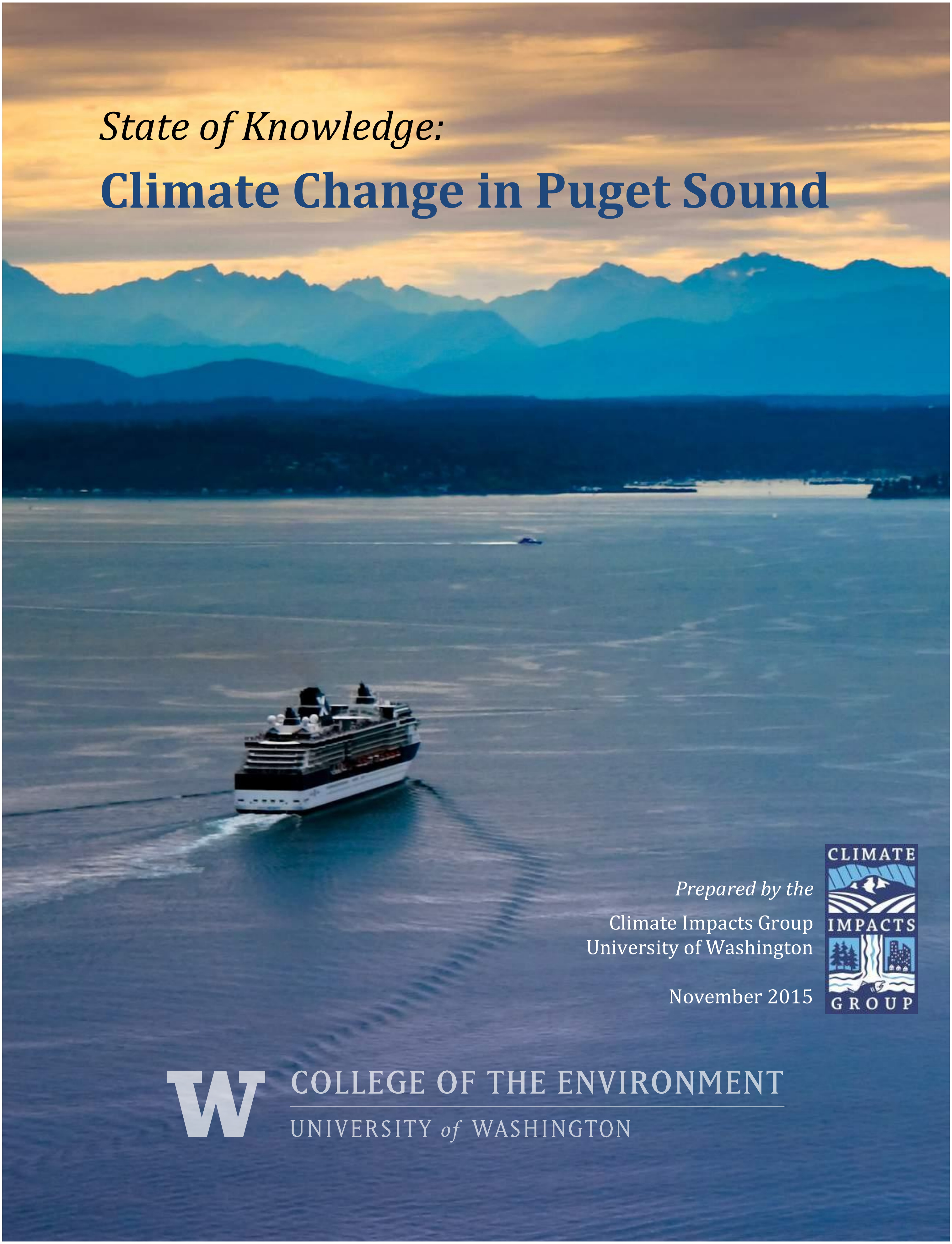

State of Knowledge:

Climate Change in Puget Sound

Prepared by the

Climate Impacts Group
University of Washington

November 2015

COLLEGE OF THE ENVIRONMENT
UNIVERSITY *of* WASHINGTON

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This report is available for download at:

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All contributors volunteered their time and specific field of expertise to provide comments and contributions to our synthesis of climate impacts science and adaptation efforts in Puget Sound. A total of 34 individuals contributed to the preparation of the Puget Sound Synthesis (33 individuals listed below and 1 anonymous reviewer).

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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:*
	    o Corrected low and high projections for annual temperature, 2080s RCP 4.5 and RCP 8.5,
	    o Corrected average projection for fall temperature, 2080s RCP 8.5,
	    o Corrected average projection for spring precipitation, 2040s RCP 4.5,
	    o 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.

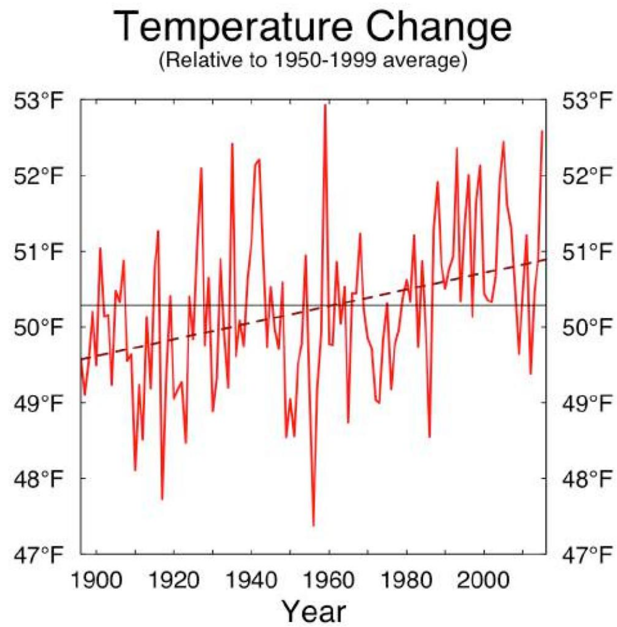

Figure ES-1. The Puget Sound region warmed by +1.3°F from 1895 to 2014. The red line shows average annual temperature for the Puget Sound Lowlands climate division,[A] the horizontal black line corresponds to the average temperature for 1950–1999 (50.3°F), and the dashed red line is the estimated trend.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

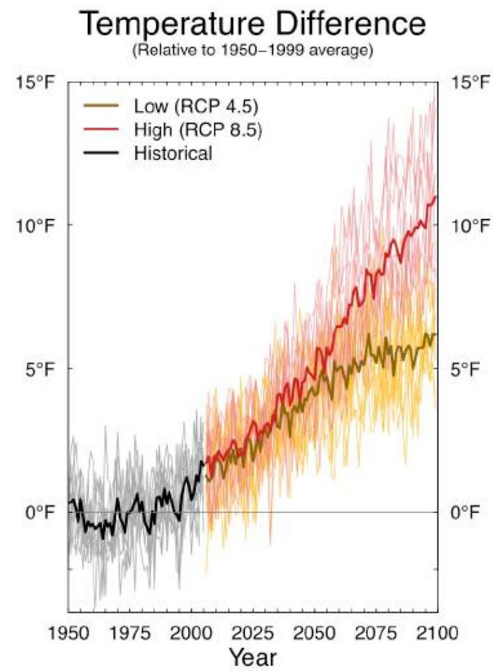

Figure ES-2. The Puget Sound region is projected to warm considerably in the 21st century. The graph shows average annual air temperatures projected by climate models, relative to the average for 1950-1999 (horizontal gray line; the average annual temperature for the Puget Sound region is 44°F). Thin 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]

- **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)*

- **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).*

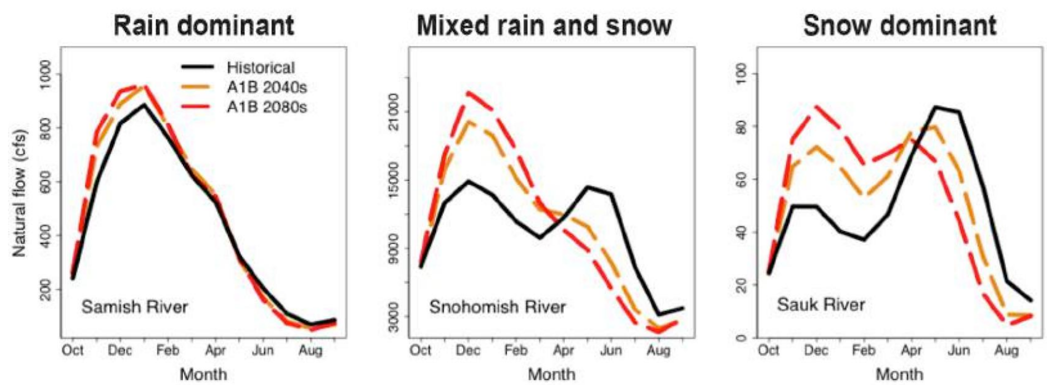

Figure ES-3. Streamflow is projected to increase in winter and decrease in summer, and changes are greatest for watersheds located near the current snowline. Changes in the seasonal timing of streamflow, on average, for three illustrative watersheds in Puget Sound: The Samish River, a warm basin (left); 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.

> *"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]

- **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.

- **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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1 (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

2 Snover et al. 2013. *Introduction: The Changing Northwest*, Chapter 1 of *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities. Washington, DC. Island Press*

3 Hamlet, A.F. et al., 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. *Atmosphere-Ocean* 51(4): 392-415. doi: 10.1080/07055900.2013.819555

4 Mote, P. W. et al., 2015. *Integrated Scenarios for the Future Northwest Environment*. USGS ScienceBase. Data set accessed 2015-03-02 at https://www.sciencebase.gov/catalog/item/5006eb9de4b0abf7ce733f5c

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10 "*Adapting to Sea Level Rise at the Port of Bellingham*" case study, prepared for the Successful Adaptation in the Coastal Sector: Washington Practitioners Workshop, sponsored by the Climate Impacts Group at the University of Washington, March 20, 2013.

11 City of Anacortes. 2012. "*City of Anacortes, Water Treatment Plant, Climate Change Impact Mitigation."* Presentation to Washington State Senate Environment Committee by City of Anacortes Public Works, Committee Working Session, November 30.

12 Reeder, W.S. et al., 2013. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

SECTION 1
Making Sense of Climate Change Projections

Globally, greenhouse gas concentrations have risen substantially as a result of human activities, and have been a primary driver of warming. To make projections of future climate, scientists use "what if" scenarios of plausible future greenhouse gas emissions to drive computer model simulations of the earth's climate. There are multiple greenhouse gas scenarios, numerous global climate models – each constructed slightly differently – and multiple techniques for "downscaling" coarse global model projections to local scales. The many possible combinations of scenarios, models, and downscaling techniques are used to estimate a range of possible future climates. The range reflects some of the important unknowns regarding future choices in energy and technology, and in our understanding of the climate system. As scientists develop new scenarios or improve models and downscaling procedures, projections are periodically updated. This section describes the ingredients for making climate projections, and provides the context for comparing results from the two most recent international climate science reports (IPCC 2007[1] and 2013[2]).

Projections of Future Climate

How much and how fast climate changes[A] occur depends on both the amount of future greenhouse gas emissions and how the climate changes in response to those emissions. Irreducible uncertainty in both future greenhouse gas emissions and the climate system's response means that projections of future climate will always be represented by a range of plausible outcomes.

- *Since it is impossible to predict the exact amount of greenhouse gas emissions resulting from future human activities,* scientists use greenhouse gas scenarios to represent a range of different future conditions.

- *We cannot know which scenario is most likely.* Since we are unable to predict the future, we cannot say with certainty which greenhouse gas scenario is most likely to occur.

- *It is important to consider a range of potential outcomes.* There is no "best" scenario, and the appropriate range of scenarios depends on the specific climate impact

[A] In this report, the terms "climate change" and "global warming" are used interchangeably to refer to the human-induced (or "anthropogenic") changes brought on by increasing atmospheric concentrations of greenhouse gases.

under consideration. Deciding which scenario(s) to use involves clarifying how climate affects a particular decision and what level of risk is acceptable.

- *Projections will continue to be updated over time.* As the science of climate change progresses, new greenhouse gas scenarios and updated climate models will inevitably replace the current climate projections.

Greenhouse Gas Scenarios

New greenhouse gas scenarios used in IPCC 2013[2,3] range from an extremely low scenario involving aggressive emissions reductions to a high "business as usual" scenario with substantial continued growth in greenhouse gases. Although these scenarios were developed using a different methodology and span a wider range of possible 21st century emissions, many are similar to greenhouse gas scenarios used in previous assessments (Table 1-1, Figures 1-1 and 1-2).[B,C,4]

- *The previous scenarios have close analogues in the newer scenarios*. For example, the A1B scenario – used in many Pacific Northwest impacts assessments – is similar to the newer RCP 6.0 scenario by 2100, though closer to the RCP 8.5 scenario at mid-century.

- *In both sets of scenarios, the high end is a "business as usual" scenario (RCP 8.5, SRES A1FI)* in which emissions of greenhouse gases continue to increase until the end of the 21st century, and atmospheric CO_2 concentrations more than triple by 2100 relative to pre-industrial levels. It is unlikely that 21st century emissions will exceed these "business as usual" scenarios: both were selected to represent the upper end of plausible future emissions.

- *The newer scenarios include an aggressive mitigation scenario (RCP 2.6),* which would require about a 50% reduction in global emissions by 2050 relative to 1990 levels, and near or below zero net emissions in the final decades of the 21st century. One recent study estimates that 41% (range: 24% to 59%) of total global emissions projected for 2010-2060 under the RCP 2.6 scenario are already "committed", given the anticipated lifetime of existing fossil-fuel infrastructure.[D,5,6]

B The latest scenarios, used in the 2013 IPCC report, are referred to as Representative Concentration Pathways (RCPs; Van Vuuren et al. 2011[3]). The previous greenhouse gas scenarios, used in the 2001 and 2007 IPCC reports, are described in the Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000[C]).

C 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.

D The study considered emissions from *existing* infrastructure, comparing these to emissions projected by greenhouse gas scenarios for 2010 through 2060. The estimates do not account for additional emissions from new fossil-fuel infrastructure that may be installed after 2010.

- *All scenarios result in similar warming until about mid-century.* Prior to mid-century, projected changes in global climate are largely driven by the warming that is "in the pipeline" – warming to which we are already committed given past emissions of greenhouse gases. In contrast, warming after mid-century is strongly dependent on the amount of greenhouse gases emitted in the coming decades.

- *Greenhouse gas scenarios are consistent with recent global emissions.* Globally, greenhouse gas emissions are higher and increasing more rapidly since 2000 than during the 1990s (Figure 1-1).[2]

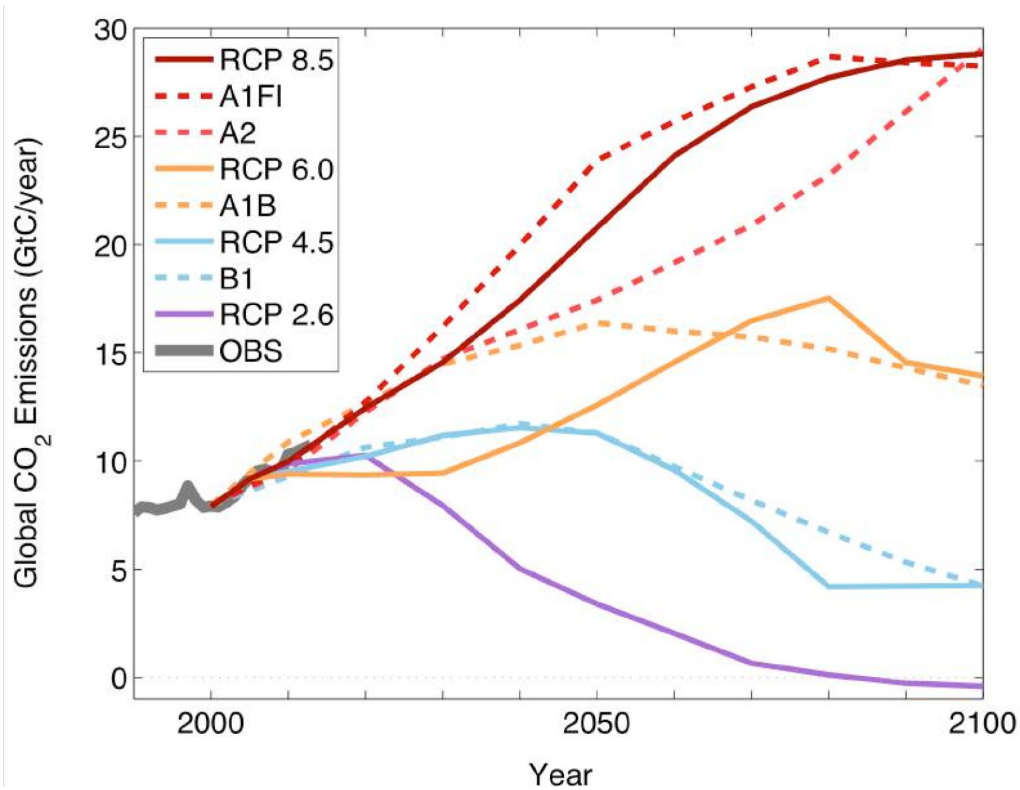

Figure 1-1. Future greenhouse gas scenarios range from aggressive reductions to large increases in greenhouse gas emissions. The figure shows annual global CO_2 emissions in gigatons of carbon (GtC). Though not the only greenhouse gas, CO_2 emissions are the dominant driver of human-caused warming. Actual emissions for 1990-2010 are shown in grey. Annual emissions projected for 2005-2100 are shown in color for two generations of greenhouse gas scenarios: the current scenarios (solid lines), and those from the previous generation (dashed lines). Similar scenarios are plotted using similar colors. Year-to-year emissions of greenhouse gases, as shown in this graph, accumulate in the atmosphere and cause CO_2 concentrations to rise, as shown in Figure 1-2. Scenarios with higher emissions cause atmospheric concentrations to rise rapidly, while lower scenarios cause concentrations to rise more slowly or decline. *Figure source: Based on data from Le Quéré et al. 2015,[7] IPCC 2007,[1] and IPCC 2013[2] (available at: http://dx.doi.org/10.5194/essdd-7-521-2014, http://tntcat.iiasa.ac.at:8787/RcpDb,[3] and http://sedac.ciesin.columbia.edu/ddc/sres/[4]).*

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Table 1-1. Previous greenhouse gas scenarios have close analogues in the new scenarios.

Current scenarios[2,3]	*Scenario characteristics*	*Comparison to previous scenarios* [1,4]	*Description used in this report*
RCP 2.6	An extremely low scenario that reflects aggressive greenhouse gas reduction and sequestration efforts	No analogue in previous scenarios	"Very Low"
RCP 4.5	A low scenario in which greenhouse gas emissions stabilize by mid-century and fall sharply thereafter	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	Similar to A1B by 2100, but closer to B1 at mid-century	"Moderate"
RCP 8.5	A high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century	Nearly identical to A1FI[E]	"High"

Global Climate Models

New climate change projections (IPCC 2013) also use new versions of the Global Climate Models (GCMs) developed to simulate changes in the Earth's climate. More models were used to develop the new projections, and they are improved relative to previous models.[8,9]

- *Global Climate Models (GCMs) are designed to represent the processes controlling Earth's climate.* These models incorporate the state-of-the-art in climate science. As a result, they are periodically updated as the science progresses.

- *It is important to consider a range of projections among multiple different climate models.* Each model simulates the earth's climate using a different set of approaches. As a result, each provides a unique estimate of the response of the climate to greenhouse gas emissions. In addition, the timing and sequence of natural variability (e.g., El Niño) is unpredictable, and will therefore be unique for each climate model simulation. For a given greenhouse gas scenario, the range among climate model projections encompasses both the range due to different climate models and due to natural variability. Since it is not known which projection is most accurate, a range of projections must be considered.

- *The range among climate model projections may not encompass the full range of potential future climate changes.* For a given greenhouse gas scenario, the range among climate model simulations provides an estimate of the uncertainty in projections. However, we cannot rule out the possibility that future changes in

E The A2 greenhouse gas scenario is between the RCP 6.0 and 8.5 scenarios.

