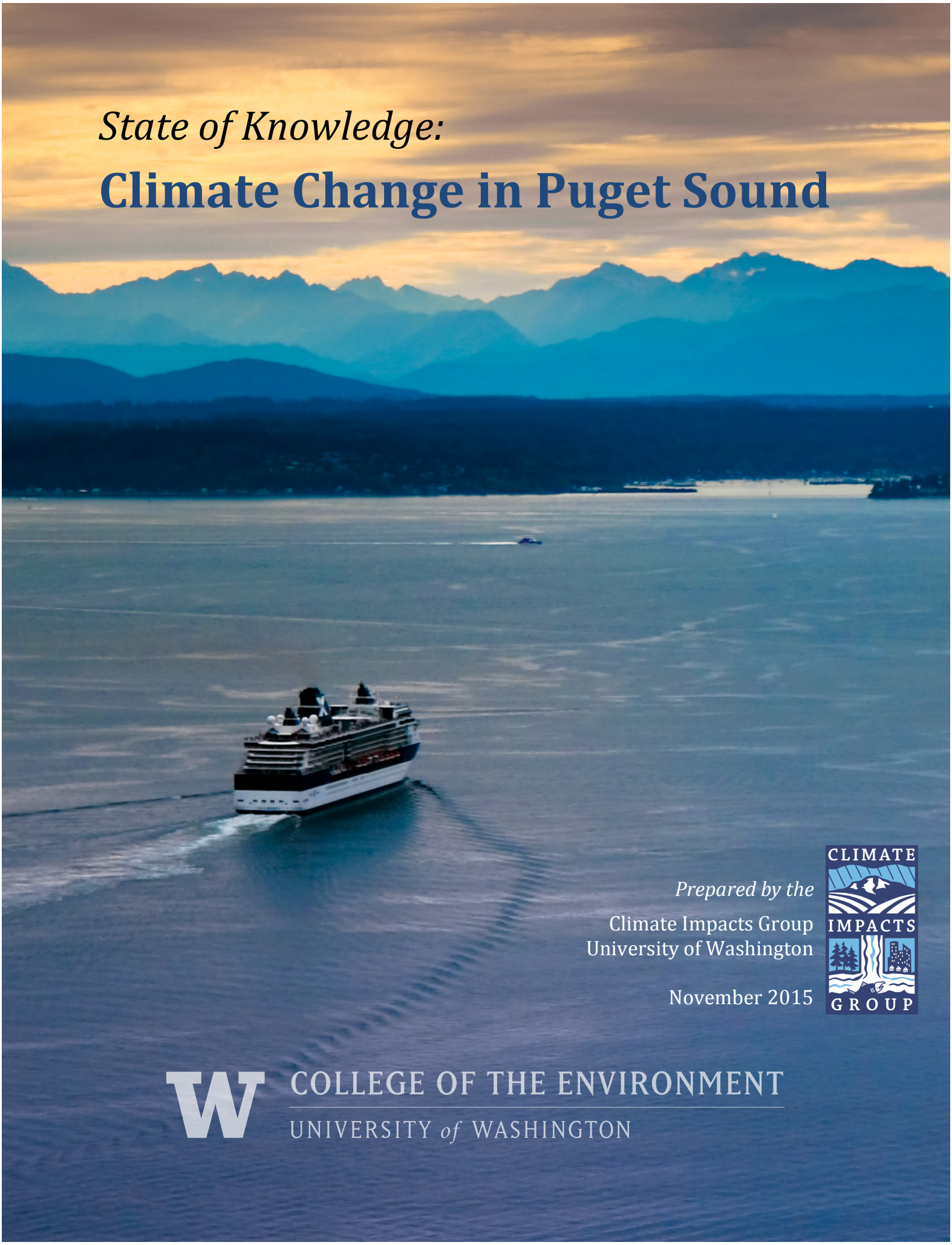
State of Knowledge:

Climate Change in Puget Sound



Prepared by the

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University of Washington

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COLLEGE OF THE ENVIRONMENT
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This report is available for download at:

