperatures significantly raise the risk of fish mortality because thermally stressed fish are less resistant to disease, and pathogen populations multiply and diseases progress more quickly in warm water [195]. As temperatures increase, pathogens that were not historically prevalent could move into the newly warm waters, compounding the other pressures fish will face under changing ocean and freshwater conditions [195]. According to an EPA review of freshwater temperature effects on salmon life stages, freshwater above 60°F (15.6°C) presents a higher risk of mortality related to disease transmission [195].

Some of the diseases expected to thrive under warming conditions include Columnaris (also known as Tail Rot), which causes infections, as well as Furnunculosis (from *Aeromonas* species), which infects the gills and peritoneal cavity, and causes hemorrhaging, tail rot, and liver infections [195]. Holt et al. found that mortality rates for fish infected with Columnaris were between 4% and 20% when the water temperature was at 59.9°F (depending on the species); at 64°F, mortality rates climbed to 52% for juvenile spring Chinook, 92% for steelhead, and 99% for coho salmon [182]. Time to death also tends to accelerate as water temperatures increase [195]. Another study by Groberg et al. found that rising temperatures led to increased mortality and accelerated time to death after infection with *Aeromonas salmonicida* and *Aeromonas hydrophila* for juvenile steelhead, coho, and spring Chinook [196].

A parasite-caused disease, Ichthyophoniasis, has been shown in studies to progress more quickly at higher temperatures; the disease also reduces swimming performance relative to non-infected fish [197]. While this disease is present in several fish species all over the world, it was unknown in Pacific salmon before the mid-1980s [198]. Since then, the disease has appeared in Chinook salmon in the Yukon River in Alaska and now infects more than 40% of returning salmon there [198]. Studies have shown that *Ichthyophonus*, the parasite that causes the disease, is most virulent at temperatures of 59°F and above [198].

Ceratomyxa shasta (C. shasta), a myxosporidian parasite endemic to most rivers in the Pacific Northwest, infects and kills pre-spawning and juvenile salmonids, including spring Chinook, coho, and sockeye salmon as well as other trout species [195, 199]. Studies of *C. shasta* have shown that the likelihood of infection increases when water temperatures are high, flows are low, or numbers of *C. shasta* are relatively high [200]. The disease also progresses more quickly when temperatures are higher [195].

Myxobacteria, a bacterial disease that thrives in warm waters, causes bacterial gill disease and also benefits from low dissolved oxygen [195]. Vibrio (*Listonella*)—generally a saltwater disease, but also present in estuaries—reportedly has optimal growth in waters above 59°F [195]. According to Tribal staff, it causes red spots and dark lesions as well as ulceration and evulsion of the eyes.

Proliferative kidney disease (PKD) has also been demonstrated to thrive in warmer temperatures. Several field and laboratory studies of salmonids in Europe and along the west coast of North America have documented increased prevalence of PKD during summer months in both wild and farmed fish [201]. Temperature is also positively correlated with incubation time and infection severity, wherein fish held at warmer temperatures have developed signs of the disease earlier than fish held at lower temperatures [202]. Furthermore, symptoms of the infection are often more severe at higher temperatures [202].

Bacterial kidney disease (BKD), which can cause high mortality in salmon, can be found in a wide range of water temperatures and appears to be most lethal at otherwise optimal temperatures for salmonids [203]. In an experiment with infected sockeye, coho, and steelhead in a range of temperatures from 39.2 to 68.9°F, the highest mortality was observed at 54°F, with lower mortality at higher and lower temperatures [203]. Therefore, it is possible rising water temperatures may correlate with lower salmon mortality due to bacterial kidney disease.

Dissolved Oxygen

Dissolved oxygen availability in freshwater streams is crucial for salmon and can affect growth and development at all life stages as well as affect feeding, swimming, and reproductive capabilities [180]. Lower levels of available oxygen can decrease salmon fitness by lengthening incubation duration, reducing growth potential and feeding behavior, impeding swimming behavior and fitness, and increasing the likelihood of predation [182]. At higher water temperatures, fish need higher dissolved oxygen levels, which could compound the stressors salmon are likely to encounter in a warming climate [204]. While multiple studies have evaluated the effects of low dissolved oxygen on salmonids [205, 206, 207], missing from the literature is an assessment of low dissolved oxygen on gamete viability. Currently available research most often focuses on the impacts to adult migration and to embryonic and larval stages.

RESEARCH NEED
How do low dissolved oxygen conditions affect gamete viability?

During the embryonic and larval stages, salmonids are highly vulnerable to low levels of dissolved oxygen [208]. Successful incubation requires adequate dissolved oxygen levels in the surrounding waters as well as in the gravel, which are generally considered to have concentrations at least 3 mg/L lower than in the water above [209]. Several studies show that embryo survival is low when dissolved oxygen content is less than 5 mg/L [182]. At sub-optimal concentrations, embryo survival is reduced, and those that do survive can experience problems such as premature or delayed hatching and reduced size [210]. A 2006 study of Snake River fall Chinook salmon eggs in dissolved oxygen levels of 4 mg/L found that they took 6 to 10 days longer to hatch and 24 days longer to emerge than eggs exposed to adequate dissolved oxygen levels [211].

Smoltification also requires adequate dissolved oxygen levels and water temperature [204]. Environments where dissolved oxygen is too low and temperature is too high can delay smoltification, causing salmon to be ill-equipped for saltwater life stages [204].

In a 2010 assessment conducted in California, salmonids were found to avoid areas of low dissolved oxygen [204]. Salmonids that encounter such areas during spawning migration must travel further to avoid these areas or spend more time waiting in more suitable habitats [204]. Since spawning salmon cease feeding once they begin their migration, this extra time spent searching for favorable routes and water conditions reduces energy available for gonad development and spawning [204].

Low dissolved oxygen could also increase exposure to pollutants and toxins in salmon [204]. To compensate for decreased dissolved oxygen concentration, fish increase respiration and water intake through the gills, which increases exposure to toxins present in the water and sediment [204]. Higher water temperatures have also been shown to increase the toxicity of several chemicals and certain heavy metals, further compounding the dangers of increased water temperature for salmonids [193].

Freshwater Acidification

The current literature has focused less on freshwater acidification than ocean acidification. In 2015, however, Ou et al. looked at pink salmon and found that simulations of future increases in carbon dioxide in freshwater adversely affected the growth, olfactory responses, and anti-predator behavior of pink salmon during early development [212].[49] With pink salmon, Ou et al. expect that higher carbon dioxide concentrations in freshwater could make fish emerge from the gravel at the usual time but at a smaller size; predators are more likely to prey on smaller fish [212]. While Ou et al. noted that these findings may not be generalizable to other salmon species, freshwater acidification also seems to diminish predator avoidance behaviors in other salmonids, possibly due to effects on olfactory sensitivity [212].

MARINE ISSUES

Predicting the effects of climate change on salmon in marine environments is much more challenging than for freshwater. Information about the behavior patterns of salmon in marine environments is limited, and uncertainties remain about how marine ecosystems will be affected by climate change [185]. However, a range of direct and indirect impacts on salmonids in open-ocean ecosystems have been projected [213]. These impacts, described below, stem predominantly from climate-driven increases in water temperature and acidity.

OCEAN TEMPERATURE

Warming ocean temperatures in the North Pacific—a principal foraging and overwintering region for most stocks of Pacific salmon—are projected to reshape, and possibly dramatically reduce, the open ocean habitat of salmon [213]. Some studies have identified a potential northward shift of the warmest thermal boundary for salmonids by the middle of the 21st century [214, 215]. Such a shift would have considerable impacts on salmon by reducing suitable habitat, particularly during summer months [216]. However, Abdul-Aziz et al. note that salmon could adapt to changes in marine temperature in various ways, including through acclimation, evolution, or changes in migration timing or routes [216].

Impacts on Nearshore and Marine Habitat

Under a moderate emissions scenario (A1B), Abdul-Aziz et al. project that by 2100, North Pacific summer habitat will decrease 86% for Chinook; 45% for sockeye; 36% for steelhead; and approximately 30% for coho, pink, and chum (compared to 1980 levels) due to warmer temperatures [216]. Projected winter habitat for sockeye is also anticipated to decrease by over one-third [216].

Nearshore and estuarine habitats are also at risk from rising water temperatures, in addition to risks from sea level rise and changes in freshwater flows [216]. These ecosystems play a critical role for salmon and

[49] Freshwater CO_2 concentrations of 1,000 and 2,000 µatm were used to simulate end-of century projections for atmospheric CO_2 conditions.

steelhead, which can spend up to a few months in them to acclimate as they transition from freshwater streams to open ocean [216].

Eelgrass, which provides habitat and forage for salmon and other marine species, could be impacted by several climate-related changes [217]. Eelgrass distribution could be altered as a result of increased sedimentation, disturbance of the substrate, reduced light availability, increased water temperature, nutrient loading, pollution, and introduction of invasive species [217]. On the other hand, increased dissolved carbon dioxide concentration benefits eelgrass by increasing rates of photosynthesis and productivity [218]. More study is needed to fully understand the potential effects of climate change on eelgrass.

Impacts on Feeding and Predation

Increased ocean temperatures could have direct physiological effects on salmon, and may reduce their survivability by altering the marine food web [188]. Increased sea surface temperatures could increase metabolic costs to salmon, reducing growth and fitness [219]. One study on juvenile Chinook salmon along the coasts of Washington and Oregon found that warmer ocean conditions increased metabolic demands, leading salmon to consume 30% more food; however, even in these circumstances, salmon were smaller and had lower return rates than those in cold-ocean regimes [220]. A study on the effects of increased atmospheric carbon dioxide on sockeye salmon also predicted that adult Fraser salmon would be smaller and less abundant [219]. On the other hand, in their summary of published literature, Beamish et al. write that ocean warming could expand feeding areas by allowing salmon to spread into new northern waters [213].

RESEARCH NEED

How will coastal hypoxia change in the Pacific Northwest as a result of climate change?

Marine temperature changes also have the potential to increase predation of salmon, as warmer waters could bring more predators such as Pacific hake and mackerel to the region [213]. These temperature increases may also reduce the number of other smaller fish in newly warmed areas, leading predators to rely more heavily on salmon [185].

Dissolved oxygen

Salmonid metabolic demands require highly oxygenated waters [182]. Salmonids have maximal swimming fitness when the daily minimum dissolved oxygen levels are above 8 or 9 mg of dissolved oxygen per liter of water (mg/L) [182]. Canadian water quality guidelines for the protection of aquatic life recommend minimum concentrations of dissolved oxygen of 8 mg/L in marine and estuarine waters [221]. Growth, food conversion efficiency, and swimming performance are reduced at dissolved oxygen concentrations below 5 mg/L [222]. Even concentrations above hypoxic levels (generally defined as less than 2 mg/L) can be dangerous to salmon: lethal impacts begin to occur when dissolved oxygen concentrations fall below 3 mg/L for longer than 3.5 days [182, 223].

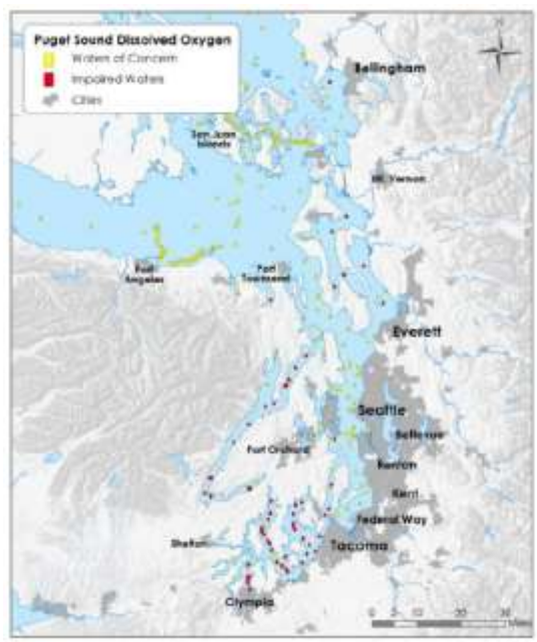


Figure 30. Areas with low dissolved oxygen (impaired waters) or waters of concern, based on a 2012 water quality assessment. Source: Washington State Department of Ecology [225].

Increased water temperature decreases dissolved oxygen [223]. As a result, climate change is predicted to increase the likelihood of hypoxia through temperature changes as well as through seasonal variations in coastal wind and upwelling patterns that bring hypoxic waters from lower depths to nearshore zones [223]. Hood Canal, in particular, has had longstanding issues with hypoxia due to a combination of nutrient runoff and geography that makes water exchange and circulation difficult [224]. Areas of low dissolved oxygen in Puget Sound and Hood Canal are shown in Figure 30 and Figure 31.

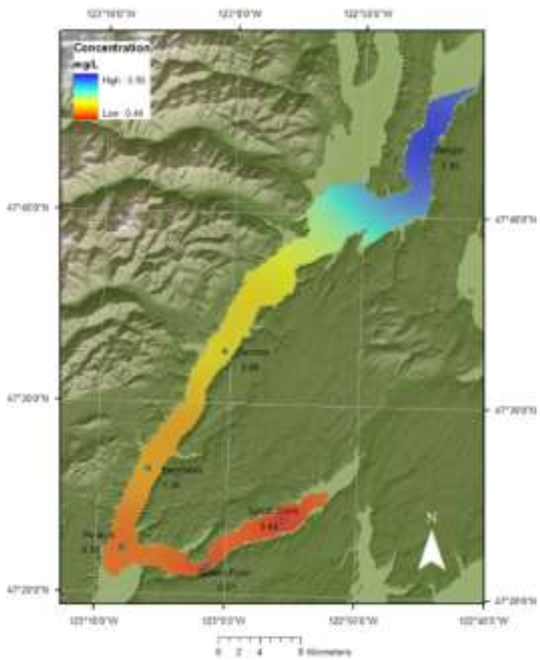


Figure 31. Measured and interpolated oxygen concentrations in Hood Canal, August 2006. Source: Hood Canal Dissolved Oxygen Program (HCDOP) citizen monitoring data and UW Spatial Analysis Lab projection [226].

Hypoxia has already resulted in massive die-offs of marine fish and invertebrates in the Pacific Northwest [223]. For species that are poorly adapted to such conditions, hypoxia can directly change behavior and reduce growth, reproductive success, and survivability [223].

OCEAN ACIDIFICATION

Few studies have researched the direct effects of projected ocean acidification on Pacific salmon species or on the ability of Pacific salmon to adapt to decreased aquatic pH levels. Studies on tropical reef fish demonstrate reduced growth, behavioral changes, and decreased survival; however, less research has been done on impacts on fish in temperate areas [227].

Studies of other types of fish, such as Atlantic cod (*Gadus morhua*), suggest that fish with high ion regulatory capacity will be able to tolerate water with lower pH levels [228, 229]. However, Ou et al. found that elevated carbon dioxide levels in seawater negatively affected the growth rates of pink salmon after they migrated to marine environments [212]. The study also noted that nearshore marine environments, where pink salmon live and grow before migrating offshore, may have highly variable acidification levels [212]. Additional research is needed on other salmon species and on the cumulative and interactive effects of climate change because ocean acidification will occur in concert with other changes to the marine environment [230].

Salmon are also likely to experience impacts from ocean acidification through food web interactions [227]. Pteropods are an important part of the marine food web and a large source of food for several fish species including juvenile pink salmon, as well as chum and sockeye salmon [230]. Pteropod populations are expected to decline as a result of ocean acidification [230]. In addition to potential reductions in available prey for some salmon species, pteropod declines could cause other species that rely on them to shift predation toward juvenile salmon [227].

For more information on ocean acidification trends and projections, see the Observed and Projected Climate Changes chapter.

HARMFUL ALGAL BLOOMS

Pacific salmon could also be negatively affected by a changing climate through increased harmful algal blooms (HABs) [227].

In particular, HABs can harm salmon through the several toxic algae species that thrive under low oxygen and lower pH marine conditions. *Heterosigma akashiwo*, a toxic algae species, has killed millions of wild and aquaculture salmon in Puget Sound since the mid-1970s [231] and thrives under increased dissolved carbon dioxide concentrations [227]. The diatoms *Chaetoceros concavicornis* and *Chaetoceros convolutus*, which cause salmon mortality through gill damage, also thrive during HABs [232].

In a study of coho salmon that were administered domoic acid (produced by the phytoplankton *Pseudo-nitzchia*) orally, the salmon showed no observable neurological effects and passed the toxin through their kidneys and bile [233]. The study also found that while most of the acid is passed without causing symptoms, some of the toxin remains in the tissue for several days [233]. This asymptomatic condition means that fish might be able to continue feeding during toxic blooms; in doing so, they would continue to accumulate and pass on the toxin through the food web. Salmon only exhibited neurotoxic symptoms when injected with domoic acid rather than through oral gavage methods designed to mimic natural exposure [233].

Refer to the Harmful Algal Blooms chapter for more information on HAB causes and projected impacts to other ecosystems and species.

LOOKING AHEAD

Based on the climate science projections and the review of relevant literature, Tribal staff concluded the following about possible changes for Hood Canal salmon populations:

- **Change in development timing:** Current recovery could backslide due to earlier intergravel egg development, earlier emergence, and earlier outmigration. If salmonid food sources are not readily available, salmon may grow more slowly and be more vulnerable to predation.

- **Increased pathogens and disease:** Higher temperatures could trigger many issues, such as elevated pathogen vulnerability and respiratory stress. Disease outbreaks may therefore increase. Respiratory stress in adults could reduce egg—and possibly sperm—viability, which could lead to reduced spawn-to-fry survivals. If non-viable eggs become a source for the fungus *saprolegnia*, this could suffocate adjacent live eggs. Meanwhile, respiratory stress in juveniles could increase vulnerability to predation and reduce growth rates, both of which would further affect survival.

- **Lethal temperatures / dissolved oxygen exposure:** Direct mortality is likely to occur, especially during times of severe drought.

Interviews

Experts interviewed for this chapter agreed that coho and stream Chinook, which spend more time in freshwater, will likely be hardest hit by climate change impacts in Puget Sound. They will have fewer migration options as streams heat up, and their eggs will be vulnerable to increased winter flooding events.

Salmon are likely to remain available for income and sustenance, but some species will be more readily available than others. Interviewees expected that warm-adapted species like chum and pinks would be less vulnerable. Washington could look more like California does now, where temperatures are warmer and salmon populations are still stable.

There were somewhat differing opinions on steelhead, with one interviewee indicating that they are relatively tolerant of warmer waters and another interviewee noting that some tributaries could become unsuitable for steelhead.

> "Tribes may have to be flexible in what they expect from salmon populations. For example, there may not be large king salmon available in the future, so they may have to rely on pinks, chum, etc. I expect that biomass will still be adequate but will likely consist of different species than what is currently relied upon.
>
> "It is important to note that salmon are already stressed due to anthropogenic impacts such as pollution, habitat disconnection due to development, and water withdrawals. As a result, salmon populations already have reduced resilience to climate variability. Habitat restoration is vital to increase natural resilience."
>
> **Lisa Crozier, Research Ecologist**

Some locations will be affected more than others; for example, streams in already rain-dominated systems will be less affected than streams that will see a shift from snow to rain.

In terms of timing, interviewees expected to see more impacts on salmon within the next 30 to 40 years. One noted that it will take a while for the climate change signal to dominate natural variability in salmon populations; the most severe impacts and rapid population declines will happen when extreme natural variability overlaps with climate change.

Habitat restoration efforts—such as riparian restoration projects that increase shading of streams as well as floodplain reconnection projects—are already important today and will also help to increase resilience to climate change impacts in the future. For example, well-connected floodplains with diverse channels and different flow and temperature regimes give salmon more options for migration, rearing, and protection from flushing.

One interviewee also noted that more data would help inform consideration of climate impacts during restoration planning. For example, mapping thermal refugia and deploying more thermographs in particular watersheds would help identify high priority locations for restoration actions.

> "I expect we will be seeing regular impacts on salmon by the 2050s and 2060s. We might see shifts in distribution with climate change, but not a complete loss of salmon. The diversity of life histories has given salmon lots of ways to deal with climate variability."
>
> **Tim Beechie, Research Fish Biologist, NOAA**

FORAGE FISH AND CRITICAL PREY

INTRODUCTION

Forage fish play a critical role in marine ecosystems and are culturally and economically vital for the Port Gamble S'Klallam Tribe. Not only do they serve as a source of food and income, they also form a critical link in the marine food web between plankton and other fish, marine mammals, and birds [234]. Forage fish are found in every marine nearshore habitat in Washington state—the most common being Pacific herring (*Clupea pallasii*), surf smelt (*Hypomesus pretiosus*), and Pacific sand lance (*Ammodytes hexapterus*) [234]. According to the Tribe's Natural Resources staff, other important species of forage fish and critical prey for the Tribe include northern anchovy (*Engraulis mordax*), plainfin midshipman (*Porichthys notatus*), and three-spined stickleback (*Gasterosteus aculeatus*).

There are significant knowledge gaps in terms of forage fish abundance, assemblage, and their roles in marine ecosystems [234]. Most of the research and monitoring conducted in Puget Sound has focused on Pacific herring, while comparatively little has been directed to Pacific sand lance, surf smelt, northern anchovy, and others [234]. Most of what is known about forage fish and their lifecycles is related to spawning, which occurs in nearshore marine habitats [234].

Forage fish are vulnerable to several climate stressors. Impacts that could likely affect forage fish include increased water temperatures [235], lower dissolved oxygen levels in nearshore habitat [236], reductions in suitable habitat [237], predator and prey lifecycle event asynchrony [238], and sea level rise [46]. However, the vulnerability of forage fish to such impacts is less than certain due to a lack of knowledge regarding the lifecycles of many forage fish species.

MARINE ISSUES

Forage fish and other critical prey species live in marine ecosystems, which will be affected by climate change primarily through changes in sea surface temperature, altered upwelling patterns, lower dissolved oxygen, increases in harmful algal blooms, reduced spawning habitat, changes in zooplankton community, and increasing acidity [46].

Table 14 lists known optimal temperature, salinity, and dissolved oxygen ranges for forage fish and other critical prey species. Thresholds for some species and thresholds for pH were not found in the literature review.

Table 14. Critical thresholds for forage fish and other critical prey species

Species	Temperature	Salinity	Dissolved oxygen
Pacific herring	40 – 68°F 41 – 50°F (spawning) [239]	0 – 35 ppt 8 – 28 ppt (spawning) [239]	Moderate to high
Pacific sand lance	28 – 75°F [240]	---	---
Surf smelt	---	---	---
Northern anchovy	44 – 85°F [241]	---	---
Plainfin midshipman	---	>15 ppt [242]	---
Three-spined stickleback	---	---	---

The remainder of this section describes potential impacts on forage fish health, reproduction, and survival as a result of projected changes in climatic conditions.

SURVIVAL AND SPAWNING

Ocean Temperature

Ocean temperatures in the Northeast Pacific are projected to increase by around 2.2°F by the 2040s [46]. Warmer water is directly stressful to cold water fish, including herring and anchovy, and could cause fish populations to shift northward in search of suitable habitat [243]. Spawning and smaller juvenile cohorts of herring have already been observed shifting north in Washington, a trend that could continue as waters warm [243]. Shallow water spawning areas are likely to be more heavily influenced by air temperatures [243].

RESEARCH NEED: What are the sub-lethal effects of temperature increases, and how do they affect salmon survival?

Temperature also directly controls the rates of metabolic processes in fish, which impact swimming, digestion, and enzyme activity. Warm temperatures increase these rates and can be stressful, especially for larvae and juvenile fish [244]. Temperature also controls incubation time for eggs, with warmer temperatures resulting in shorter incubation times and earlier hatching [240]. More research is needed to better understand the relationship between temperature and growth to further project potential impacts on forage fish as the climate changes.

Dissolved Oxygen

Higher water temperatures will also result in less dissolved oxygen. Pacific herring require moderate to high levels of dissolved oxygen for survival [245], while other species, such as sand lance and midshipman, can withstand hypoxic conditions at least temporarily as they are often exposed to air at low tide [240]. Sand lance in particular can withstand temporary dissolved oxygen concentrations as low as 2 ml/L when they are buried and dormant in exposed sand [240].

Low dissolved oxygen concentrations have been demonstrated in studies to increase incubation time and egg mortality; in one study on sand lance, eggs failed to hatch at concentrations of 2.1 ppm [240]. Another study on herring egg incubation found that the minimum dissolved oxygen requirement at egg surface was 2.5 mg/ml [246].

Salinity

Several species of forage fish are euryhaline, meaning that they can tolerate a wide range of salinities [240]. Still, at spawning times, optimal salinities can be more restricted than the full range of adult tolerance in some species [240]. Because different species of forage fish and different stocks within species spawn at different times in Puget Sound, the impacts of any changes in salinity on forage fish (e.g., via changes in freshwater streamflow into estuaries, changes in evaporation rates, and changes in sea ice) will vary. More research is needed to determine what these specific impacts could be.

Changes in water temperature and salinity, as well as projected delayed and shorter upwelling patterns, all have the potential to impact forage fish at various life stages, although the timing, scale, and interaction of these changes is uncertain [243]. One study found that increased water temperature was associated with slower growth and higher mortality [246]. The age of irreversible starvation after forage fish consumed their yolk-sac decreased from 8.5 days at a water temperature of 43°F to 6 days at a temperature of 50°F [246].

FOOD WEBS

Forage fish serve a critical function in the marine food web by transferring energy between trophic levels [245]. Growing pressure from climate change, in addition to commercial fishing and other anthropogenic stressors, could have ripple effects not only for forage fish populations, but also for the larger marine food web [245]. In an example of potential implications of reduced forage fish productivity, an analysis of forty years of inconsistently sampled catch data showed that individual basins within Puget Sound have shown divergent trends in species composition and forage fish population abundance [245]. Central and south Puget Sound exhibited greater differences from historic conditions than northern basins (Whidbey and Rosario) [245]. These basins also experienced large increases in the proportion of jellyfish catches, while northern basin catches remained fish-dominant with higher fish species richness [245]. According to Greene et al. (2015), jellyfish have fewer predators than fish, and the shift to jellyfish abundance could indicate a truncated food web with little energy transfer to higher trophic levels and reduced capacity to support forage fish [245]. While this particular trend was better explained by anthropogenic stressors (population density) than by climatic drivers, an increase in jellyfish populations worldwide is hypothesized to be linked to climate change [247].

Using the A2 climate change scenario, various food web and predator-prey models do show changes in the structure of coastal marine food webs [248]. More specifically, they show that future food webs could be composed of smaller species and become highly disconnected, which would likely impact overall ecosystem functionality [248].

Harmful Algal Blooms

Forage fish feed on planktonic organisms and therefore are already exposed to negative impacts from harmful algal blooms (HABs). HABs are predicted to worsen under changing climate conditions and warmer ocean temperatures (more information can be found in the Harmful Algal Blooms chapter). Paralytic shellfish toxins have been detected in several forage fish species such as anchovy and herring [249], which have served as vectors for domoic acid toxin transfer to higher levels of the food web, resulting in the death of birds and marine mammals [250].

Ocean Acidification

Little research has been done on the direct effects that ocean acidification will have on forage fish; however, it will likely indirectly impact them through their main sources of food. Forage fish feed primarily on plankton; copepods are a primary food source for sand lance, herring, and surf smelt and are negatively impacted by ocean acidification [240, 251]. While this could potentially lead to increased competition for less food, more research needs to be done on the complex food web interactions to understand the cascading impacts of ocean acidification on forage and other fish species [252].

Predation

Predation is also a major factor affecting the abundance of herring and other forage fish [253]. Pacific hake, whose current northernmost distribution extends to British Columbia, prey on several species of forage fish [254]. However, as temperatures warm, hake could move farther north and increase predation on herring and other fish stocks [254].

PATHOLOGY

Diseases of Concern

Temperature plays a key role in regulating physiological processes related to disease susceptibility and progression in fish [251]. Common pathogens affecting Pacific herring and other forage fish in Puget Sound are *Ichthyophonus hoferi*, the viral hemorrhagic septicemia virus, and the erythrocytic necrosis virus [251]. *Ichthyophonus hoferi* is a parasite that causes heart and liver lesions in several species of fish, including Pacific herring and surf smelt [255]. While more research needs to be done on possible linkages between climate change and increased prevalence of these marine diseases, a synthesis of the current literature found increased infection prevalence, disease progression, and mortality on different fish species at elevated temperatures, as well as decreased swimming ability [255].

Susceptibility to disease can also be impacted by other external factors, such as exposure to hydrocarbons and other chemicals in water and sediments [256]. More research is needed on how these concurrent factors, many of which could become worse as the human population of the Puget Sound area grows, will exacerbate the impacts of climate change on forage fish, as well as their predators at higher trophic levels.

SHORELINE ISSUES

CRITICAL HABITAT

Most of what is known about the lifecycle of forage fish focuses on spawning stages when they are present in the nearshore environment [234]. Forage fish are found in every marine and estuarine nearshore habitat in Puget Sound, and various species of forage fish have different habitat requirements and use different areas of beach and intertidal zones for spawning at different times of the year [234].

Figure 32. Forage fish spawning location map [257].

Figure 32 shows spawning and holding areas for several forage fish species near the Port Gamble S'Klallam reservation.

Eelgrass beds, which are favored by forage fish species for spawning and egg deposition, are also under threat from non-climate stressors such as shoreline development and armoring, as well as climate change impacts like sea level rise and temperature change [258]. Optimal Puget Sound eelgrass growth conditions include temperatures between 41 and 46°F and high salinity [217]. Lower spring streamflows and increased water acidity (and thus carbon dioxide availability) have the potential to increase eelgrass productivity [217]. However, increased water temperature and reduced sunlight for photosynthesis as water depth increases or epiphyte growth increases could negatively impact productivity [217]. More research is needed to better understand the impacts of climate change on this type of forage fish habitat.

The most common forage fish species in Washington—Pacific herring, surf smelt, and sand lance—as well as plainfin midshipman all utilize nearshore zones and beaches for spawning [234]. Other forage fish species such as northern anchovy do not spawn on beaches but spend parts of their life in nearshore habitat and thus are also vulnerable to impacts to these areas [234].

Figure 33. Herring eggs deposited on eelgrass [251].

Pacific herring utilize the shallow subtidal and lower intertidal zones of sheltered bays, inlets, sounds, and estuaries for spawning rather than open coastlines [234]. Herring deposit their eggs primarily on eelgrass, as well as algae substrates and some other types of marine vegetation (see Figure 33) [234]. Sand lance and surf smelt both spawn on beaches [234]. Surf smelt spawn in the upper intertidal areas of beaches with coarse sand and gravel [259]. They deposit eggs a few inches deep in the sand, which adhere to the sand granules while they incubate [256]. Sand lance spawn on fine sand and gravel beaches by burrowing and depositing eggs in the sand and also spend parts of their life dormant, burrowing into the sand (see Figure 34). They also appear to spawn in the habitat they spend their lifecycles in without migrating [240].

Nearshore ecosystems, including intertidal areas and estuaries, are among the most threatened environments with regard to climate change [261]. As a result, the possibility of the loss of spawning grounds for forage fish is likely.

Figure 34. Pacific sand lance burrowing into the sand [260].

IMPACTS FROM HUMAN DEVELOPMENT

The construction of structures like docks, bulkheads, houses, and roads, as well as activities like shipping, logging, and aquaculture along Washington's coast, is not uncommon and can threaten forage fish with loss of spawning habitat [262]. Removal of vegetation, dredging, beach grooming, and especially shoreline armoring (see the following section for more discussion on this issue) can all change the quality and quantity of sediment available for spawning [234]. Disruptions of these ecosystems and natural processes can not only destroy critical habitat such as beach and eelgrass beds, but also change predator-prey relationships and disrupt fish behavior [263].

Shoreline Armoring in Response to Sea Level Rise

Sea level rise has the potential to adversely impact forage fish and other critical prey species by directly reducing habitat available for spawning, especially where shoreline armoring restricts inland migration of intertidal habitat [264]. Sea level in the Puget Sound region will vary from place to place depending on local rates of vertical land motion. See the Observed and Projected Climate Changes chapter for detailed projections.

In response to rising sea levels, some communities are increasing shoreline armoring to protect infrastructure and development close to the water (see Figure 35) [265]. Shoreline armoring disrupts natural processes of wave and sedimentation patterns and, because the beach cannot move inland, causes further beach erosion and habitat degradation [265]. As water levels come closer to the armoring infrastructure, critical beach habitat will be lost for several forage fish species [265]. According to a study on the impacts of sea level rise on surf smelt and sand lance habitat, since much of Puget Sound shoreline is already armored and armoring will likely increase with rising sea levels, extensive habitat loss has occurred and is likely to continue to occur in the next few decades, and most spawning habitat could disappear by 2100 [266].

Figure 35. Seahurst Park Seawall in Burien. Photo credit: John Ryan / KUOW [267]

LOOKING AHEAD

Forage fish serve a critical function for marine ecosystems and are a source of prey for other important species such as salmon, pinnipeds, and birds. Since comparatively little is known about these species in general, further research is necessary to assess their populations and the risks posed to them by climate change.

Puget Sound has 2,500 miles of shoreline, yet only 760 miles have been surveyed for forage fish. In 2015, Governor Inslee signed a bill initiating a comprehensive study of forage fish in Puget Sound, including spawning habitat and mid-water trawl surveys [268]. The results will provide more information about these species as well as help develop conservation and adaptation strategies [268]. The study is due to be completed by mid-2017 [268]. This may, in addition, help resource managers evaluate whether various species of forage fish should be considered threatened or endangered under the Endangered Species Act (ESA). For example, while past petitions to list Puget Sound herring stocks found that such stocks were not threatened or endangered, future monitoring will be needed to assess altering conditions due to climate change that may impact forage fish enough to warrant a listing under the ESA.

SHELLFISH

INTRODUCTION

For thousands of years, the Port Gamble S'Klallam Tribe has depended upon shellfish as a source of food and as a resource for income, trade, and ceremonial purposes. In the 1855 Point No Point Treaty, the Tribe reserved the right to continue to harvest shellfish from usual and accustomed areas. A 1994 U.S. District Court decision established that Tribes have the right to take up to 50% of the harvestable shellfish—clams (including cockles and geoduck), oysters, crab, shrimp, sea urchins, and sea cucumber—on western Washington beaches and state-owned aquatic lands. Today, the Port Gamble S'Klallam Tribe still relies heavily on the harvest of clams, oysters, crab, and shrimp for subsistence and ceremonial purposes [269].

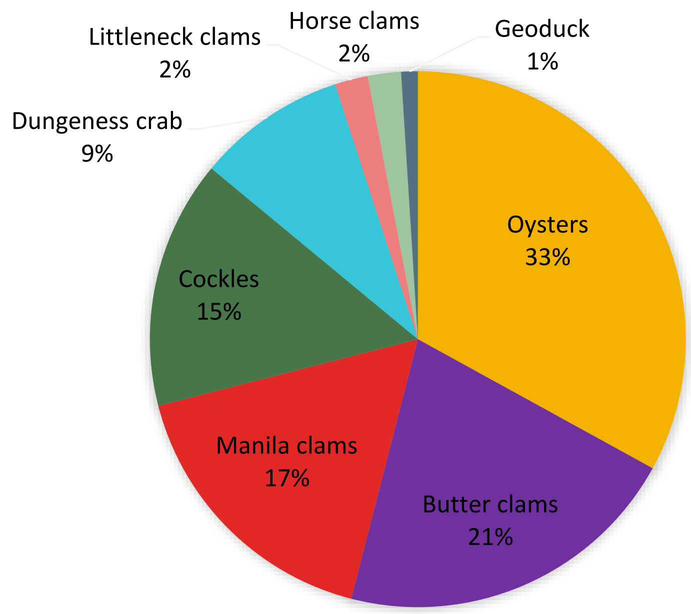
Even before the impacts of a warming climate became known, the Tribe already faced challenges in its shellfish harvests. The population of some wild shellfish species has been reduced through stressors such as habitat loss from development, pollution, eutrophication (often associated with nutrient pollution via runoff from urban and agricultural lands), and overfishing [270]. Climate change and ocean acidification now pose significant additional stress on top of these existing pressures.

IMPORTANCE OF SHELLFISH TO TRIBAL SUBSISTENCE, CULTURE, AND ECONOMY

Shellfish are a vital part of many Tribal members' diets. In 2014, the Tribe recorded a total of 192 members engaged in shellfish harvesting—most of whom harvested multiple species. This number is down from 2013, which saw 213 members engaged in shellfish harvests. Between 2005 and 2014, the most popularly harvested shellfish species among Port Gamble S'Klallam Tribal members was the Manila clam, followed by crab and oyster. Figure 36 shows the 2014 subsistence harvest by species.[50]

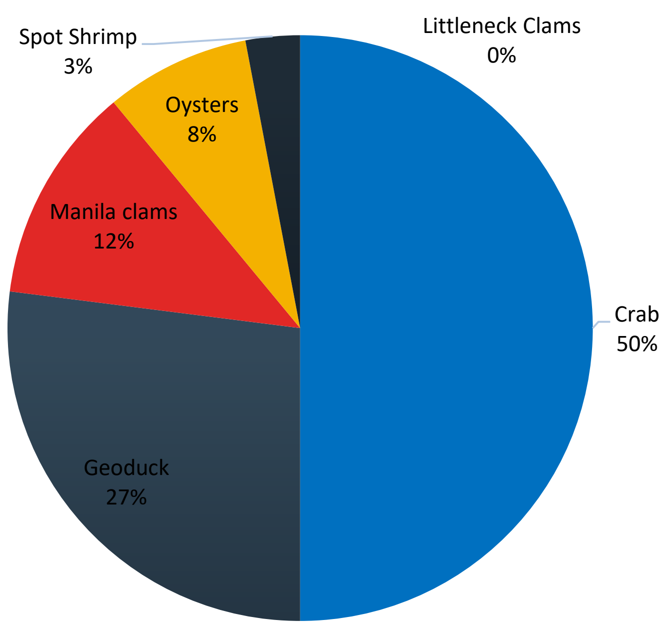
[50] It should be noted that these numbers are based on what is reported to the Tribe. 100% accurate subsistence numbers are not available given gaps in reporting from Tribal members.

Figure 36. PGST 2014 subsistence shellfish harvest.



In addition to subsistence, shellfish harvests are an important source of income for Port Gamble S'Klallam Tribal members. Statewide, the economic value of commercial shellfish is approximately $270 million [271]. For the Port Gamble S'Klallam Tribe, the most economically important shellfish species are Dungeness crab, geoduck, Manila clams, oysters, littleneck clams, and spot shrimp. Figure 37 shows the 2014 commercial shellfish harvest by species.

Figure 37. PGST 2014 commercial shellfish harvest.



RESEARCH NEED: What are some potential benefits of warmer water temperatures to shellfish in Puget Sound?

Climate change effects such as warming water and air temperatures, sea level rise, more extreme weather events, and the associated issue of ocean acidification (particularly eutrophication-induced local acidification) have the potential for direct impacts on shellfish populations, habitat, and harvesting opportunities for the Port Gamble S'Klallam Tribe. These and other changes consistent with what is expected with climate change have already been observed throughout Western Washington and the Puget Sound region—including on the Tribe's reservation and usual and accustomed areas—and are predicted to become even more severe over the coming decades due to rising greenhouse gases [46]. This chapter details the impacts that climate change is projected to have on shellfish in the Puget Sound region, including harmful algal blooms, ocean acidification, hypoxia, and habitat loss or change. Table 15 lists the optimal temperature, salinity, and pH ranges for those shellfish species important to PGST.

Table 15. Optimal temperature, salinity, and pH ranges for shellfish species that are ecologically and economically important to PGST [272, 273, 274, 275, 276, 277, 278, 279, 280, 281].

Species	Temperature	Salinity	pH
Pacific oyster	50 – 85°F	10 – 30 ppt.	8.0 – 9.0
Olympia oyster	56 – 65°F	15 – 35 ppt.	8.0 – 9.0
Cockles	50 – 69°F	20 – 30 ppt.	6.5 – 8.5
Geoduck	43 – 61°F	27.5 – 32.5 ppt.	6.8 – 8.5
Manila clam	53 – 64°F	20 – 30 ppt.	6.5 – 8.5
Butter clam	---	---	---
Littleneck clam	50 – 59°F	27 – 32 ppt.	---
Horse clam	40 – 64.4°F	27 – 33 ppt.	---
Dungeness crab	53 – 60°F for mating. 48 – 60°F for egg brooding. 50 – 57°F for larvae. 50 – 60°F for adults.	25 – 30 ppt.	7.1 – 8.0
Shrimp	45 – 54°F	25.2 – 30.8 ppt.	7.6 – 8.1

WATER TEMPERATURE INCREASES

Temperature is an important factor influencing the physiology and development of shellfish species, as their body temperature and metabolism fluctuates with temperature variations [282]. Warming water temperatures will likely result in changing rates of growth, development, and productivity for shellfish; spatial shifts of marine life, increases in the number of hypoxic zones, and an increase in harmful algal blooms that can threaten human health will also occur [283].

Warmer water temperatures may provide certain benefits to some shellfish species. According to the Washington Department of Fish and Wildlife (WDFW), Pacific oysters, specifically, are most likely to have a successful spawning period when water temperatures reach 65°F [284]. As a result, warmer water temperatures could generate a longer spawning period for Pacific oysters and similar species.[51] A 2016 study by Valdez and Ruesink found that Pacific oyster recruitment in Hood Canal increased between 1942 and 1992, and correlated with increasing average July/August temperatures over the same timeframe [285]. However, studies on the response of Pacific oysters to extreme heat shocks of 98°F show that oysters, especially post-spawning oysters, have limited adaptability to extreme temperatures, often resulting in mortality [286]. Extensive research has been conducted around summer mortality of juvenile oysters as well, showing mortality can occur at temperatures of 64°F [287]. This suggests that any benefits of warmer temperatures to the Pacific oyster are restricted to a certain temperature range, and will end once temperatures become too high. Research is needed to determine if there are any potential benefits of a warming climate for the other shellfish species important to the Tribe.

RESEARCH NEED: Is it possible for shellfish species important to the Tribe to become acclimated to warm water and see reduced levels of toxicity that would otherwise be caused by HABs?

HARMFUL ALGAL BLOOMS

Harmful algal blooms (HABs) can cause a range of environmental effects and are expected to increase in scope and frequency under future climate regimes that project continued warming [288]. Some HABs produce toxins that can accumulate in filter-feeding shellfish. These toxins can then be passed through the food chain, leading to a variety of illnesses or even death when consumed by humans. Some research suggests that these toxins can also have certain physiological and behavioral impacts on marine invertebrates, such as reduced filtration capacity or inability for some mussels to create byssus threads [289, 290]. Additionally, the decomposition of algal blooms, toxic or non-toxic, can lead to decreases in dissolved oxygen with varying implications for shellfish and other marine life [291]. Information on the other impacts of HABs can be found in the Harmful Algal Blooms chapter.

Shellfish Poisoning

The most common human health risk associated with HABs is paralytic shellfish poisoning (PSP) [292]. PSP is spread to humans who eat filter-feeding shellfish that have accumulated toxins produced by the algae [293]. Although the accumulated toxins in shellfish are not thought to harm the health of the shellfish, these toxins can have varying health impacts on humans and animals that consume them. In Puget Sound, *Alexandrium catenella* is most often associated with the creation of these toxins, collectively referred to as paralytic shellfish toxins (PSTs) [288].

PSP is signified by a number of physiological responses that can begin nearly immediately after consumption of contaminated shellfish [293]. PSP reactions usually include tingling around the mouth that progresses to a numbness that spreads through the face and neck [294]. More severe symptoms include incoherent speech, loss of coordination of limbs, general weakness, muscular paralysis, and even death [295]. Up to 75% of victims in severe cases who do not receive supportive treatment die within twelve hours [294].

[51] This does not assume that Pacific oysters will indeed spawn more, only that the period in which Pacific oysters can spawn is likely to increase with warmer waters. This does not account for how other climate impacts may affect Pacific oyster reproduction.

PSP is not the only type of shellfish poisoning present in the Puget Sound region. Other biotoxin-induced poisonings include diarrhetic shellfish poisoning (DSP), from toxins also attributed to HABs, have been recorded in South Puget Sound and Sequim Bay, where three people were treated for DSP after eating toxic mussels harvested there [296]. These toxins have been found in Hood Canal as well [297]. Much like PSP, DSP is caused by consuming shellfish that have accumulated toxins from HABs, in this case those consisting of the dinoflagellate *Dinophysis* [298]. Symptoms of DSP include acute gastrointestinal distress, such as nausea, abdominal pain, and vomiting, which can last up to 72 hours with supportive treatment [299]. Clams and oysters, which accounted for 20% of PGST's commercial shellfish harvest and 75% of the subsistence harvest in 2014, are among the most common transvectors of PSP and DSP.

Phytoplankton blooms also carry the threat of causing amnesic shellfish poisoning (ASP) in humans. ASP is caused by consuming shellfish that have accumulated domoic acid, a biotoxin produced by the diatom *Pseudo-nitzschia* [300]. As with PSP and DSP, the species of shellfish commonly found in Puget Sound are often transvectors of ASP. According to a 2004 study by Jeffery et al., domoic acid has been observed to accumulate in a broad range of invertebrates, including cockles, crabs, and clams [300]. Each of these species are important to the subsistence and economic vitality of the Port Gamble S'Klallam Tribe. The Washington State Department of Health reported that ASP is characterized by both gastrointestinal and, in severe cases, neurological issues including permanent short-term memory loss, seizures, and possibly death [301]. Diatom blooms responsible for the creation of domoic acid are thought to be increasing in frequency and toxicity world-wide [302], and studies indicate that this growth is triggered by climate change-related impacts such as increasing sea surface temperatures and altered weather patterns [303].

When HAB conditions for shellfish toxins are monitored, dangerous recorded levels can lead to closures of shellfish beds and beaches. This can disrupt commercial and subsistence harvesting activities and result in varying degrees of economic losses, health concerns, and the unavailability of shellfish for subsistence and ceremonial uses. For example, closures have occurred in various waterways in Puget Sound as a result of domoic acid found in commercial shellfish with accumulated levels of the toxin above the regulated limit of 20 ppm [304]. In June 2015, nearly all of the recreational shellfish beaches along Hood Canal were closed or under advisory because of toxins [305]. A study by Moore et al. published in 2009 examined closures occurring in Puget Sound from 1993 to 2007 and found that closures were often preceded by periods of warm air and water temperatures, and low streamflow [293]. These conditions correlated specifically with higher levels of PSTs in Puget Sound during that timeframe, and climate projections indicate that such conditions will become more common [293]. However, a study conducted in 2015 by Farrell et al. showed that some species of shellfish, when acclimated to warmer water temperatures (71°F and warmer), were significantly less toxic after being exposed to PSTs [306].

This suggests that future climate scenarios may favor the development of HABs, but some shellfish may be able to adapt to the increased water temperatures and maintain low levels of toxicity.[52] It also showcases the need for more advanced HAB monitoring technologies, in particular those that can conduct streamlined detection of harmful algae and provide early warnings of changing conditions. One such system is being developed by NOAA's Northwest Fisheries Science Center and is called the Environmental Sample Processor (ESP) [307]. ESP performs on-site, automatic water sampling to remotely detect toxins produced by harmful algae [307].

[52] It should be noted that there are species-specific differences in biotoxin uptake rates and detoxification rates, including how biotoxins are stored within bivalves and any physiological or behavioral effects that happen as a result [658].

Hypoxia from HABs

HABs can also indirectly harm shellfish by increasing cases of hypoxia (when oxygen levels become too low to support marine life). In cases where HABs create excess organic matter that decomposes and causes reductions in dissolved oxygen levels, massive fish and shellfish kills can happen as a result [308]. More mobile invertebrates, like Dungeness crab, show particular sensitivity to hypoxic zones, having been shown to avoid hypoxic areas even if food is present [309].

Currently, relatively few cases of hypoxia directly related to high biomass HABs have been documented in the United States [270]. However, the apparent linkages between climate change, HABs, and stratification of coastal waters suggest that hypoxia could become more prevalent in the future. Together, the projected increases in hypoxic zones, if realized, would prove to have significant impacts on shellfish populations in Puget Sound, and consequently adverse economic impacts on those dependent on shellfish for their livelihoods.

For more information, see the chapter on Harmful Algal Blooms.

VIBRIO

The presence of naturally occurring *Vibrio spp.*, like PSP and DSP due to HABs, are associated with increasing water temperatures. *Vibrio spp.* are a type of marine bacteria that can cause vibriosis, a gastrointestinal illness usually contracted from exposure to seawater or consumption of raw or undercooked shellfish and other seafood [310]. *Vibrio parahaemolyticus and V. vulnificus* pose a significant variety of risks to humans in Washington State, including gastroenteritis, bullous lesions, and death [310]. As with other toxins, the detection of *Vibrio* in coastal habitats can force the closure of shellfish beds and beaches [311].

The State of Washington has enacted a control plan in an effort to prevent oysters contaminated with *Vibrio* from reaching consumers [312]. The plan applies to all oyster harvesters during the months of May through September, and places stringent requirements on harvesters to monitor water and internal oyster temperature and to abide by specific conveyance and cooling methods triggered by temperature thresholds [312]. Oyster harvesting is completely prohibited during July and August whenever water or oyster-tissue temperatures reach 70°F; prohibitions last for twenty-four hours, and are extended at twenty-four hour intervals until temperatures fall below 70°F [312].

A 2012 study done by Newton et al. showed that vibriosis cases have increased in the U.S. over the past decade [313]. From 1996 to 2010, Washington, along with seven other states, was categorized as "high incidence" for reported cases of vibriosis [313]. Increasing water temperatures over the same timeframe may provide an explanation: a study done by Won Kim et al. (2012) showed that *Vibrio* growth is highly dependent upon temperature, with growth occurring at water temperatures of 52°F and above [314]. According to water temperature tracking data produced by NOAA, average summer time water temperatures in Puget Sound range from 53 to 55°F [315].