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climate will be outside of the range projected by climate models.[10]

- *New climate models project similar climate changes for the same amount of greenhouse gas emissions.* Differences between the changes projected for the 2007 and 2013 IPCC reports are mostly due to differences in greenhouse gas scenarios: both sets of models project about the same amount of warming for similar greenhouse gas emissions (Figure 1-3).[8,11,12]

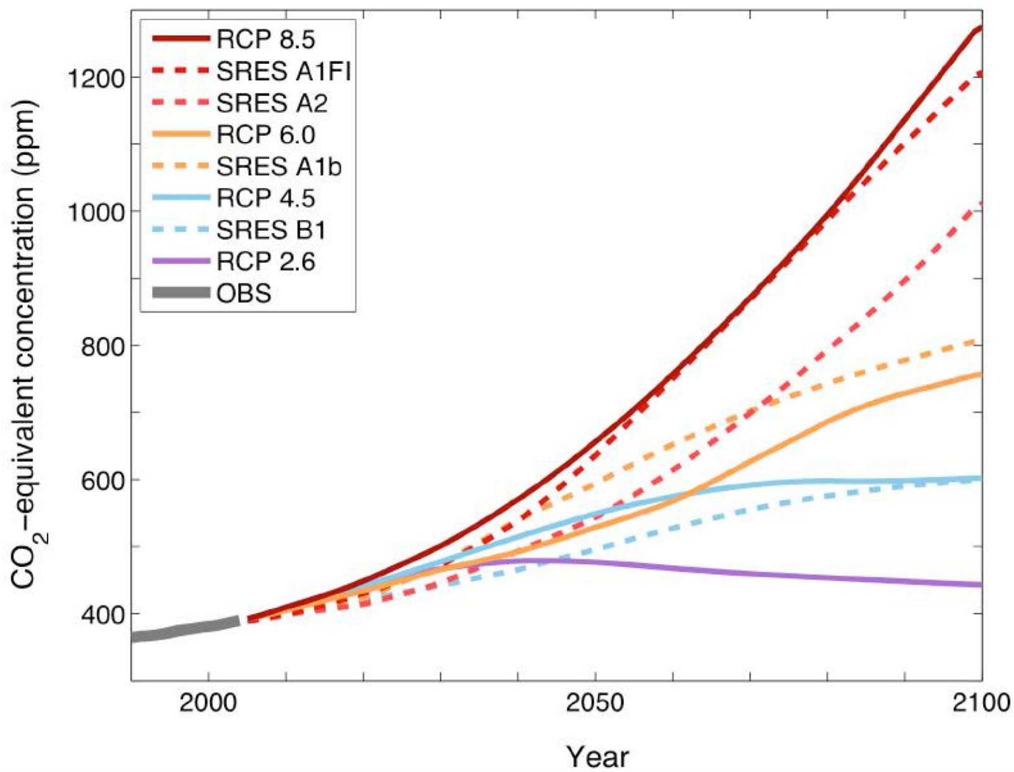

Figure 1-2. All scenarios project continued growth in atmospheric levels of greenhouse gases for the next few decades. The figure shows the equivalent CO_2 concentration, in parts per million (ppm), for each greenhouse gas scenario. CO_2-Equivalent is a measure that accounts for the global warming impact of all atmospheric greenhouse gases. Observed concentrations for 1990-2005 are shown in grey. Projected concentrations for 2005-2100 are shown in color for two generations of greenhouse gas scenarios: the current scenarios (solid lines), and those from the previous generation (dashed lines). Similar scenarios are plotted using similar colors. *Figure source: Based on data used in IPCC 2007[1] and IPCC 2013[2] (http://tntcat.iiasa.ac.at:8787/RcpDb[3] and http://sedac.ciesin.columbia.edu/ddc/sres/[C]).*

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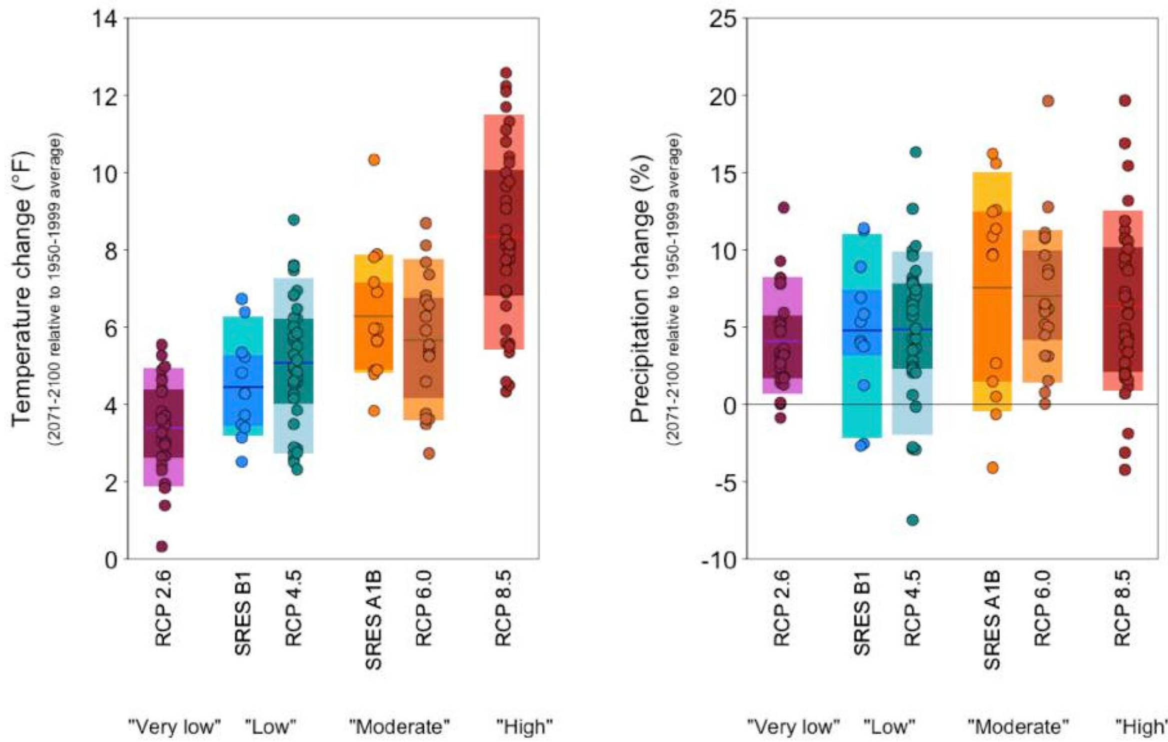

Figure 1-3. Differences in the change projected for the Puget Sound region by the current (IPCC 2013[2]) and previous (IPCC 2007[1]) global climate model simulations are primarily due to differences among greenhouse gas scenarios. Projected changes are shown for average annual temperature (left) and precipitation (right) for the Puget Sound region (46.5°-49.5°N, 123.5°-120.5°W) for the 2080s (2071-2100, relative to 1950-1999). Projections include all four new scenarios: RCP 2.6 ("very low"), 4.5 ("low"), 6.0 ("moderate"), and 8.5 ("high"), along with the two previous scenarios used in many regional impacts assessments: B1 ("low") and A1B ("moderate"). Individual climate model projections for each greenhouse gas scenario are shown using colored dots. Boxes show the average projected change (in °F for temperature and percent change for precipitation), along with the 10th, 25th, 75th, and 90th percentile values among all climate model projections. The black horizontal line on the precipitation graph denotes zero change. *Figure source: Based on climate projections used in the IPCC 2013 report.[2] and Figures 2.5b and 2.6 of Mote et al., 2013.[13]*

Downscaling

Climate change impacts are often assessed by first "downscaling" coarse resolution global model projections to local scales. Global Climate Models (GCMs) simulate changes at coarse spatial scales (~50-100 miles from one grid cell to the next), and therefore do not adequately represent local-scale weather and climate patterns.

- *Downscaled climate projections translate coarse resolution global model projections to a level of detail that is more relevant to management and decision-making.* This

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increased resolution (usually about 5 to 10 miles from one grid cell to the next) often provides a better representation of local climate, but also entails additional assumptions, which means that different approaches can give different results.

- *"Statistical downscaling" uses observed relationships between weather observations and coarse-scale GCM weather patterns.* An advantage of statistical downscaling is that it is inexpensive to implement. A disadvantage is that it does not capture the local-scale processes that can alter the response to warming at any particular location.

- *"Dynamical downscaling" uses a physical model, such as a regional climate model (RCM), which is driven by coarse-resolution GCM weather patterns.* An advantage of dynamical downscaling is that the model can capture important local-scale changes that cannot be represented with a statistical approach. A disadvantage is that it is expensive to implement, although RCM simulations are becoming increasingly feasible.

Implications for Puget Sound Climate Impacts Assessments

Impacts assessments that are based on the previous set of projections (IPCC 2007[1]) are likely very similar to those based on the newer projections (IPCC 2013[2]). New climate models project similar warming for the same amount of greenhouse gas emissions, and all scenarios result in similar warming until about mid-century. Although the current projections include a very low greenhouse gas scenario, this may not be achievable given the anticipated lifetime of existing fossil fuel infrastructure. The primary distinction between the current and previous projections is that the high-end scenario in the newer projections includes a much greater increase in greenhouse gas concentrations over the course of the 21st century. Although this does not affect projections for mid-century, the high-end projections for the end of the 21st century are substantially warmer in the newer projections.

- *Projected climate changes in the Puget Sound region are similar for current (IPCC 2013[2]) and previous (IPCC 2007[1]) scenarios of medium and low greenhouse gas emissions.* The Washington Climate Change Impacts Assessment (WACCIA)[14] and many other regional climate impact studies used the B1 and A1B greenhouse gas scenarios.[15,16] These are comparable to RCP 4.5 and RCP 6.0, respectively, at the end of the century, in terms of both greenhouse gas concentrations (Table 1-1, Figure 1-2) and resultant changes in climate projected for the Puget Sound region (Figure 1-3).

- *Newer scenarios for very low and high greenhouse gas emissions result in a wider range in projected late-century warming for the Puget Sound region.* Previous regional assessments have typically considered a narrower range of greenhouse gas scenarios.

- The newer scenarios include an aggressive greenhouse gas mitigation scenario (RCP 2.6), which assumes much lower emissions than in other scenarios. The older projections do not include a comparable scenario. Recent research shows that nearly half of the total greenhouse gas emissions projected under this scenario are already committed, given the anticipated lifetime of existing fossil-fuel infrastructure.[5,6]

- The highest scenarios commonly used in many previous climate impacts assessments (A1B, A2) are much lower than the high-end scenario in the current projections (RCP 8.5). It is unlikely that 21st century emissions will exceed the RCP 8.5 scenario: it was selected to represent the high end of plausible future emissions.

- *The importance of differences between the current and previous climate change projections will depend on the specific impact under consideration and the sensitivity of the decision being made.* For example, projected changes in annual average temperature are likely to differ by less than 1°F under similar greenhouse gas scenarios from IPCC 2007 and 2013, while projected changes in annual average precipitation are likely to differ by only a few percentage points (see Section 2, Figure 2-2). Other differences between the scenarios have not yet been explored.

- *Most existing climate change impacts assessments are based on statistical downscaling.* This means that some projections may change as dynamically downscaled simulations become more widely available. Although some comparisons have been made,[17] there has been no comprehensive assessment of the differences in projections between statistical and dynamical downscaling approaches.

This Report

In this report, the specific greenhouse gas scenarios and the number of climate models used are listed for each projection. Whenever possible, we report the range among projections. In addition, the future time frame of each projection is listed, along with the historical period to which it is compared (e.g., 1970-1999). Unless otherwise noted, all projections are based on a statistical downscaling of global model projections.

1 (IPCC) Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

2 (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

3 Van Vuuren, D. P. et al., 2011. The representative concentration pathways: An overview. *Climatic Change,* 109(1-2), 5-31.

4 Nakicenovic, N. et al., 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, U.K., 599 pp. Available online at: http://www.grida.no/climate/ipcc/emission/index.htm

5 Davis, S. J. et al., 2010. Future CO2 emissions and climate change from existing energy infrastructure. *Science*, *329*(5997), 1330-1333.

6 Davis, S. J., & Socolow, R. H. 2014. Commitment accounting of CO2 emissions. *Environmental Research Letters*, *9*(8), 084018.

7 Le Quéré, C. et al. 2015. Global carbon budget 2014. *Earth System Science Data*, *7*(1), 47-85. http://dx.doi.org/10.5194/essd-7-47-2015

8 Taylor, K. E. et al., 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485-498, doi:10.1175/BAMS-D-11-00094.1

9 Knutti, R. et al., 2013. Climate model genealogy: Generation CMIP5 and how we got there. *Geophys. Res. Lett*, *40*, 1194-1199, doi:10.1002/grl.50256

10 Flato, G., J. et al., 2013: Evaluation of Climate Models. 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* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available at: http://www.climatechange2013.org/report/full-report/

11 Andrews, T. et al., 2012. Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models. *Geophysical Research Letters*, *39*(9), doi: 10.1029/2012GL051607

12 Rupp, D. E., et al. (2013). Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. *Journal of Geophysical Research: Atmospheres*, *118*(19), 10-884.

13 Mote, P. W. et al., 2013. Climate: Variability and Change in the Past and the Future. Chapter 2, 25-40, in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

14 Climate Impacts Group, 2009. *The Washington Climate Change Impacts Assessment*, M. McGuire Elsner, J. Littell, and L Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. Available at: http://www.cses.washington.edu/db/pdf/wacciareport681.pdf

15 Hamlet, A.F., et al. 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. *Atmosphere-Ocean,* 51(4), 392-415, doi: 10.1080/07055900.2013.819555

16 Salathé, E. P., et al. 2013. *Uncertainty and Extreme Events in Future Climate and Hydrologic Projections for the Pacific Northwest: Providing a Basis for Vulnerability and Core/Corridor Assessments.* Project Final Report to the PNW Climate Science Center. Available at: http://cses.washington.edu/cig/data/WesternUS_Scenarios.pdf

17 Salathé Jr, E. P., et al. 2014. Estimates of twenty-first-century flood risk in the Pacific Northwest based on regional climate model simulations. *Journal of Hydrometeorology*, *15*(5), 1881-1899.

SECTION 2
How Is Puget Sound's Climate Changing?

Puget Sound is experiencing a suite of long-term changes that are consistent with those observed globally as a result of human-caused climate change. These include increasing air temperatures, a longer frost-free season, nighttime warming, and a possible increase in the intensity of heavy rainfall events. Continued increases in average annual and seasonal Puget Sound air temperatures are projected as a result of climate change, as well as increases in extreme heat. Projected changes in annual precipitation are generally small, although summer precipitation is projected to decrease and heavy rainfall events are projected to become more severe. Natural variability can have a strong effect on trends – as evidenced by recent regional cooling – and will continue to influence shorter-term (up to several decades) climate trends in the future.

Observed Changes

OBSERVED ***The Puget Sound region[A] has experienced long-term warming, a lengthening of the frost-free season, and more frequent nighttime heat waves.***

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

A Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

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

C In this section, 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.

D 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 (see inset in Figure 2-1) 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: http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php

- *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 (generally occurring in afternoon) warmed by +0.8°F over the same time period.[D,1]

- *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.[E,3,4]

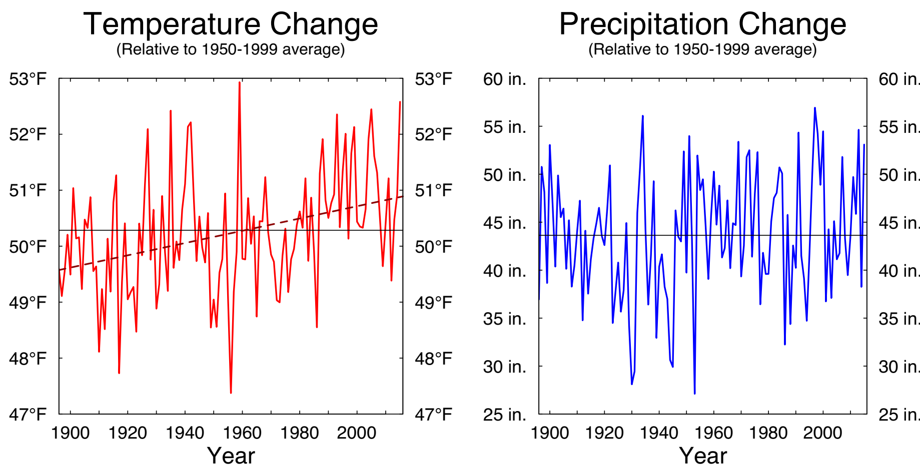

Figure 2-1. Temperature is rising in the Puget Sound lowlands, and there is no long term trend in precipitation. Average annual air temperature (top left, red, in °F) and total annual precipitation (top right, blue, in %) for the Puget Sound Lowlands climate division[D] (dark blue shading in map), shown relative to the average for 1950-1999 (black horizontal line in both graphs, corresponding to 50.3°F for annual aveage 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)[B] from 1895 to 2014. The trend for precipitation is not statistically significant, and therefore is not shown. *Data source: Vose et al. 2014.*[D,1]

E Trends are based on an average of the anomalies (difference between each year and the long-term average) for the eight Puget Sound stations used by Abatzoglou et al. (2014).[3] Stations were only included in the analysis if at least 75% of years of monitoring data available, with each year missing no more than 20% of days within a year, from 1920-2014. Data were obtained from John Abatzoglou, with trends estimated using a standard linear regression. The range gives the 95% confidence limits.

- *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[F] (1901-2009).[5] No significant trend has been found for daytime heat events.

- *Short-term trends can differ substantially from the long-term trend.* The Puget Sound region's highly variable climate often results in short-term cooling trends, as well as warming trends larger than the long-term average (Figure 2-1, Table 2-1). The cooling observed from about 2000 to 2011, for example, is similar to cooling observed at other times in the 20th century, despite overall long-term warming.

- *Long-term air temperature trends are affected by natural variability, although there is continued debate about the extent of its influence.* Natural climate variability has a strong influence on trends: one previous study estimated that about half of the observed increase in air temperature in the northern hemisphere (1900-1990) is a result of random natural variability.[6] A more recent study has presented evidence that over 80% of the observed trend in surface air temperature for Washington, Oregon, and California (1900-2012) can be explained by changes in atmospheric circulation (specifically, variations in surface pressure and winds), which may or may not result from human-induced warming.[7] Others have repeated the analysis using different datasets and found no evidence for the long-term change in circulation.[8,9]

- *Measurement biases can affect local trends, but will have a much smaller effect on regional trends.* Estimates of air temperature changes over time can be affected by changes in the location, the number of measurements made, and in the instruments used to make the measurements. The air temperature datasets reported here include corrections for these factors.[10] Even with these corrections, trend estimates can still be affected by measurement biases, and the effect will be greater when considering smaller regions or areas with sparse observations. Although potentially important for individual stations, the effect on regional average trend estimates is likely to be small: one published study analyzed annual average air temperature trends for the contiguous U.S., and found that these issues had a very small effect on long-term trends, and that the bias actually led to an underestimate of the warming trend.[11]

OBSERVED ***There has been no discernible long-term trend in precipitation for the Puget Sound region.***

- *Year-to-year variability in total precipitation is large compared to long-term trends.* Natural variability has a large influence on regional precipitation, causing ongoing fluctuations between wet years and dry years and wet decades and dry decades.

F 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.

- *Spring precipitation is increasing, but no other trends are statistically significant.* Seasonal and annual precipitation trends are generally not statistically significant, and in all cases are smaller than natural year-to-year variations. The one exception is spring (Mar-May) precipitation, which increased by +27% in the Puget Sound lowlands, from 1895 to 2014.[D,1]

- *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.[12,13,14] For example, one study found a statistically-significant +23% increase in the annual-maximum 48-hour event for the Puget Sound region (1981-2005 relative to 1956-1980).[14] Not all trends are statistically significant – results depend on the dates and methods of the analysis.

Natural Climate Variability

NATURAL VARIABILITY ***Large-scale fluctuations in weather patterns and ocean conditions drive short-term (up to several decades) natural variability in Puget Sound's climate.*** Two of the dominant patterns are the El Niño – Southern Oscillation (ENSO, otherwise known as El Niño and La Niña) and the Pacific Decadal Oscillation (PDO). These climate patterns are associated with variations in ocean temperatures, local surface winds, air temperatures, and precipitation.[15] ENSO and PDO are just two examples: other fluctuations in weather patterns can have an effect on the climate of Puget Sound.

- *ENSO and PDO are both large-scale patterns of climate variability in which sea surface temperatures over large parts of the Pacific Ocean are unusually warm in some places and unusually cool in others.* The two patterns are not entirely independent.[15,16] The main difference between them is that for ENSO, the largest changes in ocean temperatures are in the tropics, while the associated changes in the North Pacific are much smaller. The opposite is true for the PDO: larger changes in the North Pacific, smaller changes in the tropics. In addition, typical ENSO events are more seasonal and much shorter in duration: ENSO events usually persist for 6-18 months, whereas PDO events can persist for 20-30 years.[17]

- *Warm ENSO (El Niño) and warm PDO events generally increase the likelihood of warmer coastal ocean and higher air temperatures in winter for the Puget Sound region.* Conversely, cool ENSO (La Niña) and cool PDO events generally produce cooler winters. Precipitation is not strongly related to ENSO and PDO events.[15,18,19,20]

- *It is not known how ENSO might change with warming.* Some climate models project increases while others project decreases in the frequency of ENSO events. Global model projections of ocean surface temperature show a pattern of change that resembles the changes observed during an El Niño. However, the magnitude of the warming due to climate change is much lower. In addition, the global patterns of temperature and precipitation resulting from global warming (e.g., the associated changes in Puget Sound's climate) do not resemble those observed in El Niño years.[21]

- *Recent research has found that a new type of El Niño, the so-called "El Niño Modoki" (or "Central Pacific El Niño"), has become more common in the 20th century, and is projected to become still more common in the 21st century.* The changes in large-scale weather patterns brought on by an El Niño Modoki, including those affecting Puget Sound's climate, are very different than those that occur with a typical El Niño event.[G,22]

Projected Changes

PROJECTED ***The Puget Sound region is projected to warm rapidly during the 21st century.*** Prior to mid-century, the projected increase in air temperatures is about the same for all greenhouse gas scenarios, a result of the fact that a certain amount of warming is already "locked in" due to past emissions. After about 2050, projected warming depends on the amount of greenhouse gases emitted globally in the coming decades (see Section 1).[23,24]

- *All scenarios project warming.* Warming is projected to continue throughout the 21st century (Figure 2-2, Table 2-2). For the 2050s (2040-2069, relative to 1970-1999), annual average air temperature is projected to rise +4.2°F to +5.5°F, on average, for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario.[H,I,J] Much higher warming is possible after mid-century (Figure 2-2, Table 2-2).[23] Lower emissions of greenhouse gases will result in less warming.