- Full report: https://cig.uw.edu/resources/special-reports/ps-sok/
- Executive summary: https://cig.uw.edu/resources/special-reports/ps-sok/ps-sok_execsumm_2015.pdf

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Report Updates:

Version Date	*Update*
November 16, 2016	• *Page 2-5:* Replaced “September-October” with “September-November” in footnote K. • *Page 2-14:* Under the "extremes" section of this table parentheses after 2080s header indicate its 2040-2069, instead of 2070-2099. • *Page 2-15:* replaced “Projected change in Puget Sound seasonal temperature” with “Projected change in Puget Sound seasonal precipitation”

March 21, 2016	• *Page 2-7:* Replaced “occurring about eight days per year by the 2080s” with “occurring about seven days per year (range: four to nine days per year) by the 2080s”
	• *Table 2-2:* Same. Replaced “8 days / year” with “7 days / year (range: 4 to 9 dys/yr)”
	• *Page 2-5:* Replaced +5.9°F with +5.5°F
	• *Page 2-7:* Replaced “from +3 to +11%” with “from +2 to +11%”
	• *Page 2-9, Table 2-1, Table 2-2:* Adjusted box and tables to fit within each page and ensured that fonts were consistent throughout.
	• *Page 2-14:* Replaced “2080s (2040-2069” with “2080s (2070-2099”
	• *Table 2:*
	  ○ Corrected low and high projections for annual temperature, 2080s RCP 4.5 and RCP 8.5,
	  ○ Corrected average projection for fall temperature, 2080s RCP 8.5,
	  ○ Corrected average projection for spring precipitation, 2040s RCP 4.5,
	  ○ Corrected low projection for summer precipitation, 2080s RCP 4.5.
	• *Page 3-3:* Replaced −37% with −42% for projected decline in snowpack.
	• *Page 3-7:* Replaced “flood flow” with “flood volume”
	• *Pages 3-15 and 3-19:* Replaced “streamflow volume” with “streamflow”
	• *Table 4-1:* Adjusted values in Row 3 (Mote et al. 2008) to reflect absolute as opposed to relative sea level rise. Replaced “(+3.5 to +22 in.)” with “(+4 to +15 in.)”, and “(+6 to +50 in.)” with “(+7 to +37 in.)”. Replaced “(NRC 2012)” with “(NRC 2012, without uplift)”, and added an explanatory footnote.
	• *Page 4-4:* Added the following sentence to footnote ‘M’: “This is likely an underestimate of sea level rise for Seattle, since most observations suggest the land is either subsiding or not moving at all.”
	• *Figure 5-2:* Adjusted the legend to read “Percent Of Watershed Glacierized”, instead of “Glaciated”; and replaced “Rob” with “Robert” in the caption.
	• *Page 5-7:* Replaced “become more severe” with “become more intense”
	• *Page 7-8:* Replaced “It is now known” with “It is not known”
	• *Page 10-10:* Replaced Figure 10-2 to correct for missing figure text
	• *Page 13-8:* Replaced “The Vv strain was first documented in Washington State waters in 2013 and can cause a more serious infection than Vp,

	first detected in sediment from Willapa Bay, Washington in 1984. Since August 2013, *Vibrio vulnificus* (*Vv*) has been detected in routine Washington State PH Laboratory monitoring oyster tissue samples, and represents a potential shellfish-borne illness risk", and citation #33 was added. • Page B-2: Replaced "are included in the supplementary material to this report" with "are available upon request" • Appendix B: Adjusted captions to read "Robert Norheim" instead of "Rob Norheim" • Page C-2: Replaced "are included in the supplementary material to this report" with "are available upon request" • Appendix C: Replaced "°F" with "°C" in caption for figure C-16.