Research done by Chae et al. in 2009 showed that temperature also affects shellfish depuration (the discharge of contaminants) for reducing *Vibrio*, where depuration capabilities are diminished in oysters at water temperatures above 59°F [316]. Because temperature projections for the Pacific Northwest show continued increases in temperature, *Vibrio* may develop at an accelerated speed and expand in geographic scope to more northern latitudes, as well as diminish the capacity of shellfish to depurate the bacteria once contaminated.

Temperature is not the only driver of *Vibrio* growth. Salinity is an important factor in creating favorable conditions for *Vibrio* growth as well, and may be influenced in nearshore zones and estuaries by sea level rise, freshwater input, and changing precipitation patterns [317].

SPECIES DISTRIBUTION

RESEARCH NEED: What are the potential distributional effects on specific Puget Sound shellfish species due to warmer waters?

Warmer waters have the potential to affect species distribution as warm-water species' habitat range is expanded and cold-water species' habitat range is diminished [318]. The most dramatic impacts will be felt in northern latitudes, where water bodies are characterized by historically cooler seawater. One observed example of the redistribution of species resulting from warming water temperatures in Puget Sound is the growth of dinoflagellates, specifically *Alexandrium*, since the late 1950s [319]. Burrowing shrimp are also thought to be becoming more prevalent in this region, particularly in Willapa Bay [320]. The burrowing activity of these shrimps disrupts the sediment within intertidal zones used for oyster harvesting, and can result in the smothering and subsequent loss of oyster beds [321]. The increased occurrence of burrowing shrimp reported by shellfish harvesters could be linked to warmer-than-average water temperatures, which are favorable by some species of burrowing shrimps [322]. Some shellfish harvesters also attribute the prohibited use of the pesticide imidacloprid to recent infestations [320].

Warmer water temperatures may dramatically impact the physiology of marine life. Warming water temperatures affect many species' metabolism, growth, and reproduction, which can lead to further alterations in their geographic distribution [323]. Numerous studies point to the relationship between climate change and the distribution of particular species [324, 325]. Still, it is difficult to project the potential distributional effects on specific Puget Sound shellfish species, given the limited species-specific research on this topic and the potential for additive stresses from multiple environmental variables.

Invasive Species

There is potential for warming water temperatures to facilitate the introduction of nonnative, invasive species to Puget Sound shellfish habitats. One such example is the increasing prevalence of invasive tunicates in Hood Canal and across Puget Sound [326]. Invasive tunicates are a fouling organism, meaning they have the ability to attach to the surface of material immersed in water. They also have a wide tolerance to environmental variables, long breeding periods, and exhibit rapid growth [327]. These facts suggest that future attributes of Puget Sound described in climate projections (increasing water temperature and rates of salinity) may allow for invasive tunicate population expansion.

According to Cordell et al. (2013), invasive tunicates are currently presenting challenges for shellfish harvesters in Puget Sound given their tendency to appear on man-made structures used during harvesting operations, like floating docks or aquaculture facilities [328]. Additionally, invasive tunicates can impede shellfish harvesting because they have the ability to "overgrow" other fouling organisms like oysters and clams, suffocating them [328]. Figure 38 shows invasive tunicates found on mussels in Puget Sound.

Figure 38. Tunicates attached to mussels in Puget Sound [329].

Other invasive species of concern that have been recorded in Western Washington include the New Zealand mud snail and European green crab [330], as well as the Japanese oyster drill [331]. Varnish clams have been growing in number around Washington State for the past ten years, and can be harvested recreationally [332]. More research needs to be done to determine any potential ecological impacts [332].

New Zealand mud snails can survive in a variety of water temperatures and salinity, suggesting that the species will be able to adapt easily to the warmer waters predicted in climate projections for Puget Sound. While it is unclear how damaging these mud snails are to the physiological health of native shellfish, they do present a potential threat to habitat as it is very difficult to eradicate the mud snails once they have been established without causing further damage to the water body [333].

European green crabs prey on small oysters and clams, and have recently been found in Westcott Bay (San Juan Island) [334]. They can tolerate varying rates of salinity and temperatures from 32 to 90°F, meaning that they can continue to thrive even as other species are stressed by warming waters [335]. Additionally, green crabs pose threats to commercial shellfish harvests of clams, oysters, and mussels in Puget Sound, where estimated future losses vary from 3% to 64% depending on green crab population densities [336].

Another prominent example of the impact invasive species may have on shellfish populations is the Japanese oyster drill (*Ocinebrellus inoratus*). These snails feed on shellfish after "drilling" a small hole in the outer shell of a mollusk in order to insert their radula and extract the soft tissue (thereby killing the animal) [331]. Recent efforts (2013) between Washington tribes and the USDA have begun to address the threat these snails pose to shellfish harvests [331]. Oyster drills are most common in areas with low freshwater input (higher salinities) and higher temperatures [337]. They are often attracted to naturally-formed Pacific oyster reefs—given the protection from predators and abundant food source [338]. Oyster drill management typically includes manual removal of adult drills and egg capsules, but complete removal of drills from oyster beds has proven difficult—leading to the closure of some oyster beds due to extensive predation [338].

It should be noted that invasive species are often spread by means that are unrelated to climate change (e.g., recreational boats or commercial ships). However, once an invasive species has established itself in the new environment, the lack of natural predators and the potential for increasingly beneficial conditions created by climate change could allow for rapid population growth.

RESEARCH NEED: Are there specific traits that make an organism more resilient to ocean acidification, and can the development of these traits be predicted?

OCEAN ACIDIFICATION

Ocean acidification—a direct consequence of increased atmospheric carbon dioxide—carries the potential to severely impact shellfish populations in Puget Sound as pH levels lower. Current measurements of dissolved carbon dioxide in Puget Sound, as published in the *Blue Ribbon Panel Report on Ocean Acidification*, indicate that local water bodies, including Hood Canal, have been at corrosive levels for many calcifying organisms since recording began in 2008 [339]. Higher levels of dissolved carbon dioxide are likely to threaten some shellfish populations by diminishing their ability to form shells [339]. According to a 2009 study by Ries et al., the most negatively impacted species include clams and oysters [340]. However, the researchers found that calcification by other species, such as crabs and shrimp, was not impacted by the rates of dissolved carbon dioxide that proved problematic for other types of shellfish [340]. Crabs, in particular, appear more resilient to ocean acidification by their ability to regulate pH as they are building their shells [340]. There is a large and emerging literature on the effects of ocean acidification on marine organisms generally, as impacts are likely to be severe and long-lasting.

For more information on ocean acidification trends and projections, see the Observed and Projected Climate Changes chapter.

IMPACTS ON SHELL CALCIFICATION

The increase in hydrogen changes in carbonate chemistry associated with ocean acidification inhibits the calcification process for some shellfish species [341]. Increased levels of hydrogen reduce the amount of calcium carbonate available for organisms with calcium-based shells, thereby impacting shellfish throughout their entire life cycle [342]. Higher levels of acidification driven by anthropogenic carbon emissions have been projected to develop within decades, a much faster rate than previously thought [343]. These projections are based on current global emissions rates, which have been replicated in both laboratory and field studies that found such emissions create pH conditions in seawater capable of dissolving the shells of calcifying pteropods [343].

The impact of ocean acidification on shell calcification has already been observed in the Pacific Northwest. A study conducted in 2012 by Barton et al. attributed Pacific oyster declines and impacts on larval development to poor water quality from natural upwelling of deep ocean water with lower pH levels, which gave researchers a glimpse of the types of impacts expected from increased acidification in the future [344]. The specific vulnerability of larvae to acidification is echoed in a study by Waldbusser et al. in 2013, which found that bivalve larvae are most heavily impacted by acidification during early developmental and shell formation stages, namely due to excess energy used to regulate their internal chemistry [345].

Additionally, research done on Olympia oysters showed that temporary exposure to seawater with elevated levels of dissolved CO_2 can have lasting developmental impacts, even after the oysters are transported to less acidic waters [346]. This suggests that even temporary instances of lowered pH (e.g., during natural upwelling) can have cascading effects on development throughout an organism's life span and on the general population dynamics of impacted species. However, Olympia oysters have been observed brooding their larvae, which in turn helps larvae begin the calcification process before being exposed to lower pH levels [347].

RESEARCH NEED: Will increased erosion lead to the increased use of emergency HPAs in the Tribe's primary traditional use area?

Finally, a study by O'Donnell et al. (2013) found that ocean acidification has the potential to impede the development of byssal threads used to anchor mussels to rocks and other substrates, even though these are non-calcified biomaterial [348], suggesting that elevated levels of dissolved carbon dioxide can have impacts on shellfish biology beyond shell calcification.

Some research has shown that shellfish may have the potential to adapt to the increased acidity of seawater. In 2013, Pespeni et al. found the genes that control biomineralization in calcifying organisms can evolve when exposed to acidic conditions over long periods of time (50 days, post-fertilization) to ensure calcification [349]. Similarly, selectively bred larvae spawned from adult oysters after they were exposed to acidic conditions showed signs of more resilience to elevated carbon dioxide levels than wild larvae [350]. However, it is unclear if these genetic evolutions can be repeated in organisms impacted by multiple environmental stressors, such as those in Puget Sound. In any case, ocean acidification's effect on shell calcification carries the potential to disrupt entire marine ecosystems: changes in population size, dynamics, and community structure of bivalve and crustacean species could lead to species extinctions [351].

SEA LEVEL RISE

IMPACTS ON SHELLFISH HARVESTING AND HABITAT

Sea level rise has the potential to change the Puget Sound region's coastal landscapes, thereby causing habitat loss and associated impacts on shellfish populations and harvesting activities. Species that live in intertidal areas and/or depend on estuaries as nurseries—including littleneck clams, geoduck clams, Olympia oysters, butter clams, and Dungeness crab—are at risk due to habitat damage associated with higher sea levels. Due to differences in tectonic activity and subsidence rates, sea level rise projections vary even within Washington State (see Observed and Projected Climate Changes chapter), and habitat losses will not be equally distributed.

Shellfish habitat loss in the Puget Sound region

In the Pacific Northwest as a whole, it has been estimated that an increase in sea level of 27 inches would equate to the loss of nearly 65% of estuarine beach and 44% of tidal flats [115].

In a study focused on the upper Hood Canal and Kitsap Peninsula, including Port Gamble, more than half of beach land is predicted to be lost and converted to tidal flats by 2050 because of sea level rise [115]. A 2014 study by Solomon et al. showcased the effects of sea level rise on intertidal zones and the cascading impacts on oyster populations, and ultimately concluded that oyster reef survival is dependent upon the habitat's ability to move inland to maintain optimal submersion rates as sea levels rise [352]. A study by Rodriguez et al. 2014 supported that conclusion [353], but also found that intertidal oyster reef accretion kept pace with, or even benefitted from, sea level rise in modeling scenarios when reef accretion was not otherwise impeded [354]. This suggests that some human activities (e.g., shoreline armoring) would likely restrict the natural inland migration of shellfish habitat. A 2013 study by Peterson found that more pronounced long-term ecological impacts of sea level rise will be experienced where human-built dikes alter tidal influence on floodplains [355]. Remote sensing and simulations generated similar results, indicating that sea level rise will lead to significant losses of shellfish habitat around Puget Sound unless small dikes enclosing marshes are allowed to deteriorate [356]. Dikes and similar types of developments are currently found in approximately 86% of natural shoreline segments in Puget Sound [357].

Changes in habitat composition can greatly impact the Tribe's ability to harvest shellfish when these changes result in the reduction of shellfish populations or restrict access to traditional harvest areas, namely intertidal substrates. For example, in a presentation by Dewey and Cheney it was estimated that a sea level rise of approximately 6 inches in Washington State could reduce harvest time by 13% compared to the current number of harvest days due to increased water coverage; this number jumps to 31% with 12 inches of sea level rise [353]. Furthermore, the impacts of sea level rise are happening simultaneously with other impacts that affect shellfish habitat, which suggests that the estimated loss of habitat and resulting effects on shellfish could potentially be more pronounced.

Population Dynamics and Composition

It is also important to consider the effects of changing shellfish distribution, competition, and predation as sea level rises. Because sea level rise combined with nearshore development reduces the availability of intertidal habitat, shellfish species may be required to compete for limited space and may become more vulnerable to predators [358].

In a study by Ferriss et al. 2015, the primary areas used for harvesting geoduck clams in central Puget Sound produced significantly smaller yields than other shellfish-producing regions in the state, while accounting for 27% of the Tribe's commercial harvest in 2014 [359]. Even though geoduck clams represent a small portion of the overall commercial shellfish harvest in the area, they are a significant economic driver for the Tribe and may be more vulnerable to sea level rise given their low population numbers.

EXTREME EVENTS

Extreme climatic events in the form of extended drought and heavier rain events can have varying impacts on shellfish and shellfish habitat. Generally, these events have been shown to alter the delivery of nutrients and sediments, the physical-chemical properties of estuaries, and ecosystem functionality [360]. Human activities, particularly those that influence the transport of sediment from watersheds, will exacerbate the impacts of these natural events [361].

HEAVY PRECIPITATION AND EROSION

Reduced Salinity

Many climate change projections forecast an increase in extreme rainfall events, which could result in localized flooding and high-flow events for rivers [362]. A 2008 study showed that such events reduced the salinity of estuaries [362]. Reduced salinity in estuaries that provided habitat for shellfish resulted in a correlated reduction in hemocyte cells, which are used to maintain the immune system of invertebrates

[362]. This suggests that flooding and high-flow events could have a severe impact on shellfish species' health depending on the duration and amount of precipitation in the event.

Increased Sediment Loads and Erosion

Sea level rise will alter wave energy and distribution and result in increased shoreline erosion and an adjustment of the coastline [363]. A study by Allan and Komar found that deep-water wave heights off the coast of Washington are significantly greater during extreme events and cause changes in shoreline composition at faster-than-average rates [364]. These sudden alterations in beach profiles make Tribal beach seeding operations particularly difficult to plan given the unpredictability of extreme storms and threaten the loss of existing seed sets.

Heavy rainfall and subsequent flooding could potentially change sediment profiles along coastal areas as well. In 2014, Wong et al. used flood-modeling technology to demonstrate changes in fluvial processes during extreme flooding events and showed that such events can create dramatic geomorphological changes to river systems that may result in above-average sediment deposition [365]. Such events could mean quick changes in coastal habitat that give minimal time for slow-moving or stationary invertebrate species to adapt or respond. Past records of extreme floods, for example, show that high-volume deposition can result in rapid progradation of river mouths often followed by immediate post-flood recession of the "new" shoreline [366]. These circumstances could smother shellfish beds with remarkable quickness and unpredictability, leaving shellfish harvesters vulnerable to losses of shellfish product.

DROUGHT

RESEARCH NEED: How will future periods of drought in Washington State affect the growth of phytoplankton upon which shellfish feed?

As mentioned above, episodes of extreme rainfall can throw off the balance needed for stable shellfish habitats and population dynamics, particularly when it comes to salinity reductions. Research has also shown that similar effects on population dynamics can occur under drought conditions, when salinity rates in estuaries are elevated. In 2000, Attrill and Power found that even small increases in salinity brought on by reduced freshwater inflows under extended drought conditions can have dramatic effects on the composition of invertebrate species, often resulting in population decreases [367]. A 2012 study similarly concluded that large, harvestable oysters suffered more frequently from disease-related mortality under high-salinity drought conditions [368]. Together, the projections for increased drought, sea level rise, and extreme rainfall suggest that the composition of estuaries in Puget Sound is especially threatened by climate impacts.

Drought can also affect the growth and availability of phytoplankton that serve as the basis of the food chain for marine life, including shellfish. Wetz et al. 2011 found that low streamflow and increased stratification during drought conditions led to reduced levels of phytoplankton growth in estuaries and created hypoxic conditions with subsequent fish kills [360]. Research is needed to relate the influence drought has on phytoplankton growth with regional projections of future precipitation patterns in order to determine specific impacts on Puget Sound shellfish species. In theory, though, less freshwater inflow should lead to reduced phytoplankton activity [369].

LOOKING AHEAD

Recent research has found that bivalves tend to grow slower and live longer in northern latitudes than those found in southern, more tropical latitudes [370]. This could be the result of a warmer climate in southern latitudes allowing for higher metabolic rates, which leads to faster growth and shorter lifespans

[370]. As Pacific Northwest temperatures continue to increase in the future, bivalve species in this region may experience faster growth and shorter lifespans. However, our interviews with regional experts suggested that these sorts of physiological changes are unlikely within the next 20 years.

Ocean acidification and warming water temperatures are likely the biggest threat to shellfish in the Puget Sound region. The impacts of acidification and warming water temperatures can have on shellfish and shellfish harvesting are presently being observed, which suggests that these impacts will only continue (with the potential to worsen). However, regardless of the specific impact affecting shellfish, it is possible that shellfish species will be able to adapt to future conditions.

> "We probably underestimate the ability of species to adapt. Many studies that show how shellfish are impacted by acidification basically just plop the shellfish into a bucket of water that's supposed to simulate what it's going to be like in 100 years. They don't account for species' ability to adapt over time."
>
> **Austin Paul, Subtidal Shellfish Manager, Point No Point Treaty Council**

That being said, the adaptability of species relied upon by Tribal members remains to be seen. It is possible that many Tribal members, particularly those who rely on subsistence harvest of shellfish, will see diminishing opportunities to retain shellfish as a reliable source of nutrition. While technological advances in aquaculture would help ensure shellfish remain a part of the Tribe's diet, the Tribe will need to be poised to take advantage of such innovations.

Of particular importance into the future will be the continued focus on monitoring environmental changes and correlating changes in shellfish species, especially population dynamics. This will help to ensure shellfisheries are managed with climate change in mind.

HARMFUL ALGAL BLOOMS

INTRODUCTION

Harmful algal blooms (HABs) are thought to be caused by a combination of factors that allow for a sudden and exponential growth of algae (phytoplankton). These factors most likely include favorable water temperatures, currents, and the presence of nutrients on which the algae can feed [371]. However, it is difficult to pinpoint the exact cause of any particular HAB [371].

Climate change is expected to increase the overall risk of HABs occurring in water bodies throughout the U.S., and an increase in algal blooms worldwide was considered very likely by the Intergovernmental Panel on Climate Change [372]. However, it should be noted that not all HABs can be directly attributed to climate impacts. Increases in the scope, duration, and frequency of HABs have also been attributed to non-climate stressors such as nutrient enrichment of coastal water bodies from anthropogenic sources and the introduction of invasive algal species from ships' ballast water [288].

HABs can cause a range of physiological and environmental effects. Some HABs produce toxins that can accumulate in filter-feeding shellfish [373, 317]. These toxins can then be passed through the food chain, leading to a variety of illnesses or even death when consumed by humans (see the Shellfish chapter for more information on shellfish poisoning) [291]. Pacific salmon and other fish species are also vulnerable to HABs (refer to Salmon chapter for more information). Other harmful algae can be non-toxic, but attain high biomass that can lead to decreases in biodiversity of the phytoplankton community and the amount of sunlight allowed to penetrate the water's surface [374]. Additionally, the decomposition of algal blooms, toxic or non-toxic, can lead to decreases in dissolved oxygen with varying implications for marine life and habitat stability [291].

TYPES OF HARMFUL ALGAE

This chapter will discuss harmful algae that have recently been found in the Pacific Northwest—*Alexandrium*, *Pseudo-nitzschia*, *Dinophysis*, and *Heterosigma akashiwo* [375]—and how climate change (e.g., temperature increases, precipitation changes) is expected to alter the distribution, duration, and frequency of their associated blooms. Table 16 lists key traits of the aforementioned algae. Table 17 lists the environmental conditions necessary for those species' growth.

Table 16. Common species and characteristics of harmful algae found in the Pacific Northwest.

Name	Type	Seasonality[53]	Typical effects
Alexandrium	Dinoflagellate	Approx. July - November	Paralytic shellfish toxins, paralytic shellfish poisoning
Dinophysis	Dinoflagellate	Approx. June - October	Okadaic acid, diarrhetic shellfish poisoning
Pseudo-nitzschia	Diatom	Approx. April – November; most prevalent in summer	Domoic acid, amnesic shellfish poisoning
Heterosigma akashiwo	Raphidophyte	Approx. May - June	Unknown toxin, responsible for extensive fish mortality

Table 17. Temperature and salinity ranges for optimal harmful algae growth [376, 377, 378, 379, 380]. Average water temperatures during summer months in the Puget Sound region currently range between 53 and 56°F [381].

Name	Water Temperature	Salinity
Alexandrium	55 – 63°F	15 – 40 ppt.
Dinophysis	59 – 90°F	30 – 33 ppt.
Pseudo-nitzschia	56 – 65°F	15 – 40 ppt.
Heterosigma akashiwo	62 – 73°F	20 – 35 ppt.

Although not technically an algae, cyanobacteria is discussed in this chapter given its similar physiological responses to climate change and potential to cause HAB-like impacts (e.g., toxic blooms leading to beach closures).

TEMPERATURE INCREASES

This section explains how increased temperatures alter the geographic distribution, duration, and frequency of harmful algae in the Puget Sound region.

GEOGRAPHIC DISTRIBUTION

A study done by Jacobs et al. in 2015 found that blooms of *Alexandrium* have increased in geographic scope in Puget Sound since the 1950s [291]. *Alexandrium's* expanding geographic scope is evidenced by its detection in Quilcene Bay—an area previously considered biotoxin-free—during fall of 2014 [382]. In this instance, the Washington State Department of Health reported toxin levels in shellfish to be 100 times the limit for human consumption [382]. Because *Alexandrium* blooms deposit cysts that remain dormant during winter, it is possible that Quilcene Bay will see *Alexandrium* blooms in future seasons [382]; however, there was a large decrease in *Alexandrium* cysts found in January 2016 compared to 2015 [383].

[53] While seasonality refers to when blooms typically occur under normal circumstances and historical trends, studies describing when blooms occur are highly variable depending on the geographic location and environmental conditions of the study area. As such, these figures are approximations and should only be considered as a general reference. For example, it is possible for blooms to occur outside of these "seasons" depending on various environmental conditions (e.g., upwelling, excess nutrient runoff, heatwaves, etc.).

Knowing the location and quantity of dormant cysts can help managers anticipate future blooms [384]. It is unknown how many cysts are needed for a bloom to be initiated, but research is ongoing [383].

The increasing distribution of *Alexandrium* blooms has largely been attributed to warmer water [317]. Warm temperatures increase the stratification of the water column, with nutrient-rich cold water settling at further depths instead of mixing with warmer surface water. Because phytoplankton need to remain at the surface to absorb sunlight for photosynthesis, the types of phytoplankton that have high nutrient needs will not thrive under increased stratification [385]. Some research shows that with increased drought and stratification, phytoplankton will see a decline in overall growth [360]. However, dinoflagellates like *Alexandrium* and *Dinophysis* have lower-nutrient requirements and the ability to swim below the surface, and are therefore expected to be favored under stratified conditions that may be amplified under projected climate change [386]. As a result, it is possible that even if phytoplankton growth declines overall, these harmful algae will make up a larger percentage of the population.

Projected warming in the Puget Sound region is also expected to favor growth of other prominent harmful algae [46]. This is supported by a 2016 study that found unprecedented domoic acid concentrations (caused by *Pseudo-nitzschia*) in large marine mammals harvested in Alaska, in what is considered to be the first example of algal toxin poisoning there [387]. Additionally, 2015 saw what was potentially the largest continuous *Pseudo-nitzschia* bloom ever when it extended from Southern California to Alaska [388]. Growth rates of *Pseudo-nitzschia* in the English Channel were highest in water temperatures between 56 and 65°F in a study by Thorel et al. [389]. It should be noted that not all subspecies of *Pseudo-nitzschia* produce domoic acid, so it is difficult to tell if an increase in *Pseudo-nitzschia* blooms would automatically cause an increase in domoic acid or amnesic shellfish poisoning [292]. However, it is a reasonable assumption that more overall *Pseudo-nitzschia* blooms would increase the potential for amnesic shellfish poisoning and closure of beaches.

The optimal temperature range for *Heterosigma akashiwo* growth is 62 to 73°F [380]. A study by Fu et al. concluded that *Heterosigma akashiwo* could, in general, become more dominant over the next 100 years since increased temperatures, especially when combined with elevated carbon dioxide levels, stimulate its growth [390].

DURATION AND FREQUENCY

In addition to expanding in geographic scope, HABs are expected to occur at longer durations and with greater frequency. Because each of the main HAB species impacting the Puget Sound watershed rely, in part, on warm waters for growth, the global increase in the frequency of HABs can be expected here as temperatures are projected to get warmer [390]. Projections for Puget Sound show water temperature increases by the 2090s that will allow HABs to develop two months earlier in the year and persist for up to two months longer when compared to present day [317].

Recent observations of Puget Sound waters by NOAA found *Dinophysis* had a sustained presence in Western Washington from April to December of 2012, with the highest concentrations found in Quartermaster Harbor (Vashon Island) and Sequim Bay (Olympic Peninsula) [375]. *Pseudo-nitzschia* was also common during the same testing period, and was also most prevalent at Quartermaster Harbor and Sequim Bay [375]. *Heterosigma akashiwo* was found during this testing period, but with a more variable presence; Port Townsend (Olympic Peninsula) saw sustained levels of *Heterosigma akashiwo* from February to November of 2012 [375].

With regard to *Alexandrium*, Jacobs et al. in 2015 found that blooms tend to occur most often when water temperature exceeds 55°F [317]. As air and water temperatures continue to increase in the Puget Sound region, the annual window of water temperatures exceeding 55°F will expand [291]. Moore et al. in 2015 used climate change scenarios from a regional climate model to project future growth of *Alexandrium*. The study concluded that Puget Sound can expect strong warming trends in surface air temperatures and that future conditions will support both higher growth rates and a longer bloom season of *Alexandrium* relative to present day [373].

An increasing frequency of *Dinophysis* blooms is also a concern in the Puget Sound region [375]. In addition to *Alexandrium*, warmer waters have been shown to increase the growth and toxin production of *Dinophysis* as well [391]. *Pseudo-nitzchia* and *Heterosigma akashiwo* also show greater growth rates in response to elevated water temperatures [390].

PRECIPITATION

NUTRIENT RUN-OFF

Precipitation can have wide-ranging effects on the formation of HABs. One report states that the rain falling in the heaviest one percent of downpours has increased 20% over the last 100 years throughout the U.S., and that downpours are expected to become more frequent as climate change worsens [372]. Climate change is expected to lead to more heavy rainfall events [392, 46], which could increase the runoff of nutrients (e.g., nitrates, phosphates, ammonium) that are often a food source for phytoplankton [372, 393]. These nutrients are most often associated with agricultural activities (e.g., manure, fertilizer), stormwater, and wastewater (e.g., septic systems, sewage) [394]. Reproduction can happen rapidly when runoff combines with the favorable environmental conditions (i.e. temperature and salinity), where cell growth can reach up to 1,000,000 cells per liter in large blooms [393].

Outside of heavy rainfall, projections also show that the percentage of precipitation during winter months falling as rain will increase into the future [46]. More research is needed to determine if increased winter precipitation and heavy rainfall events coincide with the typical seasonality of HABs, but in such cases where abnormal runoff events do coincide with HAB seasons, the potential for HAB-related impacts could become greater.

DRIER, WARMER SUMMERS

Projections for drier and warmer summers could also affect the formation of HABs in Puget Sound and freshwater lakes. For Puget Sound, less precipitation and higher rates of evaporation mean that less freshwater will flow into the Sound [46]. This will increase the salinity of the water, which can lead to salt-stress that in turn causes certain bacterial cells to leak and release toxins [392]. Warmer freshwater inputs and increasing air temperatures will also contribute to warmer marine water temperatures region-wide, potentially leading to more stratification.

In freshwater lakes, heavy rain events followed by warm, dry conditions can result in water bodies retaining excess nutrients from runoff for longer periods of time [392]. In essence, heavy rainfall adds nutrients to a water body while high temperatures and dry weather act to close off the water body and heat it up—thus creating ideal conditions for algal blooms [395]. This is especially true for freshwater HABs and cyanobacteria blooms [395], which can be responsible for the closure of freshwater lakes to recreation and other uses.

OCEAN ACIDIFICATION

As with increased water temperatures and nutrient runoff, elevated levels of carbon dioxide in water can also catalyze the growth of some phytoplankton. Case studies based on modeling scenarios that project future carbon dioxide concentrations in lakes suggest that dissolved carbon dioxide will increase and allow for more algal blooms because algae require carbon dioxide for photosynthesis [396]. A study by Lu et al. in 2006 examined the physiological changes in two strains of cyanobacteria when exposed to seawater at 350, 600, and 800 ppm dissolved carbon dioxide, and found that growth increased by 36.7% in water at 800 ppm when compared to the 350 ppm baseline [397]. (The current level of dissolved carbon dioxide in Puget Sound is approximately 700 ppm [398].) Even though algal blooms work to remove dissolved carbon dioxide from water during photosynthesis and elevate pH levels, models show that carbon dioxide concentrations will eventually increase to a point where algal blooms will not deplete dissolved carbon dioxide effectively enough to avoid adverse impacts on water chemistry [396].

RESEARCH NEED: Will more HABs in Puget Sound create more hypoxic zones?

Cyanobacteria are particularly sensitive to increased dissolved carbon dioxide concentrations; observations of cyanobacteria blooms under elevated dissolved carbon dioxide showed increased photosynthesis, nitrogen fixation, and division rates [399]. Cyanobacteria produce cyanotoxins that function similarly to toxins produced by various types of phytoplankton described earlier [400]. Multiple studies have found that cyanobacteria carry the potential to produce paralytic shellfish toxins, for example [401, 402].

Blooms of cyanobacteria are predominantly found in freshwater ecosystems [402], so it is unclear how ocean acidification, specifically, may affect future increases in cyanobacteria growth in salt and brackish water bodies. However, it is possible for cyanobacteria to enter salt and brackish water from freshwater origins. A study published in 2015 by Preece et al. detected cyanobacteria originating from freshwater lakes with outflows to Puget Sound in local mussels [403]. This is the first known instance of a bivalve species accumulating cyanotoxins that entered Puget Sound from freshwater sources [403]. While further research is needed, it is possible that these instances may become more frequent as the acidity of local estuaries increases.

Lastly, acidification has been observed to affect the growth of many species of phytoplankton, and is thought to have become a more influential contributor in the development of HABs worldwide under current carbon emissions scenarios and when acting in concert with other climate impacts [404]. For example, a study by Tatters et al. in 2012 found that the toxicity of *Pseudo-nitzchia* blooms, specifically, is increased by acidifying ocean waters—calling it "carbon fertilization" [405].

HYPOXIA FROM HABS

Algal blooms, harmful or not, can indirectly impact marine life by increasing cases of hypoxia. Hypoxia refers to oxygen depletion in marine ecosystems to the point that oxygen levels become too low to support marine life. Algal blooms contribute to the depletion of dissolved oxygen by creating excess organic matter that decomposes. These excessive algal blooms are often caused by eutrophication (i.e. the increased availability of one or more limiting factors needed for photosynthesis, such as sunlight, carbon dioxide, or nutrients), which can be a natural event or human-induced [406]. In such cases, hypoxic zones lead to massive fish and shellfish kills and devastation of habitat [308]. Such events can also have extensive economic impacts on coastal communities like the Port Gamble S'Klallam Tribe that rely on marine organisms for subsistence and livelihoods [407].

Hypoxia can be caused by other factors aside from algal blooms. Oxygen levels in water bodies naturally varies, for example during upwelling events [408]. Such was the case at Hood Canal in 2006, when massive fish kills were recorded after upwelling combined with altered wind patterns and kept low-oxygen water at the surface [224]. Hood Canal has a long history of hypoxia, due mostly to the Canal's underwater topography, which makes it difficult for water to exchange [409]. Human activity and climate act as additional factors to hypoxic zones in Hood Canal [409].

Since stratification is a large contributor to hypoxia, the relationship between stratification and HABs is important in understanding how HABs can lead to hypoxic zones [270]. Under usual conditions, regular mixing of bottom waters and oxygen-rich surface waters occurs, keeping decaying phytoplankton from creating hypoxic conditions; under stratified conditions, however, mixing of different layers of the water column is restricted, and depleted oxygen at further depths is not replenished [410].

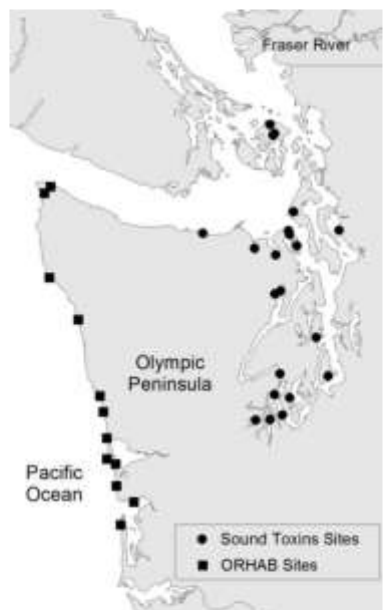
Currently, relatively few cases of hypoxia directly related to high biomass HABs have been documented in the United States [270]. However, the apparent linkages between climate change, HABs, and stratification of coastal waters suggest that hypoxia could become more prevalent in the future.

LOOKING AHEAD

As HABs have increasingly become a threat to marine ecosystems, and the wildlife and humans that rely on them, a number of monitoring and management initiatives have been developed [411]. Examples of these actions taking place in Washington State include the Olympic Region Harmful Algal Bloom partnership (ORHAB), the Pacific Northwest HAB Bulletin, and the Sound Toxins Partnership [411]. The goal of these projects is to provide sufficient warning of HAB events through collaborative monitoring and information sharing among federal, state, tribal, and local governments as well as marine resource-based businesses [411].

 shows the monitoring sites of the ORHAB and Sound Toxins projects.

Figure 39. Sound Toxins and ORHAB monitoring sites [412].



FOREST RESOURCES

INTRODUCTION

In Washington State, the most severe climate change impacts to forests are expected east of the Cascade Range; however, forests in Western Washington will also be affected [413]. It should be noted that forest impacts are also caused by human activity, including population growth, urban development, logging, long-term wildfire suppression, and mismanagement of natural resources [413]. Climate change will exacerbate these negative forest impacts in Washington State over the coming decades.

The Port Gamble S'Klallam Tribe currently manages approximately 1,500 acres of forested land on its reservation. The Tribe has taken initiative to protect timber as a valuable resource, including restricting who has access to Tribal-owned forestry preserves, controlling who can sell timber cut from reservation land, and setting up various permitting restrictions and requirements for approval of timber harvesting [414]. Additional measures may be useful as climate change affects local forests and to ensure the ability to achieve goals such as restoring and maintaining riparian habitat to support fish harvests, adhering to Clean Water Act and Endangered Species Act requirements, and maintaining the economic viability of timber harvests.

IMPACTS ON FOREST ECOSYSTEMS

Changes in the geographic distribution of tree species, forest growth and productivity, fire activity, and insect and disease outbreaks are expected as a result of climate change [415]. Climate impacts on forests are also expected to affect freshwater ecosystems.

WILDFIRE

While climate change will influence wildfire regimes in Washington State, it is important to note that past forest management practices (e.g., fire suppression, over-logging, and overharvesting) have also created conditions that increase the risk of wildfire in many areas compared to historical rates [416]. Western Washington has a lower wildfire risk today—and in the future—than Eastern Washington, given its relatively wetter climate [413]. However, a study by Littell et al. concluded that it is possible for rising temperatures, decreased soil moisture, and increased evaporation rates to increase fire risk in areas of Western Washington that have not been historically prone to wildfires [417].

RESEARCH NEED: Will wildfires significantly reduce the availability of culturally important plants and trees?

Similar conditions that led to extensive wildfires in Eastern Washington in 2015 have been observed by some fire officials in Western Washington, particularly the combination of drier vegetation and high winds [418]. The risk of fire in the Pacific Northwest is mostly driven by simultaneous drought and warm temperatures, which lower moisture content in live and dead fuels and increase flammability [419]. On the Olympic Peninsula, fires are more frequent among the drier western hemlock, subalpine fir, and Douglas fir forests on the eastern side of the peninsula [420, 421, 19]. Past fire records indicate a strong correlation between warm, dry summers and higher rates of area burned for the Pacific Northwest region [419]. This correlation indicates that fire risk in Western Washington is likely to increase, at least generally, as temperatures rise and summers become drier in a changing climate. Wildfires that were rare in the past, such as the 2015 Queets rainforest fire in Olympic National Park, are expected to become more common with the anticipated fire regime changes in Western Washington [422]. However, the role of climate change in shifting fire regimes in Western Washington is still being evaluated [422].

The majority of wildfires in the Pacific Northwest are human caused (e.g., through unattended campfires, burning debris, discarded cigarettes, or arson). As a result, population growth in the region is likely to increase wildfire frequency at the same time that optimal wildfire conditions are becoming more common [88]. Population growth is also increasing the number of people residing in the wildland-urban interface, resulting in more homes damaged or destroyed by wildfire throughout the United States [423]. Fire intensity and severity is also projected to increase in parts of the Western U.S., following a trend supported by evidence recorded over the past 20 years [88]. According to Peterson and Littell, increases in frequency and severity will likely contribute to large-scale ecological changes in forests for this region [88]. The area burned across the Pacific Northwest is projected to double by 2040 and triple by 2080 relative to 1916–2006 levels [413]. As a result, extensive wildfires are expected to influence forest structures by shifting vegetation toward more fire-tolerant species [424]. Such large-scale changes would likely impact the Tribe's forest management practices, the availability of timber as a resource, and key wildlife habitat.

Forest management practices in parts of the Western United States are currently being adapted to changing fire regimes to help avoid the impacts described in this chapter and any cascading effects that could result [425]. Examples of adaptive actions include removing surface fuel; reducing stand densities to lower risk of canopy fires; and incorporating species that are more tolerant of warmer, drier climates in planting projects both before and after a wildfire [425].

INSECT OUTBREAKS

Mountain Pine Beetle

Rising temperatures and drought have expanded the climatically suitable habitat for the mountain pine beetle (MPB), leading to significant forest degradation across the Western U.S. over the past decade [426]. The mountain pine beetle is a native insect in Northwest forests that can affect lodgepole (its main host species), ponderosa, white, and whitebark pines as well Douglas-fir and true firs. Studies on the impacts of climate change on mountain pine beetle find that the beetle's range is likely to expand through mid-century as warmer seasonal temperatures reduce winter larvae mortality and accelerate life stage development, favoring longer and more frequent outbreaks [427, 417]. Warmer temperatures also allow outbreaks to move northward and higher in elevation [417]. This shift is facilitated by the potential for increased drought stress in host trees, which may weaken defense responses [428].

Figure 40. Example of forest degradation resulting from the MPB outbreak. Dead trees (also called "beetle kill") turn a reddish brown [430].

Figure 40 shows an example of forest degradation caused by the MPB outbreak. Kurz et al. concluded that the current MPB outbreak is unprecedented in scale and severity and is due in large part to the effects of increased summer temperatures, warmer minimum winter temperatures, and drought throughout higher elevations of the Western U.S. and Canada [429]. Past forest management practices also played a part in the outbreak's size and severity.

Forestry practices in response to insect outbreaks have varied, including the increased use of silviculture practices (e.g., thinning at-risk pine stands) and the use of chemical pheromones to repel the insects [431]. Other measures include forest restoration in areas previously affected by outbreaks to reduce any potential economic and ecological impacts associated with extensive forest degradation [432]. These actions may be required more often or at greater scale as insect outbreaks become increasingly prevalent under future climate regimes.

By the end of the century (2080s), the amount of habitat considered climatically suitable for mountain pine beetle is actually projected to *decrease* [417]. Some of these losses come at higher elevations: as habitat suitability moves higher in elevation, the amount of available habitat decreases. Meanwhile, at low elevations, increased warming could accelerate beetle life stage development to the point of creating asynchrony, or a mismatch in the timing of adult emergence and the growing season that ultimately reduces opportunities for rapid reproduction, synchronized mass attacks on trees, and overwintering during the most cold tolerant life stages (larvae) [417]. More severe drought stress in host trees can also reduce beetle populations when depleted or dried phloem tissue limits survival and brood production [427]. Finally, more frequent fires could lead to more diversity in age class and stand density in Northwest pine forests, reducing the potential for larger outbreaks [433].[54]

Spruce Beetle

Similar findings are reported for western North America for the spruce beetle [428, 434]. Like the mountain pine beetle, these beetles are natural parts of forest ecosystem processes but can cause extensive forest degradation during extended outbreaks [435]. Warmer winter temperatures favor the beetle's life cycle, increasing the probability of more rapid (i.e., annual rather than semi-annual) offspring production. However, projected decreases in the range of Engelmann spruce (the insect's primary host) could limit that expansion in the West. Projected range changes in Sitka spruce, which is common to the Olympic Peninsula, are less certain although Halofsky et al. 2011 note that Sitka spruce forests on the Olympic Peninsula—which are typically not stressed in the summer months—are likely to experience increased summer drought stress [90].

Douglas-fir Beetle

Increasing summer drought stress due to climate change may also favor the Douglas-fir beetle, particularly in areas where weather events (e.g., wind or heavy snow and ice events) have created downed or damaged trees favored by Douglas-fir beetle populations [90, 434]. As the population builds, healthier standing trees can also be attacked. Halofsky et al. noted that mortality associated with past Douglas-fir beetle outbreaks in the Olympic Peninsula has been higher historically in the Peninsula's drier, eastern habitats [90].

Douglas-fir beetles also benefit from tree stress induced by western spruce budworm outbreaks. This suggests another climate change impact pathway for Douglas-fir beetles; if climate change increases the frequency, duration, or intensity of western spruce budworm outbreaks, Douglas-fir beetle outbreaks could lead to higher tree mortality. Like the mountain pine beetle, climate change may favor expansion of the western spruce budworm range and better synchronization of emergence timing with tree development in

[54] Pine stands are more susceptible to mountain pine beetle attack as the stand approaches 60–80 years old [433].

higher elevations [434]. However, warming at lower elevations may result in asynchronous emergence, reducing budworm populations [434].

Other Insects

Other insects that could affect tree species important to the Port Gamble S'Klallam Tribe include the Western hemlock looper and Western spruce budworm. McCloskey et al. suggested that climate change may contribute (along with changes in forest cover due to industrial logging) to an increase in the frequency, size, and severity of western hemlock looper outbreaks in southern British Columbia due to the combined effects of more frequent summer drought and projected expansion of western hemlock range [436]. Temperature effects on the looper's life cycle could also be a factor. June temperatures that are significantly above average[55] increase the potential for outbreak onset within a single growing season by favoring survivorship in critical early life stages.[56] Warmer and drier conditions over the length of the growing season favor the onset of outbreaks up to two years later by supporting the progressive growth in population to the point of reaching outbreak levels. Non-climate factors that could still limit looper outbreaks include parasite, predators, and diseases.

Table 18 below lists key insects and their host trees common in Washington State and important to the Tribe.[57] The table does not include temperature or precipitation thresholds for each insect because the specifics around what can lead to an outbreak vary by location as well as by species [437]. Nonetheless, warmer temperatures and extended drought along with past forest management practices are major influences driving all current outbreaks, allowing for faster insect reproduction and growth and increased host trees' susceptibility to attack [437].

Table 18. Insects and their host trees found in Washington State [438, 439, 440, 441, 442].

Insect	Host tree(s)
Mountain pine beetle	Most common: Lodgepole, ponderosa, and white pines. Less common: Whitebark, Douglas-fir, and true firs. Non-host trees are occasionally attacked when nearby pines are infested.
Spruce beetle	All species of spruce within its range (including Sitka spruce).
Douglas-fir beetle	Douglas-fir, average age of 120 years.
Western hemlock looper	Most common: Western hemlock, Douglas-fir, western redcedar. Less common: Sitka spruce.
Western spruce budworm	Most common: Douglas-fir, subalpine fir Less common: Pacific silver fir, western hemlock, western white pine

[55] In addition to below average precipitation and higher soil moisture deficits.

[56] Based on outbreaks occurring between 1906 and 2004.

[57] This table emphasizes the insects that are known to impact the tree species most important to PGST, and is not intended to be a comprehensive list of all insects that can affect the trees found in Washington State.

DISEASE AND PATHOGENS

Diminished tree health and increased temperatures in the Pacific Northwest could result in favorable conditions for pathogens and the spread of disease [443]. For example, Swiss needle cast (Figure 41), which causes premature needle loss and reduced growth in Douglas-fir trees throughout Western Washington [444], is expected to increase in distribution and prevalence as winter temperatures steadily increase in the Pacific Northwest [91]. Western white pine is a common host for white pine blister rust, which can cause extensive tree mortality [445]. Cold temperatures inhibit the spread of white pine blister rust, suggesting that a warming climate will increase rates of infection [446]. Specific temperature and precipitation ranges for each disease's growth were, representing a gap in the current literature. Aside from white pine blister rust and Swiss needle cast, other diseases found to affect common species in Washington State are listed in Table 19.[58]

Figure 41. Douglas-fir needles showing the effects of Swiss needle cast (Phaeocryptopus gaeumannii) infection. Photo: USDA Forest Service.

Table 19. Diseases and their host trees found in Washington State [447, 448, 449, 450].

Disease	Host tree (s)
Swiss needle cast	Douglas-fir, most common in young, dense Douglas-fir stands
White pine blister rust	All North American white pines
Cedar leaf blight	Western redcedar
Rhabdocline needle cast	Douglas-fir

The spread of most plant diseases depends on environmental conditions. Climate changes are expected to alter the interaction between the host and pathogen in ways that will result in diseases with more impact [92]. Climate change will also affect the life cycles of many tree species and pathogens, thereby creating disturbances in the phenology (i.e., timing of biological events such as flowering) of tree hosts, spore release by pathogens, and the activity of insect vectors [92]. Decreases in forest productivity and weakening due to drought can increase trees' vulnerability to disease.

GEOGRAPHIC DISTRIBUTION AND GROWTH

A study by Ettinger et al. found that species distributions may shift as some trees become more suited to grow at higher elevations due to warmer temperatures and increased moisture stress at lower elevations

[58] This table emphasizes the diseases that are known to impact the tree species most important to PGST, and is not intended to be a comprehensive list of all tree diseases found in Washington State.

[451]. In addition to growth and productivity, the geographic distribution of species will also be influenced by wildfire, pest outbreaks, and disease.

Trees have historically responded individualistically to climate variations given each species' unique climate tolerances with regard to precipitation and temperature [452]. Increasing air temperatures and drier summer conditions are likely to reduce the area of climatically suitable habitat for Douglas-fir and ponderosa pine in lower elevations of the Puget Sound region, which would particularly impact seedling establishment [453]. However, western hemlock, whitebark pine, and western redcedar could expand their ranges under climate change by the end of the century [415]. These conditions will extend growing seasons at higher elevations of the Olympic and Cascade ranges at the same time they increase water stress due to drought [454]. In spite of an extended growing season, water stress could be severe enough to decrease forest productivity in some areas, depending on the balance between water stress and temperature. The ability for species to expand their ranges also depends on how quickly these changes in climatically suitable habitat occur, because such a shift for species—particularly trees, which migrate and grow slowly—can take a considerable amount of time [455]. It remains a possibility that the climate will change more rapidly than trees can migrate to areas of suitable habitat, leading to the potential for species disruption or, in extreme cases, extinction [456, 457].

The balance between growing season and water stress will not be uniform across the Puget Sound region and will depend on moisture levels available to support a longer growing season [458]. The North Cascades are expected see declines in forest productivity in spite of a longer growing season due to a lack of available water [459], whereas the Southwest Olympic Peninsula is expected to have enough moisture to support a longer growing season and bolster productivity [460].

Changes in phenology (e.g., flowering dates) that impact tree growth may also affect the timing and availability of plant resources relied upon by pollinators and other species [461]. These changes could potentially impact the availability of materials used for tribal ceremonies and traditions as well.

FOREST IMPACTS AND FRESHWATER ECOSYSTEMS

Forests play an essential role in maintaining the quality of freshwater resources and act as

THE IMPORTANCE OF THE FORESTS AND FISH REPORT

The 1999 Forests and Fish Report, which was presented to the Forest Practices Board and the Governor's Salmon Recovery Office, was the result of an influential collaboration of federal, state, tribal, and local governments; nonprofit agencies; and other forest stakeholders all focused on creating forest management practices that benefit aquatic resources in Washington [647]. The involvement of tribes in particular was vital to ensure that forest management decisions do not harm the aquatic resources upon which tribal treaty fishing rights depend [647]. Because forests provide essential services in maintaining the water quality of streams [648], the Forests and Fish Report has served as an important foundation for implementing forest management practices throughout the state [251].

It is essential that forest management practices address climate change to achieve the goals set in the Forests and Fish Report (see below) and maintain adequate water quality to sustain freshwater ecosystems.

Goals in the 1999 Forests and Fish Report:

1. Provide compliance with the Endangered Species Act for aquatic and riparian-dependent species on non-federal forest lands.
2. Restore and maintain riparian habitat on non-federal forest lands to support a harvestable supply of fish.
3. Meet requirements of the Clean Water Act for water quality on non-federal forests lands.
4. Keep the timber industry economically viable in the State of Washington.

a delivery mechanism for supplying streams with precipitation via groundwater [462]. Headwaters and riparian zones are vital to overall ecosystem health and can be particularly sensitive to disturbances—due to climatic changes as well as human influences such as development or logging [462]. The 1999 Forests and Fish Report documented the significance of forests in maintaining water quality and is the result of a partnership between multiple Washington stakeholders, including tribes, to address forest management through an aquatic resources lens (see text box on next page).

The following sections provide more detail on riparian zones and forest hydrology.

Riparian Zones

Riparian zones are ecosystems that create the banks of rivers and streams. A study by Seavy et al. concluded that this forest-water interface provides important ecosystem services that benefit wildlife and ecological stability [463]. Riparian zones can enhance connectivity for species when climate change causes distributional shifts for organisms [463]. They also link aquatic and terrestrial systems, allowing for each to become more ecologically diverse [463].