- *Warming is projected for all seasons.*[K] The projected increase in summer air temperature is greater than for other seasons.[23]

G Based on an analysis of 6 global climate model projections and a moderate (A1b) greenhouse gas scenario.

H 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.

I Greenhouse gas scenarios used in this report generally range from a low (RCP 4.5) to a high (RCP 8.5) greenhouse gas scenario (both of which are used in the recent IPCC report,[27] see Section 1). The implications of the lowest greenhouse gas scenario – RCP 2.6, which assumes aggressive reductions in emissions – are not discussed in the text of this section because there are no published projections specific to the Puget Sound region that are based on this scenario.

J 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.[25]

K Unless otherwise noted, seasons are defined as follows in this report: Winter (December-February), Spring (March-May), Summer (June-August), Fall (September-October).

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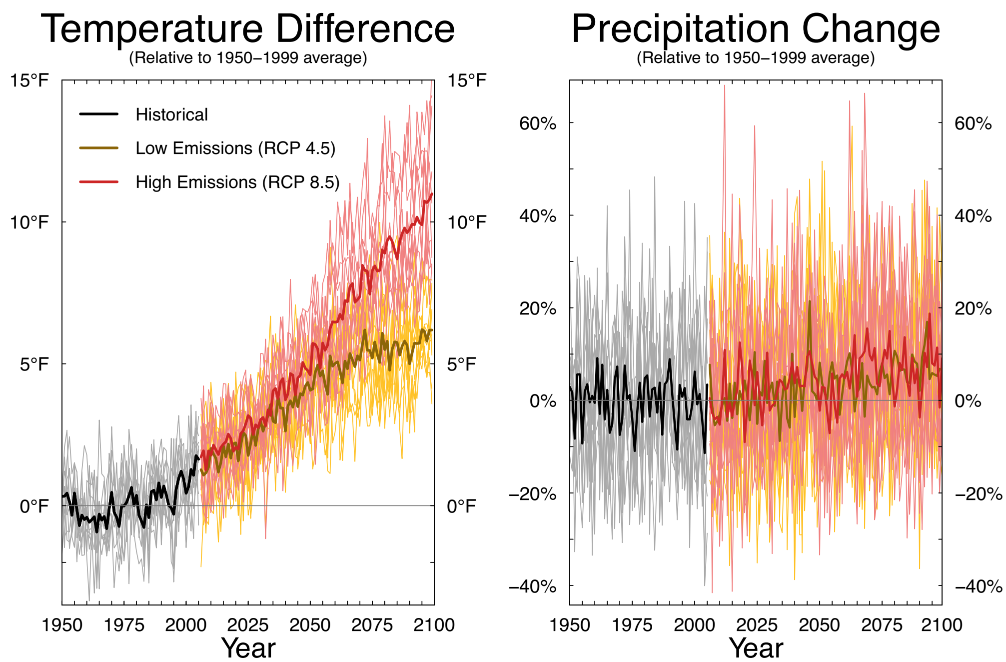

Figure 2-2. All scenarios project warming in the Puget Sound region for the 21st century; projected changes in annual precipitation are small compared to year-to-year variability. The graphs show average yearly air temperature and precipitation for the Puget Sound region, relative to the average for 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 grey 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. *Data source: Downscaled climate projections developed by Abatzoglou and Brown (2011).*[26,23,27]

- *More extreme heat is likely, although the increase may be moderated by changes in weather patterns.* There is strong agreement among climate models that extreme heat events will become more frequent while extreme cold events will become less frequent.[23,24] Recent research has suggested that changes in atmospheric circulation will cause heat waves to increase less rapidly (in terms of both the frequency and intensity of heat events) in coastal areas such as the Puget Sound region.[28,29]

- *Ongoing variability will continue to play a role in regional climate.* Natural variability will remain an important feature of global and regional climate, at times amplifying or counteracting the long-term trends caused by rising greenhouse gas emissions. Important modes of natural variability for the Puget Sound region include the El Niño/Southern Oscillation (ENSO, otherwise known as El Niño and La Niña) and the Pacific Decadal Oscillation (PDO). Current research is inconclusive as to how ENSO and other modes of climate variability may change as a result of warming (see

Section 6).[30,31]

- *The projected warming for the Puget Sound region is large compared to year-to-year variability.* The Puget Sound region is likely to regularly experience average annual air temperatures by mid-century that exceed what was observed in the 20th century.[L,23]

PROJECTED Changes in annual and fall, winter, and spring precipitation will continue to be primarily driven by year-to-year variations rather than long-term trends. All models project a decline in summer precipitation for the Puget Sound region.

- *Small changes in annual precipitation are projected.* Projected changes in total annual precipitation are small (relative to historical variability)[M] and show increases or decreases depending on models. The projected changes for the 2050s (2040-2069, relative to 1970-1999) range from a decline of −2% to an increase of +13%.[J,23]

- *Summer precipitation is projected to decline.* In contrast to annual precipitation, all scenarios project drier summers (June-August),[K] for the Puget Sound region.[25] Models project a decline of −22%, on average, for the 2050s (2040-2069, relative to 1970-1999) for both a low and a high greenhouse gas scenario.[J,23] One individual model projection shows a −50% decrease in summer precipitation. Because only about 10% of annual precipitation falls in this season, these reductions would not represent a large change in rainfall. However, summer rains help reduce both municipal and agricultural water demand at a time when water availability is limited.

- *Projected changes in fall, winter, and spring precipitation are mixed.* Although some models project decreases, a majority of models project increases in winter, spring, and fall precipitation for the 2050s (2040-2069, relative to 1970-1999), ranging from +2 to +11%, on average.[J,23]

- *Winter precipitation extremes are projected to increase.* Heavy rainfall events – so-called "Atmospheric River" events – are expected to become more severe. Global models project that the heaviest 24-hour rain events in western Oregon and Washington[F] will intensify by +22%, on average, by the 2080s (2070-2099, relative to 1970-1999). These high intensity events are also projected to occur more frequently: occurring about seven days per year (range: four to nine days per year)

L Specifically, all scenarios project that, by mid-century (2040-2069), average annual air temperature will be warmer than the warmest year historically (1950-1999).

M Year-to-year variations in precipitation are about ±10 to 15%, on average.

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by the 2080s in comparison to two days per year historically.[N,32] Another study evaluating extreme rainfall projections for the Sea-Tac weather station reported similar results.[14]

- *Research is lacking regarding the effect of climate change on thunderstorms and lightning in the Puget Sound region.* Thunderstorms are rare in the Puget Sound region due to cold ocean temperatures and warm upper air. Climate change results in competing effects: reductions in summer precipitation may cause thunderstorm activity to decrease, while increased land surface temperatures may trigger more thunderstorms. Changes in atmospheric circulation could also affect thunderstorm activity.[33,34] It is not known how these effects will combine to affect the frequency and intensity of thunderstorms.

- *Projected shifts in the storm track are small.* Possible increases in variability in the speed or position of the jet stream are speculative and may not significantly affect precipitation in the Puget Sound region. Warming is expected to cause the storm tracks to shift towards the poles, and possibly alter the frequency and magnitude of high and low pressure events. The climate model projections used in IPCC 2013[26] project a northward shift of about 1° latitude in the average position of the North Pacific storm track – this is a small shift and would not substantially alter the precipitation reaching the Puget Sound region.[35] Similarly, climate models do not project a change in wind speed or the strength of low pressure systems. Although some studies suggest that warming will result in a "wavier" (i.e., more variable) storm track,[35,36,37] this is considered highly speculative. 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.[38,39] In addition, it is unclear how such changes might affect the Puget Sound region.[40]

Although the projected change in annual and seasonal precipitation is smaller than historic variability, the change in heavy precipitation is not. Projected changes in annual and seasonal precipitation are generally small, throughout the 21st century, compared to the variability in precipitation resulting from natural year-to-year fluctuations. In addition, projected changes are not consistent among models: some project increases while others project decreases.[24] This is in contrast with the large changes projected for heavy precipitation events, which are expected to exceed the range of variability shortly after mid-century.[32]

For more details on observed and projected changes in Puget Sound climate, see Tables 2-1 and 2-2.

[N] 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 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.

Online Tools and Resources

The following tools and resources are suggested in addition to the reports and papers cited in this document.

Historical Observations:

- Trends in temperature, precipitation, and snowpack for individual weather stations across the Pacific Northwest: http://www.climate.washington.edu/trendanalysis/
- Trends in temperature and precipitation for Washington State and specific regions within the state: http://charts.srcc.lsu.edu/trends/
- Centralized resource for observed climate trends and data in Washington State: http://climate.washington.edu/
- Centralized resource for observed climate in the Western U.S.: http://www.wrcc.dri.edu/

Climate Variability:

- **NOAA Climate Prediction Center:** Provides information on seasonal weather predictions and large-scale weather patterns such as El Niño. http://www.cpc.ncep.noaa.gov/
- **Joint Institute for the Study Atmosphere and Ocean PDO website:** Provides a brief overview, along with figures, links, and references on the Pacific Decadal Oscillation (PDO). http://research.jisao.washington.edu/pdo/

Climate Change Projections:

- **Global Climate Model (GCM) projections:** Interactive tool to explore global climate model projections of changing temperature and precipitation in the Pacific Northwest, including separate results for coastal and inland areas: http://cig.uw.edu/resources/analysis-tools/projections/
- **Time of Emergence:** This dataset serves data and figures that show the "Time of Emergence" of climate trends throughout the region, defined as the year in which a particular climate trend emerges from natural year-to-year variability. http://toe.cig.uw.edu
- **Local-Scale Projections:** Interactive tools to visualize MACA (Multivariate Adaptive Constructed Analogs) statistically downscaled climate projections: http://maca.northwestknowledge.net/

Downscaled Climate Change Projections

The following datasets provide location-specific information about climate change effects to support identification and reduction of risks associated with a changing climate. Some resources are designed so that any user can easily browse, view, and download products; others assume more technical knowledge.

- **Climate, hydrologic, and vegetation change scenarios.** The Pacific Northwest Climate Impacts Research Consortium recently completed a new set of projections, which include changes in climate, hydrology, and vegetation. The projections are produced at a daily time step and a spatial resolution of about four miles, and are based on the newest set of climate model projections (IPCC 2013,[27] see Section 1). http://climate.nkn.uidaho.edu/IntegratedScenarios/index.php

- **Climate and hydrologic scenarios.** The Climate Impacts Group provides downscaled daily historical data and projected future temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and specific streamflow locations throughout the Columbia River basin and the western U.S. The projections are produced at a daily time step and a spatial resolution of about four miles, and are based on the previous set of climate model projections (IPCC 2007).[Error! Bookmark not defined.] http://warm.atmos.washington.edu/2860,[Error! Bookmark not defined.] http://cig.uw.edu/datasets/wus/[Error! Bookmark not defined.]

- **Fine scale climate scenarios for the lower 48 states.** Produced by NASA, this dataset provides projections of future monthly air temperature and precipitation, developed using updated statistical downscaling methods. The projections are produced at a daily time step and a spatial resolution of about half a mile, and are based on the new climate projections included in IPCC 2013.[26,27] https://portal.nccs.nasa.gov/portal_home/published/NEX.html

- **Regional climate model projections for the Pacific Northwest.** Regional climate model simulations (dynamical downscaling) over the Pacific Northwest are currently archived and under development at the Climate Impacts Group. Among other advantages, these data are more accurate for projecting changes in extremes.[Error! Bookmark not defined.] The projections are produced at a 6-hourly time step and a spatial

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resolution of about seven miles, and are based on projections from both IPCC 2007**Error! Bookmark not defined.** and 2013.[27] http://cig.uw.edu/datasets/wrf/

- **Regional climate model projections for the western U.S.** This dataset includes a large ensemble of regional climate model projections, based on a high greenhouse gas scenario (A2). Simulations are archived for numerous different regional and global climate models, all at a spatial resolution of about 30 miles. These are based on projections in IPCC 2007.[26] http://narccap.ucar.edu/

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Table 2-1. Observed trends in Puget Sound climate.

Variable	Observed Change [C]
Temperature	
Annual	Warming: +1.3°F (range: +0.7°F to +1.9°F for 1895-2014)[B,C,D,1]
Seasonal	Warming in most seasons (1895-2014)[D,1]
	Fall Warming: +0.12°F/decade (range: +0.07 to +0.17)
	Winter Warming: +0.13°F/decade (range: +0.02 to +0.24)
	Spring No significant change
	Summer Warming: +0.13°F/decade (range: +0.07 to +0.19)
Extremes	Statistically significant increase in nighttime heat events west of the Cascade Mountains in Oregon and Washington (1901-2009).[5] No significant trends in daytime heat events.
Freeze-free Season	Lengthening: +30 days (+3 days/decade for 1920–2014).[E,3,4]
Precipitation	
Annual	No significant change (1895-2014) [D,1]
Seasonal	Wetter springs (1895-2014)[D,1]
	Winter No significant change
	Spring Increasing: +2.3%/decade
	Summer No significant change
	Fall No significant change
Extremes	Most studies find increases in the frequency and intensity of heavy precipitation events, but few are statistically significant. Results depend on the dates and methods of the trend analysis. [12,13,14]

Table 2-2. Projected trends in Puget Sound climate.

Variable	Projected Long-term Change
Temperature	
Annual	Annual average air temperatures are projected to increase. Warming is projected for all greenhouse gas scenarios, and the amount of warming depends on the amount of greenhouse gases emitted. *Projected change in Puget Sound average annual air temperature:* **2050s** (2040-2069, relative to the average for 1970-1999):[J,23] Low emissions (RCP 4.5): +4.2°F (range: +2.9 to +5.4°F) High emissions (RCP 8.5): +5.5°F (range +4.3 to +7.1°F) **2080s** (2070-2099, relative to the average for 1970-1999):[J,23] Low emissions (RCP 4.5): +5.5°F (range: +4.1 to +7.3°F) High emissions (RCP 8.5): +9.1°F (range: +7.4 to +12°F)
Seasonal	Warming is projected for all seasons for the Puget Sound. *Projected change in Puget Sound seasonal air temperature:* **2050s** (2040-2069, relative to 1970-1999):[J,23] *Fall* Low emissions (RCP 4.5): +4.1°F (range: +2.6 to +5.6°F) High emissions (RCP 8.5): +5.6°F (range: +3.9 to +7.2°F) *Winter* Low emissions (RCP 4.5): +3.9°F (range: +2.8 to +5.0°F) High emissions (RCP 8.5): +4.9°F (range: +3.2 to +6.5°F) *Spring* Low emissions (RCP 4.5): +3.9°F (range: +2.4 to +5.3°F) High emissions (RCP 8.5): +4.8°F (range: +3.0 to +7.6°F) *Summer* Low emissions (RCP 4.5): +5.1°F (range: +3.3 to +7.5°F) High emissions (RCP 8.5): +6.8°F (range: +4.8 to +9.7°F) **2080s** (2070-2099, relative to the average for 1970-1999):[J,23] *Fall* Low emissions (RCP 4.5): +5.2°F (range: +3.7 to +7.1°F) High emissions (RCP 8.5): +9.0°F (range: +6.5 to +11°F) *Winter* Low emissions (RCP 4.5): +5.0°F (range: +4.3 to +6.3°F) High emissions (RCP 8.5): +8.3°F (range: +6.0 to +10°F) *Spring* Low emissions (RCP 4.5): +5.3°F (range: +3.8 to +8.2°F) High emissions (RCP 8.5): +7.9°F (range: +5.2 to +11°F)

Variable	*Projected Long-term Change*
	Summer Low emissions (RCP 4.5): +6.4°F (range: +4.6 to +9.1°F) High emissions (RCP 8.5): +11°F (range: +8.8 to +15°F)
Extremes	Heat waves are projected to intensify, while cold snaps are projected to become less severe. *Projected changes in Puget Sound air temperature extremes:* **2050s** (2040-2069, relative to 1970-1999):[O,23] Temperature of hottest days: +6.5°F (+4.0 to +10.2°F)[P] Temperature of coolest nights: +5.4°F (+1.3 to +10.4°F)[Q] Heating degree days: −1600 deg-days (−2300 to −1000)[R] Cooling degree days: +17 deg-days (+5 to +56) Growing degree days: +800 deg-days (+500 to +1300) **2080s** (2070-2099, relative to 1970-1999):[O,23] Temperature of hottest days: +9.8°F (+5.3 to +15.3°F)[P] Temperature of coolest nights: +8.3°F (+3.7 to +14.6°F)[Q] Heating degree days: −2306 deg-days (−3493 to −1387)[R] Cooling degree days: +52 deg-days (+6 to +200) Growing degree days: +1280 deg-days (+591 to +2295)
Precipitation	
Annual	Projected changes in precipitation are small. All models project changes that are small relative to year-to-year variability.

O Projections are based on 10 global models and two greenhouse gas scenarios (RCP 4.5 and 8.5), statistically downscaled following the procedures described by Mote et al. 2015.[23] For each metric, the average among all twenty scenarios is listed, along with the range in parentheses.

P Projected change in the 99th percentile of daily maximum temperature.

Q Projected change in the 1st percentile of daily minimum temperature.

R Cooling and heating degree days are measurements used in energy markets to estimate demand. In the United States, a cooling degree day is counted for each degree the average temperature for a day moves above 75°F. For example, if the average temperature for the day was 80°F, that would count as 5 cooling degree days. One heating degree day is counted for each degree that average daily temperature falls below 65°F. Growing degree days are calculated in the same way as cooling degree days, using a base temperature of 50°F.

Variable	*Projected Long-term Change*
	Projected change in annual Puget Sound precipitation: **2050s** (2040-2069, relative to 1970-1999):[J,23] Low emissions (RCP 4.5): +4.2% (range: +0.6 to +12%) High emissions (RCP 8.5): +5.0% (range: −1.9 to +13%) **2080s** (2070-2099, relative to the average for 1970-1999):[J,23] Low emissions (RCP 4.5): +6.4% (range: −0.2 to +10%) High emissions (RCP 8.5): +6.9% (range: +1.0 to +9.4%)
Seasonal	Precipitation is generally projected to decrease in summer and increase in fall, winter, and spring. For all seasons except summer, most models project wetter conditions while others project drier conditions. All models project decreases in summer precipitation. *Projected change in Puget Sound seasonal temperature:* **2050s** (2040-2069, relative to 1970-1999):[J,23] *Fall* Low emissions (RCP 4.5): +5.5% (range: −5.7 to +13%) High emissions (RCP 8.5): +6.3% (range: −2.4 to +19%) *Winter* Low emissions (RCP 4.5): +9.9% (range: −1.6 to +21%) High emissions (RCP 8.5): +11% (range: +1.8 to +19%) *Spring* Low emissions (RCP 4.5): +2.4% (range: −9.4 to +13%) High emissions (RCP 8.5): +3.8% (range: −7.7 to +13%) *Summer* Low emissions (RCP 4.5): −22% (range: −45 to −6.1%) High emissions (RCP 8.5): −22% (range: −50 to −1.6%) **2080s** (2070-2099, relative to 1970-1999):[J,23] *Fall* Low emissions (RCP 4.5): +12% (range: +1.6 to −21%) High emissions (RCP 8.5): +10% (range: +1.9 to +15%) *Winter* Low emissions (RCP 4.5): +11% (range: +1.3 to +16%) High emissions (RCP 8.5): +15% (range: +6.2 to +23%) *Spring* Low emissions (RCP 4.5): +1.6% (range: −3.2 to +9.3%) High emissions (RCP 8.5): +2.5% (range: −6.7 to +11%) *Summer* Low emissions (RCP 4.5): −20% (range: −37 to −10%) High emissions (RCP 8.5): −27% (range: −53 to +10%)

Variable	***Projected Long-term Change***
Geography of Change	*Changes in precipitation are expected to be different from place to place, but it is not known how patterns will shift with warming.*
Heavy Precipitation	*Heavy precipitation events are projected to become more intense.* Projected changes in western Oregon and Washington precipitation extremes for the 2080s (2070-2099, relative to 1970-1999) for a high (RCP 8.5) greenhouse gas scenario:[N,32] Annual 99th percentile of 24-hour precipitation: +22% (range: +5 to +34%) Frequency of exceeding the historical 99th percentile of 24-hour precipitation: Historical (1970-1999): 2 days / year Future (2070-2099): 7 days / year (range: 4 to 9 dys/yr)

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SECTION 3

How will Climate Change Affect the Water Cycle?