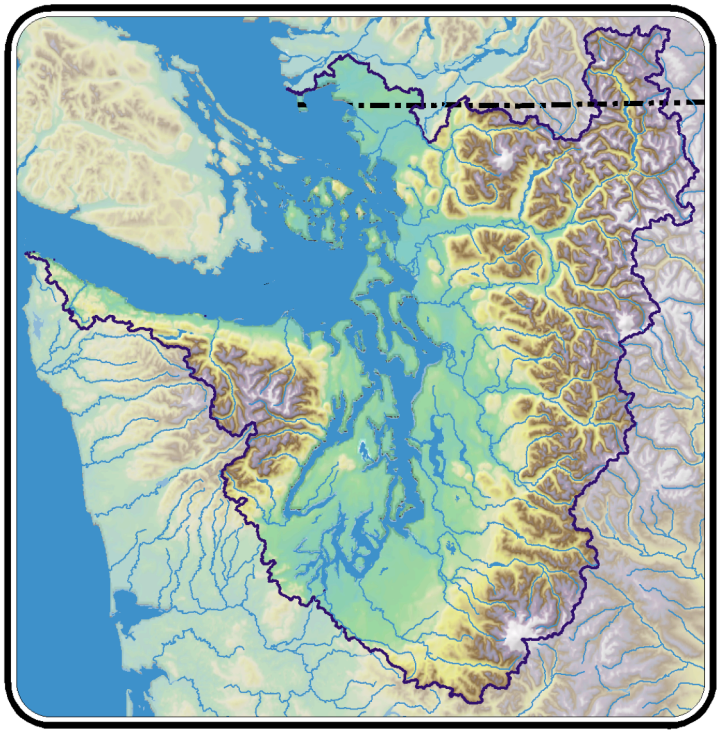
Table of Contents

How to Read this Report

This report is designed to serve as a reference for individuals interested in understanding the state of the science on climate change and its effects within the Puget Sound region. We define the Puget Sound region to include the water bodies of Puget Sound and the Strait of Juan de Fuca, as well as any United States land areas that ultimately drain into these waters, as outlined in the map below.

Written so that the reader can choose a level of specificity that is appropriate to her/his needs, research findings are summarized within 13 sections, each focusing on a specific topic area. Each section provides a synthesis of the peer-reviewed literature on climate-related changes in Puget Sound. Some sections also include references to the gray literature (reports, PhD theses, and other previous syntheses) and a few include the results of unpublished data analyses. For transparency, the source of all data and statements is provided in the text. Although the sections refer to one another when necessary, each is written to serve as a stand-alone reference for that topic. Summary tables in Sections 2 through 4 provide a terse listing of the raw numbers associated with the findings listed within the text.

In most sections, the first sub-topic is entitled *"Climate Drivers of Change"*, which provides a summary of the mechanisms by which climate could effect change. Similarly, most sections include a final sub-topic entitled *"Climate Risk Reduction Efforts"*, which details recent and ongoing efforts by communities, agencies, tribes, and organizations that are working to prepare for the effects of climate change. Since the sections cover a wide range of sectors and impacts, some of which have been studied more thoroughly than others, not all of the same elements are included in each section.



The Puget Sound region, as defined in this report.
Figure Source: Robert Norheim.

The Soul of the Sound

Between upthrust cragged ranges, glacial carvings of
rugged beauty with great mountain peaks,
templed forests and crests of snow-

To Pacific Ocean beaches and coastal waters,
pulses Puget Sound and environs we strive to know!

Her dynamic hydro-keyboard is powered by ocean tides,
melted snow, river runoff, winds, and rain

And with her temperature, currents, salinity, density and
depth, develops a rhythmic gain

The Aleutian Low is the conductor
on the Sound's Pacific latitude,

And directs a fugue in bass clef pitch as it
compresses or extends its longitude!

This energy signals southerly winds,
laden with tropical moisture,

To the Sound or to Alaska in obeyance
to pressuring posture!

– Excerpted, with permission, from Ebbesmeyer et al. 1989[1]

[1] Ebbesmeyer, C. C., Coomes, C. A., Cannon, G. A., & Bretschneider, D. E. (1989). Linkage of ocean and fjord dynamics at decadal period. *Aspects of Climate Variability in the Pacific and the Western Americas*, 399-417. http://dx.doi.org/10.1029/GM055p0399

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EXECUTIVE SUMMARY

From the peaks of the Cascades and Olympics to the saltwater of the Sound, climate shapes the physical landscape of the Puget Sound region and where and how people, plants and animals inhabit that landscape.