Many of the above benefits of riparian zones were echoed in a study by Thomas et al. that found riparian zones help maintain water temperature and discharge [464]. The study specifically cited the importance of such in sustaining salmonid species populations [464]. A study by Naiman et al. found that riparian zones also absorb heat and provide a thermal refuge for organisms (see the Salmon chapter for more detail) [465]. Preserving riparian zones may be especially important under climate change as riparian zones have the potential to reduce the adverse effects of climate change by improving ecological resilience [463].

Forest Hydrology

Forested watersheds account for 65%of the water supply in the Western U.S. [466]. High-elevation forests where headwater catchments store snow during the winter are especially important because they help maintain balanced streamflow through spring and summer [466]. However, changes in precipitation will affect the hydrologic cycle and forest processes—many of which are essential to water quality, aquatic habitats, and aquatic species [466].

Historically speaking, the most influential modifiers of forest hydrology have been disturbances (e.g., wildfire, pest outbreaks) and forest management (e.g., harvesting) that cause the loss of forested areas or degrade ecosystem stability [467]. As forests are lost or degraded, from climate impacts or other causes, these disturbances affect the pathway of water within the ecosystem and in turn affect downstream users, including fish, wildlife, and people [467].

Research need: How will vegetation change in headwater areas important to the Tribe?

Vegetation plays an important part in forest hydrology, particularly by affecting the amount of precipitation that reaches streams (i.e., water yield) instead of being captured by leaves and eventually evaporated or transpired [468]. Less vegetation generally increases water yields while more vegetation decreases yields [468]. A forest's water yield and its timing during the year have important influences on aquatic habitat and fisheries management decisions. The relative unpredictability of forest vegetation and water yields in future climate scenarios may present new challenges to fisheries if water yields and streamflow cannot be planned for or considered in fisheries management plans.

If climate changes reduce vegetation and increase water yields during periods of low streamflow, these changes could benefit fisheries, namely salmonid species survival [468]. However, some climate projections indicate the potential for more vegetation in headwater areas through warmer temperatures increasing growth of some tree species at higher elevations in parts of Washington State by 2100 at the same time that lower elevation habitats become too stressful for adequate tree growth [415]. If more growth does occur in headwater areas, this change will increase the chance of increasing growth coinciding with drought conditions, which would lower water yields and impact downstream uses.

WILDLIFE HABITAT

Climate impacts on forests may reduce wildlife habitat or food sources for species of significance to the Port Gamble S'Klallam Tribe, such as elk and deer. Climate change is also expected to have additional impacts on elk and deer (e.g., disease); more detail on these other impacts can be found in the Mammals and Upland Wildlife chapter.

ELK

Roosevelt elk are the most prevalent subspecies of elk in Western Washington and are considered non-migratory [469]. Habitats vary in spite of herds being mostly stationary: some herds live in high-elevation (montane) meadows and others in lowland rainforests [470]. According to Zald et al., climate change is influencing tree-line movement in areas of the Pacific Northwest and resulting in tree migration into montane meadows [471]. Zald et al. found that tree invasion has been absent in lowland meadows while increasing in montane meadows [471], which is consistent with other regional studies of forest productivity increases at high elevations [415, 451]. The potential loss of montane meadows suggests that non-migratory species of elk that currently rely on the forage foods found in montane meadows are at risk of relocating to lowland meadows, where interactions with other elk herds may increase the potential for issues associated with approaching carrying capacity (e.g., lack of food, spread of disease).

DEER

The most common species of deer found in Western Washington is the black-tailed deer, which prefer habitats consisting of coniferous forests and brushy lands [472]. Like elk, black-tailed deer in the Pacific Northwest rely on forage foods—particularly buds and leaves of various trees and shrubs such as western redcedar and pine species like Douglas-fir [473]. Considerable losses of areas that are climatically suitable for pine productivity are expected in the Pacific Northwest [417], which could decrease the availability of food sources for black-tailed deer. However, habitat for black-tailed deer is wide ranging and extends from the coastal islands of Alaska to Baja Mexico [474], suggesting that black-tailed deer populations may be able to migrate in response to climate impacts locally. Migration may make species such as black-tailed deer less accessible as a resource to the Tribe at the same time it supports the species' survival.

WESTERN REDCEDAR AND OTHER IMPORTANT SPECIES

This section describes climate impacts and projections for specific tree species ecologically and culturally important to the Port Gamble S'Klallam Tribe—including western redcedar, Douglas-fir, and western hemlock. It is difficult to assess the optimal temperature and precipitation range for each tree species' health or growth, given their long life-cycles and the difficulty of replicating those in experimental settings. Table 20, below, shows ranges in frost-free days, precipitation levels, and elevation that species common in

Western Washington currently experience across their entire range (unless otherwise noted). This information tells us the known ranges in which these trees are currently able to grow and survive, although it does not necessarily tell us the exact threshold points at which trees would be adversely impacted in Western Washington in a changing climate. We can anticipate that the elevation ranges would change in tandem with changes in temperature and precipitation (assuming room for shifts, given human development and other potential barriers), and not as an independent variable.

Table 20. Current range-wide environmental conditions for species common in Western WA [475, 476, 477].

Species	Frost-free days per year	Annual precipitation	Elevation
Western redcedar	120 days along its coastal habitat; 75 days minimum across entire distribution	28–260 inches	0–7,500 feet
Douglas-fir	80–260 days on average	In the Pacific Northwest: 24–134 inches	In WA and OR: 0–5,000 feet
Western hemlock	<100–280 days on average	15–262 inches	0–7,000 feet
Pacific silver fir	40–250 days on average	38–262 inches	0–6,000 feet
Pacific yew	60–300 days on average	19 – 157 inches	0 – 8,000 feet
Sitka spruce	111–294 days on average	26–221 inches	0–3,000 feet
Lodgepole pine	90–200 days on average	10–200 inches	Up to 7,000 feet
Bigleaf maple	70–350 days on average	22–260 inches	Up to 7,000 feet
Western white pine	60–200 days on average	30–79 inches	0–10,990 feet
Red alder	160–210 days on average	16–220 inches	Most abundant below 2,460 ft. Highest known stand = 3,610 feet

The following sub-sections summarize research findings on the climate vulnerabilities of western redcedar and pine family species.

IMPACTS ON WESTERN REDCEDAR

Growth and Distribution

A study by Seebacher in 2007 found that that high-elevation western redcedars show more resilience to climate impacts (such as drought) when compared to lower elevation redcedars in the same geographic area [478]. Low-elevation redcedars in some parts of the Pacific Northwest have experienced developmental issues (e.g., smaller ring widths, lower ring densities) that created vulnerabilities to moisture stress [478]. These developmental issues and subsequent diebacks were likely caused by a combination of climate impacts and inadequate forest management practices in the past [478].

Results from a 2011 study by Coops and Waring concur with Seebacher's findings that western redcedars can be resilient to climate change. Among 15 of the most prominent tree species in the Pacific Northwest, western redcedar is projected to show more resilience to climate change under a high emissions scenario

(A2) [479]. Coops and Waring determined less than 10% of the western redcedar's range is vulnerable to future climate change [479].

Increased temperatures during late winter and early spring have correlated with increased average redcedar growth across the species' U.S. distribution [480]. However, increased summer temperatures adversely impact redcedar growth when accompanied by drought conditions, especially in lower elevations where temperatures are typically higher [480]. In other words, redcedars tend to decline only when warm temperatures and drought are combined. Projections for Washington State show that increased temperatures and lower rainfall are likely during summer months, which suggests that redcedar productivity may decline due to increased moisture stress [415]. Redcedars may shift to higher elevations, where possible, given that temperatures at high elevations will not be as extreme and moisture stress is less likely to significantly impact growth in the coming decades. If climatic suitability shifts too rapidly though, redcedars may not be able to migrate quickly enough to counterbalance losses, thus species would remain only in areas that overlap with their current range [455].

Climate Impacts on Phenology

Western redcedar is likely to experience changes in phenology as climate change worsens. Budburst, when new leaves begin to grow, could potentially change in timing since budburst is based on temperature. The western redcedar times budburst based on a "chilling requirement" that is usually met during winter's sustained low temperatures [481]. Once this chilling requirement is met, budburst commences as the frost-season transitions to spring [481]. A study by Nitschke and Innes has shown that increased temperature variability during winter could lead to western redcedar budburst occurring before the frost-season has actually ended, leading to frost damage when temperatures fall again [481]. Delayed budburst is also possible if chilling requirements are not met due to above average winter temperatures.

RESEARCH NEED: Will climate impacts result in a lower resistance to insects among western redcedars?

Vulnerability to Insects and Disease

Cedar leaf blight (Didymascella thujina, see Figure 42 below) is a common disease found among western redcedars in the Pacific Northwest [482]. Cedar leaf blight is a fungus, and signs of the disease include small, bleached spots found on the surface of leaves [482]. The disease causes mortality in seedlings, and can result in branch death and other growth issues in more mature redcedars [483]. According to Gray et al., this disease prefers warm, moist, coastal low-elevation environments and is therefore expected to increase in intensity through the 2020s under multiple climate projections [483]. However, it will likely decrease in prevalence by the 2080s as climate projections indicate the likelihood of more prolonged periods of drought throughout the Pacific Northwest [483].

Insects often damage in western redcedars but do not usually cause tree mortality without interacting with other stressors [484]. While redcedars rarely suffer insect damage severe enough to kill affected trees, redcedars do host many insects, including bark beetles, wood borers, defoliators, and seed and cone insects [484]. Although western redcedars have shown high resistance to insects, it is unclear whether climate change will expose redcedars to new insects or lead to more redcedars being killed from insect damage.

Figure 42. Western redcedar infected with cedar leaf blight (Didymascella thujina) [485].

Fire Resistance

Western redcedar is considered to have a low resistance to wildfire [486]. This species has also shown higher mortality rates among seedlings on previously burned mineral soil [486]. Low resistance is thought to be the result of the thin bark typical of redcedars and the tree's shallow roots, which can be scorched during surface fires [487, 488]. It can therefore be assumed that western redcedars will likely see higher rates of mortality due to wildfires as climate change induces fire regime shifts.

IMPACTS ON PINE FAMILY SPECIES

The pine family (Pinaceae) represent some of the most abundant and commercially used trees in the Northwest. Table 21 below lists the trees within the pine family that are most important to the Tribe.

Table 21. Trees within the pine family that are important to PGST.

Common name	Scientific name
Western white pine	*Pinus monticola*
Lodgepole/shore pine	*Pinus contorta*
Sitka spruce	*Picea sitchensis*
Douglas-fir	*Pseudotsuga menziesii*
Western hemlock	*Tsuga heterophylla*
Pacific silver fir	*Abies amabilis*
Mountain hemlock	*Tsuga mertensiana*

Growth and Distribution

Climatic suitability for Douglas-fir is projected to decline by 32% by 2060 (relative to 1990s levels) across Washington State, with noticeable losses in the South Puget Sound and Southern Olympics regions [417]. Yet suitable habitat is not expected to decline for all pine species common in Western Washington. For example, the western white pine shows resilience even under extreme warming trajectories and wildfire regimes [489].

Climate Impacts on Phenology

Multiple studies have shown climate change is altering the phenology of pine family species in the Pacific Northwest but with varying impacts [490, 491]. Gould et al. found that warmer temperatures influence Douglas-fir trees by leading to earlier budburst [490]. Conversely, Harrington et al. found that budburst in the spring is sometimes delayed following a warmer winter because Douglas-fir trees time budburst based on a chilling requirement that is usually met during winter low temperatures [491]. Mountain hemlock has also been shown to experience similar growth and development issues pertaining to phenology as a result of climatic variability [492].

Vulnerability to Insects and Disease

Some pine species are particularly susceptible to insect outbreaks as the climate changes. Outbreaks of western hemlock looper (Figure 43), a common insect that feeds on foliage, have caused widespread mortality in western hemlock stands in the past [493]. According to McCloskey et al., past outbreaks often followed periods of drought and sustained above average temperatures in the Pacific Northwest [436]. The potential for increased frequency of western hemlock looper outbreaks is considered high for the Pacific Northwest since climate projections predict warmer, drier summers and an expanded range of western hemlock [436]. Douglas-fir beetles may also increase in population because these beetles successfully attack host trees previously weakened by some sort of physiological stress, such as drought or wildfire [494]. Other pine species will be increasingly vulnerable to MPB outbreaks as well [429].

Figure 43. Western hemlock looper caterpillar (left) and adult moth (right) [381].

Increases in two needle cast fungus diseases have been observed among Douglas-fir in the Pacific Northwest: Rhabdocline and Swiss needle cast [495]. Both diseases cause premature needle loss and thinning foliage as well as target newly expanding needles (budburst) [495]. Mild winters are thought to favor growth and production of the fungi, which suggests that they may continue increasing in prevalence as average temperatures rise [496].

Fire Resistance

Fire resistance among pine species varies, with Douglas-fir typically showing more resistance than its associated species [497]. Records from two fires in Washington State, at Mount Rainier (1973) and in Olympic National Park (1978), indicate that Douglas-fir had a higher survival rate than a number of other species, including western hemlock, western redcedar, bigleaf maple, and Sitka spruce [497]. Douglas-fir's fire resistance is likely due to its deep root structure that offers protection from heat, thick bark, and concentration of foliage near the upper parts of the tree that helps avoid crown fires [497]. Western hemlock has a low fire resistance due to thin bark, flammable foliage, shallow roots, and low branches when compared to Douglas-fir [498]. Past records of wildfires show that western hemlock has not typically been vulnerable to wildfire due to its preferred habitat (i.e., cooler, wetter habitats), but the species may see an increased vulnerability as climate change will likely alter fire regimes in the Pacific Northwest [498].

LOOKING AHEAD

According to interviews with regional experts, the biggest threat to any forest comes from stressors that reduce growth and regeneration. Although there is still uncertainty about how climate change will impact the forests of Western Washington, the potential combination of more severe wildfires, insect outbreaks, droughts, and increasing temperatures could create a complex of stressors that would likely impact tree growth.

Given the long lifespans of trees, forests will likely remain fairly stable despite climate impacts up to 20 to 50 years from now. The year 2100 seems to be the most appropriate benchmark date to expect significant observable changes in forest structure. It should be noted that some of these changes will likely be in the form of increased growth in subalpine areas and increased regeneration of high elevation species. Effective forest management will be essential to avoid significant adverse climate impacts to forested areas by 2100.

> "The biggest thing to remember is that trees rarely go extinct. They might shift or go through other changes, but they have always remained on the landscape because of genetic diversity...The 'game changer' will be in the form of extreme, short-term disturbances that don't give forests the chance to adapt."
>
> **David Peterson, Senior Research Biologist, U.S. Forest Service**

It is important to consider the possibility that tree species may possess more adaptive capacity than currently understood. Mature trees are likely resilient to slow, gradual climatic changes such as temperature increases or precipitation changes. The most threatening impacts for mature stands will come from short-term, sudden disturbances that reduce a forest's chances to adapt—such as extensive wildfires or insect outbreaks. However, under future climate scenarios, regeneration and seedling survival would likely decrease, especially if mature stands have been degraded from disturbances.

WETLANDS

INTRODUCTION

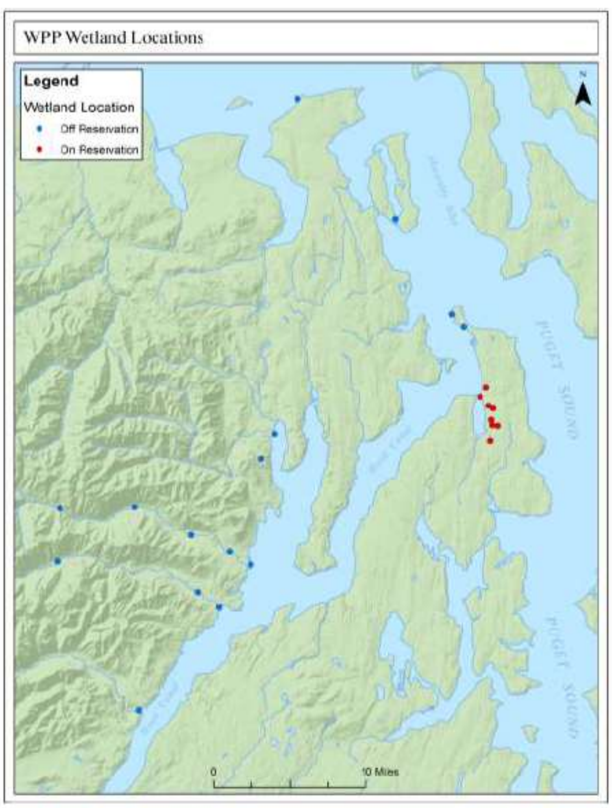
The Port Gamble S'Klallam Tribe places great value on wetlands as a cultural resource. Coastal and inland wetlands provide habitat for species that are important for subsistence, economic, and cultural reasons—including elk, deer, shellfish, and salmon—as well as traditional medicines. Wetlands also protect coastlines from storm damage, help to filter runoff from developed areas, and provide recreational opportunities for wildlife viewing, hunting, and fishing [499].

In 1992, there were 86 acres of palustrine wetlands (inland non-tidal areas like swamps) and 8 acres of salt marsh on the reservation; lands that have received Trust status since then have additional wetlands [500]. Figure 44 maps some of the wetlands that the Tribe considers to be particularly significant. In addition to wetlands on the reservation (see text box), these include wetlands in the upper and lower Dosewallips and Duckabush and associated deltas, as well as the Hamma Hamma delta, Quilcene, Foulweather Bluff, Twin Spits, Kilisut Harbor, and Devil's Lake [500]. Some of the Tribe's wetlands have particular cultural significance, and associated data are therefore carefully protected [500].

Definition: Wetlands are lands that are transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.

Federal Geographic Data Committee (FGDC) Standard

Figure 44. Map of preliminary selection of significant wetlands within the Tribe's usual and accustomed areas (2014) [500].



On-reservation wetlands include [500]:

Miller Lake
Middle Creek/Dump Plume
Shipbuilders Creek
Creek behind Reservation Cabins
Wetland on trust land adjacent to Martha John tribs
Wetland at Martha John East WQ monitoring site
Point Julia salt marsh
Other unnamed wetlands

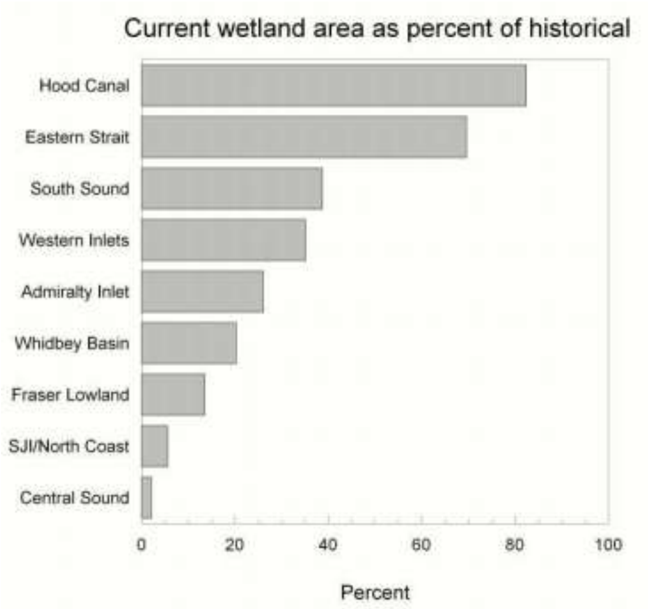
Puget Sound's wetlands have been affected for many years by human activity, such as agricultural expansion, conversion to urban land use, and construction of ports and industrial facilities [500]. A 2006 study found that the most common cause of wetland degradation in Hood Canal and the Strait of Juan de Fuca was fill associated with transportation infrastructure (e.g., railroads) or with residential development [501]. Collins and Sheikh estimated that current tidal wetlands in Puget Sound only cover 17% to 19% of their historical extent; the median size of the remaining wetlands is also smaller than before [502]. The rate of wetland loss across the U.S. has dropped since the late 1990s, due to federal programs and wetland reestablishment projects; however, reestablishment projects have been more successful in upland areas than in coastal areas, perhaps due to costs, competing land use interests, logistical challenges, coastal storms, and sea level rise [499].

Non-climate stresses such as development and pollution are likely to remain the lead degraders of wetlands [503], but climate change adds another layer of stress that puts wetlands at even greater risk. The Port Gamble S'Klallam Tribe has a wetlands program and a Wetland Conservation Program Plan (WCPP) that cover both wetlands on the reservation and those in usual and accustomed areas. The WCPP highlights the importance of considering sea level rise and other climate change projections when making decisions about future wetlands monitoring, assessment, protection, and enhancement [500].

The Point Julia salt marsh and wetland is a priority concern for the Tribe in the context of climate change. This area could be inundated as a result of sea level rise; the Tribe is also anticipating that it could be affected by increased erosion, sedimentation, and damage from extreme coastal weather events. See the Observed and Projected Climate Changes chapter for more information on sea level rise projections. Additional research is being conducted in partnership with the University of Washington in 2017.

Most of the tidal wetlands in Puget Sound have historically been comprised of the estuaries of large rivers, particularly on the eastern side of the Sound. In the past, only 1% of tidal marsh area in Puget Sound was made up of fan-delta estuaries draining the Olympic Mountains to Hood Canal and the Strait of Juan de Fuca through the Hamma Hamma, Duckabush, Dosewallips, Quilcene, Dungeness, and Elwha rivers; these are key parts of the Port Gamble S'Klallam Tribe's usual and accustomed area [502]. However, over time, the north Sound has lost a greater percentage of its historical wetland area than has Hood Canal (see Figure 45) [502]. As a result, the "steep" estuaries of the Olympic Peninsula now make up more—5%—of the region's tide marsh area [502].

Figure 45. Hood Canal has lost proportionally less of its tidal wetland area than other parts of Puget Sound. Source: Collins and Sheikh, DNR 2005 [502].



IMPACTS ON COASTAL WETLANDS

This chapter places special emphasis on coastal wetlands—such as tidal and intertidal wetlands and pocket estuaries—because of their important role as habitat for salmon and shellfish, which are key resources for the Tribe. As the climate changes, coastal wetlands are likely to be affected by sea level rise, changes in precipitation and associated shifts in streamflow and sediment delivery from coastal rivers, and increasing air and sea temperatures. As detailed below, the anticipated consequences include changes in wetland extent, their ability to provide adequate habitat, and, in the end, species composition and abundance.

CHANGES IN EXTENT

Sea Level Rise

As the sea level rises, and more land is inundated, estuarine beaches and tidal swamps are expected to shrink, while some tidal flats and salt marshes are expected to expand. In Puget Sound, estuarine beach area is projected to decrease by 7%, tidal freshwater marsh by 24%, and tidal swamp by 77% between 2000 and 2100, given mid-range sea level rise of 27 inches [115]. At Port Townsend, Admiralty Inlet, and Whidbey Island, specifically, there could be a 72% loss of estuarine beach by 2050; by 2100, an estimated 74% of brackish marsh and 29% of inland fresh marshes could be converted to salt marsh and tide flat [115]. Meanwhile, the tidal flat area could increase by an average of 240% [504]. Under a more extreme sea level rise scenario, USGS scientists found that most coastal wetlands around the world would disappear [505]. Storm surge on top of sea level rise will contribute to increased erosion of shorelines.

Sediment Delivery

Streams bring new sediment to tidal wetlands. With declining snowpack and more intense winter precipitation, more sediment is expected to be brought downriver. It is not currently known whether this increased sediment will be enough to help Puget Sound's tidal wetlands keep up with rising sea levels, however [504]. While a recent study in the Snohomish estuary found that soils in preserved sites without dikes are keeping pace with current estimated sea level rise [506], on average across the U.S., soil accretion will have to occur two to seven times more quickly over this century in order to keep up with rising sea levels [507]. If insufficient sediment arrives, tidal wetlands need to be able to migrate to higher ground in order to survive; armored shorelines, roads, and other development prevent this from happening in many places [505]. Steeper slopes also provide fewer opportunities than shallow slopes and level areas for new wetland creation as the sea level rises [506].

Soil accretion can happen more quickly when there are rootmats and vegetation to help trap sediment, pointing to wetland restoration and planting as useful adaptation strategies [506]. The carbon dioxide fertilization effect may also help with sediment accumulation. Experiments at the Smithsonian's Global Change Research Wetland found that as emissions continue to rise, increased carbon dioxide will speed the creation of new wetland soil because higher carbon dioxide increases the growth of some plant species [508]. Plant root production contributes to organic soil formation, which complements sediments delivered from rivers and the sea [507]. This increased soil creation could help to offset the pace of inundation from rising sea levels in some places.

RESEARCH NEED: Will sediment be delivered from local rivers at a fast enough rate to help wetlands keep up with sea level rise?

SPECIES COMPOSITION

Studies show that while wetland plants can often cope with increases in single stressors, it is much harder for them to adapt to multiple stressors [507]. Climate change adds a number of new threats on top of the development pressures already affecting these ecosystems.

In addition, because wetland plants and animals are located in a transition zone between aquatic and terrestrial environments, they are particularly sensitive to small, permanent changes in conditions [509]. A small drop in water levels, for example, can turn an inland wetland into dry ground, whereas it would have less impact on a lake [510].

Warming sea temperatures will affect coastal ecosystems with shallow water—like tidal wetlands—sooner than deeper ocean waters [223]. Higher water temperatures could affect the composition of plant and animal populations in these areas [115]. If these species have the time and pathways to migrate, and there are alternative habitats available, they may move.

Changes to water salinity and soil salinity induced by ocean acidification and sea level rise may also create conditions that are beyond the tolerance of some plants and invertebrates [217]. In coastal wetlands, sea level rise increases salinity exposure for plants that may, for example, prefer brackish water [509].

WILDLIFE HABITAT

The aforementioned impacts will specifically affect the habitat and survivability of animals that are of particular importance to the Port Gamble S'Klallam Tribe, such as a range of salmon, forage fish, shellfish, and various bird species.

FISH

Salmon rely on coastal marshes and other nearshore ecosystems for feeding and refuge from predation as they move into the ocean life stage (see Figure 46). Different salmon species spend different amounts of time in estuaries before moving on to the open ocean; juvenile Chinook and chum are particularly dependent on estuaries and pocket estuaries [115]. Chinook, pink, and chum fry and fingerlings may stay in these areas for up to 180 days [511]. Estuarine sampling done in North Hood Canal by researchers working with the Port Gamble S'Klallam Tribe found that coho and chum salmon were particularly abundant at tidal creek sites, and chum and pink salmon were most abundant at independent marsh sites [512].

RESEARCH NEED: Are the Tribe's inland wetlands more dependent on receiving water from precipitation, or from groundwater? Those relying on precipitation will be affected more directly by climate change.

Figure 46. Nearshore marine and estuarine habitat use by salmonid species in the Pacific Northwest. Adapted from Glick et al. 2007 citing Williams and Thom 2001 [115].

	Nearshore marine and estuary use		
	Adult residence	Adult and juvenile migration	Juvenile rearing
Chinook	Extensive	Extensive	Extensive
Chum	Little or unknown	Extensive	Extensive
Coho	Some	Extensive	Some
Sockeye	Little or unknown	Extensive	Little or unknown
Pink	Little or unknown	Extensive	Extensive
Source: Williams, G.D. and R.M. Thom. 2001. *Marine and Estuarine Shoreline Modification Issues* (Sequim, WA: Battelle Marine Sciences Laboratory/Pacific Northwest National Laboratory), p. 14.			

Changes in wetland extent will affect salmon directly, through habitat availability, and indirectly, through the food web. Studies in the Gulf of Mexico show that there is a complicated relationship between estuarine-dependent fish species and vegetation loss in intertidal areas: in that region, large areas of wetland have been lost, but fisheries have not suffered greatly [507]. One hypothesis is that this is because in the short term, fragmentation of marshes creates more of the marsh edges that serve as critical habitat [507]. Still, the longer-term effects of continued wetland degradation will ultimately be negative for these fish species. Meanwhile, in Puget Sound, forage fish like herring, surf smelt, and sand lance, which spawn on beaches, are an important food source for salmon [115]. Lost beaches and tidal flats, therefore, will have a cascading effect on salmon through their food chain.

Other climate change impacts on wetlands will also affect salmon. A 1998 literature review found that there were four main reasons cited as being responsible for limiting the residence time of juvenile salmon in estuaries; these included increases in summer water temperature, a lack of preferred prey, extreme river discharge, and increases in antagonistic interactions among juvenile fish when densities increased [513]. Two of these—increases in summer water temperature and extreme high and low river discharge events—are projected to occur as the climate continues to change.

It is worth noting that salmon are not the only fish species likely to be affected by sea level rise and changes in coastal wetlands. Groundfish—including various types of rockfish and sole, as well as Pacific cod and lingcod—also rely on nearshore habitats for juvenile rearing and other uses [115].

See the Salmon chapter and the Forage Fish and Critical Prey chapter for more information.

BIRDS

Birds that rely on coastal or inland wetlands for nesting or migration routes may be affected by changing precipitation and water availability during critical seasons [509]. Shorebirds, for example, often rely on coastal and intertidal flats for feeding in winter and during times of migration [514]; changes in the extent of those flats and the availability of invertebrates will affect the number of shorebirds supported in and near Port Gamble S'Klallam Tribal lands. Studies in other parts of the globe have found reduced numbers of shorebirds corresponding to losses in mudflats [514]. If armoring and development do not prevent wetland migration to shallow upland areas, new habitats could be created, but they may not be created fast enough to avert losses in shorebird populations [514].

Ducks, geese, and seabirds also rely on marshes, beaches, and tidal flats, and on the forage fish that have historically been found in those areas, and are likely to be affected by sea level rise and associated changes in the ecosystems [115].

See the Birds chapter for more information.

SHELLFISH

As the sea level rises, deeper waters threaten to reduce shellfish production. For example, Dungeness crabs use estuaries as nurseries; changes to local estuaries would therefore affect survival and reproduction of crabs [115]. On the other hand, the projected increase in tidal flat area in Puget Sound could be favorable for production. See the Shellfish chapter for more information.

IMPACTS ON INLAND WETLANDS

RESEARCH NEED: How do juvenile salmon use various nearshore habitats across Hood Canal? What environmental factors (e.g., salinity) are most important for juvenile salmon? [501]

While this chapter has primarily focused on tidal wetlands and estuaries, the Port Gamble S'Klallam Tribe is also concerned about inland wetlands that are also sensitive to climate change impacts. For example, inland wetlands can be affected by rising air temperatures, which increase evaporation and transpiration rates and can lead to drying that reduces wetland size [503]. Shallow seasonal ponds that provide breeding ground for amphibians may change dramatically or disappear with changing precipitation and increasing air temperatures [515]. Those same changes in hydrology and temperature will also affect species composition in bogs and fens [509]. In addition, riparian wetlands that get inputs from streams will be affected by changes in precipitation and reduced snowmelt at the headwaters [503] and areas that juvenile salmon use for off-channel rearing and flood refuge habitat. Wetland trees may shift in response to rising air temperatures, if climatic conditions do not shift too quickly for them to migrate and re-establish populations in new locations [510]. Studies in the Cascades found that climate change would reduce overall water availability for wetlands, increase the frequency of pond drying, and lengthen the summer dry spell [515].

Movement and migration may not be possible; just as shoreline armoring and coastal development prevent the migration of coastal wetlands as the sea level rises, inland wetlands are often constrained by dams, roads, drainage, and other barriers, as well as soil type and topography [510].

LOOKING AHEAD

The Tribe's WCPP includes planned future activities that will help to increase understanding of climate change impacts on local wetlands and build resilience. For example, the Plan includes deploying water level/temperature loggers at five sites to help monitor climate change and related changes in hydrology, sea level, and sediment deposition [500]. Other activities, such as ensuring that appropriate buffers and protections are applied to wetlands during forest practice operations, will also have indirect climate resilience benefits.

The Tribe is also a partner in the Kitsap Forest & Bay Project (KFBP), along with Kitsap County, the Suquamish Tribe, and several NGOs and other organizations and agencies. The project aims to conserve 6,700 acres of forest around Port Gamble Bay, including for the purpose of preserving marine and freshwater habitats [516]. The first phase covered 535 acres along the Port Gamble Shoreline, across the bay from the Port Gamble S'Klallam reservation; this land was protected as a park in early 2014.

These existing and ongoing efforts are critical to address non-climate pressures—such as development and pollution—on wetlands, and will be even more important as climate change places additional stress on local wetlands that provide important habitats for fish, shellfish, and birds.

BIRDS

INTRODUCTION

Birds are important to the Port Gamble S'Klallam Tribe for a variety of reasons, including recreation and hunting, their role as indicator species, and their predatory interactions with other key cultural and subsistence resources.

Eagles, blue heron, cormorants, grebes, osprey, belted kingfishers, and loons all call Port Gamble Bay home for some or all of the year. Within the broader U&A area, there are additional species of interest, such as spotted owls and marbled murrelets, that can provide an indication of broader ecosystem health and resilience. From an ecological perspective, predatory birds are also important because of their impact on other key resources, such as juvenile salmon.

The Tribe has hunting seasons and corresponding hunting restrictions for a number of migratory birds, including ducks (mallard, canvasback, pintail, redhead, scoter, merganser), American coots, geese (except dusky Canada geese), band-tailed pigeons, brant, Wilson's snipe, and mourning dove. The Tribe anticipated a total harvest of fewer than 200 migratory birds for the 2015 to 2016 season [517]. Non-migratory birds mentioned in the Tribe's hunting regulations include grouse, quail, pheasant, and turkey. Hunting these birds is an important part of Tribal culture. Grouse, for example, are a traditional food. They are also used as a food supply when hunting for other species, as they can be harvested using rocks and slings without making any noise.

CLIMATE IMPACTS ON BIRDS

Recent studies indicate that climate change impacts such as temperature increases, precipitation change, and sea level rise are likely to have direct effects on bird distributions and survivability. Some of these effects are already visible. According to a scientific literature review covering 570 studied bird species, 24% have been negatively affected by climate change (e.g., through shrinking ranges), while 13% experienced positive impacts [518]. Impacts are still unclear for other species [518]. Other studies indicate that the number of species that will decline in distribution and abundance is twice as large as the number that will expand [518].

RESEARCH NEED: Do local models project the potential extinction of any birds in the Pacific Northwest as a result of climate change?

In 2016, the UW Climate Impacts Group assessed local vulnerabilities of some bird species in a report for the Stillaguamish Tribe, concluding that most species will still be stable in the 2050s and some will even increase in abundance [519]. Birds' ability to move easily to find new areas of climate suitability helps reduce their vulnerability. On the other hand, some species have tended to live in specific thermal niches and will be less prepared for expected temperature variations [519]. Few other available studies focus on Western Washington, but studies that assess trends across North America can provide insight into the potential consequences for bird species of interest to the Port Gamble S'Klallam Tribe.

TEMPERATURE AND GEOGRAPHIC DISTRIBUTION

As climate change increases average temperatures, many bird species are already shifting northward to follow suitable climatic conditions. According to a study by Hitch and Leberg, published in 2007, the average northern latitude of breeding birds in North America shifted northward by 2.35 km (1.46 miles) per year from the 1967–1971 baseline period to 1998–2002 [520].[59] Species did not tend to shift southward, which led the authors to conclude that the shift was likely primarily due to a change in climate, rather than to other factors [520]. At the same time, the studied species were not abandoning the southern portions of their distributions.

In a study of over 300 species, National Audubon Society scientists found that species are wintering an average of 40 miles north of where they wintered in the 1960s [521]. A study by Bateman found that some species—particularly insect eaters, meat eaters, and species that forage on the forest floor or high in the trees—are shifting their breeding ranges as quickly as 3 miles per year [522]. Woodpeckers, non-migrants, and plant eaters are shifting less quickly or not at all at this point [522].

Landbirds make up 87% of all bird species [523]. A 2016 study of 285 landbird species found a mean rate of change in potential breeding distributions of 1.27 km (0.79 miles) per year over the past 60 years, mainly to the north or west [524]. Birds in the west coast lowlands, including Puget Sound, shifted less quickly (0.45 km or 0.3 miles per year) compared to species in other parts of the country [524]. Bird species shifted geographies more quickly than tree species and marine species, indicating that they may either be particularly flexible given their high degree of mobility or especially climate-sensitive [524].

Bird species may have varying levels of success in adapting to climate change by altering their ranges. Northward shifts could potentially be a problem if food sources cannot move north as rapidly [520] or if suitable land cover (e.g., the right amount of forest, grassland, or other land cover type) is not present in the new geographic area [524]. Climate change could also change the timing of food availability in the oceans such that it no longer coincides with the changing breeding or migration seasons of coastal birds [525]. Many forest birds have large ranges and high reproductive potential, making them relatively less vulnerable to climate change impacts. Species that depend heavily on specific resources or forest types are important exceptions [525]. For example, the marbled murrelet, spotted owl, and western grebe have very specialized diets which can increase their vulnerability (see descriptions of each species below).

TEMPERATURE AND ELEVATIONAL DISTRIBUTION

In addition to shifting northward, many bird species are moving upslope to follow preferred temperature or precipitation conditions [526]. While non-climate stressors like habitat loss have primarily affected lowland species, montane species may be greatly affected by climate change impacts on temperature [523]. Species with narrower elevation ranges will be more vulnerable to climate change, as small range size is already a predictor of extinction from non-climate stressors like land use change [526, 523]. New disease vectors may also appear at higher elevations as temperatures rise, with impacts on bird health [523].

A global study by Sekercioglu et al. estimated that a worst-case warming scenario (6.4°C warming by 2100) and upslope shifts in suitable bird ranges would result in the extinction of 30% of all landbirds in the Western Hemisphere; 21% of those species are already threatened with extinction today [523]. Migratory birds had lower projected levels of extinction due to their mobility [523]. Given that this projection may not

[59] This study looked at birds such as sparrows, warblers, chickadees, and flycatchers; it did not include birds dependent on aquatic habitats.

accurately quantify what can be expected in specific locations, such as Western Washington, further analysis using local climate and ecological models would be useful [523].

Further study is also needed to document the current elevation limits of bird species to understand vulnerabilities and monitor impacts [523]. In 2011–2012, scientists collected data on elevation ranges of birds in Olympic, Mount Rainier, and North Cascades National Parks [526]. This study will provide a baseline against which to monitor shifts in elevation ranges as the climate changes [526]. The data include species such as the band-tailed pigeon, bald eagle, and several types of woodpecker, jay, chickadee, warbler, sparrow, and finch, among others [526].

TEMPERATURE AND REPRODUCTION

While no studies were found that focused specifically on changes in the laying dates of birds in the Pacific Northwest, studies in other regions found correlations between increasing temperatures and advances in laying dates.

In a study of pied flycatchers in Europe, researchers found that increasing temperatures caused these migratory birds to lay their eggs earlier in the year and to lay more eggs [527]. As the warming trend continues, the birds' ability to further advance their lay date may be constrained by the timing of their arrival at the breeding ground [527]. Bird populations could remain stable if the timing of peak food supply advances at the same rate as laying dates or if food is abundant enough that the peak timing is less important [528].

A 2014 review of 196 relevant studies by Dunn and Møller found that increased temperatures have been correlated with advances in laying dates and that these advances were larger for herbivorous or predatory birds that had multiple broods per season [528]. They did not find evidence that changes in laying date were affecting overall population trends but noted that effects are likely to differ across different types of species [528].

PRECIPITATION AND WATER AVAILABILITY

RESEARCH NEED: Have increasing temperatures affected laying dates of bird species in the Pacific Northwest?

Species are shifting faster than the shift in temperature alone because temperature is not the only climatic factor affecting bird species' survivability [524]. Precipitation, water availability, pH, humidity, and extreme conditions also play a part [524]. These other factors affect survival and reproductive success by affecting food availability, disease vectors, and vegetation structure, among other things [524, 529]. While increasing temperature has been linked to shifts northward, precipitation changes may explain why some bird species also shift westward [524]. A study focused on Western North America concluded that precipitation was a major determinant of changes in the abundance of terrestrial bird species over a 32-year period [529]. This study found that precipitation was a more important predictor than temperature in the abundance and distribution models.

Combined changes in precipitation and temperature—leading to increased evapotranspiration—will also have impacts, such as on the extent of inland wetland habitats for birds. One-third of the 165 wetland breeding species in the country are ranked as having medium or high climate change vulnerability, however this study did not specify the time period or the temperature increase used to make these determinations [525]. These vulnerable species include the Western grebe.

SEA LEVEL RISE

Tidal sand and mud flats provide important foraging habitat for shorebirds. Rising sea levels may reduce the extent of this foraging habitat [530]. Increasing water temperatures and storms will also affect habitats and the availability of food sources [525].

A 2007 study by the National Wildlife Federation looked at several study sites in Puget Sound, including one that included Port Gamble and other parts of the upper Hood Canal. The study's projections for 2050 with 11.2 inches of sea level rise were no change in tidal fresh marsh acreage, a 60% loss of estuarine beach, minor expansion of estuarine open water (1%), and extreme expansion of tidal flat (1,455%) and saltmarsh (6,533%). Projections for 2100 with 1.5 meters of sea level rise were no change in tidal fresh marsh habitat, an 85% loss of estuarine beach, minor expansion of estuarine open water (4%), and extreme expansion of tidal flat (1,411%) and saltmarsh (4,960%) [115]. Table 22 lists some of the species that the National Wildlife Federation noted could be vulnerable given these amounts of sea level rise and other climate change impacts.

Table 22. Sea level rise impacts on waterfowl and seabirds [115].

Climate change impact	Type of birds that could be affected	Sample species
Reductions in habitat quality due to sea level rise and other impacts	Diving ducks	Canvasbacks, greater and lesser scaup, goldeneyes, bufflehead
Loss of tidal flats	Dabbling ducks and geese	Gadwalls, American wigeon, mallards, northern pintails, green-winged teal, snow geese, brant
Reductions in forage fish and other food sources due to sea level rise	Seabirds	Surf scoters, common murres, pigeon guillemots, marbled murrelets, Caspian turns, rhinoceros auklets, brown pelicans

See the Wetlands chapter for more details about climate change impacts on shoreline ecosystems.

SPECIES

This section summarizes potential vulnerabilities of some of the key species of interest to the Port Gamble S'Klallam Tribe.

BALD EAGLE

In Olympic National Park, bald eagles have been detected between 7 and 102 meters of elevation [526]. Across the U.S., the bald eagle is projected to lose 74% of its current summer range by 2080 but acquire significant summer range in new places if adequate habitats and food sources are available [531]. The bald eagle could be vulnerable to climate change impacts if large nest trees are damaged by fire or flooding [519]. Other impacts on forests—such as pest and disease outbreaks—could also affect the quality and extent of eagle habitat. The Climate Change Sensitivity Database gave the bald eagle a sensitivity score of 47 (medium) with a confidence score of 3 (fair) [532]. Changes in eagle abundance would have a cascading effect on their prey, which are primarily fish but also include wading birds [532, 533].

Audubon models found that the following bird species of importance to the Port Gamble S'Klallam Tribe could be seriously threatened by climate change at the national level [531]:

Climate endangered (may lose over 50% of current range by **2050**)

- Bald eagle
- Black oystercatcher
- Mallard
- Osprey
- Redhead
- Spotted owl

Climate threatened (may lose over 50% of current range by **2080**)

- Band-tailed pigeon
- Brant

GREAT BLUE HERON

In 2010, the Tribe found signs that a family of herons had built a rookery on the reservation [534]. The great blue heron is not expected to be especially vulnerable to climate change impacts because it is mobile and has a flexible diet that includes fish, insects, amphibians, mice, and crustaceans, among other creatures [519]. While some of these food sources could be adversely affected by climate change—for example, crustaceans are likely to be affected by ocean acidification—the great blue heron can shift to other food sources as needed. Rookeries could be impacted by coastal flooding and sedimentation, and marsh and estuary habitats are also sensitive to climate change [519]. Herons could be affected by increases or decreases in predation risk, depending on how climate and non-climate stressors affect predators such as bald eagles [533].

SCOTER

Scoters winter in the Puget Sound region. The scoter depends on coastal marshes, estuaries, and beaches, which are likely to be affected by sea level rise, as well as small lakes, which could be impacted by rising temperatures and drought [535]. A large portion of the scoter's diet is made up of shellfish, which may become less abundant in the context of ocean acidification and rising water temperatures [536]. Scoters have already declined in Puget Sound in the last three decades, possibly due to contaminated shellfish [536]. Continued increases in harmful algal blooms may exacerbate that problem, as harmful algae leads to shellfish toxicity (see the Harmful Algal Blooms chapter for more detail). The Climate Change Sensitivity Database entry gave the scoter a sensitivity score of 45 (medium) with a confidence score of 2 (poor) [535]. More research would be needed to better undertand their vulnerability.

BRANT

The Climate Impacts Group found that the Climate Change Vulnerability Index (CCVI) ranked brant in Puget Sound as "presumed stable" for both the 2050s and the 2080s because the species has a flexible diet and can easily move to new places if necessary [519]. The species has a range of more than 100 km [519]. The

CCVI did not, however, specifically examine whether increased coastal flooding or sedimentation could affect the birds' ability to forage for eelgrass, green algae, or other plants. Audubon's climate model shows that the black brant is likely to be more affected by climate change impacts in the winter than in other seasons and that the suitable wintering area may be further north in the future [531].

NORTHERN SPOTTED OWL

Northern spotted owls—which are listed as "threatened" under the Endangered Species Act—help to indicate the health of old-growth forests [537]. Impacts on forests, such as disease outbreaks and forest fires that damage trees and corresponding habitats, would have repercussions for spotted owl health (see the Forest Resources chapter for more information). Non-climate stresses such as logging and forest thinning also affect the spotted owl, including by affecting its primary food source: the northern flying squirrel [519].

The spotted owl is somewhat sensitive to temperature. Rising temperatures could affect the spread and dominance of the barred owl, whose competition creates a continued non-climate stressor for the spotted owl [519, 538]. In a vulnerability assessment for the Stillaguamish Tribe, the Climate Impacts Group found that the CCVI ranked the spotted owl as "presumed stable" for the 2050s but "extremely vulnerable" by the 2080s. Meanwhile, the Climate Change Sensitivity Database gave the spotted owl a sensitivity score of 71 (high) with a confidence score of 3 (fair) [539].

MARBLED MURRELET

The marbled murrelet, a small seabird that nests in old-growth forests and feeds in the ocean, is listed as threatened in Washington, Oregon, and California [540]. In 2011, the Marbled Murrelet Recovery Implementation Team (RIT) met to evaluate the causes of murrelet decline, noting climate variability and change as relevant threats. The RIT noted that murrelets' terrestrial habitat and nesting areas could be affected by changing wildfire risk or changes in temperature and moisture that alter moss growth [541]. They also noted the potential impact of climate variability and change on food webs, such as through harmful algal blooms (see the Harmful Algal Blooms chapter for more detail). Marbled murrelets also eat mollusks and crustaceans [519], which could be affected by ocean acidification. These birds have been observed to defer breeding during food shortages [519]. The CCVI ranked the marbled murrelet as "presumed stable" for the 2050s and "moderately vulnerable" by the 2080s for the nearby Stillaguamish region. The University of Washington, U.S. Forest Service, and U.S. Fish and Wildlife Service are currently doing research to better understand how a range of changes—including in climate and associated changes in forage food availability—affect the abundance and distribution of murrelets [542]. In a 2016 article, they reported that factors influenced by climate variability and change (e.g., wildfires and insects) contributed to the loss of nearly 27,000 acres of nesting habitat between 1993 and 2012 across the bird's range [543].

OSPREY

Across the country, osprey are projected to lose 79% of their current summer range by 2080 at the same time that their winter range will grow [531]. Osprey are likely to be directly affected by climate change impacts on fish, which make up nearly all of their diet [544]. Reciprocally, changes in osprey abundance would in turn affect the quantity of fish in the area. The Climate Change Sensitivity Database entry gave the osprey a sensitivity score of 55 (medium) with a confidence score of 2 (poor) [544].

WESTERN GREBE

The western grebe is sensitive to changes in flood and drought cycles, which will be affected by climate change. It also depends on wetlands with adequate water levels to support nesting. The grebe builds a floating nest mat connected to a snag or plant, and increased flooding could damage this construction [519]. As temperatures rise and precipitation patterns change, available wetland habitat could shrink [545]. The grebe also relies on nearby accessible fish prey, which could in turn be affected by rising ocean temperatures, ocean acidification, and other climate change impacts [519]. As the grebe rarely flies outside of the migration season, it depends on having adequate food sources close to its breeding ponds [519].

LOOKING AHEAD

In general, birds will likely be impacted through the combination of reductions in habitat quality, loss of habitat (e.g., tidal flats), and reductions in food sources (e.g., forage fish).

The Tribe is also concerned that if marbled murrelet populations drop any lower—as a result of climate change impacts or other stresses—it will increase the chances of having fishing restrictions with Tribal gillnets, as these birds occasionally get caught in fishing nets. This would in turn dramatically lower fishing opportunities for Tribal members.

The Tribe has partnered with Northwest Indian College and Kitsap Audubon Society to count and catalog bird species found around Port Gamble Bay [546]. This kind of effort will help provide monitoring data to understand trends in populations affected by both climate and non-climate stressors.

MAMMALS AND UPLAND WILDLIFE

INTRODUCTION

Subsistence hunting of species such as elk, deer, and bear has historically been as important to Western Washington tribes' survival as the harvest of salmon and shellfish [547]. It is estimated that the consumption of wild game provides $1,500 to $2,000 worth of food per family per year, allowing tribal members to rely on these species as a food resource. The Port Gamble S'Klallam Tribe's hunting committee, whose members are appointed by Tribal Council for three-year terms, works with the Council to maintain the hunting code and reviews regulations produced by Natural Resources Department staff.