The Puget Sound region is projected to experience an ongoing decrease in snowpack and glaciers, a continued shift from snow to rain, increasing stream temperatures, a continued shift to earlier peak streamflows, an increase in the frequency and extent of flooding, and declining summer flows. These changes, which have widespread implications for people, infrastructure, and ecosystems, will be most pronounced in mid-elevation basins that have historically received a mix of rain and snow during winter. Most Puget Sound watersheds will be rain-dominant by the end of the 21st century. Combined with sea level rise and an increase in the intensity of heavy rain events, the decrease in snow accumulation will contribute to a widespread increase in the frequency and size of winter flood events. Impacts on water users and ecosystems vary, but generally point to increased competition for water during the summer and increased flood risk in winter. Efforts to address hydrologic impacts are increasing, particularly in the areas of flood risk reduction, water supply planning, and hydropower.

Climate Drivers of Change

DRIVERS ***Changes in snowpack, streamflow, and other aspects of the water cycle are driven by changes in temperature, heavy rainfall, and seasonal precipitation.*** Non-climatic factors, including reservoir management and changes in land use and land cover can also have an important influence.

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2] As a consequence, there is high confidence in the warming-related changes in water resources.
- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[3]
- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year variability. Overall, there is much lower confidence in the precipitation-dependent changes in water resources.[2]
- *Although climate is a major driver of changing hydrology, there are other factors that*

can have an important effect on streamflow and water availability. For instance, changes in land use and land cover – both due to development and forest management – can dramatically affect the hydrology of the region.[4] Similarly, many watersheds contain reservoirs, which are often used to control the timing and amount of river flows. Changes in reservoir operations can have substantial effects on streamflow, and represent potential adaptation opportunities. Although some studies have recently begun assessing the combined effects of changes in climate, water management, and land use,[4,5,6,7] previous studies have typically evaluated the effect of climate change in the absence of changes in other factors influencing the region's hydrology. Unless otherwise noted, the hydrologic projections cited in this report consider only the effects of climate change, against which the effects of other changes can be compared.

Observed Changes in Snow, Ice, and Streamflow

OBSERVED ***Long-term changes in snow, ice, and streamflows reflect the influence of warming on the hydrology of the Puget Sound region.***[A]

- *Spring snowpack is declining.* Spring snowpack fluctuates substantially from year-to-year, but declined by about –25% (or about –4%/decade) in the Washington Cascades[B] from the mid-20th century to 2006.[8,9,10] This trend is due primarily to regional warming, but reflects the influence of both climate variability and change.[11,12] Natural variability can dominate over shorter time scales. For example, there was an apparent (though not statistically-significant) increase in spring snow accumulation from 1976 to 2007.[C,8]

- *Most Puget Sound glaciers are in decline.* Observed decreases range from a –56% (±3%) loss of glacier area in the North Cascades (1900-2009)[13] to a –34% decline in area in the Olympic Mountains (1980-2009).[14] In addition to the observed declines in glacier area, observations show consistent decreases in glacier volume and the total number of glaciers remaining.[14,15] One recent study found that the number of glaciers in the Olympics had declined by –31% (from 266 glaciers in 1980 to 184 in 2009).[14] Trends vary substantially from decade-to-decade. 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.[13,16] In the North Cascades, 10% to 44% of total summer streamflow is estimated to

A Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see *"How to Read this Report"*, page *vi*).

B 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.

C In this section, trends are reported if they are statistically significant at the 90% confidence level or more.

originate from glaciers, depending on the watershed.[17]

- *Trends in annual streamflow are weak, but dry years are becoming drier for some rivers*. There is no statistically significant trend in annual average streamflow.[18,19] However, some Puget Sound rivers show a statistically significant trend towards lower streamflow in dry years (i.e.: "dry years get drier").[18,20,21]

- *The timing of streamflow is shifting earlier.* 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.[22]

Projected changes in Hydrology

PROJECTED ***As is the case for much of the western U.S., the Puget Sound region is projected to experience decreasing snowpack, a continued shift from snow to rain, increasing stream temperatures, earlier streamflow timing, increased flooding, and declining summer minimum flows.*** The largest changes are projected for mid-elevation basins with significant snow accumulation (today's so-called "mixed rain and snow" watersheds; Figures 3-1 and 3-2, Table 3-2).[D,E,23]

PROJECTED ***Snowpack and glaciers in the Puget Sound region are projected to decline.*** As air temperatures warm, snow is projected to accumulate less in winter and melt more rapidly in spring and summer.

- *Snowpack is projected to decline.* 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 and a high greenhouse gas scenario.[F,G,H,I,24]

D Watersheds are classified based on the proportion of precipitation that falls as snow versus rain during winter (October-March). "Rain dominant" basins (i.e., watersheds with warm winter air temperatures), receive less than 10% of winter precipitation as snow. In contrast, colder watersheds are classified as "snow dominant" if they receive more than 40% of winter precipitation as snow. "Mixed rain and snow" basins are middle elevation basins, near the current snowline, that receive between 10 and 40% of winter precipitation as snow. These different basin types will experience different changes as a consequence of warming. Washington watershed classifications are shown in Figure 3-1.

E In this section, projected changes are primarily reported for the 2080s. Longer planning horizons are often most applicable to infrastructure planning, water resource management, and forest management. Other management situations (e.g., agriculture, public health) are more suited to shorter planning horizons.

F 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 more details.

G These numbers indicate 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 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).

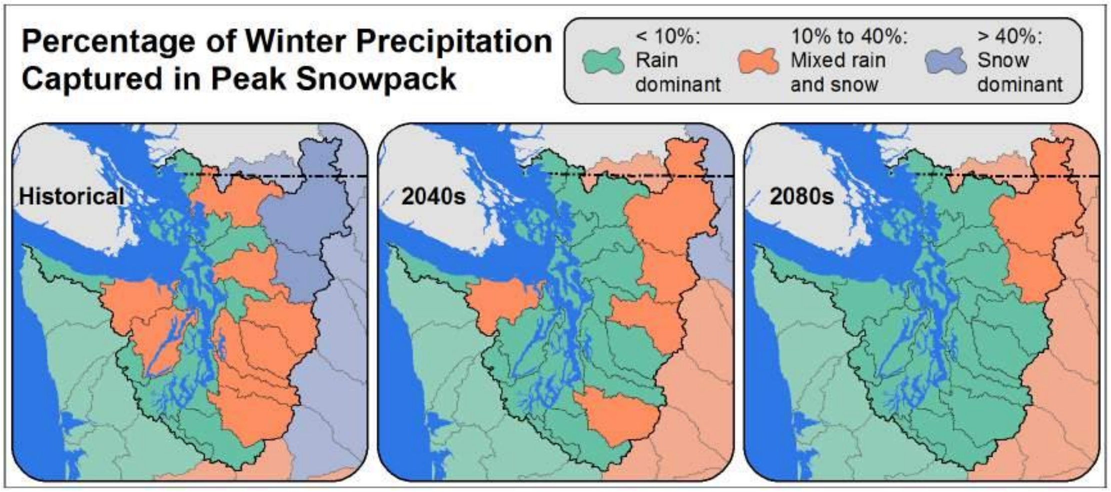

Figure 3-1. Models project a dramatic shift to more rain-dominant conditions in Puget Sound watersheds. Maps above indicate current and future watershed classifications, based on the proportion of winter precipitation stored in peak annual snowpack. Graphs below indicate current and future average monthly streamflow for these watershed types. Both compare average historical conditions (1970-1999) and average projected future conditions for ten global models, two time periods: the 2040s (2030-2059) and the 2080s (2070-2099), and a moderate greenhouse gas scenario (A1B). Green shading in the maps indicates *warm ("rain-dominant") watersheds*, which receive little winter precipitation in the form of snow. In these basins, streamflow peaks during winter months and warming is projected to have little effect (below, left). Blue indicates *cold ("snow-dominant") watersheds,* that is, cold basins that receive more than 40% of their winter precipitation as snow. Depending on elevation, these basins are likely to experience increasing winter precipitation as rain and increased winter flows (below, right). The most sensitive basins to warming are the *watersheds that are near the current snowline ("mixed rain and snow")*, shown in red shading in the maps. These are middle elevation basins that receive a mixture of rain and snow in the winter, and are projected to experience significant increases in winter flows and decreases in spring and summer flows as a result of warming (below, center). 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.*[24]

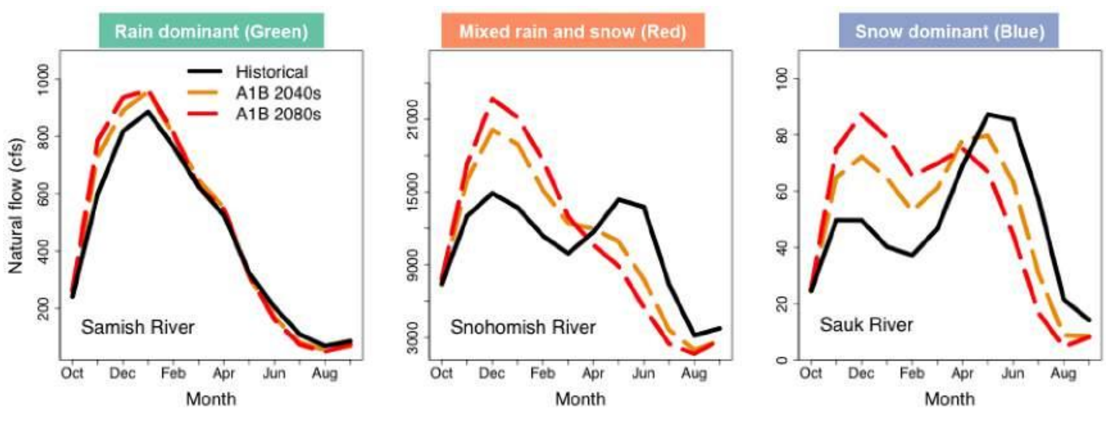

Figure 3-2. Streamflow is projected to increase in winter and decrease in spring and summer for all basin types, with the biggest changes occurring in "mixed rain and snow" watersheds. Results are shown for the Samish River, a warm basin (left); the Sauk River, a cold basin with source waters at high elevations (right) and the Snohomish River, a middle-elevation basin with substantial area near the current snowline (middle). Projections are described in the caption for Figure 3-1. *Data source: Hamlet et al., 2013.*[24]

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- *Although only two studies have assessed the implications of 21st century climate change for Puget Sound glaciers, both indicate that continued recession is likely.* One study found that only two of the 12 North Cascades glaciers with annual measurements are expected to survive under current climate conditions, regardless of future warming.[27] Another study modeled glacier response in three Puget Sound tributaries (Thunder Creek and the Cascade and Nisqually Rivers). All scenarios showed that glaciers remained in 2100, but that glacier area declined substantially, particularly after mid-century.[28]

PROJECTED ***As watersheds become increasingly rain dominant, streamflow is projected to increase in winter and decrease in spring and summer, and the timing of peak flows is projected to shift earlier.*** Although total annual streamflow is only projected to change slightly, the seasonal timing of streamflow is projected to shift earlier in snow-influenced watersheds, with warming bringing higher flows in winter and lower flows in summer. Changes in streamflow are smaller in lowland basins due to the lack of winter snow accumulation; in these basins, land use and development patterns may have a larger influence than climate change.

- *Watersheds will become increasingly rain-dominant*. By the end of the 21st century, the dominant form of precipitation in most Puget Sound watersheds will be rainfall (Figure 3-1). In contrast, many have historically been strongly influenced by snowfall in winter. The two exceptions are the Upper Skagit and Sauk watersheds in the North Cascades: due to their relatively higher elevation, snow accumulation is projected to remain important through 2100, in spite of substantial declines in winter snowpack.

- *Streamflow timing is projected to shift earlier.* The spring peak in streamflow is projected to occur earlier in mixed-rain and snow and snow-dominant basins (see red and blue shading in Figure 3-1). For the 12 major Puget Sound watersheds analyzed, peak streamflow is projected to occur about two to six weeks earlier, on average, by the 2080s (2070-2099, relative to 1970-1999) for a moderate greenhouse gas scenario (A1B).[J,K,L,24]

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

I There are two principal datasets that 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,[25] which stem from the newer 2013 IPCC report,[26] and (2) the previous set of projections, developed by Hamlet et al. in 2010,[24] based on the climate projections used in the IPCC's 2007 report[32] 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. For comparison, we have included a summary of the newer projections in Appendix A.

J Projected changes in streamflow were calculated for 12 Puget Sound watersheds. Listed in clock-wise order, starting at the US-Canadian border, they are: the Nooksack R. at Ferndale (USGS #12213100), Samish R. Nr. Burlington (USGS #12201500), Skagit R. Nr. Mt Vernon (USGS #12200500), Stillaguamish R. (Flows were obtained for the NF Stillaguamish R. Nr. 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

- *Projected increase in annual streamflow is small.* Annual streamflow is projected to increase by +6 to +7% on average for the Puget Sound region by the 2080s (2070-2099, relative to 1970-1999).[H,24] These changes are likely to be dwarfed by natural year-to-year variations through the end of the century.

- *Winter streamflow is projected to increase*. Total winter streamflow for the Puget Sound region is projected to increase by +28 to +34% on average by the 2080s (2070-2099, relative to 1970-1999).[H,24]

- *Summer streamflow is projected to decrease*. Total summer streamflow for the Puget Sound region is projected to decrease by −24 to −31% on average by the 2080s (2070-2099, relative to 1970-1999).[H,24]

- *There are no published projections of changing streamflow variability.* Although the shift to a more rain dominant regime could lead to more variability in winter streamflow, no study has quantified the effect.

- *Most streamflow projections do not consider the effects of reservoir operations.* Although there are exceptions (discussed below), few of the published studies account for the effects of reservoir management on changing streamflows. In basins with sufficient reservoir capacity, some of the previously cited changes (e.g., decreasing summer streamflow) could potentially be mitigated via changes in flow regulation.

- *Land-use change could have a greater effect than climate change on the magnitude and timing of streamflow in some lowland basins.* One study recently evaluated changes in streamflow due to land cover and climate change for the Puget Sound basin for 2050 (2035-2065, relative to 1970-1999), based on a moderate (A1B) greenhouse gas scenario.[M] The simulations showed that changes in streamflow for snow-influenced watersheds are primarily driven by climate change, but that low-elevation (rain dominant) watersheds could be more strongly influenced by changes in development and land use.[5,7] The climate change simulations did not include recent projections for an increase in the intensity of heavy rain events (see below),[29] which could alter the results for lowland basins.

PROJECTED ***Flood risk is projected to increase.*** Multiple factors combine to drive large increases in flood risk: declining snowpack, intensifying heavy rain events, and rising seas.

- *Peak river flows are projected to increase.* The highest river flows are expected to increase by +18% to +55%, on average, for 12 Puget Sound watersheds[J] by the

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#12101500), Skokomish R. Nr. Potlach (USGS #12061500), Dungeness R. at Dungeness (USGS #12049000), and Elwha R. at McDonald Bridge Nr. Port Angeles (USGS #12045500).

K Calculations are based on the change in streamflow "Center Timing" (CT). CT is defined as the day of the water year (starting on October 1st) when cumulative streamflow reaches half of its total annual volume.

L Projected change for ten global climate models for a moderate (A1B) greenhouse gas scenario.

M Land use and land cover change scenarios, which were compared to climate change projections, were based on the years 2002, 2027, and 2050.

2080s (2070-2099, relative to 1970-1999), based on a moderate (A1B) greenhouse gas scenario.[H,24] Although most scenarios project increases in flood flows, some project small decreases for rain dominant watersheds, where changes in winter snow accumulation are minor. These projections do not include projected increases in the intensity of heavy rain events.

- *Increases in heavy rainfall events could further increase flood risk.* Heavy rainfall events are projected to become more severe by mid-century (see Section 2). Global models project that the heaviest 24-hour rain events in the Pacific Northwest will intensify by +19%, on average, by the 2080s (2070-2099, relative to 1970-1999).[N,3] These changes are not included in current hydrologic change modeling for the region, but would likely lead to a further increase in peak streamflows, adding to the projected increases cited above.[24,25]

- *Changes in flood management may not always be sufficient to mitigate increases in flood risk.* In the Skagit River, for instance, with current flood management practices, the magnitude of the 100-year peak streamflow event is projected to increase by +49% on average by the 2080s (2070-2099, relative to 1970-1999).[O] Simulations indicate that even with changes in water management designed to decrease peak flows, the 100-year flood flow will still increase by +42% (only 7% less than with current practices). The risk of flooding remains high because the dams on the Skagit only affect a portion of the watershed – other major uncontrolled tributaries contribute substantially to downstream flooding.[P,5,6]

- *Sea level rise will exacerbate coastal river flooding*. Higher sea level can increase the extent, depth, and duration of flooding by making it harder for flood waters in rivers and streams to drain to Puget Sound. In the Skagit River floodplain, 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 larger floods.[Q,30,31,32] A similar study found that the 10-year event would flood +19% to +69% more area in the lower Snohomish River floodplain by the 2080s.[R,33]

N Projections are based on an analysis of the 99th percentile of daily water vapor transport, the principal driver of heavy rain events in the Pacific Northwest. Projections stem from 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 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.

O Projected change based on five global climate models and a moderate (A1B) greenhouse gas scenario.

P Results are based on a reservoir operations model, five global climate model simulations, and the moderate A1B greenhouse gas scenario.

Q Sea level rise projections were obtained from the 2007 IPCC report[32]; streamflow projections were based on 10 global climate model projections and a moderate (A1B) greenhouse gas scenario. Flood simulations assume all levees would remain intact, although they could be overtopped. When levee failure scenarios are included, the increase in flooded area is much less pronounced. With levee failure, much of the floodplain would be inundated even in the absence of climate change – increased flows and higher sea levels do increase water depths, but do not significantly change the area flooded.

PROJECTED ***Low flow extremes are projected to become more severe.***

- *Summer minimum flows are projected to lower.* Low summer streamflow conditions are projected to become more acute in all Puget Sound watersheds analyzed, decreasing by –16% to –51% on average for the 2080s (2070-2099, relative to 1970-1999).[L,J,24] Rain dominant and mixed rain and snow basins show the greatest and most consistent decreases in minimum flows; changes in snow dominant basins are smaller.[34] These projections do not account for expected changes in the supply of meltwater from glaciers.

- *Summer meltwater from some glaciers may initially increase, but the supply of meltwater is projected to decline sharply by the end of the century.* Projections indicate that glaciers may augment minimum flows through mid-century due to the increased rate of melt, but nearly all scenarios show a sharp decline in glacial meltwater in the late 21st century as glaciers diminish further in size.[28]

PROJECTED ***Water temperatures are projected to increase.*** Stream temperatures are doubly affected by climate change: both by warmer air temperatures and declining summer flows.

- *Stream temperatures are projected to increase.* River and stream temperatures generally track air temperatures, but do not change as rapidly. In Puget Sound, stream temperatures are projected to increase by +4.0°F to +4.5°F by the 2080s (2070-2099, relative to 1970-1999),[S,35] in response to increasing air temperature and decreasing summer streamflow.

- *Puget Sound rivers are projected to more frequently exceed thermal tolerances for cold-water fish species.* By the 2080s, the number of river miles with August stream temperatures in excess of thermal tolerances for adult salmon (64°F) and charr (54°F)[T,36] is projected to increase by 1,016 and 2,826 miles, respectively.[S,35] Many are projected to exceed thermal tolerances for the entire summer season, despite rarely being in excess of these temperatures in the recent past.[37]

- *The duration of time exceeding thermal tolerances is projected to increase.* One study examining 37 Puget Sound stream monitoring stations found that 12 of the 37 sites currently experience weekly average stream temperatures in excess of 64°F.[T,36] By the 2080s (2070-2099, relative to 1970-1999), these 12 streams are projected to experience an increase in the duration of stream temperatures above the 64°F

R 2070-2099, relative to 1970-1999. Projections are based on 10 global climate model simulations and the moderate (A1B) greenhouse gas scenario.

S Based on a composite of ten global climate model projections for a moderate (A1B) greenhouse gas scenario.

T In this report we use the regulatory thresholds listed in EPA (2007),[36] which defines 12°C (54°F) and 17.5°C (64°F) as the criteria for protecting adult charr and salmon, respectively. Note that some analyses consider the average monthly water temperature for August, which will likely result in an underestimate of the implications for maximum weekly August temperatures. Optimal water temperature ranges for Pacific salmon are species-, life-stage-, and size-dependent, so individual responses to warming streams will vary.

threshold, ranging from an average annual increase of +0 to +7.5 weeks.[U,44]

PROJECTED ***Year-to-year variability will continue to cause some periods that are abnormally wet, and others that are abnormally dry.*** For the foreseeable future, the region will continue to experience years and decades with conditions that temporarily mask or amplify the projected changes in water resources, even as long-term trends continue. For example, even late in the 21st century individual years can have as much spring snowpack as the historical average, in spite of substantial declines overall.