In addition to important natural variations, we know now that the Earth's climate is changing, and expected to continue to change in ways that will alter our local environment, the nature and health of our ecosystems, and the risks and opportunities facing our communities.

> *"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems…*

This report summarizes the current state of knowledge concerning observed and likely future climate trends and their effects on the lands, waters, and people of the Puget Sound region. It describes:

- Changes in the key factors shaping our local environment: temperature, precipitation, sea level, ocean chemistry, and natural variability,
- Implications for Puget Sound lands: freshwater resources, landslides, sediment transport, agriculture, and ecosystems,
- Consequences for Puget Sound's marine waters: coastal and marine ecosystems, water quality, and circulation,
- Impacts on the region's population: health, tribes, and infrastructure, and
- Climate risk reduction activities underway in climate-sensitive sectors across the Puget Sound region.

> *…Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen."*
>
> *– IPCC Synthesis Report, Summary for Policy Makers, 2013*[1]

This report, State of Knowledge: *Climate Change in Puget Sound,* is designed to be an easy-to-read summary that both complements and points to the foundational literature (peer-reviewed science, community and agency reports, and publicly available datasets) from which it draws.

REPORT HIGHLIGHTS

Key Drivers of Change

Climate variability and change will affect the Puget Sound region by altering key climate-related factors shaping the local environment.

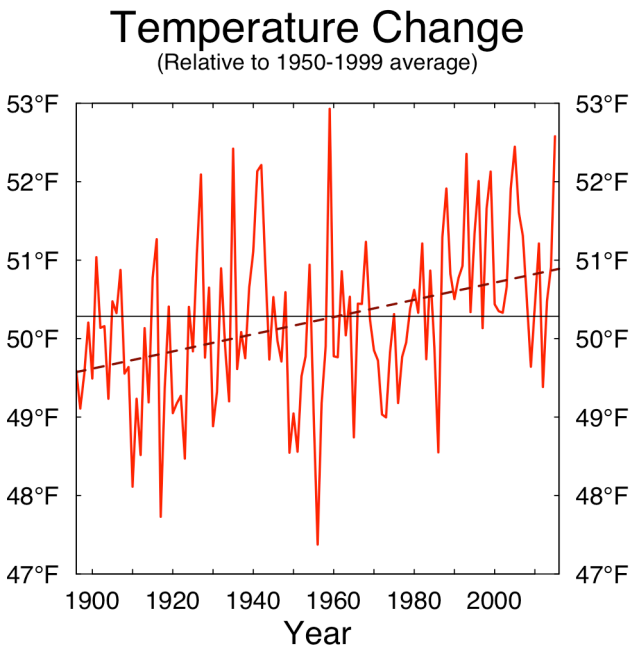

Figure ES-1. The Puget Sound region warmed by +1.3°F from 1895 to 2014. The red line shows average annual temperature for the Puget Sound Lowlands climate division,[A] the horizontal black line corresponds to the average temperature for 1950–1999 (50.3°F), and the dashed red line is the estimated trend. *Data source: Vose et al. 2014.*[A]

- **TEMPERATURE:** The Puget Sound region warmed in the 20th century: all but six of the years from 1980-2014 were above the 20th century average (Figure ES-1). Additional warming for the 21st century is projected to be at least double that experienced in the 20th century, and could be nearly ten times as large (Figure ES-2). *(Section 2)*

- **PRECIPITATION:** There are no statistically significant trends towards wetter or drier conditions (evaluated for seasons and years) over the 20th century**.** Large year-to-year and decade-to-decade variations in precipitation are expected to continue, and to be much larger than the long-term changes projected for the 21st century. *(Section 2)*

- **HEAVY RAINFALL:** Future occurrences of heavy rainfall are projected to be more frequent and more intense. This will exacerbate flood risks in many watersheds**.** *(Section 2)*

- **SEA LEVEL:** Over the last century, sea level rose at many locations along the shorelines of Puget Sound. Rates vary**,** however, as local land motion, weather patterns, and ocean currents can amplify or mask regional trends in sea level. Sea levels are projected to rise over the coming century, with a wide range of possible future amounts, depending on the rate of global greenhouse gas emissions. Increases in sea level will amplify the risk of coastal flooding. *(Section 4)*

- **OCEAN ACIDIFICATION:** As a result of accumulating carbon dioxide (CO_2) in the atmosphere, the waters of the North Pacific Ocean and Puget Sound are experiencing a reduction in pH, a process known as acidification. This acidification is projected to continue. *(Sections 7 and 11)*

- **NATURAL VARIABILITY:** Seasonal, year-to-year, and decade-to-decade variations will remain an important feature of local climate, at times amplifying or counteracting the long-term trends caused by rising greenhouse gas emissions.