Other mammalian species aside from hunted ones are important to the Tribe because they play critical roles in maintaining the health and balance of ecosystems. These include mountain lions, beavers, and other ecologically important species discussed in further detail below.

In general, climate change is expected to impact these culturally and ecologically important mammals by altering habitat, trophic structures, food availability, and disease prevalence. This chapter provides a more in-depth look at these impacts and notable non-climate stresses that exacerbate or are exacerbated by climate impacts.

HUNTED SPECIES

Deer, elk, and bear are the species most commonly hunted by Tribal members.[60] Table 23 below shows the number of hunting tags issued by the Tribe and number of animals harvested in the 2015-2016 season.

Table 23. Number of tags issued by species to Port Gamble S'Klallam Tribal members and amount harvested in 2015-2016 season.

Species	Tags Issued	Amount Harvested
Deer	222	61
Elk	104	8
Bear	74	1

Mountain goats are also seen as culturally significant by Tribal members and hunters, but no mountain goats were harvested in the 2015-2016 season.

These species occupy, at least in part, areas at an increased risk of degradation due to climate change. For example, rising temperatures, decreased soil moisture, and increased evaporation rates are expected to increase wildfire risk in Western Washington's forested landscapes, potentially affecting areas that provide habitat for elk, deer, and bear [46]. Other causes of forest degradation and change—such as insect outbreaks and changes to tree phenology—are also expected to increase with projected climate change.

[60] The amount of tags issued to Tribal members to hunt these species exceeded those for other hunted species (e.g., mountain goat, mountain lion, and bobcats) in the 2015-2016 season.

Alpine habitats and subalpine forests occupied by mountain goats are also susceptible to climatic changes, particularly warming temperatures. More information regarding climate impacts on forests can be found in the Forest Resources chapter.

Animals themselves could see direct adverse impacts from climate change in addition to the indirect impacts of habitat loss. Climate change will play a role in changing the types and prevalence of disease, changes to habitat structure, survival rates, and potential physiological impacts to hunted species.

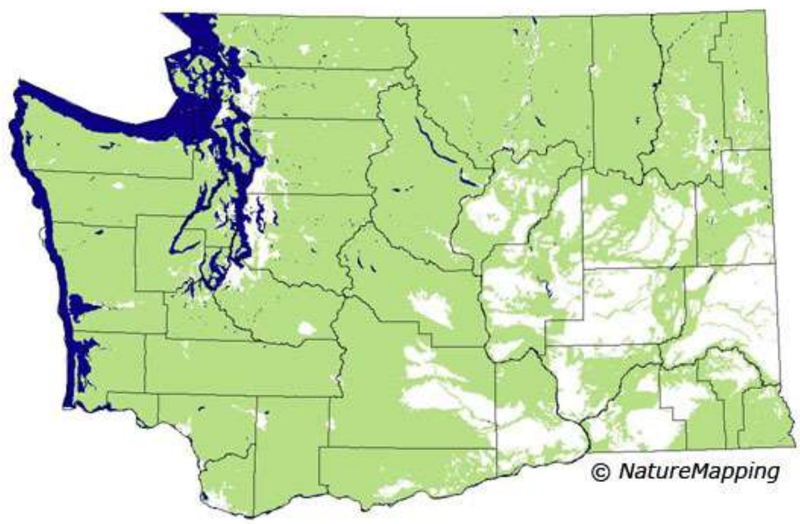
The following sections highlight four species that are important to Tribal hunters: Black-tailed deer, Roosevelt elk, black bear, and mountain goat.

RESEARCH NEED: Are the drought conditions that caused major damage to deer habitat and populations in the Rocky Mountains likely to happen in Western Washington, and, if so, when?

BLACK-TAILED DEER

Black-tailed deer are a subspecies of the more common mule deer found throughout Washington State and across much of the western United States [474]. Figure 47 shows the mule deer's range in Washington.

Figure 47. Mule deer habitat (shown in green) in Washington State [548].



Impacts on Habitat

According to the Western Association of Fish and Wildlife Agencies, black-tailed deer on the Olympic Peninsula fall into the Coastal Rainforest Ecoregion (one of seven separate ecoregions of black-tailed deer habitat across its entire range). In this ecoregion, black-tailed deer have suffered losses of forage food and losses or changing structures of habitat due to urban development, past forest management practices (e.g., long-term fire suppression), and the introduction of invasive species (e.g., knapweed) [474]. Black-tailed deer are expected to remain vulnerable to anthropogenic stresses into the future [519].

Any black-tailed deer population relies on habitat where water, food, and cover are consistently available and arranged in a way that provides the population with adequate nourishment as well as plenty of cover to survive and safely reproduce [474]. Deer are edge species, wherein their preferred habitat is at the interface of openings and cover patches (e.g., thickets) [549]. It is in these areas where they are most successful in finding the forage foods they require without travelling too far from cover [549].

Examples from Wyoming and Colorado show that mule deer declines from 2002 to 2012 were the result of a combination of fragmentation and extended drought in that region [550]. The ultimate decline in population by 25% was due, in part, to a lag in the rebounding of degraded habitat after the drought stress [550]. While warmer, drier summers are projected to increase in Washington State beyond 2100 [46], more research is needed to determine if and when the extended drought conditions seen in other western states have the potential to be replicated in Western Washington [46]. Increases in average annual temperature and changed precipitation regimes are expected to affect flowering and seed germination for some species in the Pacific Northwest [551], but more work is needed to identify specific phenological changes for specific species and how those changes could affect wildlife.

Impacts on Health

Research by Thalmann et al. in California found that extended periods of drought can lower the body and antler size of male black-tailed deer when drought conditions persist through *in utero* development, birth, and early life stages [552]. In these instances, young are born small and remain small into adulthood, although it is unclear if the smaller size presents a significant threat to deer health [552, 553]. Typically for ungulates, a larger body size indicates better physical condition and correlates with better chances of survival and reproduction [554].

In Oregon, the warm temperatures and drought in 2014 were determined to be the likely cause of the spread of adenovirus among black-tailed deer herds [555]. The virus is considered fatal, as it restricts a deer's ability to feed while causing extensive damage to its digestive system [555]. Given that warm temperatures and drought were at least a factor in the spread of adenovirus in 2014, increased warming and drought conditions in the future could increase the risk of further disease spread. Drought conditions also cause deer to associate together more closely around diminished food sources, which can worsen disease outbreaks.

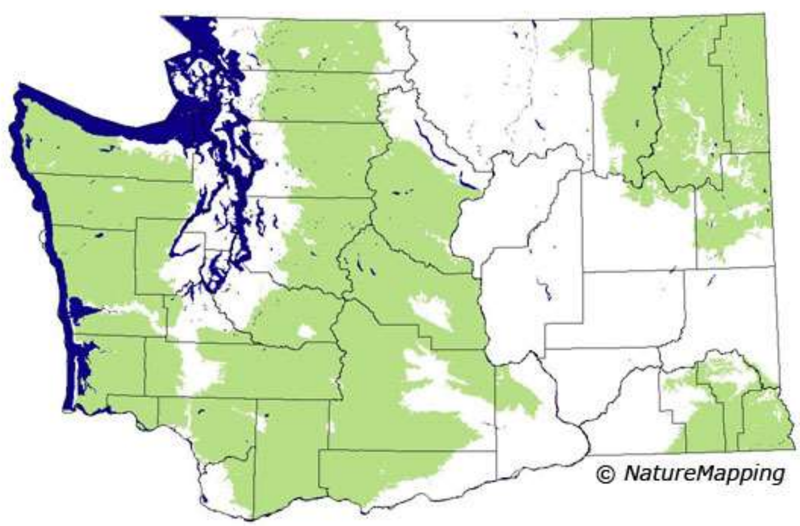
Black-tailed deer are also susceptible to hair loss syndrome, which is caused by an allergic reaction on the skin of the deer from the presence of an invasive louse [556]. Many deer affected by hair loss syndrome die from complications related to the skin allergy; mortality is especially high among infected fawns [556]. A 2010 study of fawns on the Olympic Peninsula found that three-quarters of the 126 fawns being monitored died from complications arising from hair loss syndrome [557]. As a result, several tribes and the Washington Department of Fish and Wildlife halted antlerless deer harvest [558]. Since it was first detected in 1996, hair loss syndrome has affected black-tailed deer throughout its range in Western Washington [556]. Research by Bildfell et al. found that the deer that succumbed to hair loss syndrome had correlating health issues (e.g., internal parasites, low body mass) [559]. It is possible that stress on deer health, from climate impacts or otherwise, may make black-tailed deer more vulnerable to hair loss syndrome and vice-versa. Figure 48 shows symptomatic deer affected by hair loss syndrome.

Figure 48. Examples of hair loss caused by hair loss syndrome [556].

ROOSEVELT ELK

Two subspecies of elk can be found in Washington State: the Roosevelt elk and the Rocky Mountain elk [470]. In Western Washington, Roosevelt elk are the more predominant of the two subspecies, with the highest concentration currently found in Olympic National Park [470]. Figure 49 shows elk habitat across Washington State.

Figure 49. Elk habitat (shown in green) in Washington State [548].



Impacts on Habitat

Roosevelt elk require habitat that includes productive grasslands, meadows, or clear-cuts interspersed with closed-canopy forests as well as large amounts of forage foods (e.g., grasses, sedges, sprouts, flowering plants) that are available year-round [470]. Roosevelt elk are unique among other subspecies of elk in that they are generally non-migratory due to less seasonal variability of food in their primary habitats [560]. This suggests that any shift that results in decreased plant productivity and decreased availability of forage foods will impact areas of suitable habitat for Roosevelt elk.

However, a study by Wang et al. found that some elk herds (in this case, those in the Rocky Mountains) may benefit in the short-term from warming temperatures and/or increased rainfall because these changes could result in increased available forage food [561]. More research is needed to determine if Washington State elk populations could see such benefits and how long those benefits could persist.

Impacts on Health

Elk reproduction cycles are timed such that mating occurs during the fall with birth during early summer (usually May or June) the following year [562]. Births are timed to optimize calf survival so that the risk of cold, inclement weather is minimized while allowing adequate time for calf development before the next winter season [562].

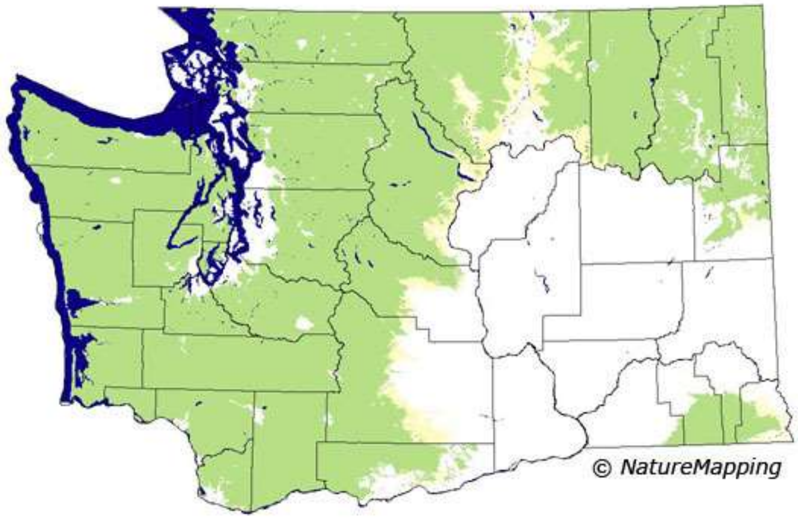
RESEARCH NEED: How will near-term and longer-term climate changes affect forage availability for elk herds on the Olympic Peninsula?

Some research suggests that milder winters as a result of climate change would allow for an elk population increase of +28% across the species' entire range [563]. This is likely due to the higher potential for juvenile survival. Whether this increase would benefit the species is debatable, as such increases could present issues with competition for food and habitat as carrying capacity is approached (or surpassed); additionally, higher population densities can lead to disease spread and more human-elk interactions [563]. It should be noted that projected elk population increases in response to climate change will likely not be uniform across the species' range [561], making it difficult to say whether such increases could be anticipated in Washington State.

BLACK BEAR

Across the state of Washington, the adult black bear population is estimated to be approximately 17,000 and they are found in nearly every county [564]. Much like deer and elk, black bear will likely see climate change impacts related to food/habitat availability and health. Figure 50 shows the black bear's range in Washington.

Figure 50. Black bear habitat (shown in green) in Washington State. Areas in yellow are potential habitat [548].



Impacts on Habitat

Black bears, like other large species near the top of the food chain, require large, cohesive habitat zones that allow them adequate food and shelter within their home ranges as well as access to areas outside home ranges for breeding [565]. More research is needed to determine how and where climate impacts like drought and warmer temperatures, and cascading effects like wildfire, will affect black bear habitat in Washington State. However, climate change is likely to contribute to and exacerbate the impacts of habitat fragmentation [566]. For example, many species have ranges that cover large geographic areas, often including human-dominated sections. In some extreme cases, a small population of a species occupying an area embedded within such human-dominated sections can go extinct when environmental conditions change [566]. When looking at the species' entire range, these small extinctions can resemble distribution shifts, and suggest the importance of understanding how spatial features across landscapes can influence population dynamics [566].

RESEARCH NEED: How will climate impacts and habitat fragmentation affect black bear habitat in Washington State?

Impacts on Health

Hibernation cycles of black bears are dependent on environmental conditions like temperature, day length, and food availability [567]. There could be potential impacts to bear hibernation if climate change alters the timing or occurrence of these conditions (e.g., warmer winter temperatures). Warmer winters can cause some bears to end their hibernation early [567]. Such circumstances can cause the bear to leave their dens before the nourishment needed immediately following hibernation becomes available [567]. In these cases, bears are less likely to find the food they need. Given that female black bears typically give birth during January and February, foregoing the protection of the winter den too early could make cubs especially vulnerable to starvation, predators, or other health impacts [567].

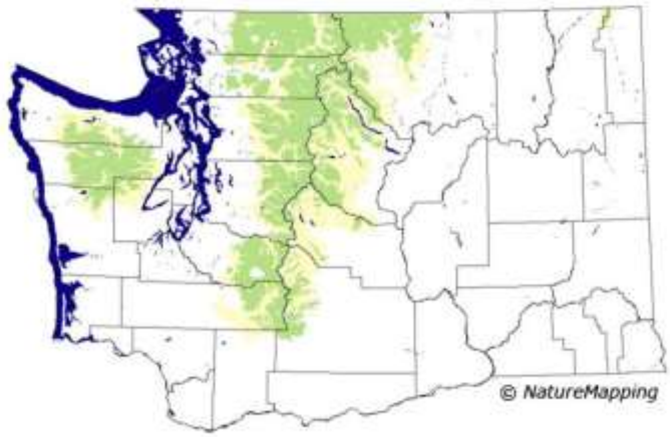
Black bears are susceptible to a wide range of pathogens, some of which are zoonotic (i.e., can be transmitted from animals to humans) [568]. Therefore, any increase in these pathogens presents an issue that is two-fold: 1) diminished health of black bear populations, and 2) more potential for human health impacts. In a study of Northern California black bears, *Toxoplasma gondii*—the pathogen that causes toxoplasmosis— was among the most common zoonotic diseases found in the bears' blood (28% of bears tested) [568]. Black bears, in particular, are known to have high rates of infection of *Toxoplasma gondii* given their scavenging feeding habits [569]. *Toxoplasma gondii* is considered the most prevalent zoonotic parasite on earth, and multiple studies suggest that climate impacts such as warming temperatures and

changing precipitation will cause an increase in infection rates among humans [570, 571, 572]. *Toxoplasma gondii* is most often spread to humans through the ingestion of contaminated animal tissue [572], which assumes that an increase in the infection rate of *Toxoplasma gondii* in black bears could put more humans at risk of contracting the pathogen since black bears are a game species. More research is needed to determine how vulnerable Washington State black bears are to an increase in *Toxoplasma gondii*, and whether an increase in black bear infection rates is likely to lead to an increase in human infections for this region. More information on human health impacts can be found in the Human Health and Safety chapter.

MOUNTAIN GOAT

Although the mountain goat is not considered a native species to the Olympic Peninsula [573], historical evidence suggests that the modern mountain goat's ancestors occupied nearby parts of the Pacific Northwest, including Vancouver Island, during the last Ice Age (around 12,000 years ago) [574]. Today, mountain goats are found throughout the Cascade and Olympic Ranges, and are particularly suited to virtually any alpine or subalpine habitat [573]. Approximately 290 mountain goats are thought to occupy the Olympic Peninsula based on population estimates conducted in 2012 [575]. Figure 51 shows mountain goat habitat in Washington State.

Figure 51. Mountain goat habitat in Washington State. Areas in yellow are potential habitat [548].



Impacts on Habitat

Increased warming is likely to cause considerable impacts to alpine and subalpine regions occupied by mountain goats. Glacial retreat and reduced snowpack will alter the hydrologic cycle of these ecosystems, increasing runoff during melting and then reducing runoff as ice mass diminishes over time [576]. While these changes could result in a longer growing season (i.e. frost-free period) for high-elevation plant life, any reductions in water availability will outweigh these benefits by negatively impacting growth [576]. As a foraging species, mountain goats would be adversely impacted by such declines in plant growth. Although increased temperatures in alpine regions would theoretically allow the upward migration of montane forests (perhaps leading to increased vegetation in alpine habitats), the pace of projected climatic change is now expected to be more rapid than the speed at which forests can migrate [576, 577, 578]. Therefore the window of opportunity for forests to migrate upslope may close before forests are able shift.

In Olympic National Park, mountain goats are typically found above 5,000 feet during summer months, likely to avoid extreme heat, and occupy lower elevations during cooler months [579]. However, future increases in average temperature during cooler months could cause mountain goats to move up in elevation to find climatically suitable habitat.

Impacts on Health

Mountain goats' movements typically peak during morning, midday, and evening as they travel between forage sites [580]. They have been observed reducing their activity during hot summer days, exhibiting a certain sensitivity to above-normal temperatures [580]. A 2014 study of chamois (a species similar to mountain goat) in Italy's alpine areas linked warming temperatures to increased population densities and decreased forage activity, resulting in long-term declines in body mass [581]. As with other ungulates, a mountain goat's body mass indicates its chances of reproductive success and survival [581]. Researchers noted that the body mass declines were not the result of changing phenology or food production in the alpine habitat, but rather the effect of increased competition for food and decreased time spent foraging (due to heat stress) [581]. The current literature on Pacific Northwest mountain goats has not addressed this topic specifically, but it is possible that the conditions leading to declining body mass could be replicated in Washington State under projected climate change.

ECOLOGICALLY IMPORTANT SPECIES

Washington State has many species that are integral to overall ecosystem health and stability. These species are sometimes called "keystone" species when their presence is critical in maintaining the composition of their ecological communities [582]. It will be important to consider how climate change will impact keystone species in order to better understand what sort of cascading effects may come from a potential loss or decline in their populations. This section briefly describes various species important for overall ecosystem health and how climate change is expected to impact them.

PREDATORS

The presence of predators in a given habitat can lead to more diverse and resilient ecosystems [583]. In essence, predators are considered to be the controllers of species' densities throughout the trophic levels below them [582]. The removal of carnivores from their habitats often results in decreased biodiversity in those areas [582].

Wolf

As an apex predator, wolves play a vital role in maintaining the populations and trophic composition of various species within their habitat [584]. In Olympic National Park, where wolves were extirpated in the early 1900s, their absence has been tied directly to the increase in ungulates and the correlating over-browsing of riparian shrubs and other vegetation [584]. As a result, the trophic cascade resulting from the removal of wolves contributed to the deterioration and ecological instability of riparian habitat in Olympic National Park [584]. The re-introduction of wolves can help avoid cascading effects from increases in the survival rates of large mammals [583].

Mountain lion

Like the wolf, the mountain lion is an apex predator with a top-down influence on the trophic levels below it [585]. In a study of the browsing habits of mule deer in Yosemite National Park, Ripple and Beschta found that the absence of mountain lion as a predator of deer beginning in the 1920s led to greater densities of herbivores - resulting in a decline in oak and other vegetation [585]. These results echo those found in the trophic cascade studies of wolves mentioned previously.

It can be assumed that, like other top predators, mountain lions will play a part in maintaining ecosystem stability under climate change by ensuring a balanced predator-prey ratio [583]. Given the mountain lion's expansive range, it is not currently considered vulnerable to climate impacts at a large scale [586]. More research is needed to determine if that vulnerability changes at local or regional scales, however. According to the IUCN, mountain lions are most negatively impacted by habitat fragmentation resulting from human activity [586], and climate change impacts could eventually present an added stress on mountain lions and their habitats. It is possible for a segment of a species' population embedded within human-dominated areas to go extinct when environmental conditions change because they are restricted from accessing other parts of their natural range due to human activity (such as development) [566].

Coyote

As a mesocarnivore (i.e. diet consisting of 50–70% meat), coyotes can have a collective ecological impact similar to that of larger apex predators [587]. Mesocarnivores are important for ecosystem health in a variety of ways, including acting as seed dispersers, facilitating the distribution of prey across ecosystems, and maintaining ecosystem structure and dynamics in the absence of larger carnivores [587].

Coyotes' food choices can be diverse. One study of Western Washington coyotes found their diet consisted of mostly fruits and small mammals [588]. Coyotes are also scavengers, most notably for elk carcass [589]. The food choices of coyote fluctuate based on availability, typically determined by season [589], as well as location (urban vs. rural environments).

American Marten

Although the American marten is an opportunistic feeder whose diet includes fruit and nuts, it mainly feeds on small mammals (e.g., squirrels) and is considered a predatory species [590].

A 2011 study of marten habitat in the Northern Rockies found that climate change will likely result in reduced habitat connectivity for martens, fragmenting them into smaller and less genetically diverse populations [591]. Martens rely on deep snowpack, and tend to avoid lower elevations during warmer seasons [591]. Given their snowpack requirement, winter temperature increases will likely result in fewer areas of climatic suitability for the marten, although this is dependent upon specific qualities of the landscape, particularly whether climatically suitable areas are naturally separated by river valleys or other geographic features [591]. More research is needed to determine whether martens in Western Washington are at risk of increased habitat fragmentation like the populations in the Northern Rockies.

Harbor Seal

In Puget Sound and Hood Canal, harbor seals are the most abundant marine mammal and are seen as sentinels of ecosystem health [592]. Harbor seals are important for ecological stability and maintaining species diversity given their highly variable diet [593]. While harbor seals are preyed upon by larger mammals in parts of their range, harbor seal populations in Puget Sound are considered a particularly significant predator of fish species, including salmonids during various life stages [592].

Across their range, harbor seals are primarily threatened by human activity and disease, including morbillivirus [593]. Multiple studies suggests it is possible that environmental conditions related to climate warming exacerbate mass-die offs during morbillivirus outbreaks when those conditions impact the physical health of seals or cause seals to spend more time on land prior to the outbreaks [594, 595]. In a 2013 study of harbor seal pup mortality on Smith Island, WA, various bacterial infections, including *Salmonella* and *Streptococcus*, were the cause of death for several pups [596]. More research is needed to determine if harbor seals' susceptibility to these pathogens will increase with future climate change.

Seals and other pinnipeds may also be subject to reproductive impacts as water temperatures rise [594]. Seal pups have shown higher rates of mortality during El Niño events, likely due to reduced food sources resulting from increased sea surface temperatures [594]. These events offer a glimpse of the potential impacts of future temperature regimes [594].

Given their predation of salmon in the Puget Sound region, it can be assumed that impacts on harbor seals will have a cascading effect on salmon. These effects could be positive or negative for salmonids in this region.

NON-PREDATORS

While predators and prey are perhaps the most recognizable keystone species, ecological "mutualists" and "modifiers" can also be considered keystone species even though they may not easily fall into the predator or prey categories [582]. Mutualists are those animals that are essential to the survival of various plant species, thereby supporting other food webs (e.g., pollinators) [582]. Modifiers are animals that impact habitat features but may not have direct effects on the food web (e.g., beaver) [582]. Of the non-predator species, beavers are of particular importance for ecosystem health on the Tribe's reservation and Usual and Accustomed area.

Beavers are unique in their ability to change the hydrological attributes and biotic dynamics of their ecosystems, and are vital in maintaining biodiversity at the landscape scale [597].

Although there is little research to date regarding the potential climate change impacts on beavers in the Pacific Northwest, they are considered a possible tool for improving the resilience of ecosystems—particularly those in more drought-prone regions [598]. Hood and Bayley studied wetland growth in Alberta, Canada between 1948 and 2002, and found that wetlands showed more stability to climate variability when beavers were present [598]. Beginning with beaver reintroduction to the area in 1954, Hood and Bayley found a resulting 9-fold increase of open water space during the study's timeframe [598]. The researchers concluded that the removal of beavers from aquatic systems can have the same impact on wetlands as in-filling and groundwater withdrawal [598]. In addition to wetlands, a 2016 study by Bouwes et al. found beaver dams have watershed-scale benefits to steelhead populations in Oregon [599]. Stream channels immediately downstream of a beaver dam tend to deepen as water is forced to cascade over the dam [599]. These areas, referred to as "plunge pools", can provide important foraging opportunities and thermal refugia for juvenile steelhead [599]. Bouwes et al. found increases in density, survival, and production of juvenile steelhead when beaver dam structures were present, as well as no impact to steelhead migrations [599].

In an assessment focused on the Stillaguamish watershed, beavers were presumed stable through the 2080s, however warmer winter temperatures and increased precipitation could increase the risk flooding imposes on this species [519]. Conversely, decreased precipitation during summer could lead to habitat degradation [519]. These impacts would be exacerbated by non-climate stressors, including urban development or other anthropogenic barriers [519].

LOOKING AHEAD

The key threats to wildlife on the Tribe's reservation and traditional use areas will likely come from the combination of simultaneous non-climate and climatic stresses in the coming decades. Larger mammals like black bear and elk, as well as large predatory species like mountain lion, rely on expansive, interconnected habitat to ensure food availability and reproductive success. The connectedness of these ecosystems is vulnerable to increased urban development, which in turn could make the species within these fragmented ecosystems more susceptible to climate impacts as they occur (e.g., wildfire, drought). In addition to changes in habitat, changes in the phenology of plant life that provide vital food resources and the increased potential for disease will likely affect each of the species discussed in this chapter.

As a result, the Tribe's efforts to restore habitat and work with the hunting committee to engage the public and ensure the effective management of wildlife will continue to be critical in the years ahead.

Impacts on Human Systems

Infrastructure

Human Health and Safety

Cultural Resources

INFRASTRUCTURE

INTRODUCTION

This chapter examines anticipated climate change impacts on infrastructure elements that are important for the Tribal community, such as transportation, energy supply, water systems, and buildings.

The Tribe currently maintains multiple critical infrastructure assets on the reservation, including 184 housing units, a business park, and a building complex for administrative, cultural, and human services offices.

Also crucial to the reservation is Point Julia, a marshy, low-lying spit jutting westward into Port Gamble Bay. Point Julia provides essential access to the beach for boat launches and shellfish harvesting, as well as to the Tribe's salmon hatchery. The remaining shoreline is lined with sandy bluffs ranging from 20 to 60 feet high, making access to the beach more difficult [600].

FACILITIES AND HOUSING

The majority of the Tribe's facilities and housing can be found along the eastern side of Port Gamble Bay. As a result, the Tribe has continually studied the impacts natural coastal processes can have on this part of the reservation—with Tribe-commissioned studies dating as far back as 1975, and including specific focuses on slope failure, slide activity, and bluff erosion. Even though the majority of the residences and other structures along the bluff will likely remain safe for many years, relocation or abandonment of those structures may eventually be required since bluff erosion is expected to speed up with increased precipitation and faster rates of sea level rise [37]. For more information on bluff erosion, refer to text box on page 151.

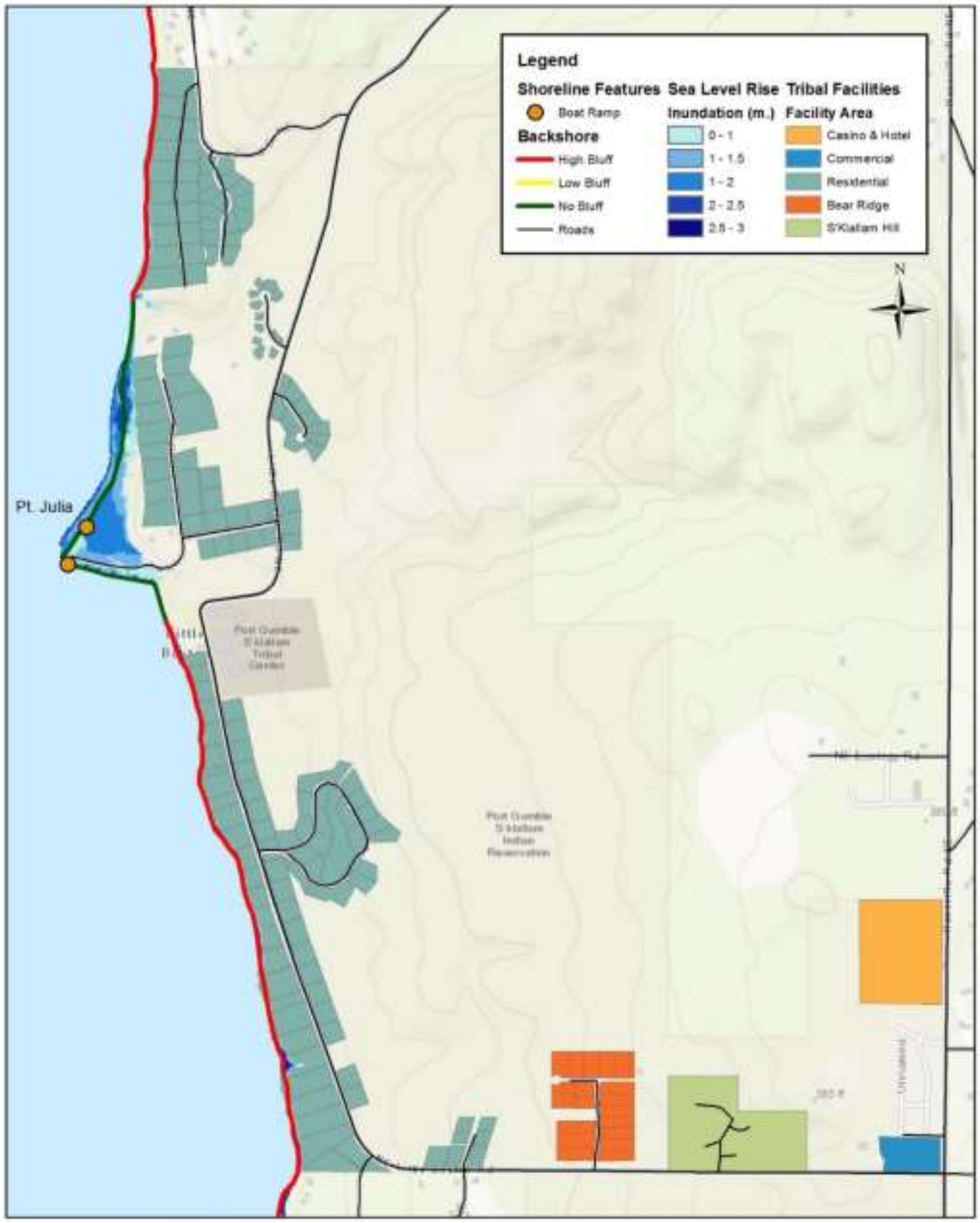
FACILITIES

Buildings that are vital to the function of governmental, social, cultural, and economic programs on the reservation include the Tribe's Administration Campus (holding several administrative, social services, health, and educational facilities), and the Tribal business park, which consists of a casino, minimart, wellness center, and maintenance facilities. A new wastewater treatment facility and 94-room hotel next to the casino are in mid-construction.

These facilities are likely to be relatively resilient to anticipated climate change impacts due to their design and location. For example, all buildings are situated on concrete slabs or over crawl spaces, at high elevations, and away from the bluff, suggesting that they would not be exposed to sea level rise or bluff erosion or highly sensitive to inland flooding. However, changes to the frequency of wildfire, landslides, and extreme storms could affect the Tribe's facilities, and will require more monitoring and analysis to determine specific risks.

In contrast, at Point Julia, the lower elevation makes boat launches and other nearby facilities more vulnerable to flooding due to sea level rise; flooding would be exacerbated during storm or extreme high tides (see Figure 52).

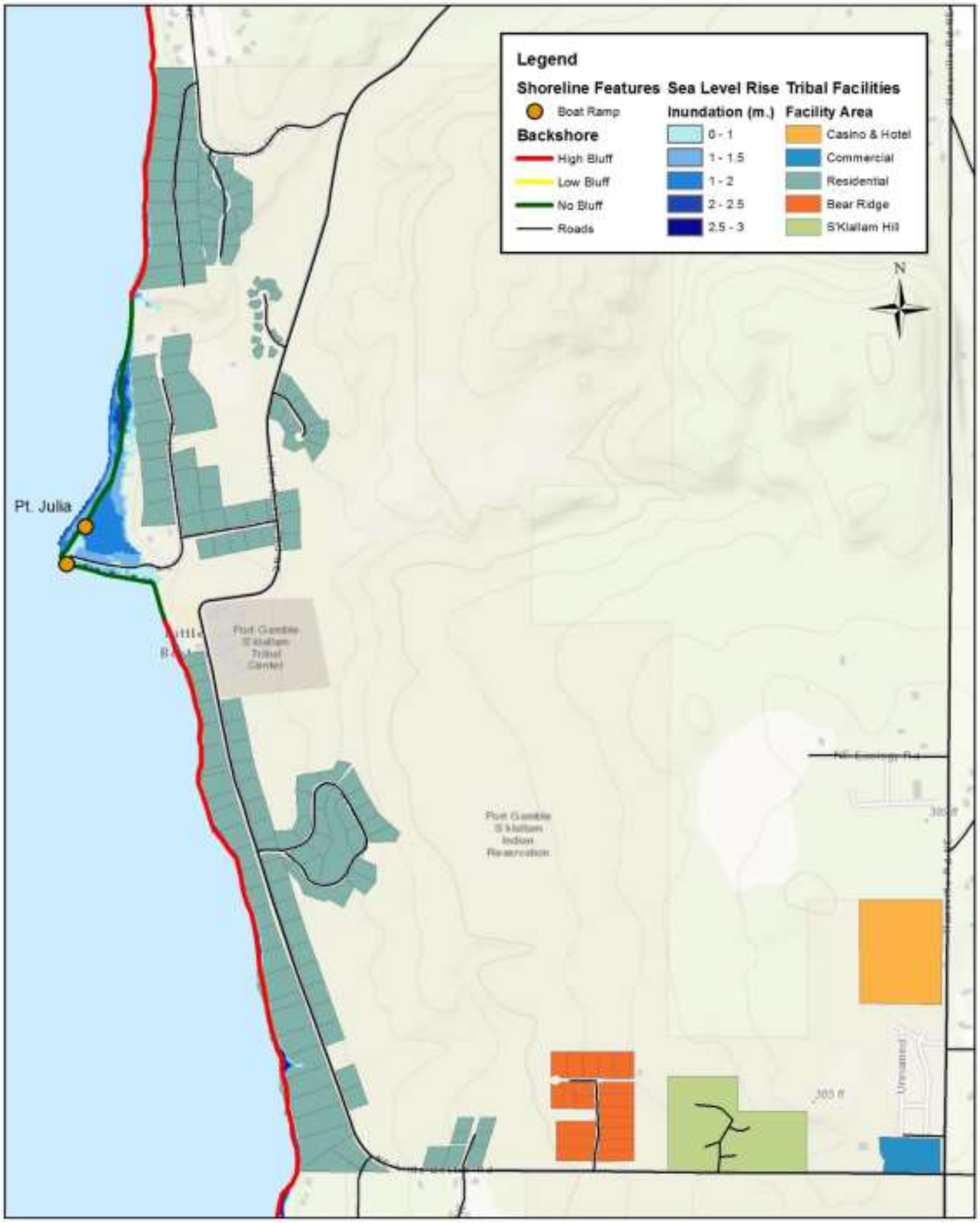
Figure 52. Potential inundation of Point Julia and adjacent areas under a scenario with 6 feet (1.83 meters) of sea level rise.



Data Sources: Point No Point Treaty Council and National Oceanic and Atmospheric Administration

In a study on climate change preparedness on the Olympic Peninsula, researchers used models based on the A1F1 "business as usual" scenario, and found a 50% probability that Port Townsend sea levels will rise by 28 inches by 2100, relative to 2000 levels [37]. More information on sea level rise can be found in the Observed and Projected Climate Changes chapter.

Figure 53. Sea level rise and bluff line map at Port Gamble S'Klallam Reservation. Projections reflect a 50% chance of sea level rise of 28 inches by 2100 at Port Townsend, used as a proxy here. Point Julia is the area most likely to be inundated by sea level rise; bluffs to the north and south will experience increased erosion due to sea level rise. Tribal facilities away from the bluff have been mapped for perspective and scale. Data is from a 2000 Point No Point Treaty Council analysis.



Data Sources: Point No Point Treaty Council and National Oceanic and Atmospheric Administration

BLUFF EROSION ALONG PORT GAMBLE BAY

Bluff erosion is an existing concern that will become more serious in the context of climate change, as sea level rise and increased heavy rainfall events are expected to speed up the process [37]. Bluff erosion can also be exacerbated by upland development, which increases surface water runoff and decreases infiltration rates, effectively pushing surface water to the shore and contributing to faster rates of erosion along the coast [601]. It is important to note that all buildable lots along Port Gamble Bay within the Tribe's reservation have already been developed, likely due to a combination of the aesthetic qualities of coastal property and the deep cultural connection the Tribe has to its coastal resources [601]. As a result, the Tribe may need to consider relocating some of those facilities and homes to avoid impacts related to bluff erosion [601].

Historically, bluff erosion along Port Gamble Bay has not been caused by tidal action or wave activity; slope failure from a combination of surface water erosion and seepage of subsurface sediment has been the primary cause [649]. However, given the incremental nature of slope failure, a slope stability analysis performed in 1987 concluded that the bluff was indeed safe for permanent developments [649]. Increased slide activity along the bluff prompted another assessment in 1997. This assessment found that slopes were indeed stable under dry conditions, but heavy rains leading up to the 1997 assessment were reducing the strength of the topsoil and underlying layers of sediment, leading to more slides [645]. Like the 1987 stability analysis, the 1997 assessment maintained that the primary driver of bluff erosion was the combination of surface water erosion and subsurface seepage [645]. Some residential lots were vacated because of stability concerns. Septic drain fields located along the bluff edge may have contributed to earlier periods of slope instability, but the drainfields have since been abandoned for sewer connections. The Tribe's 2015 Hazard Mitigation Plan acknowledges the role of surface and subsurface water in bluff erosion, but places particular emphasis on wave action (which is expected to increase with rising sea levels) as a major contributor to bluff erosion [601].

A 2017 study considered the risk of bluff erosion to property and the role of bluff erosion on shoreline functions important for natural resources [653]. Previous studies of the reservation shorelines were more focused on the risk to specific locations in response to sudden events like landslides.

The 2017 study considered the larger perspective from tidelands to uplands with recognition of tribal priorities, considering the potential for property abandonment alongside engineered stabilization measures like bulkheads. Bulkheads and other shoreline stabilization structures are largely absent from the reservation shoreline. Field investigations revealed the presence of specific geological units and areas of groundwater emergence. The study found the bluffs north of Shipbuilders Creek to be at lower risk of landslides and erosion than the bluffs south of Point Julia. The study notes that the toe of the coastal bluff will be subject to increased erosion due to sea level rise and larger storm events. Tribal staff have instituted a monitoring program to understand baseline conditions and to capture changes in the bluffs over time in accordance with study recommendations.

Bluff Erosion along Port Gamble Bay

The Port Gamble Bay Cleanup Project involves structure removal, excavation, and armored capping of shorelines at the former Port Gamble Mill site. A consultant evaluated shoreline erosion at the site in response to two wind storms in 2016 [654]. The wind speed was recorded at a buoy northwest of the site in Hood Canal and a recurrence interval was calculated for the event, with a 50-year return period for a 46 mph wind. This event resulted in considerable erosion of existing riprap and debris at the site, however, the site is not naturally sloped and the pre-storm condition of the riprap varied. The evaluation also considered sea-level rise and found that while the surf zone may move landward with increased overtopping at the top of bank, the shear stress on the protective cap at lower intertidal elevations would be reduced.

A wind-wave analysis was completed by the consultant for wind conditions with 2 and 20 year return periods using data in the above mentioned analysis with some outliers removed **[655]**. The analysis determined a 2-year return period wind speed of 22 to 39 mph and a 20-year return period of 28 to 49 mph, depending on wind direction. The model predicted wave height for the southeast shoreline of the mill site (inside the Bay) was 2.0 feet for the 2-year storm and 2.5 feet for the 20-year storm, corresponding to wind speeds of 36 and 49 mph, respectively. Deepwater wave conditions off shore of the site (outside the Bay) were predicted to range from 2 to 3 feet for the 2-year storm and 3 to 4 feet for the 20-year storm.

A wind-wave analysis completed for the site of the Tribe's net pens estimated maximum significant wave heights between 2.7 and 3.6 feet based on wind recorded at McChord Air Force Base on October 12, 1962, which is the storm of record for western Washington. This site is in the north-center of the bay in deep water and the analysis used the maximum southerly fetch. A breaking wave height was estimated at 4.1 to 5.4 feet [656].

Regular and routine monitoring could be useful going forward, especially in the context of climate change.

HOUSING

Roughly half of Tribal members live on the reservation. There are 184 housing units composed of a mix of multifamily and single-family dwellings, located primarily in 10 neighborhoods throughout the reservation. Approximately half of the homes are renter-occupied and managed by the Housing Authority, and the other half are owner-occupied. Most of the homes are heated by electricity and/or wood-fired stoves, with relatively few using propane furnaces.

The primary concern for potential damage to housing on the reservation is from higher rates of bluff erosion (see box on page 151) [601]. Areas away from the bluff are susceptible to erosion and landslides as well, especially those adjacent to moderate and steep slopes [601]. Flood risk due to sea level rise or heavy rainfall is not currently a threat to the housing stock on the reservation. Smaller-scale, localized flooding on the reservation has yet to cause any serious damage to Tribal property [601]. Regardless, Tribal leadership is taking precautionary steps to address concerns that flooding will worsen in the future as development on the reservation increases, including incorporating stormwater management measures into new development [601]. While this planning is not explicitly considering climate change projections, it can be assumed that better stormwater management will increase the Tribe's resilience to flooding regardless of what is driving it.

Although climate change is generally expected to alter the environmental conditions that buildings are designed to withstand, it is difficult to accurately predict how changes will impact specific buildings on the reservation and to determine if those impacts could be attributed to climate change. However, due to housing demand, the Housing Authority and Planning Department are already planning to develop 100 more neighborhood lots, all of which are located away from low lying areas or the bluff.

UTILITIES

Climate change-driven alterations to rainfall patterns and wildfire risks may impact the reliability of utilities, such as electricity, water, and wastewater treatment systems, in the future.

ELECTRICITY AND HEATING

The reservation, like all of north Kitsap Peninsula, receives electricity from Puget Sound Energy (PSE) [602]. PSE's electricity generation mix consists of 36% hydropower and 60% fossil fuel-based power, produced from power plants across the Pacific Northwest [603, 602]. For more information on PSE's energy mix see Table 24 and Table 25 below.

Table 24. PSE 2015 Fuel Mix [603].

Fuel Type	Percentage	Energy (MWh)
Coal	35%	7,658,643
Hydroelectric	36%	7,936,093
Natural gas	24%	4,362,426
Nuclear	1%	243,433
Wind	3%	584,879
Total	100%	21,888,487

Projected increases in temperature and changes in precipitation are expected to impact the seasonal production of hydropower regionally [413]. Peak streamflow timing will shift over the next few decades from spring (primarily driven by snowmelt) to winter (driven by rainfall) due to changes in seasonal precipitation levels and temperatures [413]. As a result, projections show a modest increase in winter hydropower production (0.5% to 4.2% by 2040), and a substantial decrease in production in the summer months (13% to 16% by 2040) [413]. For the same reason, water levels in reservoirs will be lower during warm weather months, putting stress on shared resources for municipal water supply systems and hydropower production [413]. However, given that PSE's fuel mix contains well below average hydropower (36% compared to the Washington state average of 65%), the direct impact of low water storage on the PSE fuel mix is lower than it would be for other state utilities [603, 604].

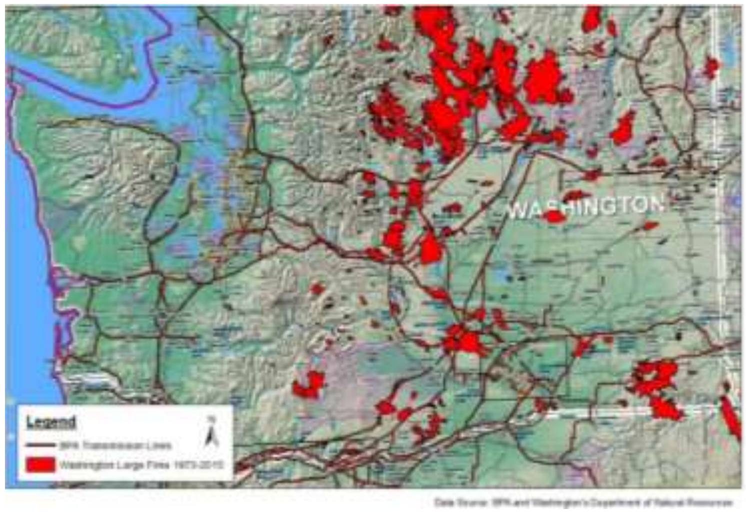
Table 25. PSE Major Power Plants (over 400,000 MWh) [603].

Power Plant Name	Majority Fuel Type	Energy (MWh)
Colstrip (A)	Coal	4,444,130
Rocky Reach (B)	Hydro	1,152,091
Mint Farm (C)	Natural Gas	1,266,143
Wells (D)	Hydro	1,033,637
Goldendale (E)	Natural Gas	1,014,519
Ferndale Cogen (F)	Natural Gas	712,072
Rock Island (G)	Hydro	649,961

Figure 54. PSE's Major Power Plants (over 400,000 MWh).

Five of the seven largest electricity generators for PSE are located east of the Cascade Mountains, with the largest and furthest plant located in eastern Montana (see Figure 54). This means that their transmission lines cross areas that are wildfire-prone (see Figure 55) and could be at increased risk in the future under a changing climate. Drier, hotter conditions are expected to triple the annual statewide area burned by the 2040s, particularly along the Cascade Range and Columbia Basin, a major corridor for electricity transmission [413]. As such, transmission lines through these areas may become increasingly vulnerable to damage from flames, heat, and smoke [413], which could result in temporary but widespread interruptions to electricity generation, transmission, and distribution. Even if infrastructure is not directly damaged by wildfires, smoke from wildfires can de-energize the transmission lines, causing temporary interruptions in power to the reservation [46, 413]. Depending on the severity and timing of the interruption, residents on the reservation could experience electricity price fluctuations and/or loss of power during business hours, community events, or emergency procedures.

Figure 55. Electricity transmission lines and locations of large (100+ acre) fires between 1973 and 2015 in Washington State.



Many homes on the reservation also use wood-fired stoves for heating and cooking, largely because wood is a less costly fuel source. The Tribe has designated two areas for alder and Douglas fir wood harvesting on the reservation (see Figure 56). More information on climate impacts on forests and their long-term wood generation can be found in the Forest Resources chapter.

Figure 56. Wood harvesting areas on the Port Gamble S'Klallam Reservation.

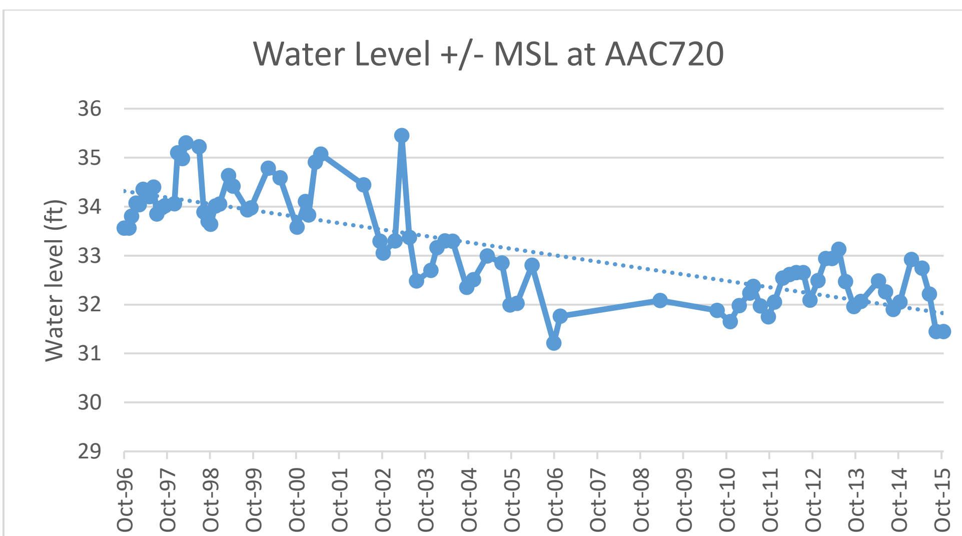
WATER

While much of the Puget Sound population's water supply comes from water reservoirs fed by rivers and snowmelt, the reservation relies exclusively on groundwater refilled by precipitation [46, 605]. Tribal water systems rely predominantly on two on-reservation water wells. Water is fed from the wells into three water storage tanks, which in turn provide water to all buildings on the reservation except the business park (which receives its water from nearby wells through the Kitsap Public Utility District (Kitsap PUD). The Tribe's system is connected via an intertie to the Kitsap PUD #1 water system in case of emergency water shortages.