PROJECTED ***These changes will have far-reaching consequences for people, infrastructure and ecosystems across the Puget Sound region.*** Climate change effects on water resources will pose increasing challenges in the decades ahead. The examples below indicate the potential sector-specific consequences of climate change in the absence of management adjustments to reduce impacts. Although not included in these projections, changes in water management to alleviate the effects on one sector – i.e., hydropower production, irrigation or municipal supply, or instream flows for fish – could exacerbate the effects on other sectors.[38]

- *Hydropower production is projected to decrease in summer, and increase in winter and spring.* Hydropower production is projected to reflect the seasonal changes in streamflow: increases in winter, and decreases in summer. Estimating the specific effects on hydropower systems is challenging, given the relatively rapid changes in demand, energy markets, and regulation. For the Skagit watershed, hydropower production is projected to increase in winter and spring and decrease in summer, though there is debate about the exact amount of change, given the large influence of reservoir management.[P,39] In the Columbia River basin, an important source of power for much of Puget Sound, hydropower production is projected to increase by +5% in winter (January-March) and decrease by −12 to −15% in summer (July-September) by the 2040s (2070-2099, relative to 1970-1999).[H,V,40] These declines could translate into an inability to meet summer power demands with hydropower alone – this would require energy suppliers to seek other energy sources, possibly at higher cost.[41,42]

- *Many Pacific salmon populations could be harmed by warming stream temperatures, increasing winter peak flows, and decreasing summer low flows.* These changes may affect salmon growth and survival across many life stages and habitats,[43] particularly for salmon populations that have an in-stream rearing life stage (e.g., steelhead, stream-type Chinook salmon, sockeye salmon, and Coho).[44] Some species and sub-populations may remain relatively unharmed by climate change or may have access to cold water "refugia" within their normal range, affording them some

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U Based on an average of 10 global climate model projections and a moderate (A1B) greenhouse gas scenario.

V The Columbia River Treaty, which governs flood control and power generation benefits provided by Columbia basin reservoirs in the U.S. and Canada, is due to be updated. Any revisions to the treaty may require changes in reservoir operations on both sides of the border, which would have consequences for hydropower.

protection from increased temperatures elsewhere. Population diversity may also provide a buffer for species decline, as populations that are more adapted to warm conditions survive and reproduce in greater numbers (see Section 10).

- *Flood protection and stormwater management could become more costly.* Increases in flooding can increase the cost of protecting and maintaining infrastructure, affect water quality via increasing sediment and nutrient loads, and result in increased landslide risk (see Sections 5 and 12).[45]

- *Existing studies find that the reliability of municipal water supply is largely unaffected.* Assuming no change in demand, new sources of supply or significant changes in operating procedures, water supply for Everett is projected to remain near 100% reliability (no water shortages) through the 2080s (2070-2099, relative to 1970-1999) and decrease to 93-96% for Tacoma under low and moderate greenhouse gas scenarios.[W,X,46] For Seattle, previous studies found that supply is projected to exceed demand in nearly all years through the end of the 21st century.[46,47] Current work, based on the high end of the latest set of climate projections, suggests that Seattle's water supply could be more strongly affected by warming.[Y]

- *Small increases in municipal demand are projected for the greater Seattle area*. Municipal demand in Seattle is projected to increase by +1% in 2025, +2% in 2050, and +5% in 2075 (relative to 2000), assuming current population forecasts, no new conservation measures, and the warming projected based on a high greenhouse gas scenario.[Z,46,47]

- *Consequences for management are likely to be greatest in snow-influenced basins where water conflicts already exist.* Vulnerability to projected changes in snowmelt timing is probably highest in basins with the largest hydrologic response to warming and lowest management flexibility – that is, fully allocated mixed rain and snow watersheds with existing conflicts among users of summer water. In contrast, vulnerability is probably lowest where hydrologic change is likely to be smallest (in rain-dominant basins), where institutional arrangements are simple, and current natural and human demands rarely exceed current water availability.[W,48,49,50,51]

- *The ski season is projected to shorten.* Historically (1971-2000), Washington ski areas have experienced warm winters (average December-February air temperature above freezing) anywhere from 0 to 33% of the time, depending on location. In response to a warming of +3.6°F – the lower end of the range projected for mid-century (see Section 2) – warm winters would occur 33 to 77% of the

W Reliability is defined as the probability of meeting municipal water supply demand in a given water year (Oct-Sep).

X Average water supply reliability projected by ten global climate models. Range stems from a combination of variations among two different reservoirs supplying water to Tacoma, as well as a low (B1) and moderate (A1B) greenhouse gas scenario.

Y Based on preliminary results from research conducted by Seattle Public Utilities. At the time of this writing, the full set of model results have not yet been analyzed.

Z Projection based on the IPSL global climate model coupled with a high greenhouse gas scenario (A2).

time.[AA,52]

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Many Puget Sound communities, government agencies, and organizations are preparing for the effects of climate change on water resources.*** Most are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

River flooding:

- *King County has begun modifying its flood infrastructure in preparation for projected flooding increases.* New projects include:
    - *Levee improvements and flood-risk reduction activities.* King County formed a new Flood Control District in 2007 to increase county capacity for addressing regional flood risks due to a variety of factors, one of which was climate change. The creation of the new District resulted in a ten-fold increase in local funding[BB] for flood risk reduction efforts. Accomplishments in 2014 include mapping of channel migration hazards along the Cedar River, completing a critical levee extension project, implementing five projects that raised structures in flood zones, and purchasing forty-two acres of floodplain on the Tolt, Snoqualmie, Cedar, and White rivers (including 20 acres in Pierce County). Public ownership of this land and removal of structures will reduce flood risks and preclude development in these flood prone areas.[53,54]
    - *Widening bridge spans and increasing the resilience of roads.* As of 2012, King County had replaced 15 short span bridges with wider span structures and 42 small culverts with large box culverts. These changes will increase resilience of bridges and roads to major flooding. In many cases these wider structures also allow for the movement of a variety of wildlife along the river's edge during normal flows and elevated flood events thereby protecting wildlife connectivity between critical habitats.[53] King County's Road Services Division[CC] will incorporate information about changes in future flooding, storm size and frequency, and landslide risk projections into roads maintenance and preservation programs and projects. [54]
- *Preparing interstate and state routes in the Skagit River basin for climate change.* WSDOT recently completed a project which developed site-specific adaptation

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[AA] The ski areas evaluated for Washington State were: Bluewood, Mt. Spokane, Mt. Baker, Crystal Mountain, Mission Ridge, White Pass, the Summit at Snoqualmie, Stevens Pass, and Hurricane Ridge.

[BB] Funding for the Flood Control District comes from a county-wide property levy of 10 cents per $1,000 assessed value. This amounts to $40 per year on a $400,000 home. The levy raises roughly $36 million a year. http://www.kingcountyfloodcontrol.org/

[CC] King County's Road Services Division maintains roads, bridges, culverts, and other related infrastructure in unincorporated King County.[54]

options to improve the resilience of Interstate 5 and state routes in the Skagit basin (Figure 12-2). For example, in response to Skagit River flooding on North SR 9 WSDOT highlighted two options that will reduce flood concerns for this route and will improve transportation infrastructure resilience to future flood events: (1) develop a new road alignment out of the floodway, and (2) raise the road in existing alignment.[55] This work complements flood hazard reduction strategies proposed by the U.S. Army Corps and Skagit County.

- *Washington State is incorporating climate change in multi-benefit flood risk management.* Through the Floodplains by Design program, the Washington State Department of Ecology is beginning to incorporate climate risk into state funding programs by prioritizing floodplain infrastructure projects that provide holistic solutions that consider the effects on people, agriculture, and ecosystems. Many projects – such as the Calistoga levee setback project in Orting – result in additional storage for flood waters, thus reducing the downstream risk of flooding. Project proposals are evaluated, in part, on the extent to which they address the risks posed by climate change.

Drinking water supply:

- *Seattle is taking steps to ensure supply exceeds demand for Seattle.* Seattle Public Utilities has undertaken numerous evaluations of climate change impacts and potential response options, including identifying no or low-cost system modifications to mitigate climate change-related water supply reductions and demand increases. Previous analyses undertaken by the City indicate that no new source of water supply is needed before 2060 and that, under the warmest scenario considered, available supply would exceed forecasted demand if all modifications are implemented. Depending on the relative timing of system modifications and climate change effects, climate change could increase the frequency of requests to customers to curtail water use.[47]

- *The new Anacortes Water Treatment Plant was designed to be robust to climate change.* Climate change 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 altered design includes elevated structures, water-tight construction with minimal structural penetrations and no electrical control equipment below the current 100-year flood elevation, and more effective sediment removal processes.[56,57]

Long-range planning:

- *The 2009 Regional Municipal Water Supply Outlook included an assessment of the effects of climate change on water supply.* The report was developed by the Central Puget Sound Water Supply Forum, a collaboration among cities and agencies within Snohomish, King, and Pierce Counties*.* The Outlook included an evaluation of the combined effects of changing municipal supply and demand in 2007, along with an evaluation of possible water supply and conservation projects. Under all climate change and demand scenarios, the study found that existing water supplies are sufficient to meet demands through 2050. By 2060, the municipal water supply shortage could be as great as 100 million gallons per day,[DD] though the study also identified about 400 million gallons per day in water supply and conservation projects.[58] Scenarios are currently being evaluated for an updated edition of the report.

For more details on projected effects on Rivers and Streams, see Tables 3-1, 3-2 and 3-3.

[DD] Based on 3 statistically-downscaled global model projections and a low (B1) and high (A2) greenhouse gas scenario.

Additional Resources on Current and Future Water Resources

The following resources provide location-specific information about climate change impacts to support identification and reduction of risks associated with a changing climate.

- **Western U.S. Streamflow Metrics.** Modeled flow metrics (e.g.: peak streamflow, flow timing) for streams in the Western U.S. for historical and future climate change scenarios. Data available for the Pacific Northwest, which includes the Puget Sound catchment. http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml

- **USGS Water Watch.** Map of current streamflow compared to historical flow for Washington. http://waterwatch.usgs.gov/?m=real&r=wa

- **Climate, hydrologic, and vegetation change scenarios.** The Pacific Northwest Climate Impacts Research Consortium recently completed a new set of projections, which include changes in climate, hydrology, and vegetation. The projections are produced at a daily time step and a spatial resolution of about four miles, and are based on the newest set of climate model projections (IPCC 2013,[26] see Section 1). http://climate.nkn.uidaho.edu/IntegratedScenarios/index.php

- **Climate and hydrologic scenarios.** The Climate Impacts Group provides downscaled daily historical data and projected future temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and specific streamflow locations throughout the Columbia River basin and the western U.S. The projections are produced at a daily time step and a spatial resolution of about four miles, and are based on the previous set of climate model projections (IPCC 2007).[32] http://warm.atmos.washington.edu/2860,[24] http://cig.uw.edu/datasets/wus/[59]

- **Coastal Resilience Floodplain Explorer.** The Nature Conservancy has created a web-based mapping tool that combines sea level projections with other information on land use, infrastructure, and ecosystems. Users can also upload their own data for viewing alongside existing layers. http://maps.coastalresilience.org/pugetsound/[60]

Table 3-1. Observed changes in water resources.

Variable	*Observed Change*
Hydrology	
Snowpack	Long-term trends in snowpack show a robust decline. ▪ Washington Cascades snowpack decreased by about −25% (or about −4% per decade) between the mid-20th century and 2006, with a range of −15 to −35% depending on the starting date of the trend analysis (which ranged from about 1930 to 1970).[8,9,10,11] ▪ The frequently-reported increase in snowpack in recent decades (1976–2007) is not statistically-significant and is most likely the result of natural variability.[8] ▪ There are no published studies that have assessed observed changes in snowpack specific to the Puget Sound basin. Most have focused on the Washington Cascades or Pacific Northwest as a whole.
Glaciers	Observations show declines in the number, area, and volume of Puget Sound glaciers. ▪ Mt. Rainier: −14% decline in glacier volume (1970-2008)[62] ▪ Olympic Mtns: −34% decline in glacier area (1980-2009)[14] −31% decline in number of glaciers (1980-2009).[14] ▪ North Cascades: −56±3% decline in glacier area (1900-2009)[13] Trends in glacial melt vary from decade to decade. ▪ Example: North Cascades [13] 1900-1958: −46±5% decline in glacier area 1958-1990: −1±3% 1990-2009: −9±3% *Overall:* −56±3% [13] ▪ In the North Cascades, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed.[17]
Annual Streamflow	Dry years are becoming more dry. Trends in annual streamflow are relatively small in comparison to year-to-year variability, and almost none are statistically significant.[18,19] However, a study examining 43 Pacific Northwest gauges (including 5 in Puget Sound) found declining trends in dry years (25th percentile in annual flow), ranging from −19% to −31% (1948-2006), with 3 of the 5 Puget Sound gauges

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Variable	Observed Change
	showing a statistically-significant trend.[18]
Timing of Peak Streamflow	The timing of streamflow is shifting earlier for most locations. ▪ The spring peak in Puget Sound streamflow has shifted earlier in many snowmelt-influenced rivers. The shift ranges from no change to about 20 days earlier (1948-2002).[22]

Table 3-2. Projected changes in water resources.

Variable	Projected Long-term Change[H]
Snow	
Snowpack	Snowpack is projected to decline substantially ▪ Declines projected for *all* greenhouse gas scenarios; specific amount depends on the amount of greenhouse gases emitted.[F] ▪ Projected change in April 1st snowpack[G], on average for Puget Sound:[H,24] 2040s (2030-2059, relative to 1970-1999): low emissions (B1): −23% (range: −34 to −6%) moderate emissions (A1B): −29% (range: −47 to −4%) 2080s (2070-2099, relative to 1970-1999): low emissions (B1): −42% (range: −59 to −12%) moderate emissions (A1B): −55% (range: −83 to −17%)
Glaciers	Although only two studies have assessed the implications of 21st century climate change for Puget Sound glaciers, both indicate that continued recession is likely. ▪ An evaluation of current glacier status found that only 2 of the 12 North Cascades glaciers with annual measurements are expected to survive the current climate.[27] ▪ Another study modeled glacier response in three Puget Sound tributaries (Thunder Creek and the Cascade and Nisqually Rivers). All scenarios showed that glaciers remained in 2100, but that glacier area declined substantially, particularly after mid-century.[28]

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Streamflow

Annual

Annual streamflow is not projected to change substantially, and some models project increases while other project decreases.

- Change in annual streamflow, on average for Puget Sound:[H,24]

  2040s (2030-2059, relative to 1970-1999):
  - low emissions (B1): +2% (range: −17 to +14%)
  - moderate emissions (A1B): +5% (range: −9 to +18%)

  2080s (2070-2099, relative to 1970-1999):
  - low emissions (B1): +6% (range: −5 to +18%)
  - moderate emissions (A1B): +7% (range: −7 to +22%)

Winter

Most models project an increase in winter streamflow.

- Change in Winter (Oct-Mar) streamflow, on average for Puget Sound:[H,24]

  2040s (2030-2059, relative to 1970-1999):
  - low emissions (B1): +15% (range: −11 to +37%)
  - moderate emissions (A1B): +22% (range: +8 to +48%)

  2080s (2070-2099, relative to 1970-1999):
  - low emissions (B1): +28% (range: +13 to +58%)
  - moderate emissions (A1B): +34% (range: +12 to +64%)

- Changes are comparable to year-to-year variability: by the 2080s, the average projected change is near the high-end of the historical range (1950-1999).

Summer

All scenarios project a decrease in summer streamflow.

- Change in Summer (Apr-Sep) streamflow, on average for Puget Sound:[H,24]

  2040s (2030-2059, relative to 1970-1999):
  - low emissions (B1): −16% (range: −24 to −8%)
  - moderate emissions (A1B): −19% (range: −33 to −11%)

  2080s (2070-2099, relative to 1970-1999):
  - low emissions (B1): −24% (range: −37 to −11%)
  - moderate emissions (A1B): −31% (range: −46 to −13%)

- Changes are comparable to year-to-year variability: by the 2080s, the average projected change is near the high-end of the historical range (1950-1999).

Streamflow timing

Peak streamflows are projected to occur earlier in many snowmelt-influenced rivers.

- Change in the timing of peak streamflow for 12 Puget Sound watersheds[J] for the 2080s (2070-2099, relative to 1970-1999).

Average and range for a moderate (A1B) greenhouse gas scenario:[L,24]

Nooksack R.:	−27 days (−40 to −19 days)
Samish R.:	−40 days (−53 to −30 days)
Skagit R.:	−22 days (−36 to −13 days)
Stillaguamish R.:	−37 days (−48 to −29 days)
Snohomish R.:	−37 days (−49 to −29 days)
Cedar R.:	−37 days (−49 to −30 days)
Green R.:	−38 days (−50 to −31 days)
Nisqually R.:	−34 days (−45 to −25 days)
Puyallup R.:	−18 days (−30 to −9 days)
Skokomish R.:	−46 days (−56 to −38 days)
Dungeness R.:	−15 days (−35 to −6 days)
Elwha R.:	−28 days (−41 to −20 days)

Stream temperatures

Water temperatures are projected to increase.

- Puget Sound rivers are projected to increasingly experience average August stream temperatures stressful to salmon (in excess of 64°F) and char (in excess of 54°F).

- Increase in the number of river miles in excess of thermal tolerances, on average for the 2080s (2070-2099, relative to 1970-1999) and a moderate (A1B) greenhouse gas scenario, for 12 Puget Sound watersheds:[S,35]

Nooksack R.:	+205 mi. (>54 °F),	+136 mi. (>64 °F)
Samish R.:	+14 mi. (>54 °F),	+27 mi. (>64 °F)
Skagit R.:	+566 mi. (>54 °F),	+121 mi. (>64 °F)
Stillaguamish R.:	+176 mi. (>54 °F),	+103 mi. (>64 °F)
Snohomish R.:	+517 mi. (>54 °F),	+262 mi. (>64 °F)
Cedar R.:	+70 mi. (>54 °F),	+5 mi. (>64 °F)
Green R.:	+173 mi. (>54 °F),	+73 mi. (>64 °F)
Nisqually R.:	+179 mi. (>54 °F),	+24 mi. (>64 °F)
Puyallup R.:	+311 mi. (>54 °F),	+9 mi. (>64 °F)
Skokomish R.:	+120 mi. (>54 °F),	+3 mi. (>64 °F)
Dungeness R.:	+32 mi. (>54 °F),	+0 mi. (>64 °F)
Elwha R.:	+64 mi. (>54 °F),	+0 mi. (>64 °F)
All Puget Sound Rivers:		
	+2826 mi. (>54 °F),	+1016 mi. (>64 °F)

- Many stream locations projected to exceed 70°F for the entire summer season by the 2080s – resulting in waters that are warm enough to impede migration and increase the risk of fish kills.[37]

Flooding

Most scenarios project an increase in peak flows..

- Projected change in streamflow associated with the 100-year (1% annual probability) flood event for 12 Puget Sound watersheds, on average for the 2080s (2070-2099, relative to 1970-1999):[J]

  Average and range for a moderate (A1B) greenhouse gas scenario:[L,24]

Nooksack R.:	+27% (+9 to +60%)
Samish R.:	+23% (−9 to +101%)
Skagit R.:	+42% (+4 to +86%)
Stillaguamish R.:	+29% (+2 to +76%)
Snohomish R.:	+23% (+1 to +58%)
Cedar R.:	+19% (+2 to +37%)
Green R.:	+32% (+15 to +73%)
Nisqually R.:	+18% (−7 to +58%)
Puyallup R.:	+37% (+10 to +88%)
Skokomish R.:	+23% (+4 to +59%)
Dungeness R.:	+55% (+20 to +116%)
Elwha R.:	+29% (+5 to +50%)

- Projected changes in heavy rainfall (Section 2 of this report) may be underestimated in the above projections. Recent research, using regional climate model simulations, indicates that heavy rain events will increase more than in the statistically-based projections cited above. This would lead to larger increases in flood risk.[29]

- Changes in flood management may not be sufficient to mitigate increases in flood risk. In the Skagit River, for instance, simulations indicate that changes in water management are largely ineffective at mitigating increased flood risks.[P,6]

- Increase in the area flooded due to the combined effects of high river flows and sea level rise, for the 2080s (2070-2099, relative to 1970-1999):

  Skagit R. (100-yr event, average change): +74%[Q,30,31]
  Lower Snohomish R. (10-yr event, range): +19% to +69%[R,33]

Minimum flows Streamflow is projected to decline for summer minimum flows.

- Projected changes in summer minimum streamflow (7Q10)[EE] for 12 Puget Sound watersheds,[J] on average for the 2080s (2070-2099, relative to 1970-1999).

  Average and range for a moderate (A1B) greenhouse gas scenario:[L,24]

Nooksack R.:	−27% (−38 to −13%)
Samish R.:	−18% (−26 to −7%)

[EE] The 7Q10 flow is the lowest 7-day average flow that occurs on average once every 10 years. 7Q10 flows are a common standard for defining low flow for the purpose of setting permit discharge limits.

Skagit R.:	−51% (−65 to −38%)
Stillaguamish R.:	−22% (−32 to −7%)
Snohomish R.:	−26% (−33 to −17%)
Cedar R.:	−25% (−32 to −13%)
Green R.:	−16% (−21 to −7%)
Nisqually R.:	−27% (−35 to −17%)
Puyallup R.:	−27% (−39 to −16%)
Skokomish R.:	−18% (−22 to −8%)
Dungeness R.:	−35% (−45 to −27%)
Elwha R.:	−39% (−49 to −27%)

- Rain dominant and mixed rain and snow basins show the greatest and most consistent decreases in minimum flows, while changes for snow dominant basins are smaller.[34]

- The above projections do not account for contributions from melting glaciers. Projections indicate that glaciers may augment minimum flows in the near term due to the increased rate of melt, but nearly all scenarios show a sharp decline in meltwater in the late 21st century as glaciers diminish in size.[28]

Table 3-3. Projected impacts on water uses.