Puget Sound Land Areas

From the mountaintops to the shorelines of Puget Sound, these climate changes will cause changes in the region's water cycle, natural resources, and ecosystems.

- **SNOWPACK AND STREAMFLOW:** Warming will cause a greater proportion of winter precipitation to fall as rain rather than snow. Snowpack is projected to decline, causing the spring peak in streamflow to occur earlier in the year. Winter streamflow is projected to increase in snow-influenced watersheds, while most locations are projected to experience a decline in summer streamflow (Figure ES-3)**.** *(Section 3)*

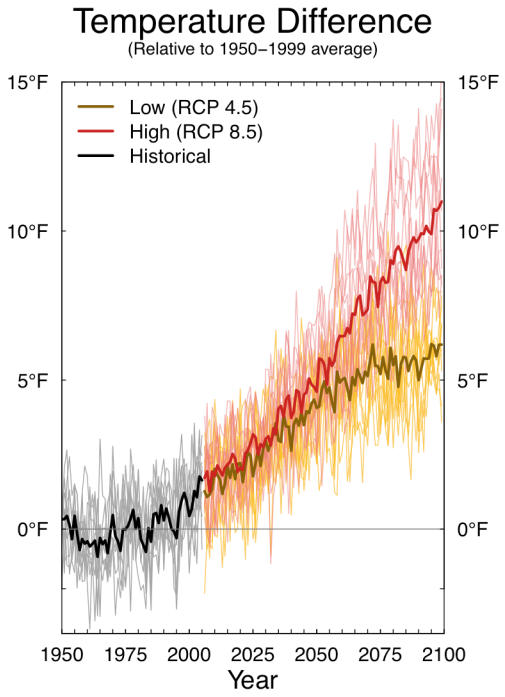

Figure ES-2. The Puget Sound region is projected to warm considerably in the 21st century. The graph shows average annual air temperatures projected by climate models, relative to the average for 1950-1999 (horizontal gray line; the average annual temperature for the Puget Sound region is 44°F). Thin colored lines show individual climate model projections; thick colored lines show the averages of the models. *Data source: Downscaled climate projections developed by Abatzoglou and Brown 2011.*[A]

- **LANDSLIDES AND SEDIMENT TRANSPORT:** Changes in rainfall, snowpack, and streamflow may lead to an increase in landslide risk, erosion, and sediment transport in fall, winter, and spring, while reducing the rates of these processes in summer. Quantitative projections of the likely changes in sediment transport and landslides are limited, in part because it is challenging to distinguish climate change effects from non-climatic factors such as development patterns and forest management. *(Section 5)*

- **FLOODING:** Both the extent and the frequency of flooding is projected to increase. Heavy rain events are projected to intensify, increasing flood risk in all Puget Sound watersheds. Continued sea level rise will extend the reach of storm surge, putting coastal areas at greater risk of inundation. In snow-accumulating watersheds, winter flood risk will increase as the snowline recedes, shifting precipitation from rain to snow. *(Sections 2, 3, 4, and 5).*