Heavy rain events are projected to become more intense in Puget Sound as a result of climate change [606], but this does not necessarily mean higher water levels in wells on the Kitsap peninsula in general. Average annual groundwater recharge amounts in Washington State are expected to remain relatively constant, but the location and timing of groundwater recharge may change, causing variability and reducing reliability [606]. Furthermore, rainfall in heavy bursts (instead of gradual precipitation over a longer period) may not adequately resupply groundwater but instead run off into nearby waterways. More research is needed on this potential impact.

The Tribe has observed steady, small declines in annual well water levels over the past several years. Data from wells on the reservation was not readily available, so data from a Kitsap PUD well (AAC720) located approximately five hundred feet southeast of the reservation was used as a proxy (see Figure 57 below) [605]. PUD data show that annual well water levels have gradually declined by an average of 0.9 inches over the past two decades, but these declines could be attributable to a variety of factors [605].

Figure 57. Kitsap PUD well level readings near Port Gamble S'Klallam Reservation [7].



WASTEWATER TREATMENT AND DISCHARGE

Each housing unit has its own septic tank that is piped to a collection facility located north of the Administration Campus. After treatment, wastewater is discharged to drainfields just east and northeast of Point Julia. Construction of a new $12 million wastewater treatment system is underway near the hotel and casino and is scheduled for completion in summer of 2016. The current system and the new system are both at high enough elevations to avoid any threat of untreated effluent leakage due to sea level rise; however, the aforementioned well water constraints could put stress on the availability of water for treatment purposes. In contrast, heavy rainfall events can increase flow rates of influent to higher than the treatment plant's capacity and reduce the system's performance.

Transportation

Many Tribal members and staff live off reservation—including on the eastern side of Puget Sound—and depend on the Washington State Highway and Ferry system whenever they commute to the reservation. This section examines how critical roadways and the ferry system will be affected by climate change.

HIGHWAYS AND ROADS

Little Boston Road N.E. is the major thoroughfare on the reservation. Beginning at the southeast corner of the reservation off of Hansville Road, it follows the southern reservation boundary and turns north, roughly paralleling the bluff's edge. Like other infrastructure located near the bluff, this and other roadways may eventually require rerouting if damaged by bluff erosion.

The roadway on Point Julia is the only low-lying road on the reservation. Like the Point itself, this road is at risk from flooding due to sea level rise, extreme high tides, and heavy rainfall. Point Julia currently experiences flooding during king tide events, indicating the likelihood of future impacts from rising sea level (see Figure 58). Other roads on the reservation are at higher elevations and are not directly impacted.

Figure 58. Point Julia during the December 21, 2015 king tide event. Both boat ramps are submerged in this photo.

Other major highways used heavily by the Tribe off the reservation, such as Hansville Road and Highway 104, are generally not at low elevations that are at risk of flooding from sea level rise, according to Washington State Department of Transportation's (WSDOT) Climate Impacts Vulnerability Assessment [607]. However, Highway 101 near Discovery Bay is at risk of intermittent flooding from king tides and storm surges in moderate- and high-severity sea level rise scenarios, which would not only prevent access to the Bay for 12-24 hours but also delay access to points west [608], particularly for hunting and fishing activities in the Tribe's primary traditional use area.

HOOD CANAL BRIDGE

The Hood Canal Bridge is essential to road transportation from the Olympic Peninsula to the reservation; all transportation must cross the bridge or detour south to Shelton to link up with other access points. In general, sea level rise is expected to increase the risk of corrosion to concrete and steel bridges due to increased contact with saline water. However, the Hood Canal Bridge is designed to pivot up and down with fluctuating tides at the transition spans, which makes it well equipped to adapt to sea level rise [609]. Additionally, regular maintenance of the Hood Canal Bridge already addresses any corrosion issues found from sea water.

The bridge closes to traffic during storms with sustained winds of 40+ miles per hour that last up to fifteen minutes or longer [257]. However, as noted in the Observed and Projected Climate Changes chapter, preliminary analysis finds that wind patterns in the Puget Sound region are not projected to change as a result of climate change.

FERRIES

Major ferry routes to the Kitsap Peninsula from East Puget Sound used by Tribal staff are Seattle-Bainbridge, Edmonds-Kingston, and Keystone-Port Townsend. The Washington State Department of Transportation has projected both positive and negative climate change impacts on the ferry system. Higher levels of rainfall are expected to increase the amount of sediment and flood debris discharge from coastal rivers into Puget Sound, which may require more frequent dredging of ferry terminals [46]. However, there are no large rivers on the Kitsap peninsula, and the aforementioned ferry terminals on the east side of Puget Sound are in urban environments devoid of large debris runoff and away from any major rivers.

Ferry crossing cancellations due to tidal conditions are normal occurrences in parts of Puget Sound. Strong low tides can prevent ferries from safely accessing shallow docks resulting in the cancellation of some ferry trips [610]. Sea level rise may help reduce the impacts of low tide and the likelihood of terminal closures [607]. However, sea level rise may adversely impact maintenance schedules at the Eagle Harbor maintenance facility, which is situated a few feet above sea level. According to WSDOT, sea level rise may eventually submerge the site permanently, requiring ferries to undergo maintenance elsewhere and placing stress on the frequency and reliability of ferry routes [607].

LOOKING AHEAD

The Tribe is currently building an updated and improved wastewater treatment system, which is scheduled to be completed in the summer of 2016. The new system's design capacity accounts for future population growth on the reservation [600] and is expected to effectively treat current and future effluent volumes for years to come.

Housing development plans consider bluff erosion in their siting assessment, but do not factor projected sea level rise into bluff erosion rates.

The Tribe is planning to install floating boat launch ramps on the south side of Point Julia; this may help account for some change in sea level, but more assessment is needed.

HUMAN HEALTH AND SAFETY

INTRODUCTION

Climate change can bring new health threats to new places and also exacerbate existing health problems that are sensitive to weather or climate [611]. This chapter explores some of these anticipated health and safety impacts from climate change, which include increased rates of the following [612]:

- Heat-related illnesses such as heat stroke and heat exhaustion.
- Air-quality-related respiratory illnesses such as asthma and allergies, resulting from increased allergen production, ground-level ozone, and wildfire smoke.
- Some diseases transmitted by food, water, and insects, such as shellfish poisoning, West Nile Virus, and fungal diseases (e.g., Valley Fever).
- Injuries resulting from exposure to extreme weather events.

The groups that are most likely to be vulnerable to climate change impacts on health include people over age 65, children, low-income individuals, people who spend a lot of time working outdoors, households that lack access to air conditioning, and people with existing cardiac, respiratory, or other underlying health problems are likely to be most vulnerable to climate impacts on health [611]. The Tribe's enrollment list has a smaller percentage of people over age 65 compared to Kitsap County more broadly (approximately 6% compared to 16.5%) [613, 614], but approximately the same percentage of children under age 5. The 2010 census showed that 15.3% of households on the reservation were below the poverty line [614].

EXISTING TRIBAL SERVICES

The Tribe's Health Services Department provides Tribal members with both medical and dental primary care services. For other services, including emergency care, the Department typically makes referrals to off-site medical facilities such as Harrison Medical Center in Bremerton. The Tribe also plans for disaster response and has a public health plan for emergency management.

Anecdotal observations by Health Services Department staff indicate that Tribal members may have higher rates cardiovascular diseases, asthma, and diabetes than the general population of the peninsula; however, funding constraints have limited the ability to study and document such differences.

CLIMATE CHANGE IMPACTS ON HEALTH

HEAT WAVES

Washington State residents can expect that climate change will bring longer and more frequent summertime heat waves, which can cause dehydration, heat stroke, heat exhaustion, or even death [615]. Globally, climate change is expected to cause 38,000 additional deaths per year between 2030 and 2050 due to heat exposure in elderly people [616]. According to the Centers for Disease Control and Prevention, in the last decade more Americans have died from extreme heat than from any other weather-related cause. In the 2003 summer heat wave in Europe, there were between 30,000 and 70,000 additional deaths [611, 616]. In King County, past extreme heat days have shown a 78% increase in diabetic-related mortality [617].[61] There may be fewer cold-related deaths as the climate warms, but researchers expect that the reduction in cold-related deaths will be smaller than the increase in heat-related deaths [611]. Some studies have even predicted that cold-weather deaths will not change as the climate warms [46].

Accurately quantifying the number of heat-related deaths is difficult because the immediate cause of death is likely to be documented as something such as respiratory or cardiovascular failure [618]. A national study by Greene et al. estimated that from 1975 to 1995 Seattle had an average of two summertime extreme heat days per year, and an estimated average of 13 deaths could have been attributable to those extreme heat events [619]. Using the A1 scenario, which assumes very fast economic growth, the same study projects that climate change may lead to an average of 51 extreme heat days per year in Seattle from 2020 to 2029, 54 days from 2045 to 2055, and 57 days from 2090 to 2099 [619]. Their algorithm estimates an average of 14–18 deaths every summer for the second half of the century, a moderate increase from the past (assuming no change in public health response) but less than the increases anticipated in the eastern United States.

A local study by Jackson et al. looked at May to September heat events in several parts of the state, with the study area closest to the Port Gamble S'Klallam Tribe being Greater Seattle (King, Pierce, and Snohomish counties). Looking at the past (1980–2006), the researchers found that the risk of death due to non-traumatic causes and circulatory causes tended to peak on the fourth day of a heat event [618]. Under the highest warming scenario, the study concluded that greater Seattle can expect 211 excess deaths in 2025, 401 in 2045, and 988 in 2085 among adults age 45 and older (but mostly among those age 65 and older) [618].[62] These rates were actually projected to be higher in the Seattle area than in eastern Washington, perhaps due to urban heat island effects or greater use of air conditioning in the eastern part of the state [618].

At the same time, people are increasingly able to tolerate extreme heat, as air conditioning becomes more prevalent and people adopt other responses [611]. The Tribe could take several actions to reduce the community's vulnerability to higher temperatures and summer heat waves. A key option is to provide cooling centers for those who do not have air conditioning. The Elders Center, Little Boston Library, and casino can serve as temporary cooling centers (although exposure to cigarette smoke in the casino may offset some of the health benefits). It will be especially important to care for children and older adults, who are most vulnerable to extreme heat. Increased public awareness and heat warnings can also help reduce the risks.

[61] This study defined an extreme heat day as one with a humidex value over 36.1 degrees C or 97 degrees F. Humidex measures the combined effects of humidity and temperature on the human body.

[62] Excess deaths are those above the normal baseline—so those attributable to the heat event as opposed to other causes.

ALLERGIES, ASTHMA, AND RESPIRATORY ILLNESS

Outdoor Air

Pollen levels tend to be higher during times of extreme heat, and climate change may lengthen the pollen season [615, 616]. The pollen season is already starting earlier for some plants in some parts of the country [620]. Health Services Department staff noted that they frequently hear community members talk about allergens, the number of allergy complaints has increased, and people seem to be having a harder time managing allergy problems with antihistamines; however it is difficult to attribute these cases directly to climate change.

A study in Alaska found that communities that experienced "unseasonable environmental conditions" in a given 30-day period were more likely to report pollen allergy and asthma symptoms (as well as injuries, frostbite, hypothermia, and mortality) during that time [621]. During those periods, study participants had observed wildfire smoke and dust from dry road and river beds—factors that would increase air pollution and that can be linked to warm, dry days [621].

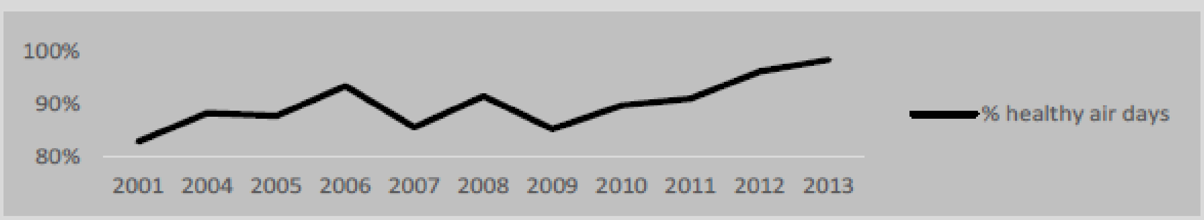
Fortunately, across both Kitsap County and Washington State, the asthma hospitalization rate has dropped significantly over the last two decades [622]. Kitsap County has also had an improving trend in healthy air days (see Figure 59) [623]. But while hospitalizations have gone down, overall asthma prevalence has gone up [611]. Asthma has been identified as an ongoing problem in the Port Gamble S'Klallam community.

Figure 59. Trend in days with healthy air across Kitsap County [622].

Particulate matter (PM) 2.5 concentration below 13.4 µ/m3 at Meadowdale monitoring station (from 2001 to April 2012) and at Spruce monitoring station (from May 2012 to 2013).

Source: Puget Sound Clean Air Agency. Trend years: 2001 and 2004 to 2013.

	2001	2013	TREND
KITSAP COUNTY	83%	99%	



As the climate changes, wildfires may also bring increased particle pollution and reduced air quality, leading to more emergency room visits for respiratory problems and asthma [611, 615]. In Chelan and Kittitas counties, the 2012 wildfire smoke contribute to 350 more hospitalizations for respiratory conditions and many school absences [624]. A study of the 1987 California wildfires found a 30% increase in hospital attendances for asthma on days of fire activity; in 1999, California saw a 52% increase in respiratory symptoms coinciding with haze [625].

Jackson et al. reported that daily maximum 8-hour ozone concentrations may be 28% higher by mid-century in King County compared to the recent past (1997–2006 baseline) [618]. Sunlight and increased temperatures contribute to the formation of ozone in the atmosphere [618]. Excess deaths in May-September due to ozone in King County are projected to increase from 69 per year (1997–2006) to 132 per year by mid-century [618]. While the Jackson study looked only at mortality, higher ozone concentrations can also lead to hospitalization for asthma as well as missed school or work days [618].

Indoor Air

Many Tribal members use wood-burning stoves because wood fuel is cheaper than electricity, but those stoves can contribute to poor indoor air quality and be inefficient. Some studies have indicated that particulates from wood smoke might have more negative consequences for human health than particulates from other sources, making both wildfires and indoor wood-burning stoves causes for concern [625]. The Health Services Department did some home visits to help residents understand what they could do to alleviate the problem associated with wood fuel and health, but the initiative was constrained by limited funding.

Finally, while more research is needed to confirm linkages, climate change has the potential to increase indoor dampness in some parts of the country through greater humidity or moisture entry into homes during heavy rain events. Increased indoor dampness can lead to increased mold and consequently to more respiratory infections and exacerbated asthma [611].

FOODBORNE ILLNESS

Climate change could also heighten the risk of some foodborne illnesses. As noted in the Shellfish chapter and the Harmful Algal Blooms chapters, warmer air and water temperatures, ocean acidification, and increased nutrient runoff during heavy precipitation events can create more favorable conditions for toxic phytoplankton and bacteria outbreaks. These can in turn cause illnesses such as paralytic shellfish poisoning, amnesic shellfish poisoning, and diarrhetic shellfish poisoning in humans. In the past, the Tribal Health Services Department has received little interest from Tribal members in its offers to do blood drawings to check for toxicity levels resulting from shellfish consumption. Tribal members have responded that eating shellfish is too fundamental to their diets and their culture to be changed easily. The Tribe believes that their members consume shellfish at approximately the same rate found in a study of Suquamish tribal members: about half a pound daily, which is four times more than the amount consumed by recreational shellfish harvesters in the area [626]. A 2016 study by the U.S. Global Climate Change Research Program noted that tribes that continue to consume traditional diets—with large amounts of fish and shellfish—may encounter greater health risks due to contamination [611]. Kitsap County has had an improving trend in the number of shoreline miles classified as "open" for shellfish harvesting [623]; however, climate change could reverse that trend in the coming decades. Closures have still happened in recent years: as noted in the Shellfish chapter, many of the recreational shellfish beaches along Hood Canal were closed or under advisory in June 2015 because of toxins [305].

Other pollutants, such as arsenic, are also significant contributors to shellfish toxicity [626]. While these stem primarily from non-climate stressors and pollution sources (i.e., an old sawmill and log dump), increased heavy rainfall events projected under climate change scenarios may increase runoff of land-based pollutants into water sources in the future.

Many other foodborne illnesses are not reportable conditions in Washington state, leaving little data for analysis [618]. There has been minimal research on how their incidence may be affected by climate change. We do know that higher temperatures can enable bacteria to grow more quickly and increase *Salmonella* prevalence in food [611, 615]. In addition, rising sea surface temperatures will contribute to greater amounts of mercury in seafood as it lets it be more readily absorbed by fish tissue [611].

WATERBORNE DISEASE

Extreme precipitation is documented as a significant climate factor for waterborne disease, as a result of runoff carrying contamination into drinking water supplies [611]. Given that the Port Gamble S'Klallam Tribe can expect to see more frequent and more intense extreme precipitation events, the Tribe may need to take steps to ensure that its wells do not become contaminated. More information on drinking water can be found in the Infrastructure chapter.

Runoff during heavy rainfall events can also contaminate lakes and the ocean. Tribal member who go swimming, fishing, or boating may be more exposed to enteric viruses from sewage runoff and therefore at risk of more gastrointestinal illnesses in the future [611].

INFECTIOUS DISEASES

Climate change can also contribute to the spread of infectious diseases, including fungal infections. It can be hard to tease out the precise role that climate plays, given that numerous other factors, including water and air quality, ecological change, health services, and migration also play key roles in the spread of such diseases [627]. Researchers will need to continue collecting data over many years to be able to make stronger conclusions [627].

One disease that has appeared recently in our region is linked to *Cryptococcus gattii,* a type of pathogenic yeast taken in by inhalation. *C. gattii* showed up in the Pacific Northwest within the last two decades, having previously been found in Southern California and places on other continents that also have warmer climates.[63] Researchers are still trying to understand what brought it to the Pacific Northwest, but climate change impacts—such as milder winters—are considered to be one of the possible contributing factors [627]. It is possible that some strains may have been present—though dormant—for a few decades in the Pacific Northwest and then emerged when land use, climate, or other factors changed [628]. Studies in British Columbia indicate that *C. gattii* is most likely to be found at low-lying elevations where daily winter average temperatures are above freezing [628].

Meanwhile, *Coccidioides*, a fungus previously found mainly in the southwest, has recently appeared in south-central Washington State. This fungus, which grows in soil after heavy rains and is then spread through the air in hot and dry conditions, can lead to Valley Fever [611].

NATURAL RESOURCES SECURITY

The health of the Tribal community can also be harmed when climate change affects the abundance or accessibility of natural resources such as water, plants, fish, and wildlife. The 2014 Community Health Assessment noted an ongoing concern about the poor health of fish and shellfish in Port Gamble Bay, which can worsen due to climate change [614]. These kinds of impacts are described in more detail in the Salmon, Shellfish, and Harmful Algal Bloom chapters. The cascading impacts can affect not only the diets and nutrition of Tribal members, but also their mental and emotional wellbeing if they are not able to carry out cultural traditions in a satisfying way [629].

CLIMATE CHANGE IMPACTS ON SAFETY

Climate change will bring more floods, droughts, storms, landslides, wildfires, and other extreme events. These events all have corresponding safety and health implications [615]. Consequences can include physical injuries, reduced availability of potable water, interruptions in communications and health care services, damage to key transportation routes, and mental health impacts [620].

[63] Although a few people have become seriously ill or died from this infection, it is not widespread or considered to pose significant risks.

The Tribe's main emergency and safety concern at this time is a big earthquake, not a climate-related disaster. However, climate change impacts may become a growing concern in the coming years, and Tribal members have already noticed changes in weather patterns. The reservation experienced three bad storms in March of 2016, which was different from past experience, as well as a very hot summer in 2015. As a Health Department staff member notes, "People are starting to think about this: is this going to be the norm now?"

In addition, many earthquake-preparedness measures—such as establishing shelters and training for emergency response—may also be helpful for dealing with storms, wildfires, or heat waves and for building climate resilience. The Tribe is building a new hotel next to the casino, for example, which could serve as an emergency shelter in different kinds of disaster situations. The Tribal gym could also serve as a shelter.

The Tribe's 2007 Comprehensive Emergency Plan includes hazard mitigation (with a focus on earthquakes) and will be updated soon. To date, this plan has looked at short-term response needs and not future risk and does not address climate change specifically. The Tribe also has a new public health plan for emergency management. There is an evacuation strategy for Tribal-owned facilities.

Tribal police and emergency responders use the incident command system (ICS) and National Incident Management System (NIMS) to respond to events and ensure continuity of operations. Given staff turnover since the last ICS training, the Tribe has noted that retraining is needed. The annual Canoe Gathering event unintentionally works as a kind of emergency preparedness drill for the Tribe, as they need to deal with large crowds and provide on-site food, shelter, and medical attention.

The Tribal Health Services Department has a generator to provide limited power for continuing medical services during power outages, which tend to happen during winter storms. Limitations in generator power during outages can prevent operation of computer systems, kitchen equipment, and other non-essential equipment, which makes it challenging for staff to keep working during such times. The Tribe is looking into ways to make adjustments to help address these limitations.

The Tribal community's ability to deal with climate and non-climate disasters and emergencies is enhanced by high levels of social cohesion. Community members often grew up together, know and take care of each other, and check on each other when incidents occur. This creates a high degree of adaptive capacity, which helps to reduce vulnerability and increase resilience. Still, it would be useful to consider climate change more explicitly in the Tribe's emergency preparedness plans and measures to further build resilience and keep community members safe.

LOOKING AHEAD

This chapter has explored a number of health and safety challenges that could face Tribal members as the climate changes. Some are exacerbations of existing problems. For example, asthma is already a concern that may be exacerbated by increased wildfires and a longer pollen season.

Another significant concern—and one that is particularly relevant to tribes—is the increasing risk of contaminated fish and shellfish. As important parts of the traditional diet and critical for the survival of cultural traditions, these resources are vital for community cohesion and mental and emotional wellbeing in addition to physical health.

Maintaining the connectedness of the community—together with proactive adaptation measures and education to protect health and safety—can help to counteract these challenges and support resilience into the future.

Going forward, the Tribe plans to consider climate change in the update to the Comprehensive Plan and obtain support from an emergency management planner to assist in this effort.

In addition, the Health Services Department runs a broad community preventative healthcare program that can help to build resilience. Four Community Health Representatives (CHRs) equivalent to 3.5 full time employees (FTEs) provide transportation to medical appointments, deliver prescriptions to individuals on the reservation, perform home visits, and work with Health Services Department staff on chronic illnesses such as hypertension and diabetes. These individuals are Tribal members who live in the community and therefore have strong relationships and a good understanding of local issues. When CHRs transport community members to health appointments, it could present an opportunity to discuss weather and climate issues. One adaptation measure worth considering would therefore be training CHRs about climate change and encouraging them to help raise awareness among the Tribal community. There is also a current effort to map the neighborhood and establish emergency contacts.

CULTURAL RESOURCES

INTRODUCTION

Given the Tribe's location on Hood Canal, many of its traditions, ceremonies, and cultural resources are rooted in the Tribe's connection to the marine waters, shoreline, and the natural environment. As a result, climate change—in particular, its effects on coastal processes—may have a pronounced impact on the Tribe's cultural and historical sites and traditions.

The Tribe's cultural resources include the historical and archaeological sites that contribute to S'Klallam and regional history. The Tribe's important resources also include gathering sites and traditional plant communities.

Many of the natural resources the Tribe relies upon for commercial and subsistence reasons also have cultural significance. These include fish, shellfish, and associated harvest areas, as well as hunting areas. In addition to continued research around the Tribe's history, Cultural Resources Department staff are responsible for maintaining and enhancing the use of the S'Klallam language and providing educational materials for visitors to the Tribe and its facilities.

This chapter first provides a brief history of the Tribe and its village at Point Julia, and then it presents a summary of climate change impacts on the Tribe's cultural resources, including traditional foods and historical sites.

BRIEF HISTORY OF THE PORT GAMBLE S'KLALLAM TRIBE

The S'Klallam were originally called the Nux Sklai Yem, or Strong People. Historically, they were part of a large group of Salish-speaking tribes that extended from northwestern Oregon to the central British Columbia coast and inland along the Fraser and Columbia rivers. The Salish people were well-established in the Puget Sound basin by the year 1400, having arrived from the interior by way of the Skagit and Fraser rivers. The Salish have long occupied the shores of the Strait of Juan de Fuca, Admiralty Inlet, and Puget Sound, adapting their lives to the natural bounty of the land, rivers, and sea. Permanent villages of plank and pole houses provided shelter for groups of extended families through the wet winters; in the spring, families made their seasonal rounds, camping at traditional fishing, hunting, and gathering sites throughout their territory.

The S'Klallams lived in at least 15 villages along the southern shore of the Strait of Juan de Fuca. They enjoyed friendly relations with their Salish-speaking neighbors the Twana and shared fishing sites with them in Hood Canal. The first known contact between the S'Klallam Tribe and Europeans occurred in 1799, when English and Spanish explorers penetrated the Strait of Juan de Fuca in pursuit of the legendary Northwest Passage. After the explorers came fur traders, missionaries, prospectors, and finally, permanent settlers.

THE S'KLALLAM VILLAGE AT POINT JULIA

In November 1853, Isaac Stevens, Governor and Superintendent of Indian Affairs for the new Washington territory, arrived in Olympia and announced that he would use his treaty-making power to extinguish the Indian land title. That same year, Tribal members were moved from other villages to Point Julia to make room for the growing Port Gamble Mill. In the winter of 1855, the S'Klallam, Chemakum, and Twana tribes gathered at the northeastern point of the Kitsap Peninsula—known as Point No Point—to negotiate a treaty with Stevens. On a cold January day, the S'Klallams signed away their title to 438,430 acres of ancestral lands.

In 1934, the United States government purchased Point Julia and surrounding parcels owned by the Puget Mill Company to create the 1,231-acre Port Gamble S'Klallam Reservation, with an official proclamation issued in 1938. That same decade, the Port Gamble S'Klallam Tribe successfully petitioned the federal government to recognize its independent Tribal status.

In 1939, gasoline was poured on some houses at Point Julia that the Health Department had previously condemned, and the village was burned to the ground. Following the arson, and under pressure from the federal government, the S'Klallams relocated to the bluff above Point Julia. Some older members of the Tribe did not want to leave the spit, having lived there most of their lives. One Tribal member recalls an elder who had to be forced out of her home: she sat in an old chair, crying and singing, while they packed her belongings out [630].

Later in the 20th century, the Port Gamble S'Klallam began to assert more authority over their economic development. The Point No Point Tribal fish hatchery was established in 1976 at the base of the bluff on Point Julia, at the mouth of Little Boston Creek. In the 1980s, the Tribe created a gas station, store, mobile home park, and 20-acre business park on reservation lands. Tribal staff was increased from about 12 to more than 50 people. An Economic Development Authority was created to support existing operations and to create new enterprises, and the Tribe began to administer Federal economic development grants [630].

Although the reservation is small, the Tribe continues to have the right to access and harvest resources in its traditional (usual and accustomed) areas beyond the reservation. The Port Gamble S'Klallams have continued their traditions of resource utilization through fishing, hunting, clam digging and other activities. Communal sharing of the reservation land has helped to preserve essential social and cultural traditions [630]. Still, as climate change affects these natural resources, it will also affect the Tribe's cultural resources, as described in the remainder of this chapter.

CLIMATE IMPACTS ON CULTURAL RESOURCES

Tribal members have observed environmental changes for hundreds of years and passed that traditional knowledge down through the generations. For example, Tribal members have reported changes in the availability of materials that they have traditionally gathered. These observations and traditional ecological knowledge can be useful today and into the future, to help the Tribe understand how climate changes could interact with other environmental changes and to determine what they could do to build continued resilience.

Climate change is expected to affect tribal and place-based communities differently than typical Western communities [631]. This is due to the fact that many tribal economies and cultural identities, including those of the Port Gamble S'Klallam Tribe, are reliant upon the use of natural resources and wildlife [631]. As climate and non-climate stressors combine, the result may be a future with reduced availability of culturally significant plants, animals, and sites [631].

FISH AND SHELLFISH

The importance of fish, especially salmon, and shellfish is widespread throughout the Pacific Northwest's tribal communities. With regard to salmon specifically, changing streamflow and increased stream temperature throughout the 21st century could affect the growth and survival of salmonids across many life stages [46]. Those impacts, while most acute for salmon in freshwater streams, will work in tandem with climate and non-climate stressors in the marine environment (e.g., ocean acidification, pollution) that could affect salmon during marine life stages [46]. Climatic changes are expected to affect salmon physiology as well as habitat.

Shellfish physiology and habitat are also being affected by climate change, and such impacts are expected to continue and increase in severity in the decades to come. Ocean acidification has been observed to impede shell formation [632]. Sea level rise is expected to reduce shellfish habitat [633]. Rising temperatures are expected to favor the growth of harmful algal blooms, which produce toxins that accumulate in shellfish and make them poisonous [634].

A severe reduction in salmon and shellfish abundance would mean the potential loss of Tribal ceremonies and customs that use these species. The Tribe's cultural resources staff note that both salmon and shellfish are important food items used at funerals, weddings, and other important community and family events. Clam bakes, in particular, are a central aspect of S'Klallam traditional foods and always a part of ceremonial events.

More information on these climate impacts can be found in the Salmon and Shellfish chapters.

TRADITIONAL FOODS AND GATHERING MATERIALS

More than 280 types of food are considered to be part of the traditional diet of the Coast Salish peoples [635]. Through the exploration of archaeological sites across the Puget Sound region and traditional knowledges passed down through generations, these foods are known to include everything from salmon and oysters to wapato and huckleberry [635]. However, modern diets are less complex and tend to include fewer food sources [635].

As with salmon and shellfish, the combination of climate change and non-climate stressors (such as land development and the privatization of traditional use areas) could impede access to and the availability of other traditional foods and gathering materials. These resources provide sustenance and form the basis of cultural connections through storytelling, ceremonies, and other community-gathering activities [636]. A 2013 study by Lynn et al. found that tribal harvesters have reported changes in the harvest times of some traditional foods [636].

Tribal staff report that the availability of traditional foods and gathering materials has already been reduced due to nearby urban development, particularly in the Tribe's primary traditional use areas. This development can lead to overexploitation or conversion of natural areas (including water resources) as competing uses (e.g., residential development, recreation, commercial fishing) reduce or restrict access to gathering sites. One such example is the loss of hunting and gathering areas on the Coyle peninsula near Dabob Bay, with increased privatization of land. With future climate change, the productivity of remaining areas could be altered or altogether lost [636].

HISTORICAL AND ARCHAEOLOGICAL SITES

The Tribal Historical Preservation Office (THPO) maintains the S'Klallam Tribe's historical and archaeological sites. THPO staff consult with federal, state, and local governments on cultural resources and possible impacts to those resources from a variety of causes.

The vast majority of the Tribe's archaeological sites are in coastal areas and are vulnerable to erosion and sea level rise. Within the reservation, the Tribe has the authority to protect these sites (e.g., Point Julia). However, culturally significant sites outside the reservation in the Tribe's primary traditional use area cannot be protected under the Tribe's authority. The Tribe can only provide input during public scoping periods or through Tribal consultations. It is therefore difficult to assess the future of culturally significant sites located away from the reservation with regard to either human development or climate change.

Because many of these sites are located along or near the coast, sea level rise is of particular concern. While relative sea level rise varies based on the geography of specific locations, it is possible that some historical and archaeological sites could be permanently inundated if no steps are taken to protect them.

LOOKING AHEAD

Over the centuries, the Tribe has created a self-reliance and cohesion that strengthens the community and contributes to its resilience in the face of a wide variety of stresses. The Tribe's cultural resources support this cohesion by allowing Tribal members to maintain a positive connection to their culture and traditions. Many Tribal initiatives therefore explicitly recognize the importance of preserving these resources.

The Tribe supports the documentation of cultural resource sites through archaeological work and ethnohistorical research. Current initiatives to protect cultural resources include archaeological work on Point Julia, as well as the documentation of Indian Island as a cultural landscape. The Tribe is currently working to learn from these sites before climate change limits access to these areas or significantly degrades them.

APPENDICES

KEY TERMS & DEFINITIONS

7Q10	The lowest 7-day average flow that occurs on average once every 10 years
100-year flood event	A flood that statistically has a 1-percent chance of occurring in any given year.
Acclimation	The change in behavior or physiology of an individual within its own lifetime in response to a changing environment (e.g. temperature).
Accretion	The gradual accumulation of additional layers or matter.
Adaptive capacity	The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.
Aggradation	The process by which a stream's or river's gradient steepens due to increased deposition of sediment
Altimetry	The measure of height or altitude.
Alevin	A very young fish that depends on its yolk sac for nourishment. The alevin stage precedes the juvenile stage.
Anthropogenic	Originating in human activity.
Atmospheric river	A narrow band of water vapor transport extending from the tropical Pacific to the west coast of North America during the winter months.
Climate	The statistics of weather. In other words, the average pattern for weather over a period of months, years, decades, or longer in a specific place.
Convergence zone	A location where airflows or ocean currents meet, characteristically marked distinctive weather conditions.
Conveyance capacity	Quantitative measure of the discharge capacity of all portions of the surface water system, either natural or man-made, that transport surface and storm water runoff.
Copepod	Any of the large subclass (Copepoda) of minute freshwater or marine crustaceans.
Emissions	The release of greenhouse gases and/or their precursors and aerosols into the atmosphere over a specified area and period.
Estuary	The entrance of a river into the ocean.
Eutrophication	Process by which a body of water accumulates excessive amounts of nutrients, typically nitrogen or phosphorous or both.
Exposure	The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected by climate change.
Extreme weather event	An event that is rare within its statistical reference distribution at a particular place.

Firn	Granular snow, especially on the upper part of a glacier, where it has not yet been compressed into ice.
Fuel load	The amount of available flammable materials around a fire. Usually expressed as weight of fuel per unit area.
Gametes	Mature reproductive cells, i.e. sperm or eggs, which fuse together during sexual reproduction to form a zygote.
Greenhouse gases	The gaseous constituents of the atmosphere, both natural and anthropogenic (including carbon dioxide, methane, and other gases), that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds.
Hypoxia	Low or depleted oxygen in a water body.
Intertidal zone	An area submerged at high tide and exposed to the air at low tide; the area between the tide marks.
Isostatic rebound	The gradual rising of land masses that were depressed by huge ice sheets during the last ice age.
Model (climate)	A mathematical representation of the climate based on physical, biological, and chemical principles.
Nonpoint source runoff	Typically refers to pollution created as runoff (e.g., rainfall running across the ground) moves and picks up natural and human-made pollutants depositing them into lakes, rivers, wetlands, coastal waters, and ground waters.
Ocean acidification	Increased concentrations of carbon dioxide in sea water causing a measurable increase in acidity (i.e., a reduction in ocean pH). This may lead to reduced calcification rates of calcifying organisms such as corals, mollusks, algae, and crustaceans.
pH	The pH scale measures how acidic or basic a substance is. It ranges from 0 to 14. A pH of 7 is neutral. A pH less than 7 is acidic, and a pH greater than 7 is basic.
Progradation	The growth of a river delta farther out into the sea over time, caused by the progressive deposition of sediment in rivers or streams.
Projection	A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. *Projections* are distinguished from *predictions* to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.
Pteropod	Type of mollusk or sea snail that swims in the ocean by flapping its two "wings"; also known as a "sea butterfly".
Redd	A spawning nest that is built by salmon and steelhead in the gravel of streams or the shoreline of lakes.
Resilience	The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.

Scenario	A plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships.
Sediment load	The total amount of all inorganic and organic particles transported in a river or stream.
Sensitivity	The degree to which a system is affected, either adversely or beneficially, by climate variability or change.
Smoltification	The series of physiological changes where juvenile salmonid fish adapt from freshwater to marine water.
Snow water equivalent	The amount of water contained within the snowpack.
Storm surge	The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds).
Substrate	Material used by an organism to grow; solid object to which a plant or animal is attached.
Trophic level	Refers to the position of an organism in a food chain. E.g., primary producer, primary or secondary consumer.
Upwelling	Process in which deep, cold water rises to the surface.
Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.
Weather	The atmospheric conditions at a specific place at a specific point in time.

These definitions are drawn from a variety of sources, including the Environmental Protection Agency (including its Glossary of Climate Terms), the U.S. Department of Agriculture Forest Service Climate Change Glossary, the Intergovernmental Panel on Climate Change, and the University of Washington Climate Impacts Group website.

WORKS CITED

[1] K. Rose, "Tribal Climate Change Adaptation Options: A Review of the Scientific Literature," U.S. Environmental Protection Agency, Office of Air, Waste, and Toxics, Region 10, 2010.

[2] G. Morishima, "Climate Change and Indigenous Peoples: A Primer," Advisory Committee on Climate Change and Natural Resource Science, 2014.

[3] R. S. Vose, S. Applequist, M. Squires, I. Durre, M. J. Menne, C. N. Williams Jr., C. Fenimore, K. Gleason and D. Arndt, "Improved Historical Temperature and Precipitation Time Series for U.S. Climate Divisions," *Journal of Applied Meteorology and Climatology,* vol. 53, pp. 1232-1251, 2014.

[4] P. W. Mote, J. T. Abatzoglou and K. E. Kunkel, "Climate: Variability and Change in the Past and the Future," in *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, M. M. Dalton, P. W. Mote and A. K. Snover, Eds., Island Press, 2013, pp. 25-40.

[5] J. T. Abatzoglou, D. E. Rupp and P. W. Mote, "Seasonal Climate Variability and Change in the Pacific Northwest of the United States," *Journal of Climate,* vol. 27, pp. 2125-2142, 2014.

[6] M. J. Menne, I. Durre, B. Korzeniewski, S. McNeal, K. Thomas, X. Yin, S. Anthony, R. Ray, R. S. Vose, B. E. Gleason and T. G. Houston, "Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.21," 2012. [Online]. Available: http://doi.org/10.7289/V5D21VHZ. [Accessed July 2015].

[7] K. A. Bumbaco, K. D. Dello and N. Bond, "History of Pacific Northwest Heat Waves: Synoptic Pattern and Trends," *Journal of Applied Meteorology and Climatology,* vol. 52, pp. 1618-1631, 2013.

[8] T. Madsen and E. Figdor, "When It Rains, It Pours: Global Warming and the Rising Frequency of Extreme Precipitation in the United States," Frontier Group and Environment America Research and Policy Center, 2007.

[9] C. Mass, A. Skalenakis and M. Warner, "Extreme Precipitation over the West Coast of North America: Is There a Trend?," *Hydrometeorology,* vol. 12, pp. 310-318, 2011.

[10] E. A. Rosenberg, P. W. Keys, D. B. Booth, D. Hartley, J. Burkey, A. C. Steinemann and D. P. Lettenmaier, "Precipitation Extremes and the Impacts of Climate Change on Stormwater Infrastructure in Washington State," *Climatic Change,* vol. 102, pp. 319-349, 2010.

[11] S. K. Moore, N. J. Mantua, J. P. Kellogg and J. A. Newton, "Local and Large-scale Climate Forcing of Puget Sound Oceanographic Properties on Seasonal to Interdecadal Timescales," *Limnology and Oceanography,* vol. 53, no. 5, pp. 1746-1758, 2008.

[12] M. Newman, G. P. Compo and M. A. Alexander, "ENSO-forced Variability of the Pacific Decadal Oscillation," *Journal of Climate,* vol. 16, no. 23, pp. 3853-3857, 2003.

[13] N. Mantua and S. R. Hare, "The Pacific Decadal Oscillation," *Journal of Oceanography,* vol. 58, pp. 35-44, 2002.

[14] A. F. Hamlet, P. W. Mote, M. P. Clark and D. P. Lettenmaier, "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States," *Journal of Climate,* vol. 18, no. 21, 2005.

[15] D. W. Pierce, T. P. Barnett, H. G. Hidalgo, T. Das, C. Bonfils, B. D. Santer, G. Bala, M. D. Dettinger, D. R. Cayan, A. Mirin, A. W. Wood and T. Nozawa, "Attribution of Declining Western U.S. Snowpack to Human Effects," *Journal of Climate,* vol. 21, no. 23, pp. 6425-6444, 2008.

[16] M. T. Stoelinga, M. D. Albright and C. F. Mass, "A New Look at Snowpack Trends in the Cascade Mountains," *Journal of Climate,* vol. 23, pp. 2473-2491, 2010.

[17] P. Mote, A. Hamlet and E. Salathé Jr., "Has Snowpack Declined in the Washington Cascades?," *Hydrology and Earth System Sciences,* vol. 12, pp. 193-206, 2008.

[18] J. H. Casola, L. Cuo, B. Livneh, D. P. Lettenmaier, M. T. Stoelinga, P. W. Mote and J. M. Wallace, "Assessing the Impacts of Global Warming on Snowpack in the Washington Cascades," *Journal of Climate,* vol. 22, no. 10, pp. 2758-2772, 2009.

[19] D. G. Gavin and L. B. Brubaker, Late Pleistocene and Holocene Environmental Change on the Olympic Peninsula, vol. 222, Springer International Publishing, 2015, p. 144.

[20] K. A. Dick, "Glacier Change in the North Cascades, Washington: 1900-2009," Master's Thesis for Portland State University, Department of Geography, 2013.

[21] J. L. Riedel, S. Wilson, W. Baccus, M. Larrabee, T. J. Fudge and A. G. Fountain, "Glacier Status and Contribution to Streamflow in the Olympic Mountains, Washington, USA," *Journal of Glaciology,* vol. 61, no. 225, 2015.

[22] J. Riedel and M. A. Larrabee, "Impact of Recent Glacial Recession on Summer Streamflow in the Skagit River," *Northwest Science,* vol. 90, no. 1, pp. 5-22, 2016.

[23] I. T. Stewart, D. R. Cayan and M. D. Dettinger, "Changes toward Earlier Streamflow Timing across Western North America," *Journal of Climate,* vol. 18, pp. 1136-1155, 2005.

[24] J. A. Church and N. J. White, "Sea-level Rise from the Late 19th to the Early 21st Century," *Surveys in Geophysics,* vol. 32, no. 4, pp. 585-602, 2011.

[25] J. A. Church, P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, M. A. Merrifield, G. A. Milne, R. S. Nerem, P. D. Nunn, A. J. Payne, W. T. Pfeffer, D. Stammer and A. S. Unnikrishman, "Sea Level Change," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, D. Qin, G. K. Plattner and P. M. Midgley, Eds., Cambridge, UK and New York, USA, Cambridge University Press, 2013.

[26] R. E. Kopp, A. C. Kemp, K. Bittermann, B. P. Horton, J. P. Donnelly, W. R. Gehrels, C. C. Hay, J. X. Mitrovica, E. D. Morrow and S. Rahmstorf, "Temperature-driven Global Sea-level Variability in the Common Era," *Proceedings of the National Academy of Sciences of the United States of America,* vol. 113, no. 11, pp. E1434-E1441, 2016.

[27] Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York, USA, Cambridge University Press, 2013.

[28] J. Church, P. Clark, A. Cazenave, J. Gregory, S. Jevrejeva, A. Levermann, M. Merrifield, G. A. Milne, R. S. Nerem, P. D. Nunn, A. J. Payne, W. T. Pfeffer, D. Stammer and A. S. Unnikrishnan, "Sea Level Change," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Eds., Cambridge, UK and New York, USA, Cambridge University Press, 2013.

[29] C. C. Hay, E. Morrow, R. E. Kopp and J. X. Mitrovica, "Probabilistic Reanalysis of Twentieth-century Sea-level Rise," *Nature,* vol. 517, pp. 481-484, 2015.

[30] U.S. Environmental Protection Agency, "Climate Change Indicators: Sea Level," [Online]. Available: www.epa.gov/climate-indicators/sea-level. [Accessed November 2016].

[31] J. A. Church and N. J. White, "Sea Level Rise from the Late 19th to the Early 21st Century," *Surveys in Geophysics,* vol. 32, no. 4, pp. 585-602, 2011.

[32] National Oceanic and Atmospheric Administration, "Laboratory for Satellite Altimetry: Sea Level Rise," 2016. [Online]. Available: www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries_global.php. [Accessed June 2016].

[33] National Research Council, "Sea-level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future," The National Academies Press, 2012.

[34] C. J. Bassin, J. B. Mickett, J. A. Newton and M. J. Warner, "Decadal Trends in Temperature and Dissolved Oxygen in Puget Sound: 1932-2009," Hood Canal Dissolved Oxygen Program Integrated Assessment and Modeling Study Report, 2011.

[35] F. A. Whitney, H. J. Freeland and M. Robert, "Persistently Declining Oxygen Levels in the Interior Waters of the Eastern Subarctic Pacific," *Process in Oceanography,* vol. 75, no. 2, pp. 179-199, 2007.

[36] F. P. Lima and D. S. Wethey, "Three Decades of High-resolution Coastal Sea Surface Temperatures Reveal More than Warming," *Nature Communications,* vol. 3, 2012.

[37] S. Petersen, J. Bell, I. Miller, C. Jayne, K. Dean and M. Fougerat, "Climate Change Preparedness Plan for the North Olympic Peninsula," A project of the North Olympic Peninsula Resource Conservation & Development Council and the Washington Department of Commerce, funded by the Environmental Protection Agency, 2015.

[38] Department of Ecology, "Preparing for a Changing Climate: Washington State's Integrated Climate Response Strategy," 2012.

[39] Washington State Blue Ribbon Panel on Ocean Acidification, "Scientific Summary of Ocean Acidification in Washington State Marine Waters," R. A. Feely, T. Klinger, J. A. Newton and M. Chadsey, Eds., National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, 2012.

[40] Washington State Blue Ribbon Panel on Ocean Acidification, Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response., H. Adelsman and L. Whitely Binder, Eds., Washington Department of Ecology, Olympia, Washington, 2012.

[41] R. A. Feely, S. R. Alin, J. Newton, C. L. Sabine, M. Warner, C. Krebs and C. Maloy, "The Combined Effects of Ocean Acidification, Mixing, and Respiration on pH and Carbonate Saturation in an Urbanized Estuary," *Estuarine, Coast, and Shelf Science,* vol. 88, no. 4, pp. 442-449, 2010.

[42] S. C. Doney, W. M. Balch, V. J. Fabry and R. A. Feely, "Ocean Acidification: A Critical Emerging Problem for Ocean Sciences," *Oceanography,* vol. 22, no. 4, pp. 16-25, 2009.

[43] A. K. Snover, G. S. Mauger, L. C. Whitely Binder, M. Krosby and I. Tohver, "Climate Change Impacts and Adaptation in Washington State: Technical Summaries for Decision Makers," Climate Impacts Group, University of Washington, Seattle, 2013.

[44] M. Meinshausen, S. J. Smith, K. Calvin, J. S. Daniel, M. T. Kainuma, J.-F. Lamarque, K. Matsumoto, S. A. Montzka, S. B. Raper, K. Riahi, A. Thomson, G. M. Velders and D. P. van Vuuren, "The RCP

Greenhouse Gas Concentrations and their Extensions from 1765 to 2300," *Climatic Change,* vol. 109, no. 1-2, pp. 213-241, 2011.

[45] P. Mote, J. Abatzoglou, D. P. Lettenmaier and D. Turner, "Integrated Scenarios for the Future Northwest Environment," Climate Impacts Research Consortium, Oregon State University, 2015.

[46] G. S. Mauger, J. H. Casola, H. A. Morgan, R. L. Strauch, B. Curry, T. M. Busch Isaksen, L. Whitely Binder, M. B. Krosby and A. K. Snover, "State of Knowledge: Climate Change in Puget Sound," Climate Impacts Group, University of Washington, 2015.

[47] C. Raymond, "Seattle City Light Climate Change Vulnerability Assessment and Adaptation Plan," Environmental Affairs and Real Estate Division, Seattle City Light, 2015.

[48] M. M. Dalton, P. Mote and A. K. Snover, Eds., Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities, Washington, DC: Island Press, 2013.

[49] M. D. Dettinger, "Fifty-two Years of Pineapple-express Storms across the West Coast of North America," U.S. Geological Survey, Scripps Institution of Oceanography for the California Energy Commission, 2006.

[50] M. D. Warner and C. F. Mass, "Changes in Winter Atmospheric Rivers along the North American West Coast in CMIP5 Climate Models," *Journal of Hydrometeorology,* vol. 16, pp. 118-128, 2015.

[51] S. M. Hagos, L. R. Leung, J.-H. Yoon, J. Lu and Y. Gao, "A Projection of Changes in Landfalling Atmospheric River Frequency and Extreme Precipitation Over Western North America from the Large Ensemble CESM Simulations," *Geophysical Research Letters,* vol. 43, no. 3, pp. 1357-1363, 2016.

[52] Y. Zhu and R. E. Newell, "A Proposed Algorithm for Moisture Fluxes from Atmospheric Rivers," *Monthly Weather Review,* vol. 126, pp. 725-735, 1998.

[53] M. D. Warner, C. F. Mass and E. P. Salathé Jr., "Wintertime Extreme Precipitation Events along the Pacific Northwest Coast: Climatology and Synoptic Evolution," *Monthly Weather Review,* vol. 140, no. 7, pp. 2021-2043, 2012.

[54] E. A. Barnes and L. Polvani, "Response of the Midlatitude Jets, and of their Variability to Increased Greenhouse Gases in the CMIP5 Models," *Journal of Climate,* vol. 26, no. 18, pp. 7117-7135, 2013.

[55] J. Liu, J. A. Curry, H. Wang, M. Song and R. M. Horton, "Impact of Declining Arctic Sea Ice on Winter Snowfall," *Proceedings of the National Academy of Sciences,* vol. 109, no. 11, pp. 4074-4079, 2012.

[56] V. Petoukhov, S. Rahmstorf, S. Petri and H. Joachim Schellnhuber, "Quasiresonant Amplification of Planetary Waves and Recent Northern Hemisphere Weather Extremes," *Proceedings of the National Academy of Sciences,* vol. 110, no. 14, pp. 5336-5341, 2013.