Variable	*Projected Long-term Change*
Water Resources	
Fish and Aquatic Ecosystems	Increasing peak flows, decreasing summer low flows, and warming stream temperatures are all projected to negatively affect salmon across many life stages and habitats,[43] particularly for salmon populations that have an in-stream rearing life stage (e.g., steelhead, stream-type Chinook salmon, sockeye salmon, and Coho).[44] (Section 10 of this report).
Hydropower production	Increasing winter and spring production, decreases in summer. ▪ *Skagit River basin.* Hydropower production (for Ross, Diablo, Gorge, Upper Baker, and Lower Baker dams) is projected to increase in winter and spring and decrease in summer, though there is debate about the exact amount of change, given that changes in reservoir operations can have a large effect on production.[P,39] ▪ *Columbia River basin.* Much of the power supplied to Puget Sound communities is generated by the Columbia River system. Projected changes in system-wide hydropower production, on average, by the 2080s (2070-2099, relative to 1970-1999)[H,V]: January-March: +8% to +11%

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Variable	Projected Long-term Change
	July-September: −21% to −17%
Municipal Water Supply	Changes in climate affect municipal water supply reliability differently for the three cities of Everett, Seattle, and Tacoma. ▪ Historically, all three cities have had at least 99% reliability, meaning that at most 1% of years experience water delivery shortfalls. ▪ Assuming no changes in demand, new sources of supply or significant changes in operating procedures, projected reliability for the 2080s (2070-2099, relative to 1970-1999): Everett: 100% Tacoma: 93 to 96%[W,46] ▪ For Seattle, previous studies found that supply is projected to exceed demand in nearly all years through the end of the 21st century.[46,47] Current work, based on the high end of the latest set of climate projections, suggests that Seattle's water supply could be more strongly affected by warming.[Y]
Municipal Water Demand	Small increases in municipal demand projected for the greater Seattle area. Municipal demand is projected to increase by 1% in 2025, 2% in 2050, and 5% in 2075 (relative to 2000), assuming current population forecasts and no new conservation measures, and the warming projected based on a high greenhouse gas scenario.[Z,47]
Ski Season	More warm winters ▪ Probability of a warm winter (average Dec-Feb air temperature above freezing) for Washington State ski resorts: Historic (1971-2000): 0 to 33%, depending on location With +3.6°F[FF] warming: 33 to 77%[52]

[FF] +3.6°F relative to 1971-2000 is near the low end of warming projected for mid-century.

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SECTION 4
How will Climate Change affect Sea Level?

The Puget Sound region is projected to experience continued sea level rise throughout the 21st century, increasing the potential for more frequent coastal flooding and increased erosion. These changes, which have significant implications for human, plant, and animal communities, will be most pronounced for places such as Seattle, where land elevations are subsiding. Sea level rise will permanently inundate some low-lying areas and will increase the frequency, depth, and duration of coastal flood events by increasing the reach of storm surge and making it harder for flood waters in rivers and streams to drain into Puget Sound. In addition to expected shifts in coastal and marine habitats, sea level rise is expected to damage coastal infrastructure, inundate commercial and industrial areas, and reduce harvest for fisheries and shellfish operations. Efforts to address sea level rise are increasing, particularly with respect to infrastructure, where sea level rise projections are being incorporated into local and regional planning.

Climate Drivers of Change

DRIVERS ***Local sea level variations are driven by global, regional, and local factors.***

- *Multiple factors affect regional sea level.*[A] The rate of sea level rise in Puget Sound[B] depends both on how much global sea level rises and on regionally-specific factors such as ocean currents, wind patterns, and the distribution of global and regional glacier melt.[C] These factors can result in higher or lower amounts of regional sea level rise (or even short-term periods of decline) relative to global trends, depending on the rate and direction of change in regional factors affecting sea level.[1,2,3,4,5]

- *Differences in land movement affect local rates of sea level rise.* Due to the active tectonics of the Pacific Northwest, land elevations are changing. For example, in

[A] This is often referred to as the "eustatic" sea level, which refers to the height of the water surface irrespective of land elevation (i.e., relative to a fixed point, such as the center of the earth).

[B] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describes the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

[C] Large ice sheets and glaciers exert a gravitational pull. In the same way that the tides are a response to the pull of the moon and the sun, glaciers can result in slightly elevated sea level within their vicinity, and slightly lower sea level elsewhere. As these glaciers melt (e.g.: in Antarctica, Greenland, and Alaska), the gravitational pull of each changes, resulting in regional changes in the height of the ocean surface.

Neah Bay the land elevation is rising at a rate of about +1 in./decade, whereas in Seattle it appears to be falling at a rate of about −0.5 in./decade.[D,3] In areas where the land is rising, the local rate of sea level rise will either be slowed or reversed. In areas where the land is subsiding, the pace of local sea level rise will increase.[1]

- *Short-term sea level variations can temporarily offset or accelerate trends.* Sea level can be temporarily elevated or depressed by up to a foot in winter as a result of natural cycles in climate patterns such as El Niño (see Section 6).[1,6,7]

- *A large earthquake could result in an abrupt increase in sea level along the outer coast, including Neah Bay.* The last great earthquake (magnitude greater than 8) to have occurred along the Cascadia Subduction zone resulted in a sudden drop in land elevation – and resulting rise in sea level – of up to 6 ft. along Washington's outer coast and the Northwest Olympic Peninsula. Although the associated rise in land elevation (drop in sea level) for interior Puget Sound will be much smaller, earthquakes occurring on other faults (e.g., the Seattle fault) could lead to an abrupt drop in land elevation in some areas.[1,8,9,10,11]

Observed Changes

OBSERVED ***Global sea level is rising, and the same is true in most of Puget Sound.*** Trends vary from location to location, including a decline in sea level in Neah Bay.[B]

- *Global sea level is rising, and the rate of rise is unprecedented.* Global average sea level rose about +8 inches from 1900-2009. Since the mid-1800s, the rate of sea level rise has been larger than in the past two millennia.[1]

- *Sea level is rising at most locations in or near Puget Sound.* At the Seattle tide gauge, one of the longest-running gauges in Puget Sound, sea level rose by +8.6 inches from 1900 to 2008 (+0.8 in./decade).[2] Although sea level is rising at most locations, records show a decline in sea level for the northwest Olympic peninsula, a region experiencing uplift. At the Neah Bay tide gauge, for example, relative sea level dropped by −5.2 inches from 1934 to 2008 (−0.7 in./decade).[2]

OBSERVED ***There is no evidence of a change in storm surge in Puget Sound, and research is lacking regarding changes in wave heights.***

- *There is no evidence of a long-term trend in storm surge.[E]* No study has comprehensively analyzed observations of storm surge heights across Puget Sound. However, one study found that trends in extreme high water levels along the Pacific

[D] In addition to tectonics, land elevation can fall as sediments become more compact over time, in response to groundwater or fossil-fuel extraction, or due to increased drainage on newly-cultivated agricultural lands. Sediment compaction is most commonly associated with wetlands or river deltas.

[E] Storm surge is the result of the high winds and low surface pressures that accompany storm events. Neither waves nor seasonal changes in sea level (e.g., due to El Niño) are included in the definition of surge.

Northwest[F] coast are simply a reflection of increases in sea level, rather than resulting from an increase in surge.[12]

- *It is not known how waves within Puget Sound will change in the future.* Previous studies have evaluated wave heights measured by offshore buoys,[13,2] but waves within Puget Sound are primarily driven by local winds as opposed to ocean swell.[G]

- *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.[14,15,16,17]

Projected Changes

PROJECTED ***Sea level is projected to continue rising through the 21st century, increasing by +14 to +54 inches in the Puget Sound region by 2100 (relative to 2000).[2]*** Local rates of rise could be higher or lower than this range, depending on the local rate of vertical land motion. For example, the relative rise in sea level projected for Seattle ranges from +4 to +56 inches by 2100 (relative to 2000).[2]

- *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.[H,I,1] All studies project an increase in global sea level for all greenhouse gas scenarios, although different approaches result in different estimates of the exact amount of sea level rise projected (Figure 4-1).

- *Differences among projections are primarily due to different methods for estimating the rate of ice melt on Greenland and Antarctica.* There are many factors that influence the range among regional sea level rise projections, including global models, greenhouse gas scenarios, and estimates of the rate of vertical land motion. The most important of these is the method used to estimate future changes in ice sheets on Greenland and Antarctica. All three of the estimates shown in Figure 4-1 employ different approaches to estimating the rate of ice sheet melt.[J,1,18]

F 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.

G "Swell" is the term used for waves that are generated by some distant weather event (e.g.: a low pressure system). These are still generated by winds, but at some remote location from which the swell originates.

H 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.

I Sea level rise projections vary with greenhouse gas scenarios. The average and associated ranges reported in IPCC 2013[1] 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.

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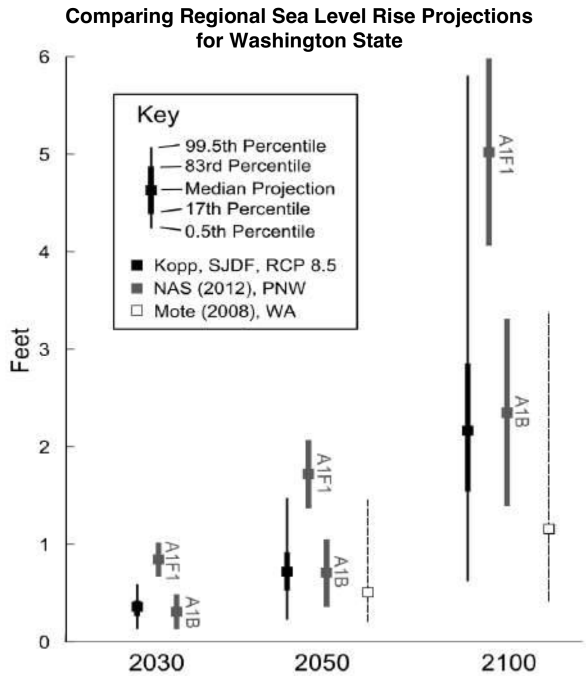

Figure 4-1, Table 4-1. **Regional absolute*[A]* sea level rise projections for Puget Sound are roughly similar among different studies, but there are important differences.** Projections are for "eustatic" sea level,[A] which is independent of changes in land elevation. Results are shown in inches for 2030, 2050, and 2100 (relative to 2000), from three regionally-specific studies:[K] Petersen et al. 2015[L,3] (based on Kopp et al. 2014),[18] NRC 2012,[M,1] and Mote et al 2008.[O,5] 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, see Section 1) scenario from Petersen et al. 2015 are included in the table. *Figure Source: Petersen et al. 2015.[3] Reproduced with permission.*

Domain	2030	2050	2100
Strait of Juan de Fuca (Petersen et al. 2015)[3,18]	+4 inches *(+1 to +6 in.)*	+7 inches *(+1 to +14 in.)*	+23 inches *(+6 to +55 in.)*
Washington State (NRC 2012, without uplift[N])[1]	+4 inches *(+1 to +8 in.)*	+9 inches *(+4 to +18 in.)*	+28 inches *(+14 to +54 in.)*
Puget Sound (Mote et al. 2008)[5]	---	+ 6 inches *(+4 to +15 in.)*	+13 inches *(+7 to +37 in.)*

J Studies take different approaches to estimating the rate of melt for the major ice sheets on Greenland and Antarctica. Some use statistical relationships to extrapolate from past trends (e.g., NRC 2012[1]), others use physical models of ice sheet dynamics (e.g., IPCC 2013[1]) and others incorporate expert judgment (e.g., Kopp et al. 2014[18]).

K Regional projections between Mote et al. (2008)[5], NRC (2012)[1], and Petersen et al. (2015)[3,18] differ due to the different approaches to estimating global sea level rise and local influences on the relative rate of rise. Among other differences, the Petersen et al. (2015) projections assign probabilities, whereas the others are scenario-based. Mote et al. 2008 do not provide projections for 2030.

L The regional sea level rise projections for the northern Olympic Peninsula in Petersen et al. (2015)[3,18] combine global sea level rise with regional factors affecting trends. They apply the probabilistic approach developed by Kopp et al. (2014).[18] Kopp et al. combined multiple projections of sea level rise and incorporated expert surveys to develop a new set of probabilistic sea level rise projections. Results listed in Table 4-2 show the median and the 99% confidence limits, based on a high (RCP 8.5) greenhouse gas scenario.

M Calculated for the latitude of Seattle, Washington (NRC 2012), assuming that the land elevation is uplifting at a rate of 1±1.5 mm/yr (~0.4±0.6 inch/decade).[1] This is likely an underestimate of sea level rise for Seattle, since most observations of vertical land motion suggest either subsidence or no motion at all. The mean value reported in NRC (2012) is based on the moderate (A1B) greenhouse gas emissions scenario. The range stems from projections for a low (B1) to a high (A1FI) greenhouse gas emissions scenario, as well as the upper and lower estimates of vertical land motion for the region.

- *Regional absolute sea level[A] is projected to rise.* According to a recent report by the National Research Council (NRC), regional absolute sea level is projected to rise an additional +14 to +54 inches in the Puget Sound region by 2100 (relative to 2000).[1]

- *Sea level rise is expected to continue for most of Puget Sound's shorelines (Tables 4-1, 4-2).* Most areas in Puget Sound are expected to experience sea level rise through 2100.[3,4,1] For example, assuming the land is uplifting at a rate of about +0.4±0.6 inch/decade (a middle estimate for Puget Sound, see Table 4-3),[3] the relative rise in sea level projected for the latitude of Seattle is +24 inches (range: +4 to +56 inches) by 2100 (relative to 2000).[M,2] How much water levels change at each specific location depends on a variety of factors, including the rate and direction of local land motion, and regional wind and ocean circulation patterns. Although some studies have quantified regional variability in sea level,[6,7] very little work has been done to comprehensively evaluate rates of vertical land motion along the coast of Puget Sound.

- *A few locations may experience declining sea level.* Previous research indicates that declining sea level is possible in the Northwest Olympic Peninsula if the rate of global sea level rise is very low and if the rate of uplift remains high.[4,5] Based on one recent analysis,[3] there is less than a 5% chance that sea level will continue fall in Neah Bay through 2100. Although unlikely, it is not yet possible to conclusively rule out a decline in sea level for that region.

- *Although the change in sea level resulting from an earthquake could be substantial, it is not possible to predict when one will occur.* Earthquakes can result in abrupt changes in land elevation, resulting in a sudden change in sea level. Long-term rates of vertical land-motion[P] may also change over time.

- *Sea level rise is not expected to occur in a consistent, linear fashion*. Based on past observations, episodes of faster and slower rise, as well as periods of no rise, are expected to continue to occur just as they have in the past.[1,7]

- *Storms that produce damaging surges are not projected to change.* Climate models do not project a change in wind speed or the strength of low pressure systems affecting the Puget Sound region.[19,20,21]

[N] The most commonly-cited projections from the NRC (2012) report incorporate an assumed uplift rate of 1.0±1.5 mm/yr (~0.4 in./decade) for all of the Pacific Northwest. The vertical rate estimate was removed from the numbers shown in this table, in order to compare projections for absolute sea level rise.

[O] The regional sea level rise projections for Washington State in Mote et al. (2008)[5] integrate projected changes in global sea level rise and potential changes in wind direction (which can push waves onshore or off shore for prolonged periods of time depending on wind direction). Low to high projections for each of these components were used to develop the low, medium, and high sub-regional sea level rise estimates. The global sea level rise projections used in these calculations range are based on a low greenhouse gas scenario (B1; for the low projection), a high greenhouse gas scenario (A1FI; for the high projection), and an average of six greenhouse gas emissions scenarios (B1 through A1FI; for the medium projection). See Section 1 for more details on greenhouse gas scenarios.

[P] Often described as "inter-seismic", referring to the time between earthquakes.

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PROJECTED ***Sea level rise increases the potential for higher tidal/storm surge reach and increased coastal inundation, erosion, and flooding.*** Even small amounts of sea level rise can shift the risk of coastal hazards in potentially significant ways.

- *Sea level rise will permanently inundate some low-lying areas.* Where and how much inundation occurs will depend on the rate of sea level rise and shoreline characteristics. Communities, tribes, and organizations that have mapped sea level rise inundation zones within the Puget Sound region include the City of Olympia,[22] City of Seattle,[23] City of Tacoma, the Port of Seattle,[24] King County,[25] Sound Transit,[26] the National Wildlife Federation (Puget Sound),[27] the Swinomish Indian Tribal Community,[28] the Jamestown S'Klallam Tribe,[29] the North Olympic Development Council,[3] and the Friends of San Juan.[30]

- *Sea level rise will exacerbate coastal river flooding.* Higher sea level can increase the extent, depth, and duration of flooding by making it harder for flood waters in rivers and streams to drain to 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).[Q,20,21,31]

- *Sea level rise will increase the frequency of coastal flood events.* Higher sea level amplifies the inland reach and impact of high tides and storm surge, increasing the likelihood of events that are considered extreme today. For example, +6 inches of sea level rise[R] in Olympia 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.[22] With +24 inches of sea level rise,[S] the 1-in-100-year flood event would become an annual event (Table 4-1).

  Coastal bluffs are projected to erode more rapidly. Over one quarter of Puget Sound's shorelines are "armored".[T] Increased erosion is expected to affect many of the remaining coastal areas as sea levels rise, although the effects depend on the geology and exposure of each location. Coastal bluffs are projected to be particularly sensitive. One study projects that coastal bluffs in San Juan County will recede by

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Q Sea level rise projections were obtained from Mote et al. (2008);[5] streamflow projections were based on 10 global climate model projections and a medium (A1B) greenhouse gas scenario. Flood simulations assume all levees would remain intact, although they could be overtopped. When levee failure scenarios are included, the increase in flooded area is much less pronounced. With levee failure, much of the floodplain would be inundated even in the absence of climate change – increased flows and higher sea levels do increase water depths, but do not significantly change the area flooded.

R A +6 inch increase in regional sea level is currently near the median value projected in Petersen et al. (2015)[3] for Seattle for 2030.

S A +24 inch increase in sea level is currently within the range (+14 to +63 inches) projected in Petersen et al. (2015)[3] for Seattle for 2100 (relative to 2000). See Table 4-4 for more detail.

T Shoreline "armoring" refers to any engineered structure used to reduce the effects of coastal erosion. http://www.psp.wa.gov/vitalsigns/shoreline_armoring.php

–75 to –100 ft. by 2100 (relative to 2000).[U,30] This corresponds to a doubling, on average, of the current rate of recession.

PROJECTED ***Sea level rise affects human, plant, and animal communities in important ways.***

- *Economic and cultural consequences for human communities are expected.* Impacts on human communities include the potential for increased damage to coastal infrastructure from storm surge or flooding,[22,25,32] permanent inundation of important commercial and industrial areas,[22,28,33] loss of culturally important sites,[28] and a reduced harvest for commercial fishing and shellfish operations.[4]

- *Sea level rise and changes in the marine environment will affect the geographical range, abundance, and diversity of Pacific Coast marine species and habitats.* Increased inundation and erosion due to sea level rise are expected to cause habitat loss and shifts in habitat types. Locations more likely to experience habitat loss include low-lying areas, locations with highly erodible sediments, and areas where inland migration of coastal habitats is hindered by bluffs or human development. Vulnerable habitat types include coastal wetlands, tide flats, and beaches (see Section 11).[27,34]

Table 4-2. Effect of sea level rise on the probability of today's 100-year coastal flood event in Olympia, WA. As sea level rises, the probability of today's 100-year flood event increases from a 1% annual probability to a 100% probability if sea level rises +24 inches or more. *Table and caption adapted from Simpson 2012.*[22]

Sea level rise amount	0 inches	+3 inches	+6 inches	+12 inches	+24 inches	+50 inches
Return frequency for a storm tide reaching the current 100-year flood level	100-yr event	40-yr event	18-yr event	2-yr event	< 1-yr event	<< 1-yr event
Equivalent annual probability of occurrence	1%	2.5%	5.5%	50%	100%	100%

Climate Risk Reduction

CLIMATE RISK REDUCTION ***Many Puget Sound communities, government agencies, tribes, and organizations are preparing for the effects of sea level rise.*** Most are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. Since most of the documented efforts are designed to protect infrastructure, these examples are also included in Section 12. For example:

U 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)[1] report and a moderate (A1B) and high (A1FI) greenhouse gas scenario.

Washington State

- *New regulatory guidance for addressing the risks posed by sea level rise.* Washington State Department of Ecology provides guidance to local government jurisdictions on addressing sea level rise along shorelines in Appendix A of their Shoreline Master Program Handbook.[35] The guidance includes: anticipated sea level rise and sediment impacts; coastal landform inventory and vulnerability; public participation, access, and use; shoreline environmental designations, modification, and restoration policies, and some specific jurisdictional examples.