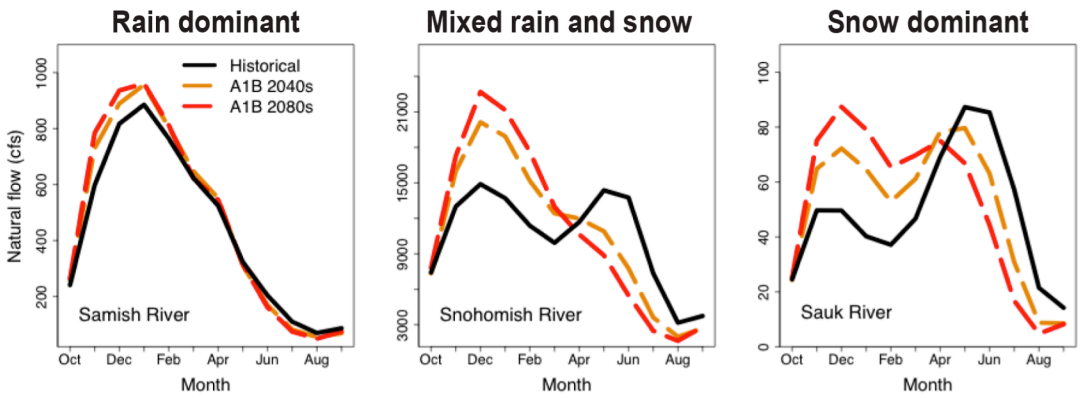

Figure ES-3. Streamflow is projected to increase in winter and decrease in summer, and changes are greatest for watersheds located near the current snowline. Changes in the seasonal timing of streamflow, on average, for three illustrative watersheds in Puget Sound: The Samish River, a warm basin (left); the Sauk River, a cold basin with source waters at high elevations (right); and the Snohomish River, a middle-elevation basin with substantial area near the current snowline (middle). *Data source: Downscaled hydrologic projections developed by Hamlet et al. 2013*[3]

- **SALMON:** Warmer streams, ocean acidification, lower summer streamflows, and higher winter streamflows are projected to negatively affect salmon. The persistence of cold water "refugia" within rivers and the diversity among salmon populations will be critical in helping salmon populations adapt to future climate conditions. *(Sections 10 and 11)*

- **TIMING OF BIOLOGICAL EVENTS:** The timing of many biological events (e.g., leaf emergence in spring, plankton blooms in lakes, spawning runs for salmon) can be altered by warming. Because each species will respond differently, climate change may cause important biological interactions to become unsynchronized. *(Sections 9, 10, and 11)*

- **SPECIES DISTRIBUTIONS:** Many species will exhibit changes in their geographic ranges, with some species experiencing expansion, while others experience contraction or migration. For example, declining snowpack is expected to lead to a decline in montane meadows as forests to expand into higher elevation habitats. Range shifts will vary among species, and will be affected by non-climatic factors such as development and management patterns. *(Sections 9 and 10)*

- **FORESTS:** Over the long-term, climate change is expected to alter the distribution and abundance of some tree species in the Puget Sound region. Growth of Douglas-fir and other species in relatively warm lower-elevation forests (where growth is currently limited by summer water availability) may decrease. In contrast, growth of cold-climate, high-elevation species such as mountain hemlock (where growth is currently limited by mountain snowpack) may increase. Increases in the risk of large wildfires

and altered ranges and timing of insects and fungal pathogens will affect the vigor, growth, and distribution of forest species in the Puget Sound region. *(Section 9)*

- **AGRICULTURE:** Warming is expected to increase the length of the growing season. Along with higher temperatures, increases in atmospheric CO_2 concentrations could increase the production of some crops. However, increases in heat stress, decreases in summer water availability, increases in flood risk, and changes in the range and timing of pests may negatively affect crops and livestock. *(Section 8)*

Box ES-1. Projected changes in several key physical drivers.

- **Average annual temperature:** By the 2050s (2040-2069), the average year in the Puget Sound region is projected to be +4.2°F (range: +2.9 to +5.4°F) warmer under a low greenhouse gas scenario and +5.5°F (range: +4.3 to +7.1°F) warmer under a high greenhouse gas scenario (RCP 4.5 and 8.5, respectively),[A] relative to 1970-1999.[B,4]

- **Heavy Rainfall:** By the 2080s (2070-2099), the wettest days (99th percentile or 24-hour precipitation totals) in the Pacific Northwest are projected to increase by +22% (range: +5% to +34%) for a high greenhouse gas scenario (RCP 8.5), relative to 1970-1999.[C,5]