[57] E. A. Barnes and J. A. Screen, "The Impact of Arctic Warming on the Midlatitude Jet-stream: Can it? Has it? Will it?," *Wiley Interdisciplinary Reviews: Climate Change,* vol. 6, no. 3, pp. 277-286, 2015.

[58] K. Thomas, "Linkages between Arctic Warming and Mid-Latitude Weather Patterns: Summary of a Workshop," National Academies Press, 2014.

[59] E. P. Salathé Jr., G. S. Mauger, C. F. Mass, R. Steed and B. Dotson, "Final Project Report: Regional Modeling for Windstorms and Lightning," Prepared for Seattle City Light by the Climate Impacts Group, University of Washington, Seattle, 2015.

[60] A. F. Hamlet, M. McGuire Elsner, G. S. Mauger, S.-Y. Lee, I. Tohver and R. Norheim, "An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results," *Atmosphere-Ocean,* vol. 51, no. 4, pp. 392-415, 2013.

[61] M. S. Pelto, "Forecasting Temperate Alpine Glacier Survival from Accumulation Zone Observations," *The Cryosphere,* vol. 4, pp. 67-75, 2010.

[62] C. D. Frans, "Implications of Glacier Recession for Water Resources," Doctoral Dissertation for University of Washington, Department of Civil and Environmental Engineering, 2015.

[63] J. Riedel and M. A. Larrabee, "North Cascades National Park Complex Glacier Mass Balance Monitoring Annual Report, Water Year 2009: North Coast and Cascades Network," National Park Service, U.S. Department of Interior, 2011.

[64] I. Tohver, S.-Y. Lee and A. F. Hamlet, "Using Physically Based Hydrology Models to Improve Fine Scale Estimates of Q100 in Complex Mountain Terrain," Final project report prepared for Olympic National Park and Olympic National Forest by the Climate Impacts Group and the Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, 2012.

[65] S.-Y. Lee, A. Hamlet and E. Grossman, "Impacts of Climate Change on Regulated Streamflow, Hydrologic Extremes, Hydropower Production, and Sediment Discharge in the Skagit River Basin," *Northwest Science,* vol. 90, no. 1, pp. 23-43, 2016.

[66] G. S. Mauger and S.-Y. Lee, "Climate Change, Sea Level Rise, and Flooding in the Lower Snohomish River Basin," Report prepared for The Nature Conservancy by the Climate Impacts Group, University of Washington, Seattle, 2014.

[67] D. J. Isaak, E. E. Peterson, J. Kershner, J. B. Dunham, J. Ver Hoef, S. Hostetler, B. B. Roper, C. H. Luce and S. J. Wenger, "NorWeST: An Interagency Stream Temperature Database and Model for the Northwest United States," U.S. Forest Service, U.S. Department of Agriculture, 2011.

[68] C. L. Raymond, D. L. Peterson and R. M. Rochefort, "Climate Change Vulnerability and Adaptation in the North Cascades Region, Washington," U.S. Forest Service, U.S. Department of Agriculture, Portland, OR, 2014.

[69] M. G. Barik, "Landslide Susceptibility Mapping to Inform Landuse Management Decisions in an Altered Climate," Master's Thesis published by Washington State University, Department of Civil and Environmental Engineering, 2010.

[70] M. Jakob and S. Lambert, "Climate Change Effects on Landslides along the Southwest Coast of British Columbia," *Geomorphology,* vol. 107, no. 3-4, pp. 275-284, 2009.

[71] C. Huggel, J. J. Clague and O. Korup, "Is Climate Change Responsible for Changing Landslide Activity in High Mountains?," *Earth Surface Processes and Landforms,* vol. 37, no. 1, pp. 77-91, 2012.

[72] L. Borgatti and M. Soldati, "Chapter 8: Landslides and Climatic Change," in *Geomorphological Hazards and Disaster Prevention*, I. Alcantara-Ayala and A. S. Goudie, Eds., Cambridge, UK, and New York, USA, Cambridge University Press, 2011, pp. 87-96.

[73] R. H. Guthrie, P. Friele, K. Allstadt, N. Roberts, S. G. Evans, K. B. Delaney, D. Roche, J. J. Clague and M. Jakob, "Mount Meager Rock Slide-debris Flow, Coast Mountains, British Columbia: Characteristics, Dynamics, and Implications for Hazard and Risk Assessment," *Natural Hazards and Earth System Sciences,* vol. 12, pp. 1277-1294, 2012.

[74] A. F. Chleborad, "Preliminary Method for Anticipating the Occurrence of Precipitation-induced Landslides in Seattle, Washington," U.S. Geological Survey, 2000.

[75] D. W. Tubbs, "Landslides in Seattle," *Washington Division of Geology and Earth Resources Information Circular,* vol. 52, no. 15, p. 1, 1974.

[76] A. F. Hamlet, "Impacts of Climate Variability and Climate Change on Transportation Systems and Infrastructure in the Pacific Northwest," A White Paper prepared for the Western Federal Lands-Highway Division by the Climate Impacts Group, University of Washington, Seattle, 2012.

[77] R. L. Strauch, C. L. Raymond, R. M. Rochefort, A. F. Hamlet and C. Lauver, "Adapting Transportation to Climate Change on Federal Lands in Washington State, USA," *Climatic Change,* vol. 130, pp. 185-199, 2015.

[78] J. Czuba, C. Magirl, C. Czuba, E. Grossman, C. Curran, A. Gendaszek and R. Dinicola, "Sediment Load from Major Rivers into Puget Sound and its Adjacent Waters," U.S. Geological Survey, 2011.

[79] L. Benda and T. Dunne, "Stochastic Forcing of Sediment Supply to Channel Networks from Landsliding and Debris Flow," *Water Resources Research,* vol. 33, no. 12, pp. 2849-2863, 1997.

[80] S.-Y. Lee and A. F. Hamlet, "Skagit River Basin Climate Science Report," Department of Civil and Environmental Engineering, Climate Impacts Group, University of Washington, 2011.

[81] J. Czuba, C. Czuba, C. Magirl and C. Voss, "Channel-conveyance Capacity, Channel Change, and Sediment Transport in the Lower Puyallup, White, and Carbon Rivers, Western Washington," U.S. Geological Survey, prepared in cooperation with Pierce County Public Works and Utilities, Surface Water Management, 2010.

[82] J. Creighton, M. Strobel, S. Hardegree and R. Steele, "Northwest Regional Climate Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies," U.S. Forest Service, U.S. Department of Agriculture, Corvallis, OR, 2015.

[83] J. S. Littell, E. E. Oneil, D. McKenzie, J. A. Hicke, J. A. Lutz, R. A. Norheim and M. M. Elsner, "Forest Ecosystems, Disturbance, and Climatic Change in Washington State, USA," *Climatic Change,* vol. 102, pp. 129-158, 2010.

[84] J. K. Agee, M. Finney and R. De Gouvenain, "Forest Fire History of Desolation Peak, Washington," *Canadian Journal of Forest Research,* vol. 20, pp. 350-356, 1990.

[85] W. G. Morris, "Forest Fires in Western Oregon and Western Washington," *Oregon Historical Quarterly,* vol. 35, no. 4, pp. 313-339, 1934.

[86] M. A. Hemstrom and J. F. Franklin, "Fire and Other Disturbances of the Forests in Mount Rainier National Park," *Quaternary Research,* vol. 18, pp. 32-51, 1982.

[87] J. A. Henderson, D. H. Peter, R. D. Lesher and D. C. Shaw, "Forested Plant Associations of the Olympic National Forest," U.S. Forest Service, U.S. Department of Agriculture, 1989.

[88] D. L. Peterson and J. S. Littell, "Risk Assessment for Wildfire in the Western United States," in *Effects of Climate Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector*, J. M. Vose, D. L. Peterson and T. Patel-Weynand, Eds., Pacific Northwest Research Station, U.S. Department of Agriculture, Forest Service, 2012, pp. 249-252.

[89] J. T. Kliejunas, "A Risk Assessment of Climate Change and the Impact of Forest Diseases on Forest Ecosystems in the Western United States and Canada," U.S. Forest Service, U.S. Department of Agriculture, 2011.

[90] J. E. Halofsky, D. L. Peterson, K. A. O'Halloran and C. H. Hoffman, "Adapting to Climate Change at Olympic National Forest and Olympic National Park," U.S. Forest Service, U.S. Department of Agriculture, 2011.

[91] J. K. Stone, L. B. Coop and D. K. Manter, "Predicting Effects of Climate Change on Swiss Needle Cast Disease Severity in Pacific Northwest Forests," *Canadian Journal of Plant Pathology,* vol. 30, no. 2, pp. 169-176, 2008.

[92] R. N. Sturrock, S. J. Frankel, A. V. Brown, P. E. Hennon, J. T. Kliejuanas, K. J. Lewis, J. J. Worrall and A. J. Woods, "Climate Change and Forest Diseases," *Plant Pathology,* vol. 60, no. 1, pp. 133-149, 2011.

[93] R. Rietbroek, S.-E. Brunnabend, J. Kusche, J. Schröter and C. Dahle, "Revisiting the Contemporary Sea-level Budget on Global and Regional Scales," *Proceedings of the National Academy of Sciences,* vol. 113, no. 6, pp. 1504-1509, 2016.

[94] I. Joughin, B. E. Smith and B. Medley, "Marine Ice Sheet Collapse Potentially Underway for the Thwaites Glacier Basin, West Antarctica," *Science,* vol. 344, no. 6185, pp. 735-738, 2014.

[95] R. M. DeConto and D. Pollard, "Contribution of Antarctica to Past and Future Sea-level Rise," *Nature,* vol. 531, pp. 591-597, 2016.

[96] R. E. Kopp, R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss and C. Tebaldi, "Probabilistic 21st and 22nd Century Sea-level Projections at a Global Network of Tide-gauge Sites," *Earth's Future,* vol. 2, pp. 383-406, 2014.

[97] P. Mote, A. Petersen, S. Reeder, H. Shipman and L. Whitely Binder, "Sea Level Rise in the Coastal Waters of Washington State," Climate Impacts Group (University of Washington) and Washington Department of Ecology, 2008.

[98] J. J. Hamman, A. F. Hamlet, S.-Y. Lee, R. Fuller and E. E. Grossman, "Combined Effects of Projected Sea Level Rise, Storm Surge, and Peak River Flows on Water Levels in the Skagit Floodplain," *Northwest Science,* vol. 90, no. 1, pp. 57-78, 2016.

[99] Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, Eds., Cambridge, UK, and New York, USA, Cambridge University Press, 2007.

[100] D. P. Simpson, "City of Olympia Engineered Response to Sea Level Rise," Prepared for the City of Olympia Public Works Department (Planning & Engineering) by Coast & Harbor Engineering, 2012.

[101] R. Dexter, D. Anderson, E. Quinlan, L. Goldstein, R. Strickland, S. Pavlou, J. Clayton, R. Kocan and M. Landolt, "Technical Memorandum OMPA-13: A Summary of Knowledge of Puget Sound Related to Chemical Contaminants," National Oceanic and Atmospheric Administration, Office of Marine Pollution Assessment, 1981.

[102] A. J. MacLennan, J. F. Waggoner, J. W. Johannessen and S. A. Williams, "Sea Level Rise Vulnerability Assessment for San Juan County, Washington," Prepared by Coastal Geologic Services for Friends of the San Juans, 2013.

[103] G. M. Kaminsky, H. M. Baron, A. Hacking and D. McCandless, "Mapping and Monitoring Bluff Erosion with Boat-based LIDAR and the Development of a Sediment Budget and Erosion Model for the Elwha and Dungeness Littoral Cells, Clallam County, Washington," Washington State Department of Ecology, 2014.

[104] A. Linderoth, "Record Rainfall Eroding Cliffs Near Dungeness Spit," *Peninsula Daily News,* 13 March 2016.

[105] S.-Y. Lee and A. F. Hamlet, "Skagit River Basin Climate Science Report," A summary report prepared for Skagit County and the Envision Skagit Project by the Department of Civil and Environmental Engineering and the Climate Impacts Group at the University of Washington, 2011.

[106] P. W. Mote and E. P. Salathé Jr., "Future Climate in the Pacific Northwest," *Climatic Change,* vol. 102, no. 1-2, pp. 29-50, 2010.

[107] J. E. Overland and M. Wang, "Future Climate of the North Pacific Ocean," *Eos, Transactions American Geophysical Union,* vol. 88, no. 16, pp. 178-182, 2007.

[108] National Oceanic and Atmospheric Administration, "What is Ocean Acidification?," [Online]. Available: www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F. [Accessed 10 November 2016].

[109] J. D. Walsh, K. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy and R. Somerville, "Chapter 2: Our Changing Climate," in *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T. C. Richmond and G. W. Yohe, Eds., U.S. Global Change Research Program, 2014, pp. 19-67.

[110] R. J. Nicholls, N. Marinova, J. A. Lowe, S. Brown, P. Vellinga, D. de Gusmao, J. Hinkel and R. S. J. Tol, "Sea-level Rise and its Possible Impacts Given a 'Beyond 4°C' World in the Twenty-first Century," *Philosophical Transactions of the Royal Society A,* vol. 369, pp. 161-181, 2011.

[111] J. J. Furst, H. Goelzer and P. Huybrechts, "Ice-dynamic Projections of the Greenland Ice Sheet in Response to Atmospheric and Oceanic Warming," *The Cryosphere,* vol. 9, pp. 1039-1062, 2015.

[112] R. E. Kopp, R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss and C. Tebaldi, "Probabilistic 21st and 22nd Century Sea-level Projections at a Global Network of Tide-gauge Sites," *Earth's Future,* vol. 2, no. 8, pp. 383-406, 2014.

[113] Seattle Public Utilities, "Projected Climate Changes," City of Seattle, 2015. [Online]. Available: http://www.seattle.gov/util/EnvironmentConservation/ClimateChangeProgram/ProjectedChanges/index.htm. [Accessed December 2016].

[114] Washington Department of Ecology, "King Tides in Washington State," Washington Department of Ecology, 2016. [Online]. Available: http://www.ecy.wa.gov/climatechange/ipa_hightide.htm. [Accessed November 2016].

[115] P. Glick, J. Clough and B. Nunley, "Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon," National Wildlife Federation, 2007.

[116] Washington Department of Fish and Wildlife, "Licensing and Permits: Hydraulic Project Approval (HPA)," Washington Department of Fish and Wildlife, 2016. [Online]. Available: http://wdfw.wa.gov/licensing/hpa/. [Accessed 24 August 2016].

[117] R. Freudenberg, E. Calvis, L. Tolkoff and D. Brawley, "Buy-in for Buyouts: The Case for Managed Retreat from Flood Zones," Lincoln Institute of Land Policy, Cambridge, MA, 2016.

[118] National Oceanic and Atmospheric Administration, "Quinault Indian Nation Plans for Village Relocation," U.S. Climate Resilience Toolkit, May 2016. [Online]. Available:

http://toolkit.climate.gov/case-studies/quinault-indian-nation-plans-village-relocation. [Accessed November 2016].

[119] Intergovernmental Panel on Climate Change, "The Regional Impacts of Climate Change: An Assessment of Vulnerability," Cambridge University Press, Cambridge, UK and New York, USA, 1998.

[120] L. Tam, "Strategies for Managing Sea Level Rise," *The Urbanist,* no. 487, 2009.

[121] United States Geological Survey, National Oceanic and Atmospheric Administration, and National Science Foundation, "Abrupt Climate Change: Final Report, Synthesis and Assessment Product 3.4," United States Climate Change Science Program and the Subcommittee on Global Change Research, 2008.

[122] W. S. Broeker, "Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-made CO2 Upset the Current Balance," *Science,* vol. 278, pp. 1582-1588, 1997.

[123] The Earth Observatory, "Paleoclimatology: Explaining the Evidence," National Aeronautics and Space Administration, [Online]. Available: http://earthobservatory.nasa.gov/Features/Paleoclimatology_Evidence/paleoclimatology_evidence_2.php. [Accessed February 2017].

[124] L. C. Jackson, K. A. Peterson, C. D. Roberts and R. A. Wood, "Recent Slowing of Atlantic Overturning Circulation as a Recovery from Earlier Strengthening," *Nature Geoscience,* vol. 9, pp. 518-522, 2016.

[125] P. U. Clark, N. G. Pisias, T. F. Stocker and A. J. Weaver, "The Role of the Thermohaline Circulation in Abrupt Climate Change," *Nature,* vol. 415, pp. 863-869, 2002.

[126] National Ocean Service, "The Global Conveyor Belt," National Oceanic and Atmospheric Administration, July 2013. [Online]. Available: http://oceanservice.noaa.gov/education/kits/currents/06conveyor.html. [Accessed February 2017].

[127] A. Levermann, A. Griesel, M. Hofmann, M. Montoya and S. Rahmstorf, "Dynamic Sea Level Changes Following Changes in the Thermohaline Circulation," *Climate Dynamics,* vol. 24, pp. 347-354, 2005.

[128] Center for Science Education, "Melting Arctic Sea Ice and Ocean Circulation," University Corporation for Atmospheric Research, 2017. [Online]. Available: https://scied.ucar.edu/longcontent/melting-arctic-sea-ice-and-ocean-circulation. [Accessed February 2017].

[129] R. J. Stouffer and S. Manabe, "Equilibrium Response of Thermohaline Circulation to Large Changes in Atmospheric CO2 Concentration," *Climate Dynamics,* vol. 20, pp. 759-773, 2003.

[130] Earth Science Communication Team, "The Relentless Rise of Carbon Dioxide," National Aeronautics and Space Administration, February 2017. [Online]. Available: http://climate.nasa.gov/climate_resources/24/. [Accessed February 2017].

[131] National Aeronautics and Space Administration, "For First Time, Earth's Single-day CO2 Tops 400 ppm," Global Climate Change, National Aeronautics and Space Administration, May 2013. [Online]. Available: https://climate.nasa.gov/news/916/for-first-time-earths-single-day-co2-tops-400-ppm/. [Accessed February 2017].

[132] K. Riahi, S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic and P. Rafaj, "RCP 8.5 - A Scenario of Comparatively High Greenhouse Gas Emissions," *Climatic Change,* vol. 109, pp. 33-57, 2011.

[133] J. D. Marshall, B. Lang, S. F. Crowley, G. P. Weedon, P. van Calsteren, E. H. Fisher, R. Holme, J. A. Holmes, R. T. Jones, A. Beford, S. J. Brooks, J. Bloemendal, K. Kiriakoulakis and J. D. Ball, "Terrestrial Impact of Abrupt Changes in the North Atlantic Thermohaline Circulation: Early Holocene, UK," *Geology,* vol. 35, no. 7, pp. 639-642, 2007.

[134] J. F. McManus, R. Francois, J. M. Gherardi, L. D. Keigwin and S. Brown-Leger, "Collapse and Rapid Resumption of Atlantic Meridional Circulation Linked to Deglacial Climate Changes," *Nature,* vol. 428, pp. 834-837, 2004.

[135] R. Fowler, "How Does the Ocean Drive Weather and Climate Extremes?," Earth Institute, Columbia University, August 2016. [Online]. Available: http://blogs.ei.columbia.edu/2016/08/30/how-does-the-ocean-drive-weather-and-climate-extremes/. [Accessed February 2017].

[136] R. Knutti and T. F. Stocker, "Influence of Thermohaline Circulation on Projected Sea Level Rise," *Journal of Climate,* vol. 13, pp. 1997-2001, 2000.

[137] M. Vellinga and R. A. Wood, "Impacts of Thermohaline Circulation Shutdown in the Twenty-first Century," *Climatic Change,* vol. 91, pp. 43-63, 2008.

[138] C. A. Boulton, L. C. Allison and T. M. Lenton, "Early Warning Signals of Atlantic Meridional Overturning Circulation Collapse in a Fully Coupled Climate Model," *Nature Communications,* vol. 5, no. 5752, 2014.

[139] D. Anthoff, F. Estrada and R. S. J. Tol, "Valuing Climate Change Catastophes: Shutting Down the Thermohaline Circulation," *The American Economic Review,* vol. 106, no. 5, p. 602=606, 2016.

[140] M. Vellinga and R. A. Wood, "Global Climatic Impacts of a Collapse of the Atlantic Thermohaline Circulation," *Climatic Change,* vol. 54, pp. 251-267, 2002.

[141] J. Hansen, M. Sato, P. Hearty, R. Ruedy, M. Kelley, V. Masson-Delmotte, G. Russell, G. Tselioudis, J. Cao, E. Rignot, I. Velicogna, B. Tormey, B. Donovan, E. Kandiano, K. von Schuckmann, P. Kharecha, A. N. Legrande, M. Bauer and K.-W. Lo, "Ice Melt, Sea Level Rise and Superstorms: Evidence from Paleoclimate Data, Climate Modeling, and Modern Observations that 2°C Global Warming Could Be Dangerous," *Atmospheric Chemistry and Physics,* vol. 16, pp. 3761-3812, 2016.

[142] M. F. Meier, M. B. Dyurgerov, U. K. Rick, S. O'Neel, W. T. Pfeffer, R. S. Anderson, S. P. Anderson and A. F. Glazovsky, "Glaciers Dominate Eustatic Sea-level Rise in the 21st Century," *Science,* vol. 317, no. 5841, pp. 1064-1067, 2007.

[143] C. F. Larsen, E. Burgess, A. A. Arendt, S. O'Neel, A. J. Johnson and C. Keinholz, "Surface Melt Dominates Alaska Glacier Mass Balance," *Geophysical Research Letters,* vol. 42, pp. 5902-5908, 2015.

[144] T. A. M. Silva, G. R. Bigg and K. W. Nicholls, "Contribution of Giant Icebergs to the Southern Ocean Freshwater Flux," *Journal of Geophysical Research: Oceans,* vol. 111, no. C3, 2006.

[145] A. Thompson, "Large Iceberg Poised to Break Off From Antarctica," Climate Central, January 2017. [Online]. Available: http://www.climatecentral.org/news/large-iceberg-poised-to-break-off-antarctica-21028. [Accessed February 2017].

[146] B. Kulessa, D. Jansen, A. J. Luckman, E. C. King and P. R. Sammonds, "Marine Ice Regulates the Future Stability of a Large Antarctic Ice Shelf," *Nature Communications,* vol. 5, 2014.

[147] J. K. Patel, "A Crack in an Antarctic Ice Shelf Grew 17 Miles in the Last Two Months," *The New York Times,* 7 February 2017.

[148] E. Rignot, S. Jacobs, B. Scheuchl and J. Mouginot, "Ice-shelf Melting Around Antarctica," *Science,* vol. 341, no. 6143, 2013.

[149] T. A. Scambos, J. A. Bohlander, C. A. Shuman and P. Skvarca, "Glacier Acceleration and Thinning After Ice Shelf Collapse in the Larsen B Embayment, Antarctica," *Geophysical Research Letters,* vol. 31, 2004.

[150] D. Jansen, A. J. Luckman, A. Cook, S. Bevan, B. Kulessa, B. Hubbard and P. R. Holland, "Brief Communication: Newly Developing Rift in Larsen C Ice Shelf Presents Significant Risk to Stability," *The Cryosphere,* vol. 9, pp. 1223-1227, 2015.

[151] C. Mooney, "Antarctica is About to Lose an Enormous Piece of Ice. The Question if What Happens After That.," *The Washington Post,* pp. https://www.washingtonpost.com/news/energy-environment/wp/2017/01/10/antarctica-is-set-to-lose-an-enormous-piece-of-ice-the-question-is-what-happens-next/?utm_term=.7e9fe33c77b5, 10 January 2017.

[152] J. Sonntag, "Close Look at a Crack on Larsen C," Earth Observatory, National Aeronautics and Space Administration, November 2016. [Online]. Available: http://earthobservatory.nasa.gov/IOTD/view.php?id=89257. [Accessed February 2017].

[153] M. McMillan, A. Shepherd, A. Sundal, K. Briggs, A. Muir, A. Ridout, A. Hogg and D. Wingham, "Increased Ice Losses from Antarctica Detected by CryoSat-2," *Geophysical Research Letters,* vol. 41, pp. 3899-3905, 2014.

[154] J. L. Bamber, R. E. M. Riva, B. L. A. Vermeersen and A. M. LeBrocq, "Reassessment of the Potential Sea-level Rise from a Collapse of the West Antarctic Ice Sheet," *Science,* vol. 324, pp. 901-903, 2009.

[155] J. A. Dowdeswell, "The Greenland Ice Sheet and Global Sea-level Rise," *Science,* vol. 311, no. 5763, pp. 963-964, 2006.

[156] A. Robinson, R. Calov and A. Ganopolski, "Multistability and Critical Thresholds of the Greenland Ice Sheet," *Nature Climate Change,* vol. 2, pp. 429-432, 2012.

[157] A. Shepherd and D. Wingham, "Recent Sea-level Contributions of the Antarctic and Greenland Ice Sheets," *Science,* vol. 315, no. 5818, pp. 1529-1532, 2007.

[158] H. Machguth, M. MacFerrin, D. van As, J. E. Box, C. Charalampidis, W. Colgan, R. S. Fausto, H. A. J. Meijer, E. Mosley-Thompson and R. S. W. van de Wal, "Greenland Meltwater Storage in Firn Limited by Near-surface Ice Formation," *Nature Climate Change,* vol. 6, pp. 390-395, 2016.

[159] R. S. W. van de Wal, W. Boot, M. R. van den Broeke, C. J. P. P. Smeets, C. H. Reijmer, J. J. A. Donker and J. Oerlemans, "Large and Rapid Melt-induced Velocity Changes in the Ablation Zone of the Greenland Ice Sheet," *Science,* vol. 321, no. 5885, pp. 111-113, 2008.

[160] S. V. Nghiem, D. K. Hall, T. L. Mote, M. Tedesco, M. R. Albert, K. Keegan, C. A. Shuman, N. E. DiGirolamo and G. Neumann, "The Extreme Melt Across the Greenland Ice Sheet in 2012," *Geophysical Research Letters,* vol. 39, no. L20502, 2012.

[161] C. D. Koven, B. Ringeval, P. Friedlingstein, P. Ciais, P. Cadule, D. Khvorostyanov, G. Krinner and C. Tamocai, "Permafrost Carbon-Climate Feedbacks Accelerate Global Warming," *Proceedings of the National Academy of Sciences,* vol. 108, no. 36, pp. 14769-14774, 2011.

[162] E. A. G. Schuur, A. D. McGuire, C. Schadel, G. Grosse, J. W. Harden, D. J. Hayes, G. Hugelius, C. D. Koven, P. Kuhry, D. M. Lawrence, S. M. Natali, D. Olefeldt, V. E. Romanovsky, K. Shaefer, M. R. Turetsky, C. C. Treat and J. E. Vonk, "Climate Change and the Permafrost Carbon Feedback," *Nature,* vol. 520, pp. 171-179, 2015.

[163] G. Grosse, J. E. Robinson, R. Bryant, M. D. Taylor, W. Harper, A. DeMasi, E. Kyker-Snowman, A. Veremeeva, L. Schirrmeister and J. Harden, "Distribution of Late Pleistocene Ice-rich Syngenetic Permafrost of the Yedoma Suite in East and Central Siberia, Russia," United States Geological Survey, United States Department of the Interior, 2013.

[164] M. O. Leibman, A. I. Kizyakov, A. V. Plekhanov and I. D. Streletskaya, "New Permafrost Feature - Deep Crater in Central Yamal (West Siberia, Russia) as a Response to Local Climate Fluctuations," *Geography, Environment, Sustainability,* vol. 7, no. 4, pp. 68-80, 2014.

[165] V. Pushkarev, Artist, [Art]. Russian Centre of Arctic Exploration/Siberian Times, 2014.

[166] T. S. von Deimling, G. Grosse, J. Strauss, L. Schirrmeister, A. Morgenstern, S. Schaphoff, M. Meinshausen and J. Boike, "Observation-based Modelling of Permafrost Carbon Fluxes with Accounting for Deep Carbon Deposits and Thermokarst Activity," *Biogeosciences,* vol. 12, pp. 3469-3488, 2015.

[167] C. D. Koven, W. J. Riley and A. T. Stern, "Analysis of Permafrost Thermal Dynamics and Response to Climate Change in the CMIP5 Earth System Models," Lawrence Berkley National Laboratory, United States Department of Energy, 2013.

[168] G. J. Whiting and J. P. Chanton, "Greenhouse Carbon Balance of Wetlands: Methane Emission Versus Carbon Sequestration," *Tellus: Series B, Checmical and Physical Meteorology,* vol. 53, no. 5, pp. 521-528, 2001.

[169] Edge Hill University, "Peatlands, the Carbon Cycle and Climatic Change," Edge Hill University, November 2016. [Online]. Available: https://www.edgehill.ac.uk/geography/research/environmental-processes-change-group-epc/peatlands-the-carbon-cycle-and-climatic-change/. [Accessed February 2017].

[170] M. Saunois, R. B. Jackson, P. Bousquet, B. Poulter and J. G. Canadell, "The Growing Role of Methane in Anthropogenic Climate Change," *Environmental Research Letters,* vol. 11, no. 12, 2016.

[171] S. D. Bridgham, H. Cadillo-Quiroz, J. K. Keller and Q. Zhuang, "Methane Emissions from Wetlands: Biogeochemical, Microbial, and Modeling Perspectives from Local to Global Scales," *Global Change Biology,* vol. 19, pp. 1325-1346, 2013.

[172] W. J. Mitsch, B. Bernal, A. M. Nahlik, U. Mander, L. Zhang, C. J. Anderson, S. E. Jorgensen and H. Brix, "Wetlands, Carbon, and Climate Change," *Landscape Ecology,* vol. 28, no. 4, pp. 583-597, 2013.

[173] R. H. James, P. Bousquet, I. Bussmann, M. Haeckel, R. Kipfer, I. Leifer, H. Niemann, I. Ostrovsky, J. Piskozub, G. Rehder, T. Treude, L. Vielstade and J. Greinert, "Effects of Climate Change on Methane Emissions from Seafloor Sediments in the Arctic Ocean: A Review," *Limnology and Oceanography,* vol. 61, pp. 5283-5299, 2016.

[174] A. V. Borges, W. Champenois, N. Gypens, B. Delille and J. Harlay, "Massive Marine Methane Emissions from Near-shore Shallow Coastal Areas," *Scientific Reports,* vol. 6, 2016.

[175] The Wilderness Society, "Pacific Salmon and Federal Lands: A Regional Analysis," Bolle Center for Forest Ecosystem Management, The Wilderness Society, Washington, D.C., 1993.

[176] M. Nelitz, K. Wieckowski, D. Pickard, K. Pawley and D. R. Marmorek, "Helping Pacific Salmon Survive the Impact of Climate Change on Freshwater Habitats," Pacific Fisheries Resource Conservation Council, Vancouver, BC, Canada, 2007.

[177] T. Beechie, H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney and N. Mantua, "Restoring Salmon Habitat for a Changing Climate," *River Research and Applications,* vol. 29, no. 8, pp. 939-960, 2012.

[178] N. Mantua, I. Tohver and A. Hamlet, "Impacts of Climate Change on Key Aspects of Freshwater Salmon Habitat in Washington State," in *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*, Seattle, Climate Impacts Group, University of Washington, 2009, pp. 217-254.

[179] D. H. Evans , P. M. Piermarni and K. P. Choe, "The Multifunctional Fish Gill: Dominant Site of Gas Exchange, Osmoregulation, Acid-base Regulation, and Excretion of Nitrogenous Waste," *Physiological Reviews,* vol. 85, no. 1, pp. 97-177, 2005.

[180] P. Tillmann and D. Siemann, "Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region," National Wildlife Federation, 2011.

[181] J. G. Eaton and R. M. Scheller, "Effects of Climate Warming on Fish Thermal Habitat in Streams of the United States," *American Society of Limnology and Oceanography,* vol. 41, no. 5, pp. 1109-1115, 1996.

[182] K. Carter, "The Effects of Dissolved Oxygen on Steelhead Trout, Coho Salmon, and Chinook Salmon Biology and Function by Life Stage," California Regional Water Quality Control Board, North Coast Region, Sacramento, 2005.

[183] W. C. Clarke, J. E. Shelbourn and J. R. Brett, "Effect of Artificial Photoperiod Cycles, Temperature, and Salinity on Growth and Smolting in Underyearling Coho (Oncorhynchus kisutch), Chinook (O. tshawytscha), and Sockeye (O. nerka) Salmon," *Aquaculture,* vol. 22, pp. 105-116, 1981.

[184] E. J. Ward, J. H. Anderson, T. J. Beechie, G. R. Pess and M. J. Ford, "Increasing Hydrologic Variability Threatens Depleted Anadromous Fish Populations," *Global Climate Change Biology ,* vol. 21, no. 7, pp. 2500-2509, 2015.

[185] P. Rand, "Salmon and Climate Change: Fish in Hot Water," International Union for Conservation of Nature, Gland, Switzerland, 2009.

[186] R. Warren, "WDFW Takes Steps to Reduce Effects of Drought at Fish Hatcheries," Washington Department of Fish and Wildlife, 28 July 2015. [Online]. Available: http://wdfw.wa.gov/news/jul2815a/. [Accessed 5 March 2016].

[187] H. Bernton, "Snowpack Drought has Salmon Dying in Overheated Rivers," The Seattle Times, 25 July 2015. [Online]. Available: http://www.seattletimes.com/seattle-news/environment/snowpack-drought-has-salmon-dying-in-overheated-rivers/. [Accessed 7 March 2016].

[188] J. Martin and P. Glick, "A Great Wave Rising: Solutions for Columbia and Snake River Salmon in the Age of Global Warming," Light in the River, 2008.

[189] P. Bisson, "Salmon and Trout in the Pacific Northwest and Climate Change," U.S. Department of Agriculture, Forest Service, Climate Change Resource Center, 16 June 2008. [Online]. Available: http://www.fs.fed.us/ccrc/topics/salmon-trout.shtml.

[190] D. W. Jensen, E. A. Steel, A. H. Fullerton and G. R. Pess, "Impact of Fine Sediment on Egg-to-Fry Survival of Pacific Salmon: A Meta-analysis of Published Studies," *Fisheries Science,* vol. 17, no. 3, pp. 348-359, 2009.

[191] N. Mantua, I. Tohver and A. Hamlet, "Climate Change Impacts on Streamflow Extremes and Summertime Stream Temperature and Their Possible Consequences for Freshwater Salmon Habitat in Washington State," *Climatic Change,* vol. 102, no. 1, pp. 187-223, 2010.

[192] Climate Impacts Group, "HB 1303 Interim Report: A Comprehensive Assessment of the Impacts of Climate Change on the State of Washington," University of Washington JISAO CSES Climate Impacts Group, Seattle, 2007.

[193] A. Richter and S. A. Kolmes, "Maximum Temperature Limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest," *Reviews of Fisheries Science,* vol. 13, no. 1, pp. 23-49, 2005.

[194] M. Fenkes, H. A. Shiels, J. L. Fitzpatrick and R. L. Nudds, "The Potential Impacts of Migratory Difficulty, Including Warmer Waters and Altered Flow Conditions, on the Reproductive Success of Salmonid Fishes," *Comparative Biochemistry and Physiology, Part A: Molecular & Integrative Physiology,* vol. 193, pp. 11-21, 2015.

[195] D. A. McCullough, "A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, with Special Reference to Chinook Salmon," Environmental Protection Agency, Region 10, Seattle, 1999.

[196] W. J. Groberg Jr, R. H. McCoy, K. S. Pilcher and J. L. Fryer, "Relation of Water Temperature to Infections of Coho Salmon (*Oncorhynchus kisutch*), Chinook Salmon (*O. tshawytscha*), and Steelhead Trout (*Salmo gairdner*i) with *Aeromonas salmonicida* and *A. hydrophila*," *Journal of the Fisheries Research Board of Canada,* vol. 35, no. 1, pp. 1-7, 1978.

[197] R. Kocan, P. Hershberger, G. Sanders and J. Winton, "Effects of Temperature on Disease Progression and Swimming Stamina in Ichthyophonus-infected Rainbow Trout, *Oncorhynchus mykiss* (Walbaum)," *Journal of Fish Diseases,* vol. 32, no. 10, pp. 835-843, 2009.

[198] R. Kocan, P. Hershberger and J. Winton, "Ichthyophoniasis: An Emerging Disease of Chinook Salmon in the Yukon River," *Journal of Aquatic Animal Health,* vol. 16, pp. 58-72, 2004.

[199] Oregon Climate Change Research Institute , "Fish and Wildlife," Oregon Climate Change Research Institute, 2010. [Online]. Available: http://occri.net/climate-science/potential-impacts-of-climate-change/fish-and-wildlife.

[200] PacifiCorp, "*Ceratomyxa Shasta* Fact Sheet - 2002," 2002. [Online]. Available: http://www.pacificorp.com/content/dam/pacificorp/doc/Energy_Sources/Hydro/Hydro_Licensing/Klamath_River/Ceratomyxa_Shasta_Fact_Sheet_2002.pdf.

[201] R. Hendrick, M. Kent and C. Smith, "Proliferative Kidney Disease in Salmonid Fishes," *US Fish and Wildlife Publications,* vol. 136, 1986.

[202] B. Okamura, H. Hartikainen, H. Schmidt-Posthaus and T. Wahli, "Life Cycle Complexity, Environmental Change and the Emerging Status of Salmonid Proliferative Kidney Disease," *Freshwater Biology,* vol. 56, no. 4, pp. 735-753, 2010.

[203] J. Fryer and J. Sanders, "Bacterial Kidney Disease of Salmonid Fish," *Annual Review of Microbiology,* vol. 35, pp. 273-298, 1981.

[204] J. Newcomb, L. Pierce and H. Spanglet, "Low Dissolved Oxygen Levels in the Stockton Deep Water Shipping Canal: Adverse Effects on Salmon and Steelhead and Potential Beneficial Effects of Raising Dissolved Oxygen Levels with the Aeration Facility," California Department of Water Resources, Sacramento, 2010.

[205] M. L. Dailberg, D. L. Shumway and P. Doudoroff, "Influence of Dissolved Oxygen and Carbon Dioxide on Swimming Performance of Largemouth Bass and Coho Salmon," *Journal of the Fisheries Research Board of Canada,* vol. 25, no. 1, pp. 49-70, 1968.

[206] E. T. Garside, "Effects of Oxygen in Relation to Temperature on the Development of Embryos of Brook Trout and Rainbow Trout," *Journal of the Fisheries Research Board of Canada,* vol. 23, no. 8, pp. 1121-1134, 1966.

[207] D. L. Shumway, C. E. Warren and P. Doudoroff, "Influence of Oxygen Concentration and Water Movement on the Growth of Steelhead Trout and Coho Salmon Embryos," *Transactions of the American Fisheries Society,* vol. 93, no. 4, pp. 342-356, 1964.

[208] K. Carter, "Effects of Temperature, Dissolved Oxygen/Total Dissolved Gas, Ammonia, and pH on Salmonids," North Coast Regional Water Quality Control Board, Santa Rosa, CA, 2008.

[209] U.S. Environmental Protection Agency, Office of Water Criteria and Standards Division, "Ambient Water Quality Criteria for Dissolved Oxygen," U.S. Environmental Protection Agency, Washington, DC, 1986.

[210] B. C. Spence, G. A. Lomnicky, R. M. Hughs and R. P. Novitzki, "An Ecosystem Approach to Salmonid Conservation," United States Environmental Protection Agency, 1996.

[211] D. R. Geist, C. S. Abernethy, K. D. Hand, V. I. Cullinan, J. A. Chandler and P. A. Groves, "Survival, Development, and Growth of Fall Chinook Salmon Embryos, Alevins, and Fry Exposed to Variable Thermal and Dissolved Oxygen Regimes," *Transactions of the American Fisheries Society,* vol. 135, pp. 1462-1477, 2006.

[212] M. Ou, T. J. Hamilton, J. Eom, E. M. Lyall, J. Gallup, A. Jiang, J. Lee, D. A. Close, S.-S. Yun and C. J. Brauner, "Responses of Pink Salmon to CO2-Induced Aquatic Acidification," *Nature Climate Change,* vol. 5, pp. 950-955, 2015.

[213] R. J. Beamish, B. E. Riddell, K. L. Lange, E. Farley Jr., S. Kang, T. Nagasawa, V. Radchenko, O. Temnykh and S. Urawa, "The Effects of Climate on Pacific Salmon: A Summary of Published Literature," North Pacific Anadromous Fish Commission, Vancouver, B.C., Canada, 2009.

[214] D. W. Welch, Y. Ishida and K. Nagasawa, "Thermal Limits and Ocean Migrations of Sockeye Salmon (*Onchorhynchus nerka*): Long-term Consequences of Global Warming," *Canadian Journal of Fisheries and Aquatic Science,* vol. 55, pp. 937-948, 1998.

[215] T. Azumaya, T. Nagasawa, O. S. Temnykh and G. V. Khen, "Regional and Season Differences in Temperature and Salinity Limitations of Pacific Salmon (*Onchorynthus spp*.)," *North Pacific Anadromous Fish Commission Bulletin,* vol. 4, pp. 179-187, 2007.

[216] O. Abdul-Aziz, N. Mantua and K. Myers, "Potential Climate Change Impacts on Thermal Habitats of Pacific Salmon (*Oncorhynchus spp*.) in the North Pacific Ocean and Adjacent Seas," *Canadian Journal of Fisheries and Aquatic Sciences,* vol. 68, no. 9, pp. 1660-1680, 2011.

[217] A. Snover, P. Mote, L. Whitely Binder, A. Hamlet and N. Mantua, "Uncertain Future: Climate Change and its Effects on Puget Sound," University of Washington Climate Impacts Group, Seattle, 2005.

[218] S. L. Palacios and R. C. Zimmerman, "Response of Eelgrass *Zostera Marina* to CO2 Enrichment: Possible Impacts of Climate Change and Potential for Remediation of Coastal Habitats," *Marine Ecology Progress Series,* vol. 344, pp. 1-13, 2007.

[219] S. G. Hinch, M. C. Healey, R. E. Diewert, M. A. Henderson, K. A. Thomson, R. Hourston and F. Juanes, "Potential Effects of Climate Change on Marine Growth and Survival of Fraser River Sockeye Salmon," *Canadian Journal of Fisheries and Aquatic Sciences,* vol. 52, no. 12, pp. 2651-2659, 1995.

[220] E. A. Daly and R. D. Brodeur, "Warming Ocean Conditions Relate to Increased Trophic Requirements of Threatened and Endangered Salmon," *PLoS ONE,* vol. 10, no. 12, 2015.

[221] Canadian Council of Ministers of the Environment, "Canadian Water Quality Guidelines for the Protection of Aquatic Life: Dissolved Oxygen (Marine)," in *Canadian Environmental Quality Guidelines*, Winnipeg, Canadian Council of Ministers of the Environment, 1999.

[222] T. C. Bjornn and D. W. Reiser, "Chapter 4: Habitat Requirements of Salmonids in Streams," in *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats*, W. R. Meehan, Ed., American Fisheries Society, 1991, pp. 83-138.

[223] E. Morgan and D. Siemann, "Climate Change Effects on Marine and Coastal Habitats in Washington State," Washington Department of Fish and Wildlife and the National Wildlife Federation, 2010.

[224] J. Newton, C. Bassin, A. Devol, M. Kawase, W. Ruef, M. Warner, D. Hannafious and R. Rose, "Hypoxia in Hood Canal: An Overview of Status and Contributing Factors," University of Washington and Hood Canal Salmon Enhancement Group, 2007.

[225] M. Roberts, T. Mohamedali, B. Sackmann, T. Khangaonkar and W. Long, "Dissolved Oxygen Assessment for Puget Sound and the Straits: Impacts of Current and Future Human Nitrogen Sources and Climate Change Through 2070," Washington State Department of Ecology, Olympia, 2014.

[226] J. Newton , "Hypoxia Event," Hood Canal Dissolved Oxygen Program, August 2006. [Online]. Available: http://www.hoodcanal.washington.edu/observations/hypoxia.jsp. [Accessed 15 June 2015].

[227] R. Haigh, D. Ianson, C. A. Hold, H. E. Neate and A. M. Edwards, "Effects of Ocean Acidification on Temperate Coastal Marine Ecosystems and Fisheries in the Northeast Pacific," *PLoS One ,* vol. 10, no. 2, 2015.

[228] F. Melzner, S. Goebel, M. Langenbuch, M. A. Gutowska, H. O. Poertner and M. Lucassen, "Swimming Performance in Atlantic Cod (Gadus morhua) Following Long-term (4-12 months) Acclimation to Elevated Seawater pCO2," *Aquatic Toxicology,* vol. 92, pp. 30-37, 2009.

[229] F. Melzner, M. A. Gutowska, M. Langenbuch, S. Dupont, M. Lucassen, M. C. Thorndyke, M. Bleich and H. O. Poertner, "Physiological Basis for High CO2 Tolerance in Marine Ectothermic Animals: Pre-adaptation Through Lifestyle and Ontogeny?," *Biogeosciences,* vol. 6, pp. 2313-2331, 2009.

[230] J. M. Guinotte and V. J. Fabry , "Ocean Acidification and Its Potential Effects on Marine Ecosystems," *Annals of the New York Academy of Sciences,* vol. 1134, pp. 320-342, 2008.

[231] A. J. Lewitus, R. A. Horner, D. A. Caron, E. Garcia-Mendoza, B. M. Hickey, M. Hunter, D. D. Huppert, R. M. Kudela, G. W. Langlois, J. L. Largier, E. J. Lessard, R. RaLonde, J. J. Rensel, P. G. Strutton, V. L. Trainer and J. F. Tweddle, "Harmful Algal Blooms Along the North American West Coast Region: History, Trends, Causes, and Impacts," *Harmful Algae,* vol. 19, pp. 133-159, 2012.

[232] P. J. Harrison, P. A. Thompson, M. Guo and F. J. Taylor, "Effects of Light, Temperature and Salinity on the Growth Rate of Harmful Marine Diatoms, *Chaetoceros convolutus* and *C. concavicornis* that Kill Netpen Salmon," *Journal of Applied Phycology,* vol. 5, no. 2, pp. 259-265, 1993.

[233] K. A. Lefebvre, D. P. Noren, I. R. Schultz, S. M. Bogard, J. Wilson and B.-T. L. Eberhart, "Uptake, Tissue Distribution and Excretion of Domoic Acid After Oral Exposure in Coho Salmon (*Oncorhychus kisutch*)," *Aquatic Toxicology,* vol. 81, no. 3, pp. 266-274, 2007.

[234] D. Penttila, "Marine Forage Fishes in Puget Sound," Puget Sound Nearshore Partnership Report No. 2007-03. U.W. Army Corps of Engineers, Seattle, WA, 2007.

[235] D. Scavia, J. C. Field, D. F. Boesch, R. W. Buddemeier, V. Burkett, D. R. Cayan, M. Fogarty, M. A. Harwell, R. W. Howarth, C. Mason, D. J. Reed, T. C. Royer, A. H. Sallenger and J. G. Titus, "Climate Change Impacts on U.S. Coastal and Marine Ecosystems," *Estuaries,* vol. 25, no. 2, pp. 149-164, 2002.

[236] N. N. Rabalais, E. R. Turner, R. J. Diaz and D. Justic, "Global Change and Eutrophication of Coastal Waters," *ICES Journal of Marine Science,* vol. 66, no. 7, pp. 1528-1537, 2009.

[237] A. B. Hollowed, S. J. Barbeaux, E. D. Cokelet, E. Farley, S. Kotwicki, P. H. Ressler, C. Spital and C. D. Wilson, "Effects of Climate Variations on Pelagic Ocean Habitats and their Role in Structuring Forage Fish Distributions in the Bering Sea," *Deep Sea Research Part II: Topic Studies in Oceanography,* Vols. 65-70, pp. 230-250, 2012.

[238] J. A. Thayer, D. F. Bertram, S. A. Hatch, M. J. Hipfner, L. Slater, W. J. Sydeman and Y. Watanuki, "Forage Fish of the Pacific Rim as Revealed by Diet of a Piscivorous Seabird: Synchrony and Relationships with Sea Surface Temperature," *Canadian Journal of Fisheries and Aquatic Sciences,* vol. 65, no. 8, pp. 1610-1622, 2008.

[239] D. F. Alderdice and F. Velsen, "Some Effects of Salinity and Temperature on Early Development of Pacific Herring (Clupea pallasi)," *Journal of the Fisheries Research Board of Canada,* vol. 28, no. 10, pp. 1545-1562, 1971.

[240] M. Robards, M. Willson, R. Armstrong and J. Piatt, "Sand Lance: A Review of Biology and Predator Relations and Annotated Bibliography," U.S. Department of Agriculture, Portland, Oregon, 1999.

[241] G. D. Brewer, "Thermal Tolerance and Resistance of the Northern Anchovy, *Engraulis Mordax,*" *Fishery Bulletin,* vol. 74, no. 2, pp. 433-445, 1976.

[242] R. Baxter, "Miscellaneous Species: Report on the 1980-1995 Fish, Shrimp, and Crab Sampling in the San Franscisco Estuary, California," California Department of Fish and Game, Stockton, California, 1999.

[243] Washington Department of Fish and Wildlife, "State Wildlife Action Plan DRAFT," Washington Department of Fish and Wildlife, Olympia, 2015.

[244] Pacific Herring, "Human Interaction," Hakai Institute, 2014. [Online]. Available: http://www.pacificherring.org/explorer/human-interaction. [Accessed 2 Feb. 2016].

[245] C. Greene, L. Kuehne, C. Rice, K. Fresh and D. Pentilla, "Forty Years of Change in Forage Fish and Jellyfish Abundance Across Greater Puget Sound, Washington (USA): Anthropogenic and Climate Associations," *Marine Ecology Progress Series,* vol. 525, pp. 153-170, 12 Oct. 2015.