Sound Transit

- *Assessing the vulnerability of the Sound Transit system to the effects of climate change.* The Sound Transit Climate Risk Reduction Project assessed the vulnerability of Sound Transit assets and services to climate change while creating a process and a model for transit agencies across the United States. The analysis found that while climate change exacerbates many existing issues such as sea level rise, extreme precipitation events, heat stress, mudslides, and river flooding, Sound Transit already possesses some degree of climate resilience and capacity to address climate impacts, both of which will be further enhanced by integrating climate considerations into decision making.[26]

King County

- *Building floating docks and gangways that are able to accommodate several feet of sea level rise.* In 2010, King County Marine Division replaced the existing dock and gangway in West Seattle used by the Water Taxi (owned and operated by WSDOT) with a new floating dock and gangway, which is able to handle rising sea levels.[36]

- *Incorporating sea level rise into the Wastewater Treatment Division facility siting and design procedure.* A 2008 study evaluating the effects of sea level rise on King County's Wastewater Treatment Division facilities recommended that sea level rise should be incorporated in planning for major asset rehabilitation or conveyance planning that involves the facilities included in the analysis.[37] Since the release of the report King County has modified the conveyance system and outfalls of the Wastewater Treatment Division facilities to reduce or eliminate seawater intrusions, even during high tide.[38,36] Additional preparations for limiting saltwater intrusion include installing flap gates, raising weirs, and other similar controls.[36]

Cities

- *Planning for sea level rise in the City of Olympia.* In an effort to reduce flood risk in association with sea level rise, the City of Olympia conducted GIS mapping of projected inundation zones, incorporated sea level rise considerations into the City's Comprehensive Plan and Shoreline Management Plan, and develops annual work plans to address adopted goals and priorities, key information needs, improve emergency response protocols, and survey and identify shorelines, structure elevations, and sewer basins that are vulnerable to flooding.[39]

- *Planning for sea level rise at the Port of Bellingham.* 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.[40]

- *Evaluating the robustness of the Seattle sea wall design to sea level rise.* An evaluation of sea level rise impacts on design considerations for the new Seattle sea wall found that the current sea wall height would be able to accommodate +50 inches of sea level rise and a +3 foot storm surge (a 100-year event surge).[V] As a result, the City determined that it was not necessary to build a higher structure to accommodate sea level rise over the next 100 years.[W]

- *Considering sea level rise in facilities master planning.* Seattle City Light is reviewing a facility in the Duwamish River basin for potential flooding impacts associated with sea level rise and storm surge.

<u>*Tribes*</u>

- *Adaptation planning for multiple climate-related hazards: the Swinomish Indian Tribal Community.* The Swinomish Indian Tribal Community is implementing adaptation recommendations developed in 2010. This includes revisions to shoreline codes, development of a detailed coastal protection plan for the most vulnerable 1,100 low-lying acres on the north end of the Reservation, development of a Reservation-wide wildfire risk reduction program, and development of a system of community health indicators to measure knowledge and impacts of climate change within the tribal community.[41]

- *Vulnerability assessment and adaptation plan: Jamestown S'Klallam Tribe*. The climate vulnerability assessment and adaptation plan identified key tribal resources, the expected effects of climate change, and created adaptation strategies for each resource. Moderate and high severity sea level rise scenarios project potential flooding on Highway 101 near Discovery Bay, preventing the Tribe's access to the highway for 12-24 hours. The adaptation plan recommends that the Tribe work with Washington Department of Transportation to discuss raising the vulnerable infrastructure, especially in conjunction with future repairs.[42]

V The Mean Higher High Water, which is the average of the highest daily tide at a place over a 19-year period.

W See http://sdotblog.seattle.gov/2013/01/23/sea-level-and-the-seawall/ for more details.

Additional resources for evaluating and addressing the effects of sea level rise in the Puget Sound region.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **Coastal Hazards Resilience Network** (CHRN). Convened by Washington Sea Grant and the Department of Ecology, CHRN is a network of researchers and practitioners focused on climate change and coastal hazards. The goal of the network is to improve regional coordination and, ultimately, to make Washington's coastal communities, including those in Puget Sound, more resilient. http://www.wacoastalnetwork.com/
- **Coastal Resilience.** The Nature Conservancy has created a web-based mapping tool that combines sea level projections with other information on land use, infrastructure, and ecosystems. Users can also upload their own data for viewing alongside existing layers.[43] http://maps.coastalresilience.org/pugetsound/
- **Puget Sound Coastal Resilience.** Developed by Western Washington University, The Nature Conservancy, and USGS, this tool incorporates data on future sea level, high tides, and storm surges, to map projected inundation in the Nooksack, Skagit, Stillaguamish, Snohomish, Nisqually, and Skokomish River deltas. http://spatial.wwu.edu/coastal/resilience/
- **NOAA Tides and Currents.** Central resource for information on observed trends in sea level. http://tidesandcurrents.noaa.gov/
- **NOAA Coastal Services Center.** Provides technical information and support for managing coastal hazards. https://csc.noaa.gov/ Tools and products include:
    - Sea Level Rise Viewer: creates maps of potential impacts of sea level rise along the coast and provides related information and data for community officials.
    - Coastal County Snapshots: allows users to develop customizable PDF fact sheets with information on a county's exposure and resilience to flooding; its dependence on the ocean for a healthy economy; and the benefits received from a county's wetlands.
    - Coastal LiDAR: a clearinghouse of LiDAR datasets contributed by many different entities and groups that can be used for mapping sea level rise inundation.
- **Surging Seas.** This tool, created by Climate Central, integrates sea level rise projections with topographic data to identify areas that are likely to be inundated in the future. The tool includes other information in order to identify populations and infrastructure that are particularly vulnerable to sea level rise. http://sealevel.climatecentral.org/ssrf/washington
- **Georgetown Climate Center Adaptation Clearinghouse: Rising Seas and Flooding.** Provides links to a variety of case studies and regulatory analyses related to sea level rise. http://www.georgetownclimate.org/adaptation/rising-seas-and-flooding

Table 4-3. Observed trends in sea level, vertical land motion, and surge.

Variable	Observed Change
Sea Level	
Global	Rising: +0.7 in./decade (1901-2010) +1.3 in./decade (1993-2010)[1] Rate of rise since mid-1800s is larger than in the last two millennia.[1]
Local	Mixed. ▪ Neah Bay, WA: −0.7 in./decade (1934-2008) ▪ Friday Harbor, WA: +0.4 in./decade (1934-2008) ▪ Seattle, WA: +0.8 in./decade (1900-2008)[1]
Vertical Land Motion	Both the rate and direction of vertical land movement vary from location to location across Puget Sound. ▪ Neah Bay, WA: +1.0 (±0.1) in./decade (1975-2015)[1] ▪ Port Angeles, WA: +0.4 (±0.1) in./decade (1975-2015) ▪ Port Townsend, WA: −0.3 (±0.1) in./decade (1975-2015) ▪ Friday Harbor, WA: −0.05 (±0.1) in./decade (1972-2015) ▪ Seattle, WA: −0.5 (±0.1) in./decade (1972-2015)
Storminess	There is no evidence of a trend in the intensity of winds and storms that cause damaging surge in Puget Sound. There are no published studies that have evaluated trends in storm surge within Puget Sound. However, one study found that trends along the Northwest coast are simply a reflection of increases in sea level, as opposed to an intensification of storms.[1,12]
Waves	It is not known how waves within Puget Sound will change in the future. Previous studies have evaluated wave heights measured by offshore buoys,[13,2] but waves within Puget Sound are primarily driven by local winds as opposed to ocean swell.[G]

Table 4-4. Projected changes in sea level.

Variable	Projected Change
Sea Level	
Global	Rising: +11 to +38 in. (2100 relative to 1986-2005)[H,I,1] Rate of rise depends on the amount of 21st century greenhouse gas emissions.
Local	Relative to vertical land motion, local sea level is projected to rise everywhere by 2100, with the possible exception of Neah Bay, where only the lowest scenario projects a continued drop in sea level.[5] Assuming the land is uplifting at a rate of about 0.4±0.6 inch/decade (a middle estimate for Puget Sound),[3] the relative rise in sea level projected for the latitude of Seattle, relative to 2000:[M,2] ▪ 2030: +3 in. (−2 to +9 in.) ▪ 2050: +7 in. (−1 to +19 in.) ▪ 2100: +24 in. (+4 to +56 in.)
Storminess	No change projected. Climate models do not project a change in wind speed or the strength of low pressure systems affecting the Puget Sound region.
Shoreline Erosion	Coastal bluffs are projected to erode more rapidly as a result of sea level rise (see Section 5). Projected retreat of coastal bluffs in San Juan County (2100 relative to 2000):[30] ▪ Moderate (A1B) scenario, < 5 mi. of fetch:[X] 75 ft. ▪ High (A1FI) scenario, < 5 mi. of fetch: 115 ft. ▪ Moderate (A1B) scenario, > 5 mi. of fetch: 101 ft. ▪ High (A1FI) scenario, > 5 mi. of fetch: 155 ft.
Coastal Habitats	Increased inundation and erosion due to sea level rise are expected to cause habitat loss and shifts in habitat types. Vulnerable habitat types include coastal wetlands, tide flats, and beaches (see Section 11)

X In their analysis, MacLennan et al.[30] distinguished between coastal areas with high exposure (more than 5 miles of "fetch": open water over which wind can generate waves) and areas with less exposure (less than 5 miles of fetch).

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SECTION 5
How Will Climate Change Affect Landslides, Erosion, and Sediment Transport?

The Puget Sound region is expected to experience increases in the frequency of landslides and the rate of erosion and sediment transport in winter and spring, primarily as a result of continued declines in snowpack and projected increases in the frequency and intensity of heavy rain events. In summer, these processes are expected to become less important in the future, due to diminishing streamflow and drier soils. Both natural climate variability and human modification to the landscape have a strong effect on landslide and sediment processes, and will continue to influence these processes in the future. While a lack of direct observations makes it challenging to make robust projections, communities in the Puget Sound region are preparing for changing landslide and sediment risk through targeted regulations, climate-informed design, and floodplain infrastructure aimed at mitigating anticipated impacts.

Climate Drivers of Change

DRIVERS ***Climate change can alter landslides[A,1] and sediment[B,2] processes via increasing air temperatures, higher intensity and more frequent heavy rain events, decreasing summer precipitation, and sea level rise.***[3,4,5,6] These effects vary with season and for different locations across the Puget Sound region,[C] and are affected by non-climatic factors, such as changes in land use and land cover.

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[7,8] Increasing air temperatures can facilitate soil breakdown, allow more water to

[A] Landslides are used generally in this text to describe various types of mass movement of rock, earth and debris downslope, including debris flows, lahars, mudflows, rockslides, soil creep, shallow landslides, and deep-seated landslides.

[B] Sediment is broadly defined as a collection of particles, loose or consolidated, including hillslope soils, clay, silt, sand, gravel, cobbles, and boulders. This report is focused on changes in both the rate of erosion and in the amount of sediment transported in rivers.[2]

[C] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

penetrate soils, reduce snow accumulation, and increase the risk of wildfire and other threats to forest health, all of which can affect the rates of erosion and sediment transport and the likelihood of landslides.

- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[9] These changes could result in greater erosion, higher sediment transport in rivers and streams, and a higher likelihood of landslides, primarily as a result of higher soil water content.

- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year variability.[8] Declining precipitation in summer could result in decreased erosion, a reduced rate of sediment transport, and a lower probability of landslides.

- *Nearly all scenarios project a rise in sea level.* Sea level rise is projected for all locations except Neah Bay, where a decline in sea level cannot be ruled out due to the rapid rates of uplift in that area.[10,11,12] Higher seas could limit the transport of sediment from rivers to Puget Sound and increase the rate of erosion in some coastal areas.

- *Although climate is a major driver of erosion, sediment transport, and landslide hazards, there are other factors that can have an important effect on these processes.* In particular, changes in land use and land cover – both due to development and forest management – can dramatically affect the likelihood of a landslide, the exposure of sediments to erosion, and the rate of streamflow and sediment transport.[13]

Mechanisms linking climate with landslides, erosion, and sediment transport.

Temperature. High temperatures contribute to slope instability by enhancing the thermal breakdown of rock,[3,6,28] decreasing the viscosity of groundwater (i.e., more lubricating), and thawing frozen ground so more water infiltrates.[29,30] Warm conditions can also cause increased evaporation, leading to drier soils and more stable conditions in deeper soils, especially in summer.[6,31,32] Finally, warming can intensify the cycling between wet and dry periods, which may act to widen gaps in rock and soil, contributing to a decrease in slope stability.[4]

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Precipitation. Heavy rain events reduce slope stability by rapidly raising the water table (or groundwater elevation) and by enhancing water drainage through the soil to lower layers.[6] In addition, intense rainfall can erode surface sediments, and higher streamflow during these events can transport more sediment downstream.[43] Different patterns of rainfall will affect which slopes might be destabilized, and where erosion and sediment transport are most important.[44,45,46]

Soil Water Content. Wetter soils are heavier, can absorb less precipitation (thus increasing runoff), and have greater lubrication among soil layers. For example, analysis from the recent State-route 530 landslide (Oso, 2014) indicates that the initial conditions of the soil prior to the triggering event were an important contributor to the mobility and, as a result, the severity of the landslide.[21,22]

Snowpack and Glaciers. Higher snowlines can lead to exposure of unconsolidated (erodible) sediment, more ground surface erosion, greater soil saturation, and higher streamflows.[3] Retreating glaciers uncover loose, unvegetated sediment that is vulnerable to mobilization.[3,40,41,42] Melting glaciers typically leave behind sediments that are then exposed to weather and erosion.[3]

Streamflow. Higher streamflow, which is common in winter, can erode stream banks and transport more sediment within the stream and along the stream bed. Low streamflow, which is common in summer, results in lower rates of sediment transport. In summer, the reduction in transport can increase sediment buildup within stream channels and reduce the capacity for floodwaters in subsequent events.[24]

Vegetation. Vegetation loss from water stress, wildfire, insect attacks, or disease can lead to increased soil surface erosion and sediment transport to streams during rain events.[25,26,27,33,34] Loss of vegetation from fire temporarily reduces the ability of soils to absorb moisture, increases surface runoff, and boosts sediment transport.[35] In addition, the root decay following fires can weaken slopes, especially one to three years after a fire.[36,37,38,39]

Sea level rise. Sea level rise could trap sediment within rivers and exacerbate coastal erosion.[14] Elevated sea level (for example, due to winter storm surge) could cause more sediment trapping within river and stream deltas by reducing stream velocities, which promotes sediment deposition and reduces the size of the river channel.[15,16] Higher sea levels also allow wave energy to reach further inland, eroding unarmored[D] shorelines and redistributing beach sediments.[17,18,19,20]

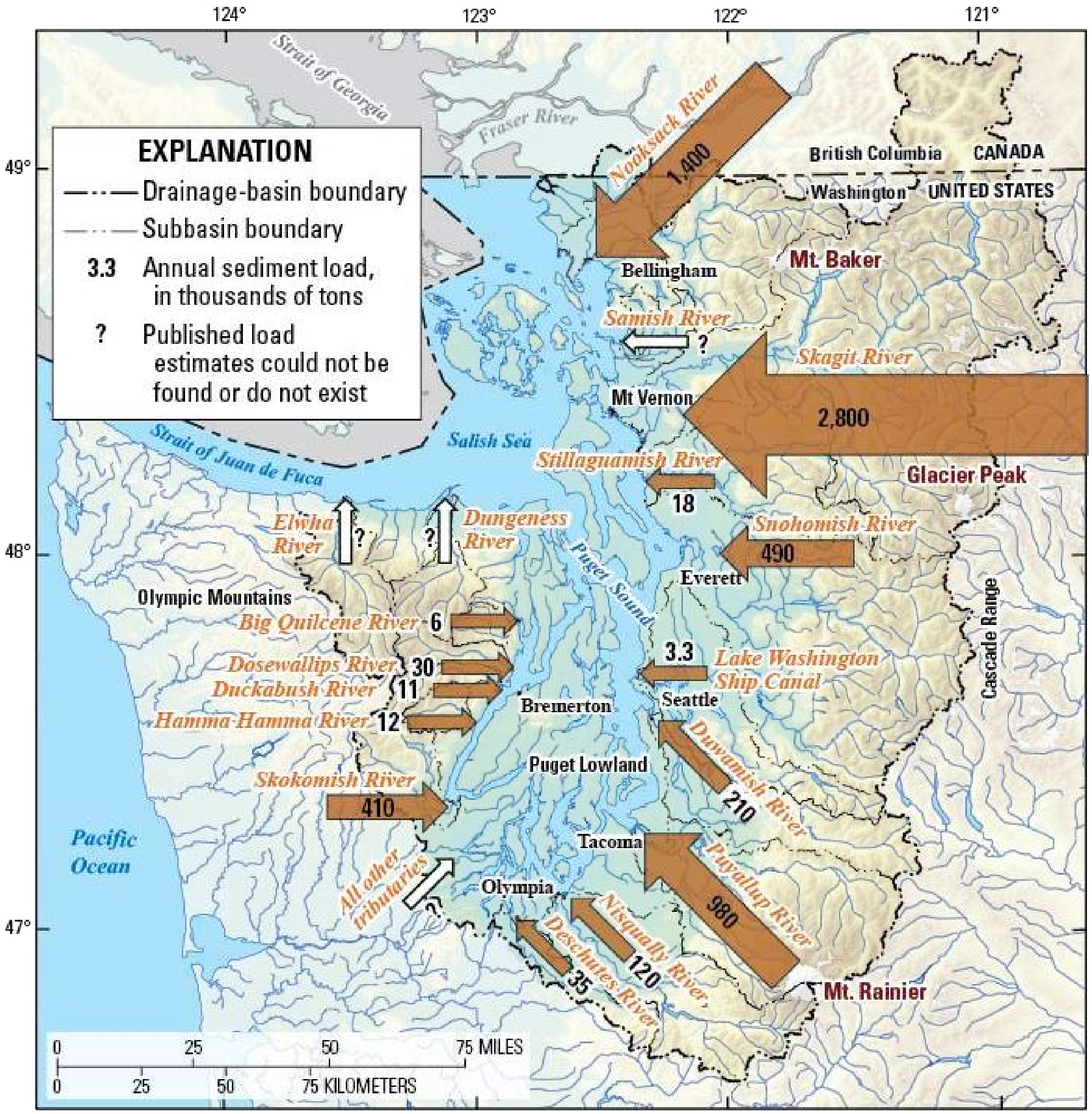

Figure 5-1. Puget Sound rivers contain massive quantities of sediment. Estimated annual sediment load (in thousands of tons) of major rivers draining into Puget Sound from measurements at or near the coast. The size of the arrow is scaled to the annual sediment load. Annually, an estimated 6.5 million tons of sediment is transported to Puget Sound; approximately 70% of the sediment is from rivers and the remaining is from shoreline erosion. *Figure Source: USGS; Czuba et al. 2011.*[47]

D Shoreline "armoring" refers to any engineered structure used to reduce the effects of coastal erosion. http://www.psp.wa.gov/vitalsigns/shoreline_ armoring.php

Observed Changes

OBSERVED ***Few studies report trends in landslides and sediment processes, and even fewer have related these changes to climate.*** However, some studies report climate-related increases in the vulnerability of land areas to erosion and landslides.[82]

- *Earlier snowmelt, which allows water to infiltrate into soils earlier in spring, is making slopes less stable.* Modeling studies suggest that pre-conditioning of hillslopes to instability[E] is occurring earlier than in the past. Specifically, model simulations indicate that the spring increase in soil water content is occurring earlier and April 1st soil water content is increasing in snow-influenced watersheds (1947-2003).[82]

- *Rising river beds.* Rivers within Mount Rainier National Park have experienced aggradation (i.e., streambed rising) during the past two decades (1997-2006), indicating increasing sedimentation. Since they occur in a national park, these changes are unlikely to be a result of logging or other human development, although the increase has not been directly linked to climate drivers.[48,49,50]

- *Higher sediment supply.* Sediment supply is greater than +1.5 times the natural rate in areas of the Skagit River basin.[51] The greatest sediment load is in the lower Skagit. It is not known what proportion of this change is due to changes in climate drivers versus other human and natural processes (e.g., land development).

- *Increased sediment desposition in estuaries.* Sediment accumulation in the subtidal portions of many large Puget Sound river deltas has been extensive since the 1850s. The main factors influencing this change are most likely related to human alterations to river channels, floodplains, and other patterns of land-use.[52]

- *Challenges in assessing trends*. There are three factors that make it difficult to interpret observed trends in landslides and sediment processes: (1) limits in the quantity and quality of observations (e.g., incomplete databases, imprecise dates), (2) the influence of non-climatic factors, including logging and development,[53,54,55] the long timeframe of landscape changes, and the lag time between triggering events and slope or stream responses,[4,41,56] and (3) the overall complexity of processes influencing the likelihood of landslides and the rates of erosion and sediment transport.[6,57,58]

E "Pre-conditioning" refers to factors that increase the chance of a slope failure (or landside) given a triggering event, such as a rainstorm.