- **Declining Spring Snowpack:** By the 2040s (2030-2059), the average year in the Puget Sound region is projected to have −23% (range: −34 to −6%) less April 1st snowpack under a low greenhouse gas scenario (B1), and −29% (range: −47 to −4%) under a moderate greenhouse gas scenario (A1B), relative to 1970-1999.[C,3]

- **Sea Level Rise:** By 2050, relative sea level in Seattle is projected to rise by +6.5 inches (range: -1 to +19 inches) for a moderate, low, and high greenhouse gas scenario (A1B, B1 ,and A1FI, respectively), compared to 2000.[6] Sea level rise at other locations may differ by up to 8 inches by 2050, due to different rates of uplift or subsidence.

- **Higher Storm Surge Reach.** Although storm surge is not projected to increase, sea level rise will cause the same events to have a greater impact. In Olympia, a +6 inch rise in sea level (the middle projection for 2050 is +9 inches) would cause the 100-year surge event to become a 1-in-18 year event.[7]

[A] 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.

Puget Sound's Marine Waters

Climate change will affect the saltwater habitats of Puget Sound, driving changes in its currents, chemistry, and ecosystems.

- **COASTAL HABITATS:** Sea level rise is projected to expand the area of some tidal wetlands in Puget Sound but reduce the area of others, as water depths increase and new areas become submerged. For example, the area covered by salt marsh is projected to increase, while tidal freshwater marsh area is projected to decrease. Rising seas will also accelerate the eroding effect of waves and surge, causing unprotected beaches and bluffs to recede more rapidly. *(Sections 4 and 5)*

- **HARMFUL ALGAL BLOOMS:** Warmer water temperatures, both in the North Pacific Ocean and in Puget Sound, will likely make harmful algae blooms more frequent and severe, and will extend the season when they can occur. Ocean acidification may increase the toxicity of some harmful algal blooms. *(Sections 7 and 11)*

- **MARINE ECOSYSTEMS**: A combination of climate-related stressors will affect marine organisms and habitats, including warmer water temperatures, loss of coastal habitat due to sea level rise, ocean acidification, and changes in water quality and freshwater inputs. Some species, like salmon and shellfish, are likely to be negatively affected by these changes; other species, such as eelgrass, may benefit. *(Section 11)*

- **CIRCULATION IN THE OCEAN AND IN PUGET SOUND:** Future changes in the circulation of Puget Sound and the near-shore Pacific Ocean are unclear. Changes in the timing and amount of river flows may affect the ability of Puget Sound's surface and deep waters to mix. Ocean upwelling may change, but projections are not conclusive. Short-term variability in upwelling (ranging from seasons to decades) will likely be more important than long-term changes related to global warming throughout the 21st century. *(Section 6)*

B Projected change for ten global climate models, for 2050-2069 relative to 1970-1999, based on a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario.

C Projected change for ten global climate models, for 2040-2059 relative to 1970-1999, based on a moderate (A1B) greenhouse gas scenario.

D 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 5 global climate model projections and a high greenhouse gas scenario (RCP 8.5), evaluated for 2070-2099 relative to 1970-1999. Projected changes in intensity were evaluated for latitudes ranging from 40 to 49N. 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.

E Projections are a particular class of global climate models called "Earth System Models". These model the carbon cycle, and can therefore provide estimates of the amount of CO_2. The numbers give the range among all models and two scenarios: both a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario.

People

The Puget Sound region is home to a growing population and a rich diversity of cultural, institutional, and economic resources, many of which will be affected by climate change.

- **TRIBES:** Rooted in place, tribes are particularly vulnerable to climate change. Puget Sound's tribal communities face a wide range of climate-related risks, including sea level rise, more frequent and larger floods, impacts on culturally-important species such as salmon and shellfish, a greater risk of wildfires, and changes in the forest, coastal, and marine ecosystems on which they rely.