[246] D. Lassuy, "Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest) Pacific Herring," U.S. Fish and Wildlife Service and U.S. Army Corps of Engineers, 1989.

[247] L. Brotz, W. W. L. Cheung, K. Kleisner, E. Pakhomov and D. Pauly, "Increasing Jellyfish Populations: Trends in Large Marine Ecosystems," *Hydrobiologia,* vol. 690, pp. 3-20, 2012.

[248] T. Hattab, F. Leprieur, F. Lasram, D. Gravel, F. Le Loc'h and C. Albouy, "Forecasting Fine-scale Changes in the Food-web Structure of Coastal Marine Communities under Climate Change," *Ecography,* vol. Early View 1, pp. 1-11, 2016.

[249] V. M. Lopes, A. R. Lopes, P. Costa and R. Rosa, "Cephalopods as Vectors of Harmful Algal Bloom Toxins in Marine Food Webs," *Marine Drugs,* vol. 11, no. 9, pp. 3381-3409, 2013.

[250] J. H. Landsberg, "The Effects of Harmful Algal Blooms on Aquatic Organisms," *Reviews in Fisheries Science,* vol. 10, no. 2, pp. 113-390, 2002.

[251] Washington Department of Fish and Wildlife, "Pacific Herring Information Summary," [Online]. Available: http://wdfw.wa.gov/conservation/fisheries/PacificHerringInformation_121911.pdf. [Accessed 9 February 2016].

[252] D. S. Busch, C. J. Harvey and P. McElhaney, "Potential Impacts of Ocean Acidification on the Puget Sound Food Web," *ICES Journal of Marine Science,* vol. 70, no. 4, pp. 823-833, 2013.

[253] G. H. Engelhard, M. A. Peck, A. Rindorf, S. C. Smout, M. Van Deurs, K. Raab, K. H. Andersen, S. Garthe, R. A. Laurburg, F. Scott, T. Brunel, G. Aarts, T. Van Kooten and M. Dickey-Collas, "Forage Fish, their Fisheries, and their Predators: Who Drives Whom?," *ICES Journal of Marine Science,* vol. 71, no. 1, pp. 90-104, 2014.

[254] R. Beamish, "Impacts of Climate and Climate Change on Key Species in the Fisheries in the North Pacific," North Pacific Marine Science Organization, Sidney, B.C., Canada, 2008.

[255] C. Burge, C. M. Eakin, C. Friedman, B. Froelich, P. Hershberger, E. Hofmann, L. Petes, K. Prager, E. Weil, B. Willis, S. Ford and C. D. Harvell, "Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society," *Annual Review of Marine Science ,* vol. 6, pp. 249-277, 2014.

[256] A. Moles and T. Wade, "Parasitism and Phagocytic Function Among Sand Lance *Ammodytes hexapterus* Pallas Exposed to Crude Oil-Laden Sediments," *Bulletin of Environmental Contamination and Toxicology,* vol. 66, pp. 528-535, 2001.

[257] Washington State Department of Transportation, "WSDOT - Hood Canal Bridge Common Questions," Washington State Department of Transportation, 2016. [Online]. Available: http://www.wsdot.wa.gov/Bridge/HoodCanal/questions.htm. [Accessed 6 June 2016].

[258] M. Bjork, F. Short, E. Mcleod and S. Beer, "Managing Seagrasses for Resilience to Climate Change," International Union for Conservation and Nature.

[259] T. Whitman, D. Penttila, P. Dionne, K. Krueger, K. Pierce, Jr. and T. Quinn, "Tidal Elevation of Surf Smelt Spawn Habitat Study for San Juan County, Washington," Friends of the San Juans and Washington Department of Fish and Wildlife, 2014.

[260] M. Lindeberg, "NOAA Photo Library," 11 June 2005. [Online]. Available: http://www.photolib.noaa.gov/htmls/fish1917.htm. [Accessed 12 Feb. 2016].

[261] C. D. G. Harley, A. R. Hughes, K. M. Hultgren, B. G. Miner, C. J. B. Sorte, C. S. Thornber, L. F. Rodriguez, L. Tomanek and S. L. Williams, "The Impacts of Climate Change on Coastal Marine Systems," *Ecology Letters,* vol. 9, no. 2, pp. 228-241, 2006.

[262] R. Carman, K. Taylor and P. Skowlund, "Regulating Shoreline Armoring in Puget Sound," U.S. Geological Survey, 2010.

[263] L. Stiffler, "The Real Story of Puget Sound's Disappearing Herring," Sightline Institute, Seattle, 2013.

[264] C. Dunagan, "Spawning Habitat for Forage Fish Being Lost to Rising Tides," Puget Sound Institute, University of Washington, 22 March 2016. [Online]. Available: https://www.eopugetsound.org/magazine/armoring-fish. [Accessed 6 October 2016].

[265] T. Whitman and S. Hawkins, "The Impacts of Shoreline Armoring on Beach Spawning Forage Fish Habitat in San Juan County," Friends of the San Juans, 2014.

[266] K. Krueger, K. Pierce, Jr. , T. Quinn and D. Penttila, "Anticipated Effects of Sea Level Rise in Puget Sound on Two Beach-Spawning Fishes," in *Puget Sound Shorelines and the Impacts of Armoring - Proceedings of a State of the Science Workshop*, 2010.

[267] J. Ryan, "Northwest Public Radio," 20 Jul. 2012. [Online]. Available: http://nwpr.org/post/new-director-aims-shore-puget-sound-agency. [Accessed 16 Feb. 2016].

[268] T. Baurick, "Governor Signs Bill for Big Study of Puget Sound Forage Fish," *Kitsap Sun,* pp. http://www.kitsapsun.com/outdoors/governor-signs-bill-for-big-study-of-puget-sound-forage-fish-ep-1075187070-354738321.html, 8 May 2015.

[269] Port Gamble S'Klallam Tribe, "Shellfish," 2015. [Online]. Available: https://www.pgst.nsn.us/tribal-programs/tribal-services/natural-resources/shellfish. [Accessed October 2015].

[270] Committee on Environment and Natural Resources, "Scientific Assessment of Hypoxia in U.S. Coastal Waters," Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health, Washington, D.C., 2010.

[271] Pacific Coast Shellfish Growers Association, "Washington Shellfish Initiative," Pacific Coast Shellfish Growers Association, 2011.

[272] C. L. Goodwin and B. Pease, "Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates: Pacific Geoduck Clam," U.S. Fish and Wildlife Service, National Wetlands Research Center, 1989.

[273] D. P. Cheney and T. F. Mumford, Jr., Shellfish and Seaweed Harvests of Puget Sound, Seattle: University of Washington Press, Washington Sea Grant Program, 1986.

[274] G. B. Pauley, D. A. Armstrong and T. W. Heun, "Species Profile: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates: Dungeness Crab," U.S Fish and Wildlife Service, National Wetlands Research Center, 1986.

[275] J. J. Miller, "Effect of Low pH on Early Life Stages of the Decapod Crustacean, Dungeness Crab (*Cancer magister*)," University of Washington (Master's thesis), 2015.

[276] W. Liu, H. Gurney-Smith, A. Beerens and C. M. Pearce, "Effects of Stocking Density, Algal Density, and Temperature on Growth and Survival of Larvae of the Basket Cockle, *Clinocardium nuttallii*," *Aquaculture,* vol. 299, pp. 99-105, 2010.

[277] R. Mann, "The Effect of Temperature on Growth, Physiology, and Gametogenesis in the Manila Clam *Tapes philippinarum*," *Journal of Experimental Marine Biology and Ecology,* vol. 38, pp. 121-133, 1979.

[278] K. K. Chew and A. P. Ma, "Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates: Common Littleneck Clam," U.S. Fish and Wildlife Service, 1987.

[279] T. H. Butler, "Growth, Reproduction, and Distribution of Pandalid Shrimps in British Columbia," *Journal of the Fisheries Research Board of Canada,* vol. 21, no. 6, pp. 1403-1452, 1964.

[280] R. K. Bechmann, I. C. Taban, S. Westerlund, B. F. Godal, M. Arnberg, S. Vingen, A. Ingvarsdottir and T. Baussant, "Effects of Ocean Acidification on Early Life Stages of Shrimp (Pandalus borealis) and Mussel (Mytilus edulis)," *Journal of Toxicology and Environmental Health, Part A,* vol. 74, pp. 424-438, 2011.

[281] R. B. Lauzier, C. M. Hand, A. Campbell and S. Heizer, "A Review of the Biology and Fisheries of Horse Clams (*Tresus capax* and *Tresus nuttallii*)," Fisheries and Oceans Canada, 1998.

[282] K. Weber, L. Sturner, E. Hoover and S. Baker, "FA151: The Role of Water Temperature in Hard Clam Aquaculture," University of Florida, Fisheries and Aquatic Sciences Division, 2007.

[283] N. Holmyard, "Climate Change: Implications for Fisheries and Aquaculture - Key Findings from the Intergovernmental Panel on Climate Change Fifth Assessment Report," University of Cambridge and the Sustainable Fisheries Partnership, 2014.

[284] Washington Department of Fish and Wildlife (WDFW), "Oyster Facts," 2015. [Online]. Available: wdfw.wa.gov/fishing/shellfish/oysters/facts.html. [Accessed October 2015].

[285] S. R. Valdez and J. L. Ruesink, "Scales of Recruitment Variability in Warmer Waters: Comparing Native and Non-native Oysters in Hood Canal, Washington, USA," 2016 (draft).

[286] Y. Li, K. Benkendorff, J. Qin, C. A. Abbott and X. Li, "Synergistic Impacts of Heat Shock and Spawning on the Physiology and Immune Health of *Crassostrea gigas*: An Explanation for Summer

Mortality on Pacific Oysters," *American Journal of Physiology,* vol. 293, no. 6, pp. R2353-R2362, 2007.

[287] L. Degremont, P. Soletchnik and P. Boudry, "Summer Mortality of Selected Juvenile Pacific Oyster *Crassostrea gigas* Under Laboratory Conditions in Comparison with Field Performance," *Journal of Shellfish Research,* vol. 29, no. 4, pp. 847-856, 2010.

[288] S. K. Moore, N. J. Mantua and E. P. Salathe Jr., "Past Trends and Future Scenarios for Environmental Conditions Favoring the Accumulation of Paralytic Shellfish Toxins in Puget Sound Shellfish," *Harmful Algae,* vol. 10, no. 5, pp. 521-529, 2011.

[289] C. Manfrin, G. De More, V. Torboli, P. Venier, A. Pallavicini and M. Gerdol, "Physiological and Molecular Responses of Bivalves to Toxic Dinoflagellates," *Invertebrate Survival Journal,* vol. 9, no. 2, pp. 184-199, 2012.

[290] H. Haberkorn, C. Lambert, N. Le Goic, M. Guegen, J. Moal, E. Palacios, P. Lassus and P. Soudant, "Effects of *Alexandrium minutum* Exposure upon Physiological and Hematological Variables of Diploid and Triploid Oysters, *Crassostrea gigas*," *Aquatic Toxicology,* vol. 97, no. 2, pp. 96-108, 2010.

[291] S. K. Moore, V. L. Trainer, N. J. Mantua, M. S. Parker, E. A. Laws, L. C. Backer and L. E. Fleming, "Impacts of Climate Variability and Future Climate Change on Harmful Algal Blooms and Human Health," *Environmental Health,* vol. 7, no. 2, 2008.

[292] D. L. Erdner, J. Dyble, M. L. Parsons, R. C. Stevens, K. A. Hubbard, M. L. Wrable, S. K. Moore, K. A. Lefebvre, D. M. Anderson, P. Bienfang, R. R. Bidigare, M. S. Parker, P. Moeller, L. E. Brand and V. L. Trainer, "Centers for Oceans and Human Health: A Unified Approach to the Challenge of Harmful Algal Blooms," *Environmental Health,* vol. 7, no. 2, 2008.

[293] S. K. Moore, N. J. Mantua, B. M. Hickey and V. L. Trainer, "Recent Trends in Paralytic Shellfish Toxins in Puget Sound, Relationships to Climate, and Capacity for Prediction of Toxic Events," *Harmful Algae,* vol. 8, no. 3, pp. 463-477, 2009.

[294] L. E. Fleming, "Paralytic Shellfish Poisoning," Woods Hole Oceanographic Institution, 31 July 2012. [Online]. Available: http://www.whoi.edu/redtide/page.do?pid=9679&tid=523&cid=27690. [Accessed October 2015].

[295] G. P. Rossini and P. Hess, "Phycotoxins: Chemistry, Mechanisms of Action and Shellfish Poisoning," *Molecular, Clinical and Environmental Toxicology,* vol. 2, pp. 65-122, 2010.

[296] A. Ahearn, "Diarrhetic Shellfish Toxin Closes Beaches in South Puget Sound for First Time," OPB.org, 24 July 2013. [Online]. Available: www.opb.org/news/article/diarrhetic-shellfish-toxin-closes-beaches-in-south/. [Accessed October 2015].

[297] Washington State Department of Health, "Hood Canal Shellfish Harvest Closed: Tests Detect Diarrhetic Shellfish Poison," Washington State Department of Health News Release, 2012.

[298] Northwest Fisheries Science Center, "Diarrhetic Shellfish Poison (DSP)," Harmful Algae and their Toxins, [Online]. Available: http://www.nwfsc.noaa.gov/research/divisions/efs/microbes/harmful_algae/dsp.cfm. [Accessed October 2015].

[299] J. K. Lloyd, J. S. Duchin, J. Borchert, H. Flores Quintana and A. Robertson, "Diarrhetic Shellfish Poisoning, Washington, USA, 2011," *Emerging Infectious Diseases,* vol. 19, no. 8, pp. 1314-1316, 2013.

[300] B. Jeffery, T. Barlow, K. Moizer, S. Paul and C. Boyle, "Amnesic Shellfish Poison," *Food and Chemical Toxicology,* vol. 42, no. 4, pp. 545-557, 2004.

[301] Washington State Department of Health, "Amnesic Shellfish Poisoning (ASP) from Domoic Acid," Biotoxins and Illness Prevention, [Online]. Available: http://www.doh.wa.gov/CommunityandEnvironment/Shellfish/BiotoxinsIllnessPrevention/Biotoxins/AmnesicShellfishPoisoning. [Accessed October 2014].

[302] K. A. Lefebvre and A. Robertson, "Domoic Acid and Human Exposure Risks: A Review," *Toxicon,* vol. 56, no. 2, pp. 218-230, 2010.

[303] S. L. Hinder, G. C. Hays, M. Edwards, E. C. Roberts, A. W. Walne and M. B. Gravenor, "Changes in Marine Dinoflagellate and Diatom Abundance under Climate Change [abstract]," *Nature Climate Change,* vol. 2, pp. 271-275, 2012.

[304] V. L. Trainer, W. P. Cochlan, A. Erickson, B. D. Bill, F. H. Cox, J. A. Borchert and K. A. Lefebvre, "Recent Domoic Acid Closures of Shellfish Harvest Areas in Washington State Inland Waterways," *Harmful Algae,* vol. 6, no. 3, pp. 449-459, 2007.

[305] V. Kuehl, "Biotoxins at Large, Shellfish Harvest Closures in Hood Canal Continue," *Port Townsend and Jefferson County Leader,* 1 July 2015.

[306] H. Farrell, F. Seebacher, W. O'Connor, A. Zammit, D. T. Harwood and S. Murray, "Warm Temperature Acclimation Impacts Metabolism of Paralytic Shellfish Toxins from *Alexandrium minutum* in Commercial Oysters," *Global Change Biology,* vol. 21, no. 9, pp. 3402-3413, 2015.

[307] Northwest Fisheries Science Center, "The Environmental Sample Processor," National Oceanic and Atmospheric Administration (NOAA), 2016. [Online]. Available: https://www.nwfsc.noaa.gov/research/datatech/tech/esp.cfm. [Accessed 8 September 201].

[308] National Oceanic and Atmospheric Administration (NOAA), "Keeping an Eye on Algal Blooms and Hypoxia," Monitoring and Understanding Our Changing Planet, [Online]. Available: http://www.noaa.gov/features/earthobs_0508/algal.html. [Accessed October 2015].

[309] J. L. Bernatis, S. Gerstenberger and I. J. McGaw, "Behavioral Responses of Dungeness Crab, *Cancer magister*, During Feeding and Hypoxia," University of Nevada-Las Vegas, Environmental Occupational Health Faculty Articles (abstract), 2007.

[310] Division of Foodborne, Waterborne, and Environmental Diseases, "Vibrio Illness (Vibriosis)," National Center for Emerging and Zoonotic Infectious Diseases, Centers for Disease Control and Prevention, 21 October 2013. [Online]. Available: http://www.cdc.gov/vibrio/. [Accessed October 2015].

[311] Washington Department of Fish and Wildlife, "Recreational Shellfishing," Fishing and Shellfishing, 2015. [Online]. Available: http://wdfw.wa.gov/fishing/shellfish/shellfish_seaweed_rules.html.

[312] Washington State Legislature, *Washington State Vibrio parahaemolyticus Control Plan,* Title 246, Chapter 246-282, WAC 246-282-006.

[313] A. Newton, M. Kendall, D. Vugia, O. Henao and B. Mahon, "Increasing Rates of Vibriosis in the United States, 1996-2010: Review of Surveillance Data from 2 Systems," *Clinical Infectious Diseases,* vol. 54, no. 5, pp. S391-S395, 2012.

[314] Y. Won Kim, S. Ho Lee, I. G. Hwang and K. S. Yoon, "Effect of Temperature on Growth of *Vibrio paraphemolyticus* and *Vibrio vulnificus* in Flounder, Salmon Sashimi and Oyster Meat," *International Journal of Environmental Research and Public Health,* vol. 9, no. 12, pp. 4662-4675, 2012.

[315] National Oceanic and Atmospheric Administration (NOAA), "Water Temperature Table of the Northern Pacific Coast," National Centers for Environmental Information, 30 November 2015. [Online]. Available: https://www.nodc.noaa.gov/dsdt/cwtg/npac.html.

[316] M. J. Chae, D. Cheney and Y. C. Su, "Temperature Effects on the Depuration of *Vibrio parahaemolyticus* and *Vibrio vulnificus* from the American oyster (Crassostrea virginica)," *Journal of Food Science,* vol. 74, no. 2, pp. M62-M66, 2009.

[317] J. Jacobs, S. K. Moore, K. E. Kunkel and L. Sun, "A Framework for Examining Climate-Driven Changes to the Seasonality and Geographical Range of Coastal Pathogens and Harmful Algae," *Climate Risk Management,* vol. 8, pp. 16-27, 2015.

[318] R. Griffis and J. Howard, "Oceans and Marine Resources in a Changing Climate: A Technical Input to the 2013 National Climate Assessment," Island Press, Washington, DC, 2013.

[319] V. L. Trainer, B. T. L. Eberhart, J. C. Wekell, N. G. Adams, L. Hanson, F. Cox and J. Dowell, "Paralytic Shellfish Toxins in Puget Sound, Washington State," *Journal of Shellfish Research,* vol. 22, no. 1, pp. 213-223, 2003.

[320] T. Vedder, "Oyster Farmers Ask to Use Pesticide Against Invasive Shrimp," KOMO News, 26 August 2015. [Online]. Available: http://komonews.com/news/local/oyster-farmers-ask-to-use-pesticide-against-invasive-shrimp-11-21-2015. [Accessed 24 August 2016].

[321] B. Dumbauld, K. Feldman and D. Armstrong, "A Comparison of the Ecology and Effects of Two Species of Thalassinidean Shrimps on Oyster Aquaculture Operations in the Eastern North Pacific," U.S. Department of Agriculture, Agricultural Research Service, 2006.

[322] B. R. Dumbauld, D. A. Armstrong and K. L. Feldman, "Life-history Characteristics of Two Sympatric Thalassinidean Shrimps, *Neotrpaea californiensis* and *Upogebia pugettensis*, with Implications for Oyster Culture," *Journal of Crustacean Biology,* vol. 16, no. 4, pp. 689-708, 1996.

[323] Washington Department of Fish and Wildlife, "Climate Change Effects on Marine and Coastal Habitats in Washington State," Publications, July 2011. [Online]. Available: http://wdfw.wa.gov/publications/01239/.

[324] A. Hollowed, B. Planque and H. Loeng, "Potential Movement of Fish and Shellfish Stocks from the Sub-Arctic to the Arctic Ocean," *Fisheries Oceanography,* vol. 22, no. 5, pp. 355-370, 2013.

[325] R. D. Brodeur, C. E. Mills, J. E. Overland, G. E. Walters and J. D. Schumacher, "Evidence for a Substantial Increase in Gelatinous Zooplankton in the Bering Sea, with Possible Links to Climate Change," *Fisheries Oceanography,* vol. 8, no. 4, pp. 296-306, 1999.

[326] W. Cornwall, "The Blob that's Invading the Sound," The Seattle Times, 20 February 2007. [Online]. Available: http://www.seattletimes.com/seattle-news/the-blob-thats-invading-the-sound/.

[327] The Western Regional Panel on Aquatic Nuisance Species, "Invasive Tunicates," The Western Regional Panel on Aquatic Nuisance Species , Seattle, Washington, 2014.

[328] J. R. Cordell, C. Levy and J. D. Toft, "Ecological Implications of Invasive Tunicates Associated with Artificial Structures in Puget Sound, Washington, USA," *Biological Invasions,* vol. 15, no. 6, pp. 1303-1318, 2013.

[329] G. Lambert, Artist, *Didemnum vexillum from the State of Washington.* [Art]. 2014.

[330] Washington State Recreation and Conservation Office, "New Zealand Mud Snail," Washington Invasive Species Council, 2009. [Online]. Available: http://www.invasivespecies.wa.gov/priorities/NewZealandMudSnail.shtml.

[331] J. Kendig, "NRCS Partners with Tribes on Invasive Japanese Oyster Drill Control," Natural Resources Conservation Service, Olympia, WA, 2013.

[332] P. Meacham, "*Nuttalia obscurata* (Purple Varnish Clam, Varnish Clam, or Dark Mahogany Clam)," Washington Department of Fish and Wildlife, 2016. [Online]. Available: http://wdfw.wa.gov/ais/species.php?Name=nuttalia_obscurata. [Accessed November 2016].

[333] Washington Department of Fish and Wildlife, "Aquatic Invasive Species: Potamopyrgus antipodarum (New Zealand Mudsnail)," Conservation, 2015. [Online]. Available: http://wdfw.wa.gov/ais/potamopyrgus_antipodarum/.

[334] M. Wagner, "Invasive Green Crab Found on San Juan Island by Citizen Science Volunteers," University of Washington, September 2016. [Online]. Available: http://www.washington.edu/news/2016/09/02/invasive-green-crab-found-on-san-juan-island-by-citizen-science-volunteers/. [Accessed November 2016].

[335] Washington Department of Fish and Wildlife, "Aquatic Invasive Species: *Carcinus maenas* (European Green crab)," Conservation, 2015. [Online]. Available: http://wdfw.wa.gov/ais/carcinus_maenas/.

[336] M. E. Mach and K. M. A. Chan, "Trading Green Backs for Green Crabs: Evaluating the Commercial Shellfish Harvest at Risk from European Green Crab Invasion," *F1000Research,* vol. 2, no. 66, 2013.

[337] L. Duckwall, "Japanese Oyster Drill *Ocinebrellus inornatus*," Olden Research Group, University of Washington, 2009.

[338] E. R. Buhle and J. L. Ruesink, "Impacts of Invasive Oyster Drills on Olympia Oyster (*Ostrea lruida* Carpenter 1864) Recovery in Willapa Bay, Washington, United States," *Journal of Shellfish Research,* vol. 28, no. 1, pp. 87-96, 2009.

[339] R. A. Feely, T. Klinger, J. A. Newton and M. Chasdey, "Scientific Summary of Ocean Acidification in Washington State Marine Waters," Washington Shellfish Initiative Blue Ribbon Panel on Ocean Acidification, 2012.

[340] J. B. Ries, A. L. Cohen and D. C. McCorkle, "Marine Calcifiers Exhibit Mixed Responses to CO2-induced Ocean Acidification," *Geology,* vol. 37, no. 12, pp. 1131-1134, 2009.

[341] H. Trim, "Spotlight on Puget Sound: Climate Change, Ocean Acidification and How We Manage Growth," FutureWise, 16 April 2013. [Online]. Available: http://be.futurewise.org/p/salsa/web/blog/public/?blog_entry_KEY=6881.

[342] L. B. Azevedo, A. M. De Schryver, A. J. Hendriks and M. A. Huijbregts, "Calcifying Species Sensitivity Distributions for Ocean Acidification," *Environmetnal Science and Technology,* vol. 49, no. 3, pp. 1495-1500, 2015.

[343] J. C. Orr, V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. M. Key, K. Lindsay, E. Maier-Reimer, R. Matear and P. Monfray, "Anthropogenic Ocean Acidification over the Twenty-First Century and its Impact on Calcifying Organisms," *Nature,* vol. 437, pp. 681-686, 2005.

[344] A. Barton, B. Hales, G. Waldbusser, C. Langdon and R. Feely, "The Pacific Oyster, *Crassostrea gigas*, Shows Negative Correlation to Naturally Elevated Carbon Dioxide Levels: Implications for Near-Term Ocean Acidification Effects," *Association for the Sciences of Limnology and Oceanography,* vol. 57, no. 3, pp. 698-710, 2012.

[345] G. G. Waldbusser, E. L. Brunner, B. A. Haley, B. Hales, C. J. Langdon and F. G. Prahl, "A Developmental and Energetic Basis Linking Larval Oyster Shell Formation to Acidification Sensitivity," *Geophysical Research Letters,* vol. 40, no. 10, pp. 2171-2176, 2013.

[346] A. Hettinger, E. Sanford, T. Hill, E. Lenz, A. Russell and B. Gaylord, "Larval Carry-Over Effects from Ocean Acidification Persist in the Natural Environment," *Global Change Biology,* vol. 19, no. 11, pp. 3317-3326, 2013.

[347] M. Floyd, "Study Finds Native Olympia Oysters More Resilient to Ocean Acidification," Oregon State University, News and Research Communications, 10 June 2016. [Online]. Available: http://oregonstate.edu/ua/ncs/archives/2016/jun/study-finds-native-olympia-oysters-more-resilient-ocean-acidification. [Accessed 24 August 2016].

[348] M. J. O'Donnell, M. N. George and E. Carrington, "Mussel Byssus Attachment Weakened by Ocean Acidification," *Nature Climate Change,* vol. 3, pp. 587-590, 2013.

[349] M. H. Pespeni, E. Sanford, B. Gaylord, T. M. Hill, J. D. Hosfelt, H. K. Jaris, M. LaVigne, E. A. Lenz, A. D. Russell, M. K. Young and S. R. Palumbi, "Evolutionary Change During Experimental Ocean Acidification," *Proceedings of the National Acadamy of Sciences of the United States of America,* vol. 110, no. 17, pp. 6937-6942, 2013.

[350] L. M. Parker, P. M. Ross, W. A. O'Connor, L. Borysko, D. A. Raftos and H. O. Portner, "Adult Exposure Influences Offspring Response to Ocean Acidification in Oysters," *Global Change Biology,* vol. 18, no. 1, pp. 82-92, 2012.

[351] H. Kurihara, "Effects of CO2-Driven Ocean Acidification on the Early Developmental Stages of Invertebrates," *Marine Ecology Progress Series,* vol. 373, pp. 275-284, 2008.

[352] J. A. Solomon, M. J. Donnelly and L. J. Walters, "Effects of Sea Level Rise on the Intertidal Oyster *Crassostrea virginica* by Field Experiments," *Journal of Coastal Research,* vol. 68, no. 1, pp. 57-64, 2014.

[353] D. Cheney and B. Dewey, *Shellfish and Climate Change: Ecological and Economic Effects,* A presentation for the Washington State Climate Conference, Olympia, WA, Washington.

[354] A. B. Rodriguez, F. J. Fodrie, J. T. Ridge, N. L. Lindquist, E. J. Theuerkauf, S. E. Coleman, J. H. Grabowski, M. C. Brodeur, R. K. Gittman, D. A. Keller and M. D. Kenworthy, "Oyster Reefs Can Outpace Sea-Level Rise," *Nature Climate Change,* vol. 4, pp. 493-497, 2014.

[355] C. D. Peterson, "Impacts of Predicted Global Sea-Level Rise on Oregon Beaches and Tidelands," Portland State University, Geology Faculty Publications and Presentations, Portland, Oregon, 2013.

[356] R. A. Park, J. K. Lee and D. L. Canning, "Potential Effects of Sea-Level Rise on Puget Sound Wetlands," *Geocarto International,* vol. 8, no. 4, pp. 99-110, 1993.

[357] K. L. Fresh, M. N. Dethier, C. A. Simenstad, M. Logson, H. Shimpan, C. D. Tanner, T. M. Leschine, T. M. Mumford, G. Gelfenbaum, R. Shuman and J. A. Newton, "Implications of Observed Anthropogenic Changes to the Nearshore Ecosystems in Puget Sound," Puget Sound Nearshore Ecosystem Restoration Project, 2011-2013.

[358] The Oregon Conservation Strategy , "Climate Change and Oregon's Intertidal Habitats," Oregon Department of Fish and Wildlife, Salem, Oregon.

[359] B. Ferris, J. Reum, P. S. McDonald, D. M. Farrell and C. J. Harvey, "Evaluating Trophic and Non-Trophic Effects of Shellfish Aquaculture in a Coastal Estuarine Foodweb," *ICES Journal of Marine Science,* vol. 72, no. 9, 2015.

[360] M. S. Wetz, E. A. Hutchinson, R. S. Lunetta, H. W. Paerl and J. C. Taylor, "Severe Droughts Reduce Estuarine Primary Productivity with Cascading Effects on Higher Trophic Levels," *Limnology and Oceanography,* vol. 56, no. 2, pp. 627-638, 2011.

[361] C. S. Hopkinson, A. E. Lugo, M. Alber, A. Covich and S. Van Bloem, "Forecasting Effects of Sea-Level Rise and Windstorms on Coastal and Inland Ecosystems," *Frontiers in Ecology and the Environment,* vol. 6, no. 5, pp. 255-263, 2008.

[362] L. R. Oliver, R. Seed and B. Reynolds, "The Effect of High Flow Events on Mussels (*Mytilus edulis*) in the Conwy Estuary, North Wales, UK," *Hydrobiologia,* vol. 202, pp. 117-127, 2008.

[363] J. M. Slott, A. B. Murray, A. D. Ashton and T. J. Crowley, "Coastline Responses to Changing Storm Patterns," *Geophysical Research Letters: Hydrology and Land Surface Studies,* vol. 33, no. 18, 2006.

[364] J. C. Allan and P. D. Komar, "Climate Controls on US West Coast Erosion Processes," *Journal of Coastal Research,* vol. 22, no. 3, pp. 511-529, 2006.

[365] J. S. Wong, J. E. Freer, P. D. Bates, D. A. Sear and E. M. Stephens, "Sensitivity of a Hydraulic Model to Channel Erosion Uncertainty During Extreme Flooding," *Hydrological Processes,* vol. 29, no. 2, pp. 261-279, 2014.

[366] P. L. Barnard and J. A. Warrick, "Dramatic Beach and Nearshore Morphological Changes Due to Extreme Flooding at a Wave-Dominated River Mouth," *Marine Geology,* vol. 271, no. 1-2, pp. 131-148, 2010.

[367] M. J. Atrill and M. Power, "Effects on Invertebrate Populations of Drought-Induced Changes in Estuarine Water Quality," *Marine Ecology Progress Series,* vol. 203, pp. 133-143, 2000.

[368] L. E. Petes, A. J. Brown and C. R. Knight, "Impacts of Upstream Drought and Water Withdrawals on the Health and Survival of Downstream Estuarine Oyster Populations," *Ecology and Evolution,* vol. 2, no. 7, pp. 1712-1724, 2012.

[369] M. S. Wetz and D. W. Yoskowitz, "An 'Extreme' Future for Estuaries? Effects of Extreme Climatic Events on Estuarine Water Quality and Ecology," *Marine Pollution Bulletin,* vol. 69, no. 1-2, pp. 7-18, 2013.

[370] D. K. Moss, L. C. Ivany, E. J. Judd, P. W. Cummings, C. E. Bearden, W. Kim, E. G. Artruc and J. R. Driscoll, "Lifespan, Growth Rate, and Body Size Across Latitude in Marine Bivalvia, with Implications for Phanerozoic Evolution," *Proceedings of the Royal Society B, Biological Sciences,* vol. 283, no. 1836, 2016.

[371] National Ocean Service, "Why Do Harmful Algal Blooms Occur?," National Oceanic and Atmospheric Administration, 10 October 2014. [Online]. Available: http://oceanservice.noaa.gov/facts/why_habs.html. [Accessed 9 February 2016].

[372] K. Knowlton, "Tides of Trouble: Increased Threats to Human Health and Ecosystems from Harmful Algal Blooms," Natural Resources Defense Council, 2010.

[373] S. K. Moore, J. A. Johnstone, N. S. Banas and E. P. Salathe Jr., "Present-Day and Future Climate Pathways Affecting Alexandrium Blooms in Puget Sound, WA, USA," *Harmful Algae,* vol. 48, pp. 1-11, 2015.

[374] K. L. Bushaw-Newton and K. G. Sellner, "Harmful Algal Blooms," in *NOAA's State of the Coast Report*, Silver Spring, MD, National Oceanic and Atmospheric Administration, 1999.

[375] Puget Sound Ecosystem Monitoring Program, "Puget Sound Marine Waters," NOAA Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workgroup, 2012.

[376] B. D. Bill, S. K. Moore, L. R. Hay, D. M. Anderson and V. L. Trainer, "Effects of Temperature and Salinity on the Growth of Alexandrium (*Dinophyceae*) Isolates from the Salish Sea," *Journal of Phycology,* 2016 (accepted manuscript).

[377] L. Basti, H. Uchida, R. Matsushima, R. Watanabe, T. Suzuki, T. Yamatogi and S. Nagai, "Influence of Temperature on Growth and Production of Pectenotoxin-2 by a Monoclonal Culture of *Dinophysis caudata*," *Marine Drugs,* vol. 13, pp. 7124-7137, 2015.

[378] L. Peperzak, G. J. Snoeijer, R. Dijkema, W. W. Gieskes, J. Joordens, J. C. Peeters, C. Schol, E. G. Vrieling and W. Zevenboom, "Development of a *Dinophysis acuminata* Bloom in the River Rhine Plume (North Sea)," in *Harmful and Toxic Algal Blooms*, Intergovernmental Oceanographic Commission of UNESCO, 1996, pp. 273-276.

[379] A. E. Thessen, Q. Dortch, M. L. Parsons and W. Morrison, "Effect of Salinity on Pseudo-nitzschia Species (*Bacillariophyceae*) Growth and Distribution," *Journal of Phycology,* vol. 41, no. 1 (abstract), 2005.

[380] R. Martinez, E. Orive, A. Laza-Martinez and S. Seioan, "Growth Response of Six Strains of *Heterosigma akashiwo* to Varying Temperature, Salinity and Irradiance Conditions," *Journal of Plankton Research,* vol. 32, no. 4, pp. 529-538, 2010.

[381] Natural Resources Canada, "Western Hemlock Looper," Natural Resources Canada, 2016. [Online]. Available: https://tidcf.nrcan.gc.ca/en/insects/factsheet/1000002. [Accessed 11 January 2016].

[382] National Centers for Coastal Ocean Science, "Harmful Algal Cyst Mapping in Washington Shows 10-fold Increase since 2013," National Oceanic and Atmospheric Administration, May 2015. [Online]. Available: https://coastalscience.noaa.gov/news/habs/harmful-algal-cyst-mapping-washington-shows-10-fold-increase-2013/. [Accessed June 2016].

[383] National Oceanic and Atmospheric Administration (NOAA) ECOHAB program - Puget Sound Alexandrium Harmful Algal Blooms (PS-AHAB), "PS-AHAB: Puget Sound Alexandrium Harmful Algal Blooms," [Online]. Available: https://catalyst.uw.edu/workspace/banasn/14943/135346. [Accessed 8 November 2016].

[384] National Oceanic and Atmospheric Administration (NOAA), "Modeling Favorable Habitat Areas for *Alexandrium catenella* in Puget Sound and Evaluating the Effects of Climate Change," [Online]. Available: https://coastalscience.noaa.gov/projects/detail?key=148. [Accessed 8 November 2016].

[385] M. Winder and U. Sommer, "Phytoplankton Response to a Changing Climate," *Hydrobiologia,* vol. 698, no. 1, pp. 5-16, 2012.

[386] T. J. Smayda, "Harmful Algal Blooms: Their Ecophysiology and General Relevance to Phytoplankton Blooms in the Sea," *Limnology and Oceanography,* vol. 42, no. 5, pp. 1137-1153, 1997.

[387] K. A. Lefebvre, L. Quakenbush, E. Frame, K. Burek Huntington, G. Sheffield, R. Stimmelmayr, A. Bryan, P. Kendrick, H. Ziel, T. Goldstein, J. A. Snyder, T. Gelatt, F. Gulland, B. Dickerson and V. Gill, "Prevalence of Algal Toxins in Alaskan Marine Mammals Foraging in a Changing Arctic and Subarctic Environment," *Harmful Algae,* vol. 55, no. 13, 2016.

[388] A. Schupak, "Toxic Algae Bloom in Pacific Ocean Could be Largest Ever," *CBS News,* 17 June 2015.

[389] M. Thorel, J. Fauchot, J. Morelle, V. Raimbault, B. Le Roy, C. Miossec, V. Kientz-Bouchart and P. Claquin, "Interactive Effects of Irradiance and Temperature on Growth and Domoic Acid Production of the Toxin Diatom *Pseudo-nitzschia australis* (Bacillariophyceae)," *Harmful Algae,* vol. 39, pp. 232-241, 2014.

[390] F.-X. Fu, Y. Zhang, M. E. Warner, Y. Feng, J. Sun and D. A. Hutchins, "A Comparison of Future Increased CO2 and Temperature Effects on Sympatric *Heterosigma akashiwo* and *Proocentrum minimum*," *Hamful Algae,* vol. 7, no. 1, pp. 76-90, 2008.

[391] T. Kamiyama, S. Nagai, T. Suzuki and K. Miyamura, "Effect of Temperature on Production of Okadaic Acid, dinophysistoxin-1, and pectenotoxin-2 by *Dinophysis acuminata* in Culture Experiments," *Aquatic Microbial Ecology,* vol. 60, pp. 193-202, 2010.

[392] U.S. Environmental Protection Agency, Office of Water, "Impacts of Climate Change on the Occurence of Harmful Algal Blooms," Environmental Protection Agency, 2013.

[393] Northwest Fisheries Science Center, "Harmful Algal Blooms," National Oceanic and Atmospheric Administration, [Online]. Available: http://www.nwfsc.noaa.gov/hab/habs_toxins/phytoplankton/algal_dynamics.cfm. [Accessed 12 February 2016].

[394] U.S. Environmental Protection Agency, "Sources and Solutions," U.S. Environmental Protection Agency, 27 January 2016. [Online]. Available: http://www.epa.gov/nutrientpollution/sources-and-solutions. [Accessed 12 February 2016].

[395] Resource Media and National Wildlife Federation, "Toxic Algae: Coming Soon to a Lake Near You?," Resource Media and National Wildlife Federation, 2013.

[396] J. M. H. Verspagen, D. B. Van de Waal, J. F. Finke, P. M. Visser, E. Van Donk and J. Huisman, "Rising CO2 Levels Will Intensify Phytoplankton Blooms in Eutrophic and Hypertrophic Lakes," *PLoS One,* vol. 9, no. 8, 2014.

[397] Z. Lu, N. Jiao and H. Zhang, "Physiological Changes in Marine *Picocyanobacterial Synechococcus* Strains Exposed to Elevated CO2 Partial Pressure," *Marine Biology Research,* vol. 2, no. 6, pp. 424-430, 2006.

[398] J. W. Murray, E. Roberts, E. Howard, M. O'Donnell, C. Bantam, E. Carrington, M. Foy, B. Paul and A. Fay, "An Inland Sea High Nitrate-Low Chlorophyll (HNLC) Region with Naturally High pCO2," *Association for the Sciences of Limnology and Oceanography,* vol. 60, no. 3, pp. 957-966, 2015.

[399] B. Rost, I. Zondervan and D. Wolf-Gladrow, "Sensitivity of Phytoplankton to Future Changes in Ocean Carbonate Chemistry: Current Knowledge, Contradictions and Research Directions," *Marine Ecology Progress Series,* vol. 373, pp. 227-237, 2008.

[400] U.S. Environmental Protection Agency, "Cyanobacteria/Cyanotoxins," Nutrient Policy and Data, 1 September 2015. [Online]. Available: http://www2.epa.gov/nutrient-policy-data/cyanobacteriacyanotoxins.

[401] L. Wormer, S. Cires, R. Agha, M. Verdugo, C. de Hoyos and A. Quasada, "First Detection of Cyanobacterial PSP (Paralytic Shellfish Poisoning) Toxins in Spanish Freshwaters," *Toxicon,* vol. 57, no. 6, pp. 918-921, 2011.

[402] D. Castro, D. Vera, N. Lagos, C. Garcia and M. Vasquez, "The Effect of Temperature on Growth and Production of Paralytic Shellfish Poisoning Toxins by the Cyanobacterium *Cylindrospermopsis raciborskii* C10," *Toxicon,* vol. 44, no. 5, pp. 483-489, 2004.

[403] E. P. Preece, B. C. Moore, F. J. Hardy and L. A. Deobald, "First Detection of Microcystin in Puget Sound, Washington, Mussels (Mytilus trossulus)," *Lake and Reservoir Management,* vol. 31, no. 1, pp. 50-54, 2015.

[404] G. M. Hallegraeff, "Ocean Climate Change, Phytoplankton Community Responses, and Harmful Algal Blooms: A Formidable Predictive Challenge," *Journal of Phycology ,* vol. 46, no. 2, pp. 220-235, 2010.

[405] A. O. Tatters, F.-X. Fu and D. A. Hutchins, "High CO2 and Silicate Limitation Synergistically Increase the Toxicity of Pseudo-nitzchia fraudulenta," *PLoS ONE,* vol. 7, no. 2, 2012.

[406] M. F. Chislock, E. Doster, R. A. Zitomer and A. E. Wilson, "Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems," *Nature Education Knowledge,* vol. 4, no. 4, 2013.

[407] National Centers for Coastal and Ocean Science, "Harmful Algal Bloom and Hypoxia Research and Control Act," NOAA, 20 June 2015. [Online]. Available: http://coastalscience.noaa.gov/research/habs/habhrca. [Accessed October 2015].

[408] P. Cheng, A. Valle-Levinson, C. D. Winant, A. Ponte, G. G. de Velasco and K. B. Winters, "Upwelling-enhanced Seasonal Stratification in a Semiarid Bay," *Continental Shelf Research,* vol. 30, p. abstract, 2010.

[409] D. Hannafious, "Hood Canal Dissolved Oxygen," Hood Canal Dissolved Oxygen Program, [Online]. Available: http://www.hoodcanal.washington.edu/aboutHC/brochure.html. [Accessed 18 February 2016].

[410] A. R. Solow, "Red Tides and Dead Zones: The Coastal Ocean is Suffering from Overload of Nutrients," *Oceanus Magazine,* vol. 43, no. 1, 2004.

[411] Northwest Fisheries Science Center, "Harmful Algal Blooms: Research Partnerships," National Oceanic and Atmospheric Administration, [Online]. Available: http://www.nwfsc.noaa.gov/hab/research/research_partnerships/. [Accessed 12 February 2016].

[412] V. L. Trainer, L. Moore, B. D. Bill, N. G. Adams, N. Harrington, J. Borchert, D. A. M. da Silva and B. T. L. Eberhart, "Diarrhetic Shellfish Toxins and Other Lipophilic Toxins of Human Health Concern in Washington State," *Marine Drugs,* vol. 11, no. 6, pp. 1815-1835, 2013.

[413] H. Adelsman and J. Ekrem, "Preparing for a Changing Climate: Washington State's Integrated Climate Response Strategy," Washington State Department of Ecology, Olympia, 2012.

[414] Port Gamble S'Klallam Tribe, "Forestry/Woodcutting, Title 12, Natural Resources, Chapter 12.01 Timber Cutting," Port Gamble S'Klallam Tribe, 2015. [Online]. Available: https://www.pgst.nsn.us/tribal-programs/tribal-services/natural-resources/forestrywoodcutting. [Accessed 7 January 2016].

[415] G. S. Mauger, J. H. Casola, H. A. Morgan, R. L. Stauch, B. Jones, B. Curry, T. M. Busch Isaksen, L. Whitley Binder, M. B. Krosby and A. K. Snover, "Section 9: How Will Climate Change Affect Terrestrial Ecosystems?," in *State of Knowledge: Climate Change in Puget Sound*, Climate Impacts Group, University of Washington, 2015, pp. 9-1 - 9-13.

[416] J. F. Franklin, M. A. Hemstrom, R. Van Pelt, J. B. Buchanan and S. Hull, "The Case for Active Management of Dry Forest Types in Eastern Washington: Perpetuating and Creating Old Forest Structures and Functions," Washington State Department of Natural Resources, 2008.

[417] J. S. Littell, E. E. Oneil , D. McKenzie , J. A. Hicke , J. A. Lutz, R. A. Norheim and M. M. Elsner , "Forest Ecosystems, Disturbance, and Climatic Change in Washington State, USA," *Climatic Change,* vol. 102, pp. 129-158, 2010.

[418] C. Dunagan, "Washington's West Side Not Immune from Wildfire Risk," *Kitsap Sun,* 6 July 2015.

[419] J. S. Littell and R. Gwozdz, "Climatic Water Balance and Regional Fire Years in the Pacific Northwest, USA: Linking Regional Climate and Fire at Landscape Scales," in *The Landscape Ecology of Fire*, Dordrecht, The Netherlands, Ecological Studies, Springer, 2011, pp. 117-139.

[420] J. A. Henderson, D. H. Peter, R. D. Lesher and D. C. Shaw, Forested Plant Associations of the Olympic National Forest, U.S. Forest Service, U.S. Department of Agriculture, 1989.

[421] S. G. Pickford, G. R. Fahnestock and R. Ottmar, "Weather, Fuel, and Lightning Fires in Olympic National Park," *Northwest Science,* vol. 52, no. 2, pp. 92-105, 1980.

[422] H. Bernton, "Burning Rain Forest Raises Concern about Future," *The Seattle Times,* 5 July 2015.

[423] S. M. Stein, S. J. Comas, J. P. Menakis, M. A. Carr, S. I. Stewart, H. Cleveland, L. Bramwell and V. C. Radeloff, "Wildfire, Wildlands, and People: Understanding and Preparing for Wildfire in the Wildland-Urban Interface," U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2013.

[424] R. F. Noss, "Beyond Kyoto: Forest Management in a Time of Rapid Climate Change," *Conservation Biology,* vol. 15, no. 3, pp. 578-590, 2001.

[425] D. L. Peterson, J. E. Halofsky and M. C. Johnson, "Managing and Adapting to Changing Fire Regimes in a Warmer Climate," in *The Landscape Ecology of Fire*, Doerdrecht, The Netherlands, Ecological Studes, Springer, 2011.

[426] A. L. Carroll, J. Regniere, J. A. Logan, S. W. Taylor, B. J. Bentz and J. A. Powell, "Impacts of Climate Change on Range Expansion by the Mountain Pine Beetle," Canadian Forest Service, 2006.

[427] E. P. Creeden, J. A. Hicke and P. C. Buotte, "Climate, Weather, and Recent Mountain Pine Beetle Outbreaks in the Western United States," *Forest Ecology and Management,* vol. 312, pp. 239-251, 2914.

[428] B. J. Bentz, J. Reginere, C. J. Fettig, E. M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negron and S. J. Seybold, "Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects," *BioScience,* vol. 60, no. 8, pp. 602-613, 2010.

[429] W. A. Kurz, C. C. Dymond, G. Stinson, G. J. Rampley, E. T. Neilson, A. L. Carroll, T. Ebata and L. Safranyik, "Mountain Pine Beetle and Forest Carbon Feedback to Climate Change," *Nature,* vol. 452, pp. 987-990, 2008.

[430] R. J. Sangosti, Artist, *Beetle-kill Rate in Colorado 'Catastrophic'.* [Art]. The Denver Post, 2008.

[431] C. Hayes, "Montana Forest Insect and Disease Conditions and Program Highlights - 2014," U.S. Department of Agriculture, Forest Service and Montana Department of Natural Resources and Conservation, 2015.

[432] Community Advisory Group on the Mountain Pine Beetle, "Mountain Pine Beetle Action Plan 2006-2011: Sustainable Forests, Sustainable Communities," B.C. Ministry of Forests, Lands, and Natural Resource Operations, 2006.

[433] C. Li, H. J. Barclay, B. C. Hawkes and S. W. Taylor, "Lodgepole Pine Forest Age Class Dynamics and Susceptibility to Mountain Pine Beetle Attack," *Ecological Complexity,* vol. 2, no. 3, pp. 232-239, 2005.

[434] A. J. Woods, D. Heppner, H. H. Kope, J. Burleigh and L. Maclauchlan, "Forest Health and Climate Change: A British Columbia Perspective," *The Forestry Chronicle,* vol. 86, no. 4, pp. 412-422, 2010.

[435] B. J. Bentz, C. J. Fettig, E. M. Hansen, J. L. Hayes, J. Hicke, R. Kelsey, J. Lundquist, J. F. Negron, R. Progar, J. Regniere, S. J. Seybold and J. Vandygriff, "Climate Change and Western U.S. Bark

Beetles: Rapid Threat Assessment," U.S. Department of Agriculture, Forest Service, unknown year.

[436] S. P. McCloskey, L. D. Daniels and J. A. McLean, "Potential Impacts of Climate Change on Western Hemlock Looper Outbreaks," *Northwest Science,* vol. 83, no. 3, pp. 225-238, 2009.

[437] B. Bentz (ed.), "Bark Beetle Outbreaks in Western North America: Causes and Consequences," U.S. Department of Agriculture, Forest Service, Beetle Bark Symposium, Snowbird, Utah, 2005.

[438] G. D. Amman, M. D. McGregor and R. E. Dolph, Jr., "Mountain Pine Beetle: Forest Insect and Disease Leaflet 2," July 2002. [Online]. Available: http://www.barkbeetles.org/mountain/fidl2.htm. [Accessed March 2016].

[439] E. H. Holsten, R. W. Thier, A. S. Munson and K. E. Gibson, "Forest Insect and Disease Leaflet 127: The Spruce Beetle," U.S. Department of Agriculture, Forest Service, November 1999. [Online]. Available: http://www.barkbeetles.org/spruce/sbfidl127.htm. [Accessed March 2016].

[440] S. Kegley, "Douglas-fir Beetle Management," U.S. Department of Agriculture, Forest Health Protection and State Forestry Organizations, 2011.

[441] C. Bell Randall, "Management Guide for Western Hemlock Looper," U.S. Department of Agriculture, Forest Health Protection and State Forestry Organizations, 2010.

[442] D. G. Fellin and J. E. Dewey, "Forest Insect and Disease Leaflet 53: Western Spruce Budworm," U.S. Department of Agriculture, Forest Service, 1992. [Online]. Available: http://www.na.fs.fed.us/spfo/pubs/fidls/westbw/fidl-wbw.htm. [Accessed April 2016].

[443] J. T. Kliejuanas, B. W. Geils, J. Micales Glaeser, E. Michaels Goshee, P. Hennon, M.-S. Kim, H. Kope, J. Stone, R. Sturrock and S. J. Frankel, "Review of Literature on Climate Change and Forest Diseases of Western North America," U.S. Department of Agriculture, Forest Service, 2009.

[444] D. Omdal and A. Ramsey-Kroll, "Swiss Needle Cast on Washington State Lands, 1999-2009," Washington State Department of Natural Resources (DNR), 2010.

[445] Department of Natural Resource Sciences Extension, "White Pine Blister Rust (*Cronartium ribicola*)," Washington State University, 2015. [Online]. Available: http://ext.nrs.wsu.edu/forestryext/foresthealth/notes/whitepinerust.htm. [Accessed 6 January 2016].

[446] D. L. Six, *Interactions of Climate Change, Host Tree Defenses, White Pine Blister Rust, and the Mountain Pine Beetle in Whitebark Pine,* University of Montana, College of Forestry and Conservation (presentation), unknown year.

[447] Swiss Needle Cast Cooperative, "Swiss Needle Cast Summary," Oregon State University, College of Forestry, 2016. [Online]. Available: http://sncc.forestry.oregonstate.edu/swiss-needle-cast-summary. [Accessed March 2016].

[448] O. C. Maloy, "White Pine Blister Rust," Plant Health Progress, Plant Management Network, 2001.

[449] Plantwise Knowledge Bank, "Plantwise Technical Factsheet: Cedar Leaf Blight (*Didymascella thujina*)," Plantwise Knowledge Bank, [Online]. Available: http://www.plantwise.org/KnowledgeBank/Datasheet.aspx?dsid=18896. [Accessed March 2016].

[450] U.S. Forest Service, "Forest Disease Management Notes: Rhabdocline Needle Cast," U.S. Department of Agriculture, unknown year.

[451] A. K. Ettinger, K. R. Ford and J. HilleRisLambers, "Climate Determines Upper, but not Lower, Altitudinal Range Limits of Pacific Northwest Conifers," *Ecology,* vol. 92, no. 6, pp. 1323-1331, 2011.

[452] M. B. Davis and R. G. Shaw, "Range Shifts and Adaptive Responses to Quaternary Climate Change," *Science,* vol. 292, pp. 673-679, 2001.

[453] J. S. Littell, D. L. Peterson and M. Tjoelker, "Douglas-Fir Growth in Mountain Ecosystems: Water Limits Tree Growth from Stand to Region," *Ecological Monographs,* vol. 78, no. 3, pp. 349-368, 2008.

[454] A. N. Zolbrod and D. L. Peterson, "Response of High-Elevation Forests in the Olympic Mountains to Climatic Change," *Canadian Journal of Forest Research,* vol. 29, pp. 1966-1978, 1999.

[455] D. W. McKenney, J. H. Pedlar, K. Lawrence, K. Campbell and M. F. Hutchinson, "Potential Impacts of Climate Change on the Distribution of North American Trees," *BioScience,* vol. 57, no. 11, pp. 939-948, 2007.

[456] M. I. Williams and R. Kasten Dumroese, "Preparing for Climate Change: Forestry and Assisted Migration," *Forest Ecology,* vol. 111, no. 4, pp. 287-297, 2013.

[457] L. K. Gray and A. Hamann, "Tracking Suitable Habitat for Tree Populations under Climate Change in Western North America," *Climatic Change,* vol. 117, pp. 289-303, 2013.

[458] P. W. Mote, E. A. Parson, A. F. Hamlet, W. S. Keeton, D. Lettenmaier, N. Mantua, E. L. Miles, D. W. Peterson, D. L. Peterson, R. Slaughter and A. K. Snover, "Preparing for Climate Change: The Water, Salmon, and Forests of the Pacific Northwest," *Climatic Change,* vol. 61, no. 1, pp. 45-88, 2003.

[459] J. S. Littell and C. L. Raymond, "Chapter 3: Climate and Climate Change in the North Cascade Range," in *Climate Change Vulnerability and Adaptation in the North Cascades Region, Washington*, C. L. Raymond, D. L. Peterson and R. M. Rochefort, Eds., U.S. Department of Agriculture, Forest Service, 2014, pp. 25-44.

[460] J. S. Littell, "Chapter 3: Future Climate on the Olympic Peninsula: Forest-Relevant Climate Scenarios," in *Adapting to Climate Change at Olympic National Forest and Olympic National Park*, J. E. Halofsky, D. L. Peterson, K. A. O'Halloran and C. Hawkins Hoffman, Eds., U.S. Department of Agriculture, Forest Service, 2011, pp. 13-20.

[461] J. S. Littell, J. A. Hicke, S. L. Shafer, S. M. Capalbo, L. L. Houston and P. Glick, "Forest Ecosystems: Vegetation, Disturbance, Economics," in *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, M. M. Dalton, P. W. Mote and A. K. Snover, Eds., Washington, DC, Island Press, 2013, pp. 110-148.

[462] Committee on Hydrologic Impacts of Forest Management, National Research Council, "Forests, Water, and People," in *Hydrologic Effects of a Changing Forest Landscape*, Washington, DC, National Academies Press, 2008, pp. 13-22.

[463] N. E. Seavy, T. Gardali, G. H. Golet, F. T. Griggs, C. A. Howell, R. Kelsey, S. L. Small, J. H. Viers and J. F. Weigand, "Why Climate Change Makes Riparian Restoration More Important than Ever: Recommendations for Practice and Research," *Ecological Restoration,* vol. 27, no. 3, pp. 330-338, 2009.

[464] S. M. Thomas, S. W. Griffiths and S. J. Ormerod, "Adapting Streams for Climate Change Using Riparian Broadleaf Trees and its Consequences for Stream Salmonids," *Freshwater Biology,* vol. 60, no. 1, pp. 64-77, 2015.

[465] R. J. Naiman, R. E. Bilby and P. A. Bisson, "Riparian Ecology and Management in the Pacific Coastal Rain Forest," *BioScience,* vol. 50, no. 11, pp. 996-1011, 2000.

[466] M. J. Furniss, B. P. Staab, S. Hazelhurst, C. F. Clifton, K. B. Roby, B. L. Ilhardt, E. B. Larry, A. H. Todd, L. M. Reid, S. J. Hines, K. A. Bennett, C. H. Luce and P. J. Edwards, "Water, Climate Change,

and Forests: Watershed Stewardship for a Changing Climate," U.S. Department of Agriculture, Forest Service, 2010.

[467] Committee on Hydrologic Impacts of Forest Management, National Research Council, "Forest Disturbance and Management Effects on Hydrology," in *Hydrologic Effects of a Changing Forest Landscape*, Washington, DC, National Academies Press, 2008, pp. 45-74.

[468] B. J. Hicks, R. L. Beschta and R. D. Harr, "Long-Term Changes in Streamflow Following Logging in Western Oregon and Associated Fisheries Implications," *Water Resources Bulletin,* vol. 27, no. 2, pp. 217-226, 1991.

[469] World Animal Foundation, "Elk," World Animal Foundation, 2015. [Online]. Available: http://www.worldanimalfoundation.org/articles/article/8948301/181061.htm. [Accessed 30 December 2015].

[470] R. Link, "Living with Wildlife: Elk," Washington Department of Fish and Wildlife, 2005.

[471] H. S. J. Zald, T. A. Spies, M. Huso and D. Gatziolis, "Climatic, Landform, Microtopographic, and Overstory Canopy Controls of Tree Invasion in a Subalpine Meadow Landscape, Oregon Cascades, USA," *Landscape Ecology,* vol. 27, no. 8, pp. 1197-1212, 2012.

[472] R. Link, "Living with Wildlife: Deer," Washington Department of Fish and Wildlife, 2004.

[473] Natural Resources Conservation Service (NRCS), "Habitat Management for Black-Tailed Deer," U.S. Department of Agriculture, NRCS-Portland, 1971.

[474] J. Nelson, D. Cottam, E. W. Holman, D. J. Lancaster, S. McCorquodale and D. K. Person, "Habitat Guidelines for Black-tailed Deer: Coastal Rainforest Ecoregion," Mule Deer Working Group, Western Association of Fish and Wildlife Agencies, 2008.

[475] R. M. Burns and B. H. Honkala, "Agriculture Handbook 654: Silivics of North America, Volume 1: Conifers," U.S. Department of Agriculture, Forest Service, 1990.

[476] R. M. Burns and B. H. Honkala, "Agriculture Handbook 654: Silivics of North America, Volume 2: Hardwoods," U.S. Department of Agriculture, Forest Service, 1990.

[477] C. A. Harrington, "Factors Influencing Initial Sprouting of Red Alder," *Canadian Journal of Forest Research,* vol. 14, pp. 357-361, 1984.

[478] T. M. Seebacher, "Western Redcedar Dieback: Possible Links to Climate Change and Implications for Forest Management on Vancouver Island, B.C.," The University of British Columbia, Masters Thesis, 2007.

[479] N. C. Coops and R. H. Waring, "Estimating the Vulnerability of Fifteen Tree Species under Changing Climate in Northwest North America," *Ecological Modelling,* vol. 222, no. 13, pp. 2119-2129, 2011.

[480] D. A. McKenzie, "Growth of Western Redcedar (*Thuja plicata*) in Relation to Past Climate and Topographic Variability," in *96th ESA Annual Meeting (conference)*, Austin, TX, 2011.

[481] C. R. Nitschke and J. L. Innes, "A Tree and Climate Assessment Tool for Modeling Ecosystem Response to Climate Change," *Ecological Modeling,* vol. 210, pp. 263-277, 2007.

[482] Oregon State University, "Western Red Cedar - Leaf Blight (Keithia Blight)," Oregon State University, Pacific Northwest Plant Disease Management Handbook, 2016. [Online]. Available: http://pnwhandbooks.org/plantdisease/cedar-western-red-thuja-plicata-leaf-blight-keithia-blight. [Accessed 11 January 2016].

[483] L. K. Gray, J. H. Russell, A. D. Yanchuck and B. J. Hawkins, "Predicting the Risk of Cedar Leaf Blight (*Didymascella thujina*) in British Columbia under Future Climate Change," *Agricultural and Forest Meteorology,* vol. 180, no. 15, pp. 152-163, 2013.

[484] D. Minore, "Western Redcedar: A Literature Review," U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, 1983.

[485] Forestry Development, "Common Tree Diseases of British Columbia," forestrydev.org, 2011. [Online]. Available: http://forestrydev.org/diseases/CTD/Group/Needle/needle1_e.html. [Accessed 26 July 2016].

[486] Ministry of Forests, "Prescribed Fire- Forest Soils Symposium Proceedings," Province of British Columbia, Ministry of Forests Research Section, Prince Rupert Forest Region, 1982.

[487] K. W. Spalt and W. E. Reifsnyder, "Bark Characteristics and Fire Resistance: A Literature Survey," U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, 1962.

[488] U.S. Forest Service, "Index of Species Information: *Thuja plicata*," U.S. Department of Agriculture, Forest Service, 2015. [Online]. Available: http://www.fs.fed.us/database/feis/plants/tree/thupli/all.html. [Accessed 8 January 2016].

[489] R. A. Loehman, J. A. Clark and R. E. Keane, "Modeling Effects of Climate Change and Fire Management on Western White Pine (*Pinus monticola*) in the Northern Rocky Mountains, USA," *Forests,* vol. 2, no. 4, pp. 832-860, 2011.

[490] P. J. Gould, C. A. Hattington and J. B. St. Clair, "Growth Phenology of Coast Douglas-Fir Seed Sources Planted in Diverse Environments," *Tree Physiology,* vol. 32, pp. 1482-1496, 2012.

[491] C. A. Harrington, P. J. Gould and J. B. St. Clair, "Modeling the Effects of Winter Environment on Dormancy Release of Douglas-Fir," *Forest Ecology and Management,* vol. 259, no. 4, pp. 798-808, 2010.

[492] D. W. Peterson and D. L. Peterson, "Mountain Hemlock Growth Responds to Climatic Variability at Annual and Decadal Time Scales," *Ecology,* vol. 82, no. 12, pp. 3330-3345, 2001.

[493] C. B. Randall, "Management Guide for Western Hemlock Looper," U.S. Department of Agriculture, Forest Service, 2005.

[494] D. Dekker-Robertson, P. Griessman, D. Baumgartner and D. Hanley, "Douglas-Fir Beetle (*Dendroctonus pseudotsugae*)," Washington State University, 2015. [Online]. Available: http://ext.nrs.wsu.edu/forestryext/foresthealth/notes/doublasbeetle.htm. [Accessed 7 January 2016].

[495] D. D. Skilling and H. L. Morton, "How to Identify and Control Rhabdocline and Swiss Needlecasts of Douglas-Fir," U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, 1983.

[496] D. Shaw, "Swiss Needle Cast of Douglas-Fir in Oregon," Oregon State University, Oregon Department of Forestry, 2008.

[497] R. J. Uchytil, "Index of Species Information: *Pseudotsuga menziesii var. menziesii*," U.S. Department of Agriculture, Forest Service, Fire Effects Information System, 1991. [Online]. Available: http://www.fs.fed.us/database/feis/plants/tree/psemenm/all.html. [Accessed 8 January 2016].

[498] J. L. Tesky, "Index of Species Information: *Tsuga heterophylla*," U.S. Department of Agriculture, Forest Service, Fire Effects Information System, 1992. [Online]. Available: http://www.fs.fed.us/database/feis/plants/tree/tsuhet/all.html#FIRE ECOLOGY. [Accessed 8 January 2016].

[499] T. E. Dahl and S. M. Stedman, "Status and Trends of Wetlands in the Coastal Watersheds of the Conterminous United States 2004 to 2009," U.S. Department of the Interior, Fish and Wildlife Service, and National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 2013.

[500] H. Barrett, H. Daubenberger, P. McCollum and J. Wisniewski, "Port Gamble S'Klallam Tribe's Wetlands Conservation Program Plan 2015-2020," Port Gamble S'Klallam Tribe Natural Resources Department, 2014.

[501] S. Todd, N. Fitzpatrick, A. Carter-Mortimer and C. Weller, "Historical Changes to Estuaries, Spits, and Associated Tidal Wetland Habitats in the Hood Canal and Strait of Juan de Fuca Regions of Washington State," Point No Point Treaty Council, Kingston, 2006.

[502] B. D. Collins and A. J. Sheikh, "Historical Reconstruction, Classification and Change Analysis of Puget Sound Tidal Marshes," Washington Department of Natural Resources, Olympia, 2005.

[503] National Wildlife Federation and Washington Department of Fish and Wildlife, "Climate Change Effects on Freshwater Aquatic and Riparian Habitats in Washington State," National Wildlife Federation and Washington Department of Fish and Wildlife, 2011.

[504] G. S. Mauger, J. H. Casola, H. A. Morgan, R. L. Strauch, B. Jones, B. Curry, T. M. Busch Isaksen, L. Whitely Binder, M. B. Krosby and A. K. Snover, "Section 11: How Will Climate Change Affect Marine Ecosystems in Puget Sound?," in *State of Knowledge: Climate Change in Puget Sound*, Seattle, University of Washington, 2015.

[505] E. Kintisch, "Can Coastal Marshes Rise Above It All?," *Science,* vol. 341, pp. 480-481, 2013.

[506] S. Crooks, J. Rybczyk, K. O'Connell, D. L. Deiver, K. Poppe and S. Emmett-Mattox, "Coastal Blue Carbon Opportunity Assessment for the Snohomish Estuary: The Climate Benefits of Estuary Restoration," ESA, Western Washington University, EarthCorps, and Restore America's Estuaries, 2014.

[507] J. W. Day, R. R. Christian, D. M. Boesch, A. Yanez-Arancibia, J. Morris, R. R. Twilley, L. Naylor, L. Schaffner and C. Stevenson, "Consequences of Climate Change on the Ecogeomorphology of Coastal Wetlands," *Estuaries and Coasts,* vol. 31, pp. 477-491, 2008.

[508] S. E. R. Center, "Global Change Research Wetland," [Online]. Available: http://www.serc.si.edu/labs/biogeochem/research_wetland.aspx. [Accessed 21 January 2016].

[509] V. Burkett and J. Kusler, "Climate Change: Potential Impacts and Interactions in Wetlands of the United States," *Journal of the American Water Resources Association,* vol. 36, no. 2, pp. 313-320, 2000.

[510] J. Kusler, "Common Questions: Wetland, Climate Change, and Carbon Sequestering," Association of State Wetland Managers, Inc., and the International Institute for Wetland Science and Public Policy, 2006.

[511] Washington Department of Ecology, "Salmon Species and Estuary Use," [Online]. Available: http://www.ecy.wa.gov/programs/sea/pugetsound/species/salmon_est.html. [Accessed 21 January 2016].

[512] R. Hirschi, T. Doty, A. Keller and T. Labbe, "Juvenile Salmonid Use of Tidal Creek and Independent Marsh Environments in North Hood Canal: Summary of First Year Findings," Port Gamble S'Klallam Tribe, 2003.

[513] U.S. Fish and Wildlife Service, "The Importance of Estuarine Habitats to Anadromous Salmonids of the Pacific Northwest: A Literature Review," Western Washington Office, Aquatic Resources Division, Puget Sound Program, Lacey, 1998.

[514] H. Galbraith, R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington and G. Page, "Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds," *Waterbirds: The International Journal of Waterbird Biology,* vol. 25, no. 2, pp. 173-183, 2002.

[515] M. Ryan, *Modeling Climate Change Effects on the Hydrology of North Cascades Wetland Ecosystems,* National Park Service.

[516] *Kitsap Forest & Bay Project,* September 2015.

[517] U.S. Fish and Wildlife Service, *Migratory Bird Hunting: Proposed Migratory Bird Hunting Regulations on Certain Federal Indian Reservations and Ceded Lands for the 2015-2016 Season,* 2014.

[518] Birdlife International and National Audubon Society, "The Messengers: What Birds Tell Us about Threats from Climate Change and Solutions for Nature and People," Birdlife International and National Audubon Society, New York, 2015.

[519] M. Krosby, H. Morgan, M. Case and L. Whitely Binder, "Stillaguamish Tribe Natural Resources Climate Change Vulnerability Assessment," University of Washington, Seattle, 2015.

[520] A. Hitch and P. Leberg, "Breeding Distributions of North American Bird Species Moving North as a Result of Climate Change," *Conservation Biology,* vol. 21, no. 2, pp. 534-539, 2007.

[521] C. Wilsey, *Climate Change in America's National Parks: Bird Conservation in a Changing Climate,* National Audubon Society, 2016.

[522] P. Saha, "The Surprising Way Birds Are Trying To Dodge Climate Change," 25 January 2016. [Online]. Available: https://www.audubon.org/news/the-surprising-way-birds-are-trying-dodge-climate-change?utm_source=Sightline%20Institute&utm_medium=web-email&utm_campaign=Sightline%20News%20Selections&utm_source=NW+Climate+Change+Science+Digest&utm_campaign=0d87da6449-NWCS. [Accessed 11 February 2016].

[523] C. H. Sekercioglu, S. H. Schneider, J. P. Fay and S. R. Loarie, "Climate Change, Elevational Range Shifts, and Bird Extinctions," *Conservation Biology,* vol. 22, no. 1, pp. 140-150, 2008.

[524] B. L. Bateman, A. M. Pidgeon, V. C. Radeloff, J. Vanderwal, W. E. Thogmartin, S. J. Vavrus and P. J. Heglund, "The Pace of Past Climate Change vs. Potential Bird Distributions and Land Use in the United States," *Global Change Biology,* vol. 22, pp. 1130-1144, 2016.

[525] North American Bird Conservation Initiative, "The State of the Birds 2010 Report on Climate Change," U.S. Department of the Interior, Washington, DC, 2010.

[526] R. B. Siegel, R. L. Wilkerson, R. C. Kuntz II, J. F. Saracco and A. L. Holmgren, "Elevation Ranges of Birds at Mount Rainier National Park, North Cascades National Park Complex, and Olympic National Park, Washington," *Northwestern Naturalist,* vol. 93, pp. 23-39, 2012.

[527] C. Both, A. V. Artemyev, B. Blaauw, R. J. Cowie, A. J. Dekhuijzen, T. Eeva, A. Enemar, L. Gustafsson, E. V. Ivankina, A. Jarvinen, N. B. Metcalfe, N. E. I. Nyholm, J. Potti, P.-A. Ravussin, J. J. Sanz, B. Silverin, F. M. Slater, L. V. Sokolov, J. Torok, W. Winkel, J. Wright, H. Zang and M. E. Visser, "Large-Scale Geographical Variation Confirms that Climate Change Causes Birds to Lay Earlier," *Proceedings: Biological Sciences,* vol. 271, no. 1549, pp. 1657-1662, 2004.

[528] P. O. Dunn and A. P. Moller, "Changes in Breeding Phenology and Population Size," *Journal of Animal Ecology,* vol. 83, pp. 729-739, 2014.

[529] J. Gutierrez Illan, C. D. Thomas, J. A. Jones, W.-K. Wong, S. M. Shirley and M. G. Betts, "Precipitation and Winter Temperature Predict Long-term Range-scale Abundance Changes in Western North American Birds," *Global Change Biology,* vol. 20, pp. 3351-3364, 2014.

[530] H. Galbraith, R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington and G. Page, "Global Climate Change and Sea Level Rise: Potential Losses of Intertidal Habitat for Shorebirds," USDA Forest Service, 2005.

[531] Audubon, "The Climate Report," [Online]. Available: http://climate.audubon.org/all-species. [Accessed 8 February 2016].

[532] A. Lankford, "Climate Change Sensitivity Database: *Haliaeetus leucocephalus* - Inland PNW," 30 July 2014. [Online]. Available: http://climatechangesensitivity.org/species/haliaeetus-leucocephalus-0. [Accessed 11 February 2016].

[533] R. W. Butler and R. G. Vennesland, "Integrating Climate Change and Predation Risk with Wading Bird Conservation Research in North America," *Waterbirds: The International Journal of Waterbird Biology,* vol. 23, no. 3, pp. 535-540, 2000.

[534] N. Higa, "Appeared in Kitsap Audubon Society Newsletter," *Kitsap Audubon Society Newsletter,* 2010.

[535] J. Tomasevic, "Climate Change Sensitivity Database: *Melanitta americana*," 26 August 2010. [Online]. Available: http://climatechangesensitivity.org/species/melanitta-americana. [Accessed 11 February 2016].

[536] Washington Department of Ecology, "Scoter," [Online]. Available: http://www.ecy.wa.gov/programs/sea/pugetsound/species/scoter.html. [Accessed 11 February 2016].

[537] Klamath-Siskiyou Wildlands Center, "Northern Spotted Owl," [Online]. Available: http://kswild.org/what-we-do-2/biodiversity/species-profiles/nso. [Accessed 8 February 2016].

[538] NatureServe, "NatureServe Explorer: An Online Encyclopedia of Life, Version 7.1," NatureServe, Arlington, 2010.

[539] M. Case, "*Strix occidentalis caurina* - Entire Range," 6 October 2009. [Online]. Available: http://climatechangesensitivity.org/node/538. [Accessed 8 February 2016].

[540] Conservation Northwest, "Marbled Murrelet," [Online]. Available: http://www.conservationnw.org/what-we-do/wildlife-habitat/marbled-murrelet. [Accessed 8 February 2016].

[541] U.S. Fish and Wildlife Service, "Report on Marbeled Murrelet Recovery Implementation Team Meeting and Stakeholder Workshop," U.S. Department of the Interior, Lacey, 2012.

[542] University of Washington Climate Impacts Group, "Marbled Murrelet Trends in a Changing Landscape and Climate," [Online]. Available: https://cig.uw.edu/our-work/applied-research/3566-2/. [Accessed 8 February 2016].

[543] U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, "Northwest Forest Plan - The First 20 Years (1994-2013): Status and Trend of Marbled Murrelet Populations and Nesting Habitat," US Department of Agriculture, Portland, 2016.

[544] A. Lankford, "Climate Change Sensitivity Database: *Pandion haliaetus* - PNW," 1 August 2014. [Online]. Available: http://climatechangesensitivity.org/species/pandion-haliaetus. [Accessed 11 February 2016].

[545] C. Moulton, "Climate Change Sensitivity Database: *Aechmophorus occidentalis* - Rangewide," 16 December 2010. [Online]. Available: http://climatechangesensitivity.org/species/aechmophorus-occidentalis. [Accessed 11 February 2016].

[546] R. Call and J. Sullivan, "Birds are Indicators of our Environmental Health - Noo-Kayet/Our Village," *Kingston Community News,* 4 November 2011.

[547] Port Gamble S'Klallam Tribe, "Hunting," [Online]. Available: https://www.pgst.nsn.us/tribal-programs/tribal-services/natural-resources/hunting. [Accessed 18 June 2016].

[548] Nature Mapping Foundation, "Washington Wildlife Distribution Maps," Washington Nature Mapping Program, [Online]. Available: http://naturemappingfoundation.org/natmap/maps/wa/. [Accessed May 2016].

[549] Washington Department of Fish and Wildlife, "Living with Wildlife: Deer," Washington Department of Fish and Wildlife, 2016. [Online]. Available: http://wdfw.wa.gov/living/deer.html. [Accessed April 2016].

[550] National Wildlife Federation, "Nowhere to Run: Big Game Wildlife in a Warming World," National Wildlife Federation, 2013.

[551] D. J. Chmura, P. D. Anderson, G. T. Howe, C. A. Harrington, J. E. Halofsky, D. L. Peterson, D. C. Shaw and J. B. St. Clair, "Forest Responses to Climate Change in the Northwestern United States: Ecophysiological Foundations for Adaptive Management," *Forest Ecology and Management,* vol. 261, no. 7, pp. 1121-1142, 2011.

[552] J. C. Thalmann, R. T. Bowyer, K. A. Aho, F. W. Weckerly and D. R. McCullough, "Antler and Body Size in Black-tailed Deer: An Analysis of Cohort Effects," *Advances in Ecology,* vol. 2015, 2015.

[553] E. D. Freeman, R. T. Larsen, K. Clegg and B. R. McMillan, "Long-lasting Effects of Maternal Condition in Free-ranging Cervids," *PLOS One,* vol. 8, no. 3, 2013.

[554] K. L. Parker, P. S. Barboza and M. P. Gillingham, "Nutrition Integrates Environmental Responses of Ungulates," *Functional Ecology,* vol. 23, pp. 57-69, 2009.

[555] M. Freeman, "Fatal Virus Resurges in Area Blacktails," *Mail Tribune,* 5 August 2014.

[556] Washington Department of Fish and Wildlife, "Conservation: Wildlife Health - Deer Hair Loss Syndrome Fact Sheet," Washington Department of Fish and Wildlife, April 2010. [Online]. Available: http://wdfw.wa.gov/conservation/health/hair_loss/. [Accessed April 2016].

[557] R. McCoy and S. Murphie, "Factors Affecting the Survival of Black-tailed Deer Fawns on the Northwestern Olympic Peninsula, Washington," Makah Tribal Forestry, Neah Bay, WA, 2011.

[558] Northwest Indian Fisheries Commission, "Tribes and State Change Harvest Levels of Black-Tailed Deer to Bolster Populations," Northwest Treaty Tribes, September 2010. [Online]. [Accessed May 2016].

[559] R. J. Bildfell, J. W. Mertins, J. A. Mortenson and D. F. Cottam, "Hair-loss Syndrome in Black-tailed Deer of the Pacific Northwest," *Journal of Wildlife Diseases,* vol. 40, no. 4, pp. 670-681, 2004.

[560] World Animal Foundation, "Elk Fact Sheet," World Animal Foundation, 2015. [Online]. Available: http://www.worldanimalfoundation.org/articles/article/8948301/181061.htm. [Accessed April 2016].

[561] G. Wang, N. T. Hobbs, F. J. Singer, D. S. Ojima and B. C. Lubow, "Impacts of Climate Changes on Elk Population Dynamics in Rocky Mountain National Park, Colorado, USA," *Climatic Change,* vol. 54, pp. 205-223, 2002.

[562] J. C. Haigh, "Reproductive Management of Elk," University of Saskatchewan, 1990.

[563] K. Robbins, *Elk Population Dynamics and the Primary Factors that Drive them,* University of Maryland, presentation.

[564] Western Wildlife Outreach, "Black Bear Biology and Behavior," Western Wildlife Outreach, 2016. [Online]. Available: http://westernwildlife.org/black-bear-outreach-project/biology-behavior-3/. [Accessed April 2016].

[565] Western Wildlife Outreach, "Large Carnivores in a Changing World," Western Wildlife Outreach, 2016. [Online]. Available: http://westernwildlife.org/large-carnivores-in-a-changing-world/. [Accessed April 2016].

[566] P. Opdam and D. Wascher, "Climate Change Meets Habitat Fragmentation: Linking Landscape and Biogeographical Scale Levels in Research and Conservation," *Biological Conservation,* vol. 117, pp. 285-297, 2004.

[567] B. C. Howard, "Warm Weather Drives Bears Out of Hibernation," *National Geographic,* 13 April 2015.

[568] N. Stephenson, J. M. Higley, J. L. Sajecki, B. B. Chomel, R. N. Brown and J. E. Foley, "Demographic Characteristics and Infectious Diseases of a Population of American Black Bears in Humboldt County, California," *Vector-Borne and Zoonotic Diseases,* vol. 15, no. 2, pp. 116-123, 2015 (abstract).

[569] Agricultural Research Service, "Toxoplasmosis," United States Department of Agriculture, January 2005. [Online]. Available: http://www.ars.usda.gov/News/docs.htm?docid=11013. [Accessed May 2016].

[570] B. G. Meerburg and A. Kijlstra, "Changing Climate - Changing Pathogens: *Toxoplasma gondii* in North-Western Europe," *Parasitology Research,* vol. 105, no. 1, pp. 17-24, 2009.

[571] C. Yan, L. Liang, K. Zheng and X. Zhu, "Impact of Environmental Factors on the Emergence, Transmission and Distribution of Toxoplasma gondii," *Parasites and Vectors,* vol. 9, no. 137, 2016.

[572] K. S. Utaaker and L. J. Robertson, "Climate Change and Foodborne Transmission of Parasites: A Consideration of Possible Interactions and Impacts for Selected Parasites," *Food Research International,* 2014 (article in press).

[573] Washington Department of Fish and Wildlife, "Living with Wildlife: Mountain Goats," Washington Department of Fish and Wildlife, 2016. [Online]. Available: http://wdfw.wa.gov/living/mountain_goats.html. [Accessed 29 June 2016].

[574] D. W. Nagorsen and G. Keddie, "Late Pleistocene Mountain Goats (*Oreamnos americanus*) from Vancouver Island: Biogeographic Implications," *Journal of Mammalogy,* vol. 81, no. 3, pp. 666-675, 2000.

[575] C. G. Rice, "Status of Mountain Goats in Washington," Washington Department of Fish and Wildlife, Olympia, WA, 2012.

[576] M. Beniston, "Climatic Change in Mountain Regions: A Review of Possible Impacts," *Climatic Change,* vol. 59, pp. 5-31, 2003.

[577] L. K. Gray and A. Hamann, "Tracking Suitable Habitat for Tree Populations under Climate Change in Western North America," *Climatic Change,* vol. 117, pp. 289-303, 2013.

[578] M. I. Williams and R. Kasten Dumroese, "Preparing for Climate Change: Forestry and Assisted Migration," *Forest Ecology,* vol. 111, no. 4, pp. 287-297, 2013.

[579] E. Schreiner and A. Woodward, "Study Documents Mountain Goat Impacts at Olympic National Park," *Park Science,* vol. 14, no. 2, pp. 23-25, 1994.

[580] S. D. Cote and M. Festa-Bianchet, "Mountain Goat (*Oreamnos americanus*)," in *Wild Mammals of North America: Biology, Management, and Conservation*, G. A. Feldhamer, B. C. Thompson and J. A. Chapman, Eds., Baltimore, MD, The Johns Hopkins University Press, 2003, pp. 1061-1075.

[581] T. H. E. Mason, M. Apollonio, R. Chirichella, S. G. Willis and P. A. Stephens, "Environmental Change and Long-term Body Mass Declines in an Alpine Mammal," *Frontiers in Zoology,* vol. 11, no. 69, 2014.

[582] L. S. Mills, M. E. Soule and D. F. Doak, "The Keystone-Species Concept in Ecology and Conservation," *BioScience,* vol. 43, no. 4, pp. 219-224, 1993.

[583] E. Sala, "Top Predators Provide Insurance Against Climate Change," *Trends in Ecology and Evolution,* vol. 21, no. 9, pp. 479-480, 2006.

[584] R. L. Beschta and W. J. Ripple, "Large Predators and Trophic Cascades in Terrestrial Ecosystems of the Western United States," *Biological Conservation,* vol. 142, pp. 2401-2414, 2009.

[585] W. J. Ripple and R. L. Beschta, "Trophic Cascades Involving Cougar, Mule Deer, and Black Oaks in Yosemite National Park," *Biological Conservation,* vol. 141, pp. 1249-1256, 2008.

[586] C. Nielsen, D. Thompson, M. Kelly and C. A. Lopez-Gonzalez, "*Puma concolor*: The IUCN Red List of Threatened Species 2015," International Union for Conservation of Nature and Natural Resources (IUCN), 2015.

[587] G. W. Roemer, M. E. Gompper and B. Van Valkenburgh, "The Ecological Role of the Mammalian Mesocarnivore," *BioScience,* vol. 59, no. 2, pp. 165-173, 2009.

[588] T. Quinn, "Coyote (*Canis latrans*) Food Habits in Three Urban Habitat Types of Western Washington," College of Forest Resources, University of Washington, 1996.

[589] R. L. Crabtree and J. W. Sheldon, "The Ecological Role of Coyotes on Yellowstone's Northern Range," *Yellowstone Science,* no. Spring, pp. 15-23, 1999.

[590] K. Stone, "*Martes americana*, American Marten," U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2010. [Online]. Available: http://www.fs.fed.us/database/feis/animals/mammal/maam/all.html.

[591] T. N. Wasserman, S. A. Cushman, A. S. Shirk, E. L. Landguth and J. S. Littell, "Simulating the Effects of Climate Change on Population Connectivity of American Marten (Martes americana) in the Northern Rocky Mountains, USA," *Landscape Ecology,* vol. 27, pp. 211-225, 2012.

[592] M. M. Lance and S. J. Jeffries, "Harbor Seal Diet in Hood Canal, South Puget Sound, and the San Juan Island Archipelago," Washington Department of Fish and Wildlife, 2009.

[593] D. Thompson and T. Harkonen, "*Phoca vitulina*: The IUCN Red List of Threatened Species 2008," International Union for Conservation of Nature and Natural Resources, 2008.

[594] M. P. Simmonds and S. J. Isaac, "The Impacts of Climate Change on Marine Mammals: Early Signs of Significant Problems," *Oryx,* vol. 41, no. 1, 2007.

[595] M. P. Simmonds and S. J. Mayer, "An Evaluation of Environmental and Other Factors in Some Recent Marine Mammal Mortalities in Europe: Implications for Conservation and Management," *Environmental Reviews,* vol. 5, pp. 89-98, 1997.

[596] J. L. Huggins, C. Leahy, J. Calambokidis, D. Lambourn, S. J. Jeffries, S. A. Norman and S. Raverty, "Causes and Patterns of Harbor Seal (*Phoca vitulina*) Pup Mortality at Smith Island, Washington, 2004-2010," *Northwestern Naturalist,* vol. 94, pp. 198-208, 2013.

[597] F. Rosell, O. Bozser, P. Collen and H. Parker, "Ecological Impact of Beavers *Castor fiber* and *Castor canadensis* and their Ability to Modify Ecosystems," *Mammal Review,* vol. 35, no. 3 & 4, pp. 248-276, 2005.

[598] G. A. Hood and S. E. Bayley, "Beaver (*Castor canadensis*) Mitigate the Effects of Climate on the Area of Open Water in Boral Wetlands in Western Canada," *Biological Conservation,* vol. 141, pp. 556-567, 2008.

[599] N. Bouwes, N. Weber, C. E. Jordan, W. C. Saunders, I. A. Tattam, C. Volk, J. M. Wheaton and M. M. Pollock, "Ecosystem Experiment Reveals Benefits of Natural and Simulated Beaver Dams to a Threatened Population of Steelhead (*Onchorhynchus mykiss*)," *Scientific Reports,* vol. 6, 2016.

[600] Port Gamble S'Klallam Tribe, "General Sewer Wastewater Facility Plan," Gray & Osborne, Inc., Little Boston, 2013.

[601] Loving Engineering and Consulting, P.S. Inc., "Port Gamble S'Klallam Tribe Hazard Mitigation Plan 2015 Update," Port Gamble S'Klallam Tribe, 2015.

[602] Puget Sound Energy, "PSE Primer," Puget Sound Energy, 2016. [Online]. Available: https://pse.com/aboutpse/CorporateInfo/Pages/PSE-Primer.aspx. [Accessed 17 May 2016].

[603] State Energy Office, "Washington State Electric Utility Fuel Mix Disclosure Reports for Calendar Year 2014," Washington State Department of Commerce, Olympia, WA, 2015.

[604] University of Washington Climate Impacts Group, "The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate - Executive Summary," in *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*, J. S. Littell, M. McGuire Elsner, L. C. Whitely Binder and A. K. Snover, Eds., Seattle, Washington: Climate Impacts Group, University of Washington, 2009.

[605] Kitsap Public Utility District (PUD), "Kitsap PUD Well Water Levels," Kitsap PUD, 2016. [Online]. Available: http://kpudhydrodata.kpud.org/APSFED_WELLS.aspx. [Accessed 17 May 2016].

[606] C. F. Pitz, "Predicted Impacts of Climate Change on Groundwater Resources of Washington State," Washington Department of Ecology, Olympia, 2016.

[607] Washington State Department of Transportation, "Climate Change Impacts Vulnerability Assessment," Washington State Department of Transportation, Olympia, 2011.

[608] Jamestown S'Klallam Tribe, Climate Change Vulnerability Assessment and Adaptation Plan, J. Petersen and J. Bell, Eds., A collaboration of the Jamestown S'Klallam Tribe and Adaptation International, 2013.

[609] M. A. Gaines, J. M. Irwin and M. L. Tragesser, "One of Eleven, but One of a Kind," *Aspire,* pp. 16-21, Summer 2008.

[610] Washington State Department of Transportation, "WSDOT - Ferries - Schedule: Spring 2016 Tidal Cancellations for Port Townsend / Coupville," Washington State Department of Transportation, 2016. [Online]. Available: http://www.wsdot.com/ferries/schedule/AddCancelBySimpleRoute.aspx?routeid=8&_ga=1.204029718.763444103.1435767855. [Accessed 6 June 2016].

[611] A. Crimmins, J. Balbus, J. L. Gamble, C. B. Beard, J. E. Bell, D. Dodgen, R. J. Eisen, N. Fann, M. D. Hawkins, S. C. Herring, L. Jantarasami, D. M. Mills, S. Saha, M. C. Sarofim, J. Trtanj and L. Ziska, "The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment," U.S. Global Change Research Program, Washington, DC, 2016.

[612] University of Washington Climate Impacts Group, "How Will Climate Change Affect Human Health in Washington?," 2013.

[613] United States Census, "QuickFacts Kitsap County, Washington," [Online]. Available: http://www.census.gov/quickfacts/table/PST045215/53035. [Accessed 11 July 2016].

[614] Port Gamble S'Klallam Tribe Health Services Department, "Community Health Assessment," 2014.

[615] Washington Department of Ecology, *Human Health: Preparing Washington for a Changing Climate,* 2012.

[616] World Health Organization, "Climate Change and Health," September 2015. [Online]. Available: http://www.who.int/mediacentre/factsheets/fs266/en/. [Accessed 20 May 2016].

[617] T. Isaksen and e. al., "Increased Mortality Associated with Extreme-heat Exposure in King County, Washington, 1980-2010," *International Journal of Biometeorology,* 2015.

[618] J. E. Jackson, M. G. Yost, C. Karr, C. Fitzpatrick, B. Lamb, S. H. Chung, J. Chen, J. Avise, R. A. Rosenblatt and R. A. Fenske, "Public Health Impacts of Climate Change in Washington State: Projected Mortality Risks Due to Heat Events and Air Pollution," *Climatic Change,* vol. 102, pp. 159-186, 2010.

[619] S. Greene, L. S. Kalkstein, D. M. Mills and J. Samenow, "An Examination of Climate Change on Extreme Heat Events and Climate–Mortality Relationships in Large U.S. Cities," *Weather, Climate, and Society,* vol. 3, pp. 281-292, 2011.

[620] EPA, "Climate Impacts on Human Health," [Online]. Available: https://www3.epa.gov/climatechange/impacts/health.html. [Accessed 31 May 2016].

[621] D. L. Driscoll, E. Mitchell, R. Barker, J. M. Johnston and S. Renes, "Assessing the Health Effects of Climate Change in Alaska with Community-based Surveillance," *Climatic Change,* 2016.

[622] Kitsap Public Health District, "2014 Community Health Status Assessment," 2014.

[623] Kitsap Public Health District, "Kitsap County Core Public Health Indicators: Summary," May 2015. [Online]. Available: https://www.kitsappublichealth.org/information/files/KPHD_Indicators_Summary.pdf. [Accessed 21 May 2016].

[624] University of Washington Climate Impacts Group, "State of Knowledge – Climate Change in Puget Sound (Section 13: How Will Climate Change Affect Human Health?)," University of Washington College of the Environment, Seattle, 2015.

[625] D. M. Bowman and F. H. Johnston, "Wildfire Smoke, Fire Management, and Human Health," *EcoHealth,* vol. 2, pp. 76-80, 2005.

[626] C. Dunagan, "Health Risks Estimated for Port Gamble Bay Shellfish," *Kitsap Sun,* 10 February 2014.

[627] C. Cooney, "Climate Change and Infectious Disease: Is the Future Here?," *Environmental Health Perspectives,* vol. 119, no. 9, pp. A 395 - A 397, 2011.

[628] K. Datta, K. H. Bartlett, R. Baer, E. Byrnes, E. Galanis, J. Heitman, L. Hoang, M. J. Leslie, L. MacDougall, S. S. Magill, M. G. Morshed and K. A. Marr, "Spread of *Cryptococcus gattii* into Pacific Northwest Region of the United States," *Emerging Infectious Diseases,* vol. 15, no. 8, pp. 1185-1191, 2009.

[629] The Swinomish Indian Tribal Community, "Indigenous Health Indicators," [Online]. Available: http://www.swinomish-nsn.gov/ihi/. [Accessed 11 July 2016].

[630] J. Gorsline, "Early History," [Online]. Available: https://www.pgst.nsn.us/land-and-people-and-lifestyle/history#point-julia. [Accessed 4 December 2016].

[631] D. Cordalis and D. B. Suagee, "The Effects of Climate Change on American Indian and Alaska Native Tribes," *Natural Resources & Environment,* vol. 22, no. 3, pp. 45-49, 2008.

[632] R. A. Feely, T. Klinger, J. A. Newton and M. Chadsey, "Scientific Summary of Ocean Acidification in Washington State Marine Waters," Washington State Blue Ribbon Panel on Ocean Acidification, 2012.

[633] P. Glick, J. Clough and B. Nunley, "Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon," National Wildlife Federation, 2007.

[634] S. K. Moore, N. J. Mantua, B. M. Hickey and V. L. Trainer, "Recent Trends in Paralytic Shellfish Toxins in Puget Sound, Relationships to Climate, and Capacity for Prediction of Toxic Events," *Harmful Algae,* vol. 8, pp. 463-477, 2009.

[635] Burke Museum, "Salish Bounty: Traditional Native Foods of Puget Sound," Burke Museum of Natural History and Culture, 14 September 2013. [Online]. Available: http://www.burkemuseum.org/blog/salish-bounty-traditional-native-foods-puget-sound. [Accessed 30 September 2016].

[636] K. Lynn, J. Daigle, J. Hoffman, F. Lake, N. Michelle, D. Ranco, C. Viles, G. Voggesser and P. Williams, "The Impacts of Climate Change on Tribal Traditional Foods," *Climatic Change,* vol. 120, pp. 545-556, 2013.

[637] J. Wray, Native Peoples of the Olympic Peninsula: Who We Are, University of Oklahoma Press, 2003, p. 57.

[638] National Oceanic and Atmospheric Administration, "El Niño Southern Oscillation (ENSO)," [Online]. Available: www.esrl.noaa.gov/psd/enso. [Accessed November 2016].

[639] Northwest Fisheries Science Center, "Pacific Decadal Oscillation (PDO)," [Online]. Available: www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/ca-pdo.cfm. [Accessed 10 November 2016].

[640] M. Collins, "El Niño- or La Niña-like Climate Change?," *Climate Dynamics,* vol. 24, no. 1, pp. 89-104, 2005.

[641] K. E. Trenberth and T. J. Hoar, "El Niño and Climate Change," *Geophysical Research Letters ,* vol. 24, no. 23, pp. 3057-3060, 1997.

[642] M. Dolan, "Ocean Acidification: Global Warming's Doppelganger," *Seattle Magazine,* 2011.

[643] P. Glick, J. Clough and B. Nunley, "Sea-level Rise and Coastal Habitats in the Pacific Northwest," National Wildlife Federation, 2007.

[644] P. Glick, J. Clough and B. Nunley, "Sea-level Rise and Coastal Habitats in the Pacific Northwest," National Wildlife Federation, 2007.

[645] Shannon and Willson, Inc., "Geotechnical Evaluation of Recent Sliding: Port Gamble S'Klallam Reservation," Port Gamble S'Klallam Housing Authority, 1997.

[646] S. P. J. McCloskey, L. D. Daniels and J. A. McLean, "Potential Impacts of Climate Change on Western Hemlock Looper Outbreaks (abstract)," *Northwest Science,* vol. 89, no. 3, pp. 225-238, 2009.

[647] Washington State Department of Natural Resources, Forests and Fish Report, Washington State Department of Natural Resources, 1999.

[648] G. E. Grant, C. L. Tague and C. D. Allen, "Watering the Forest for the Trees: An Emerging Priority for Managing Water in Forest Landscapes," *Frontiers in Ecology and the Environment,* vol. 11, no. 6, pp. 314-321, 2013.

[649] R. H. Prescott and G. Mann, "Geotechnical Evaluation: Little Boston Road Slope Failure, James Fulton Property, Kingston, Washington," Applied Geotechnology Inc. for the Port Gamble S'Klallam Housing Authority, 1987.

[650] Washington Department of Fish and Wildlife, "Marine Beach Spawning Fish Ecology, Spawning Location Map," [Online]. Available: http://wdfw.wa.gov/conservation/research/projects/marine_beach_spawning/. [Accessed 4 Feb. 2016].

[651] F. D. Granshaw and A. G. Fountain, "Glacier Change (1958-1998) in the North Cascades National Park Complex, Washington, USA," *Journal of Glaciology,* vol. 52, no. 177, pp. 251-256, 2006.

[652] A. Cazenave and G. Le Cozannet, "Sea Level Rise and its Coastal Impacts," *Earth's Future,* vol. 2, no. 2, pp. 15-34, 2014.

[653] D. Ladd, J. Selleck and A. Fain, "Port Gamble S’Klallam Tribe Geotechnical Assessment and Shoreline Management Study," 2017.

[654] K. Ketteridge and C. Patmont, *Memorandum re: Port Gamble Bay Cleanup Project Coastal Engineering Evaluation of Shoreline Erosion,* 2016.

[655] Anchor QEA, LLC, "Wave Modeling in Support of Restoration Design (Part 1) Port Gamble Mill Site Restoration," 2015.

[656] Fain Environmental LLC, "Wave Height Analysis for Port Gamble Bay FLUPSY Facility," 2016.

[657] M. M. Elsner, L. Cuo, N. Voisin, J. S. Deems, A. F. Hamlet, J. A. Vano, K. E. Mickelson, S.-Y. Lee and D. P. Lettenmaier, "Implications of 21st Century Climate Change for the Hydrology of Washington State," *Climatic Change,* vol. 102, pp. 225-260, 2010.

[658] M. McCarthy, J. O'Halloran, N. M. O'Brien and F. F. van Pelt, "Does the Marine Biotoxin Okadaic Acid Cause DNA Fragmentation in the Blue Mussel and the Pacific Oyster?," *Marine Environmental Research,* vol. 101, pp. 153-160, 2014.