> *"Whether the consequences of the climate impacts…are severe or mild depends in part on the degree to which regional social, economic, and infrastructural systems are adjusted to align with the changing climate, and the degree to which natural systems are provided with the room, flexibility, and capacity to respond. The regional consequences of climate change will also be strongly shaped by past choices—of what to build where, what to grow where—and by the laws, institutions, and procedures that shape how natural resources are managed and allocated, risks from natural hazards are identified, and trade-offs among conflicting objectives resolved." – Snover et al., 2013*[2]

- **BUILT ENVIRONMENT:** The developed areas of Puget Sound and the transportation, drinking water, wastewater, and energy systems that serve the region's population will face an increasing risk of a variety of extreme weather events (e.g., heat waves, flooding, wildfire). Consequences include flooding of low-lying infrastructure, damage to energy transmission, and higher maintenance costs for many transportation and other elements of the built environment. *(Section 12)*

- **HUMAN HEALTH:** More frequent heat waves and more frequent and intense flooding may harm human health directly. Warming may also exacerbate health risks from poor air quality and allergens. Climate change can indirectly affect human health through its impacts on water supplies, wildfire risk, and the ways in which diseases are spread. Risks are often greatest for the elderly, children, those with existing chronic health conditions, individuals with greater exposure to outside conditions, and those with limited access to health resources. *(Section 13)*

Climate Risk Reduction

Actions taken today to reduce climate risks will play an important role in determining the future consequences of climate change. Actions underway in Puget Sound include:

- **ASSESSING VULNERABILITIES:** Many Puget Sound communities and organizations are assessing their specific vulnerabilities to climate change. For example, the Jamestown

S'Klallam tribe has recently completed a vulnerability assessment, finding that scenarios for moderate and high severity sea level rise raise flood risks for Highway 101 near Discovery Bay, potentially preventing the Tribe's access to the highway for 12-24 hours.[8] *(Section 12)*

- **PARTNERSHIP BUILDING:** Agencies, organizations, and communities in Puget Sound are working collaboratively with stakeholders to identify options for responding to climate change. For example, the North Cascadia Adaptation Partnership is a U.S. Forest Service / National Park Service collaboration that joined with city, state, tribal, and federal partners to increase awareness of climate change, assess the vulnerability of cultural and natural resources, and incorporate climate change adaptation into current management of federal lands in the North Cascades region.[9] *(Section 9)*

- **CLIMATE-INFORMED PLANNING:** Puget Sound communities and practitioners are incorporating climate change impacts into planning and decisions. For example, plans by the Port of Bellingham to redevelop the 228 acre Georgia Pacific site near downtown Bellingham include raising site grades approximately +3 to +6 feet in areas with high value infrastructure as a buffer against sea level rise.[10] *(Sections 4 and 12)*

- **IMPLEMENTING ADAPTATION:** A number of Puget Sound communities have begun to implement changes in policies, practices, and infrastructure that are designed to increase climate resilience. For example, projections for increased flooding and sediment loading in the Skagit River led to design changes for the City of Anacortes' new $65 million water treatment plant. Completed in 2013, the new plant includes elevated structures, water-tight construction with minimal structural penetrations, no electrical control equipment below the current 100-year flood elevation, and more effective sediment removal processes.[11,12] *(Sections 3, 5, and 12)*

Looking Forward

Understanding the likely local effects of climate variability and change is the first step towards characterizing, and ultimately reducing, climate risks. To help catalyze and support climate risk reduction activities aimed at developing a climate resilient Puget Sound region, this report summarizes existing knowledge about observed climate change and variability in the Puget Sound region, likely future climate changes, and the current and possible future impacts associated with these changes. It is intended to serve as a credible source to inform discussions within the region about the risks associated with climate change and choices for adaptation.

It is important to recognize that this report does not serve as a crystal ball for predicting our future. The actual impacts of a changing climate will arise from the complex interactions between climate and our critical natural and human systems, but also with a multitude of non-climate factors, including development choices, patterns of energy and water consumption, land use decisions, and other economic and social factors.

The region's best future will be achieved if the early steps toward climate risk reduction can be connected and enhanced. Decisions that consider climate risks, the interactions among these risks, and the connection between these risks and non-climate stressors offer the opportunity to maintain the integrity of the ecosystems that we treasure, the reliability of the infrastructure on which we depend, and the well-being of this generation and future generations in the Puget Sound region.

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