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Projected Changes

PROJECTED ***Climate change is expected to increase the likelihood of landslides in winter and early spring and decrease the likelihood in summer.*** Although there are no published projections for changing landslide hazards in the Puget Sound region, changes in the climate drivers of landslides point to changes in the frequency and size of landslides. Landslide-prone areas are expected to become less stable in winter as more precipitation falls as rain rather than snow, temperatures rise, soil water content increases, and as heavy rainfall events become more intense.[59]

- *In winter, landslide risk is expected to increase in response to declining snowpack.* Average spring snowpack in the Puget Sound region is projected to decline by −37 to −55% by the 2080s (2070-2099, relative to 1970-1999), on average, for a low and a high greenhouse gas scenario (see Section 3).[F,G,H,60] Snow cover protects soils from raindrop erosion and can also absorb rain.[61] Projected losses in mountain snowpack will reduce the protective effect of snow and frozen ground and lead to increased soil water content, both of which could increase the probability of landslides and the rate of sediment input into streams during winter.
- *In summer, landslide risk is expected to decrease as a result of declining streamflow and soil water content.* For the 12 major Puget Sound watersheds analyzed,[I] the spring peak in streamflow is projected to occur two to six weeks earlier, on average, by the 2080s (2070-2099, relative to 1970-1999, see Section 3).[J,K,60] Earlier snowmelt could lead to decreased soil water and an increase in slope stability. Sediment transport will also likely decrease as runoff from snowmelt declines, although glacier meltwater may temporarily offset this effect in glacier-fed streams (Figure 5-2).

F 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 more details.

G These numbers indicate 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 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).

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

I Projected changes in streamflow were calculated for 12 Puget Sound watersheds. Listed in clock-wise order, starting at the US-Canadian border, they are: the Nooksack R. at Ferndale (USGS #12213100), Samish R. Nr. Burlington (USGS #12201500), Skagit R. Nr. Mt Vernon (USGS #12200500), Stillaguamish R. (Flows were obtained for the NF Stillaguamish R. Nr. 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. Nr. Potlach (USGS #12061500), Dungeness R. at Dungeness (USGS #12049000), and Elwha R. at McDonald Bridge Nr. Port Angeles (USGS #12045500).

J Calculations are based on the change in streamflow "Center Timing" (CT). CT is defined as the day of the water year (starting on October 1st) when cumulative streamflow reaches half of its total annual volume.

K Projected change for ten global climate models for a moderate (A1B) greenhouse gas scenario.

- *Winter soil water content, an indicator of landslide hazard, is projected to increase.* December 1st soil moisture, used as an indicator of landslide risk, is projected to increase up to +35% in the 2040s (2030-2059) relative to 1970-1999 along the slopes of the Cascade Mountains.[K,62]

- *Heavy rainfall events, which can trigger landslides, are expected to become more intense.* Global models project that the heaviest 24-hour rain events in the Pacific Northwest will intensify by +19%, on average, by the 2080s (2070-2099, relative to 1970-1999, see Section 2).[L,63] Combined with the projected increase in winter soil water content, the projected increase in heavy rain events is expected to result in more frequent landslides.[60,64,65]

- *"Rain-on-snow" events*[M] *are expected to become less frequent*. Landslides in the Puget Sound region are often triggered by rain-on-snow events.[66,67,68] Although little research has specifically evaluated projected future changes in these events, increasing air temperatures are likely to result in less frequent rain-on-snow events as winter snowpack and the length of the snow season decreases.[27,69]

- *Modeling studies confirm that projected changes in precipitation and air temperature will increase landslide hazards in winter.* Although there are no published estimates of landslide hazard for the Puget Sound region, one study projected a +7% to +11% increase in areas with high landslide susceptibility[N] for the Queets Basin (west slope of Olympic Peninsula),[O] by 2045 relative to 1970-1999.[P,70]

PROJECTED ***Climate change is projected to lead to increased rates of erosion and sediment transport in winter and spring and lead to a decrease in summer***. Along the coast, sea level rise is expected to increase the rate of erosion for unprotected beaches and bluffs.

- *As heavy rain events become more intense, the rates of both erosion and sediment transport are expected to increase.* More intense rainfall (see above) can erode

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L Based on an analysis of 5 global climate model projections and a high greenhouse gas scenario (RCP 8.5).

M "Rain-on-snow" events are warm rainfall events that occur in winter, after some amount of snow accumulation. During these warm events, rain falling on snow triggers rapid snowmelt, thereby increasing soil water content and streamflow.

N 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 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).

O 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.

P 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.

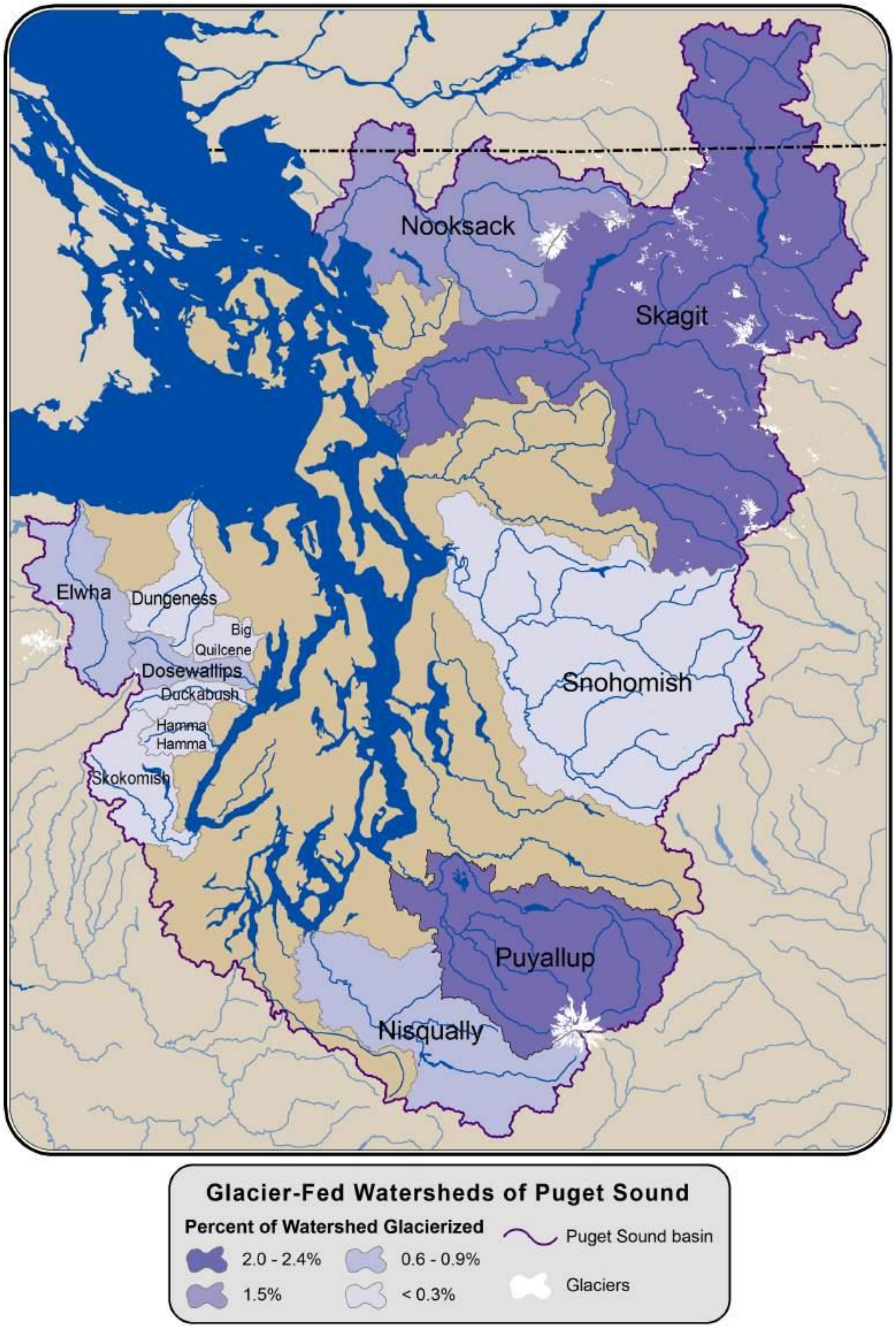

Figure 5-2. Glacially-influenced watersheds in the Puget Sound region. This map indicates Puget Sound watersheds with streamflow originating from glacier meltwater. Purple shading indicates the percentage of the watershed area covered by glacier, ranging from <0.3% to 2.4%. *Figure Source: Robert Norheim, Climate Impacts Group.*

surface sediments, contributing more sediment to streams.[34] Higher streamflow during these events can transport more sediment downstream.[40,71] Peak river flows in 12 Puget Sound watersheds are projected to increase by +18% to +55%, on average, by the 2080s (2070-2099, relative to 1970-1999), based on a moderate greenhouse gas scenario.[I,K,60]

- *Suspended sediments in the Skagit River are projected to increase substantially in winter.* The amount of sediment transported downstream past Mt. Vernon is projected to be nearly five times larger, on average in winter (+380%, range: +140 to +730%) for the 2080s (2070-2099, relative to 1970-1999) and a moderate (A1B) greenhouse gas scenario. Annual sediment transport is projected to more than double (+149%, on average) by the 2080s.[Q,72]

- *Sediments resulting from glacier melt will likely increase in the near future.* Glacier retreat is expected to initially cause an increase in sediment loads, as retreating ice uncovers new soil and meltwater increases. Over time, fine sediments carried by glacier meltwater will decrease as glaciers decline in mass and disappear, although other processes may continue to erode glacier sediment deposits thereafter.[40]

- *Shifts in vegetation and increased wildfire risk (see Section 9) could lead to more soil erosion and sediment transport.*[36] Vegetation changes and wildfires can reduce root reinforcement leading to increased landslide activity and greater erosion, increasing sediment supply to rivers.[73]

- *Unprotected coastal bluffs are projected to erode more rapidly.* Over one quarter of Puget Sound's shorelines are armored.[D] Increased erosion is expected to affect many of the remaining coastal areas as sea level rises, although the effects depend on the geology and exposure of each location. Coastal bluffs are projected to be particularly sensitive. One study projects that coastal bluffs in San Juan County will recede by –75 to –100 ft. by 2100 (relative to 2000).[R,74] This corresponds to a doubling, on average, of the current rate of recession. Another study projected that bluff erosion rates will increase by up to +4 inches per year by 2050 (relative to 2000).[S,75] As waters rise and cover more land, this additional erosion is expected to cause the shoreline to migrate inland in some places.[76,77]

Q Results are based on an integrated daily time step reservoir operations model built for the Skagit River Basin. The model simulated current operating policies for historical streamflow conditions and for projected flow for the 2040s and 2080s associated with five global climate model simulations. Sediment loading was estimated based on an empirical relationship between suspended sediment loading and flow rate.

R 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) report and a moderate (A1B) and high (A1FI) greenhouse gas scenario.

S Projection is based on an empirical model of bluff erosion, based on a high (A1FI) scenario of sea level rise.

- *It is not known if the sediment supply to Puget Sound will increase or decrease.* In the Strait of Juan de Fuca, sediments are typically transported out of estuaries. In Puget Sound, sediment is most often deposited in river deltas.[47,78] Rising sea levels could cause even more sediment to be deposited within Puget Sound estuaries.[78] Given the combination of increased erosion for coastal bluffs and increased deposition in estuaries, it is not known if the net effect will be an increase or a decrease in coastal land area.

PROJECTED ***Year-to-year and decade-to-decade variability in the region's climate influences landslide and sediment.***[79] This climate variability is expected to continue into the future (see Section 2). Soil water content, vegetation composition, erosion rates, and sea level can all be directly influenced by longer-term (up to several decades) climate variability driven by El Niño/La Niña and the Pacific Decadal Oscillation (PDO; see Section 2).[80,81,82]

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Puget Sound communities, government agencies, and organizations are preparing for the effects of climate change on erosion, sediment transport, and landslide hazards.*** Many communities have a long history of actively managing historical sediment and landslide patterns. Several communities have begun to assess the impacts of climate change, and a few are implementing adaptive responses geared towards sediment management. No adaptation efforts have been identified that address changing landslide hazards in the Puget Sound region.

- *New regulatory guidance on shoreline erosion.* Washington State Department of Ecology provides guidance to local government jurisdictions on addressing sea level rise along shorelines in Appendix A of their Shoreline Master Program Handbook.[83] The guidance includes: anticipated sea level rise and sediment impacts; coastal landform inventory and vulnerability; public participation, access, and use; shoreline environmental designations, modification, and restoration policies, and some specific jurisdictional examples.

- *Redesigning the Anacortes Water Treatment Plant.* Climate change 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, including more effective sediment removal processes.[84]

- *Lower White River Countyline Levee Setback project.* In order to accommodate sediment, increase flood-conveyance capacity, and alleviate flooding, King and Pierce counties are planning to build a setback levee in spring 2016 along the White River that is designed to accommodate a 10% increase in sediment delivery in the future.[85]

Additional Context on Landslide and Sediment Processes

Landslides and sediment processes are governed by climate, geology, soils, land cover, land use, topography, and streamflow.

- **Landslides** are ubiquitous in mountain and hilly environments, which are found in the Puget Sound region from the slopes of the Cascade Mountains to the coastal bluffs.[86]
- **Timing:** Most landslides in the Seattle area have occurred between November and April, with the highest percentage occurring in January (45%).[87,88,89,90,91]
- **Climate:** Precipitation, both prolonged and intense, is the most common trigger of landslides.[92,93] Storms have triggered a significant numbers of landslides in the Puget Sound region over the past century[94] (1933, 1972, 1986, 1990, 1996, 1997, 1998, 2003, 2006, 2009, 2011, 2012, and 2014).[29,19,95,96,97,98,99,100,101,102] In Seattle, rainfall in excess of 1.6 in (40 mm) in 24 hours is typically sufficient to cause landslides when prior soil wetness is high.[87,89] Approximately 85% of precipitation-related landslides have occurred on days when maximum air temperature was between 46° and 56°F.[29]
- **Geology:** In the Puget Sound region, ice age glaciers and volcanoes have created a terrain with varying slopes, strength, layering (or "stratigraphy"), permeability, and depth – these factors all create regional diversity in vulnerability to landslides and erosion.[30,103]
- **Topography:** The Puget Sound region is characterized by steep, narrow watersheds that rapidly convey runoff through watersheds to lower elevations and the coast.
- **Land cover and use:** Vegetation cover and human modifications to the landscape – including development, logging, and other factors – affect landslide hazard and sediment transport by modifying soil properties and the way water is absorbed and conveyed.[104,105,106]
- **Sediment Supply:** Rivers flowing into Puget Sound receive sediment from (1) shallow landsliding and debris flows into tributary streams, (2) sediment transport within tributary streams, (3) erosion of debris-flows fans and streambanks, (4) soil creep and erosion of adjacent hillsides, (5) landslides from hollows adjacent to the river, (6) volcanism and lahars (i.e., mudflows), (7) glaciers, (8) weathering, and (9) land use practices.[47,107] Landslides are the dominant source of sediment to Puget Sound rivers.[53,57] Puget Sound receives sediment from streams and rivers as well as erosion of coastal bluffs.[108]

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- **Sediment Pulses**: Sediment inputs often arrive in pulses from landslides triggered by precipitation or ground disturbance (e.g., fire, earthquake, logging).[34]

- **Transport**: Sediment is carried by streams and rivers as suspended or "wash load" within the water column or as "bedload," moving along the bottom of the water channel.[109] Watersheds transport different amounts of sediment depending on the watershed climate, geology, tectonics, human development, volcanism, glaciers, and river channel slope (Fig. 5-1).[47] On the coast, sediment moves in and out of river deltas and also along the shoreline, driven by currents, tides, and waves.[81]

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Section 6
How is Circulation in Puget Sound Projected to Change?

Circulation in Puget Sound is projected to be affected by declining summer precipitation, increasing sea surface temperatures, shifting streamflow timing, increasing heavy precipitation, and declining snowpack. While these changes are expected to affect mixing between surface and deep waters within Puget Sound, it is unknown how these changes will affect upwelling. Changes in precipitation and streamflow could shift salinity levels in Puget Sound by altering the balance between freshwater inflows and water entering from the North Pacific Ocean. In many areas of Puget Sound, variations in salinity are also the main control on mixing between surface and deep waters. Reduced mixing, due to increased freshwater input at the surface, can reduce phytoplankton growth, impede the supply of nutrients to surface waters, and limit the delivery of dissolved oxygen to deeper waters. Patterns of natural climate variability (e.g., El Niño/La Niña) can also influence Puget Sound circulation via changes in local surface winds, air temperatures, and precipitation.

Drivers of Change

DRIVERS ***Wind patterns, natural climate variability, and projected changes in temperature and precipitation can all affect circulation in Puget Sound.[A]***

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2] Increasing air temperatures will result in more precipitation falling as rain instead of snow, and snowpack melting earlier in the year. The resulting shift to earlier peak streamflow will result in more freshwater inflows into Puget Sound during winter months, and decreased freshwater inflows during summer (see Section 3).

- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[3] These changes would lead to a further increase in winter streamflow.

- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent

A Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describes the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

among models, and trends are generally much smaller than natural year-to-year variability.[2] The projected decrease in summer precipitation would accentuate the temperature-driven decrease in summer streamflow.

- *Wind patterns are not projected to change*. There are no projected changes for wind speed or the strength of low pressure systems in the region (see Section 2). Wind patterns affect upwelling, mixing, and currents within Puget Sound.
- *Although long-term changes in climate will likely influence currents and mixing in Puget Sound, natural climate variability is also expected to remain an important driver of regional circulation*. Natural variability in both weather patterns and ocean conditions will continue to affect circulation in Puget Sound. It is not known how variability might change with warming.

Circulation and mixing in Puget Sound

CIRCULATION ***Projected changes in precipitation and streamflow will alter the balance between freshwater inflows and saltwater entering Puget Sound from the North Pacific Ocean.*** North Pacific Ocean water enters Puget Sound through the Strait of Juan de Fuca, mixing with and modifying the water in the Sound. Within Puget Sound, freshwater inflows can impede the mixing between surface and deep waters, a key process for bringing nutrients to the surface and oxygen to depth.

- *The rate of exchange of Puget Sound North Pacific Ocean waters is higher when there is a greater contrast in the density of each.* The exchange occurs in two layers, with relatively warm and fresh water from Puget Sound waters flowing seaward at the surface, and relatively cold and saline Pacific Ocean waters entering the Sound at depth (Figure 6-1). This circulation is driven by differences in density, in which Puget Sound waters become less dense as a result of freshwater inflows. When this density difference is large, the rate of exchange with Pacific Ocean waters is greater. Conversely, when the difference is small the rate of exchange is reduced.[4]
- *Circulation is mediated by the degree of stratification of Puget Sound's marine waters.* Stratification occurs when water density increases with depth, with lower density water at the surface and higher density water below. Water is more dense when it is colder, more saline, and at a greater depth below the surface. Stratification in Puget Sound is weakened when water is mixed by physical mechanisms such as winds and tides. In contrast, stratification is strengthened by solar radiation, freshwater inflows, weak winds and weak circulation, all of which act to decrease the density of surface waters relative to those at greater depths.
- *Mixing of surface and deep waters is of critical importance to biology.* The degree of stratification and seasonal timing of freshwater inputs affects upwelling and the supply of nutrients to surface waters, phytoplankton growth, the delivery of dissolved oxygen to deeper waters, and the effectiveness of pollutant flushing.[5]

Stratification inhibits mixing of deeper, nutrient-rich water, up into the zone where there is enough light for photosynthetic organisms to grow (e.g., algae), and favors the formation of low oxygen zones (hypoxia, see Section 7) at depth. In winter, this is not a major limitation, since the main impediment to biological productivity is a lack of sunlight. During the growing season, in contrast, water column stratification can potentially limit the supply of nutrients to phytoplankton, and the supply of oxygen to deeper waters.[6]

- *Stratification limits the mixing effect of winds.* Greater stratification impedes mixing due to winds. One study, using model simulations of Puget Sound circulation, found that winds can directly influence currents to a depth of about 300 ft. when stratification is weak, whereas strong stratification can limit the influence of winds to the top 100 ft. below the ocean surface.[7] Climate models do not project a change in wind speed or the strength of low pressure systems (see Section 2).

- *Freshwater inflows have a strong effect on the density of marine waters.* In many areas of Puget Sound, variations in salinity are the main control on stratification, and arise as a result of freshwater inflows from rivers.[8,9] Freshwater inflows reduce water density by lowering the salinity of Puget Sound waters. Not surprisingly, density variations are the largest in surface waters near river mouths.[10]

- *Projected changes in air temperature and precipitation will result in greater freshwater inflows in winter, and decreased inflows in summer.* Although total annual streamflow is only projected to change slightly, decreases in winter snow accumulation will drive a shift in the seasonal timing of streamflow, with higher flows in winter and lower flows in summer (see Section 3). This has important implications for Puget Sound circulation, in particular affecting the ability of surface and deep waters to mix.

- *Projected changes in streamflow, could increase the rate of exchange between Pacific Ocean waters and those of Puget Sound in winter, and decrease the rate of exchange in summer.* The reduction in freshwater input during the winter 2000-2001 drought was enough to reduce the exchange through the Strait of Juan de Fuca by −75%.[5] Projected increases in winter streamflow could result in an increase in this exchange rate, whereas projected decreases in summer streamflow could result in a lower rate of exchange. In summer, the resulting increase in flushing time may lead to increased exposure to contaminants and pollutants, and decrease the rate of transport or retention of larvae and plankton.

- *There are no projections of changing stratification in Puget Sound.* Although the effects of surface warming and changing freshwater inputs are well understood, it is not known exactly how important these changes will be. There are other factors that influence stratification, including the temperature and salinity of Pacific Ocean water, ocean currents, wind patterns, and the geographic distribution of precipitation. It is not known how these factors will combine to drive changes in stratification.

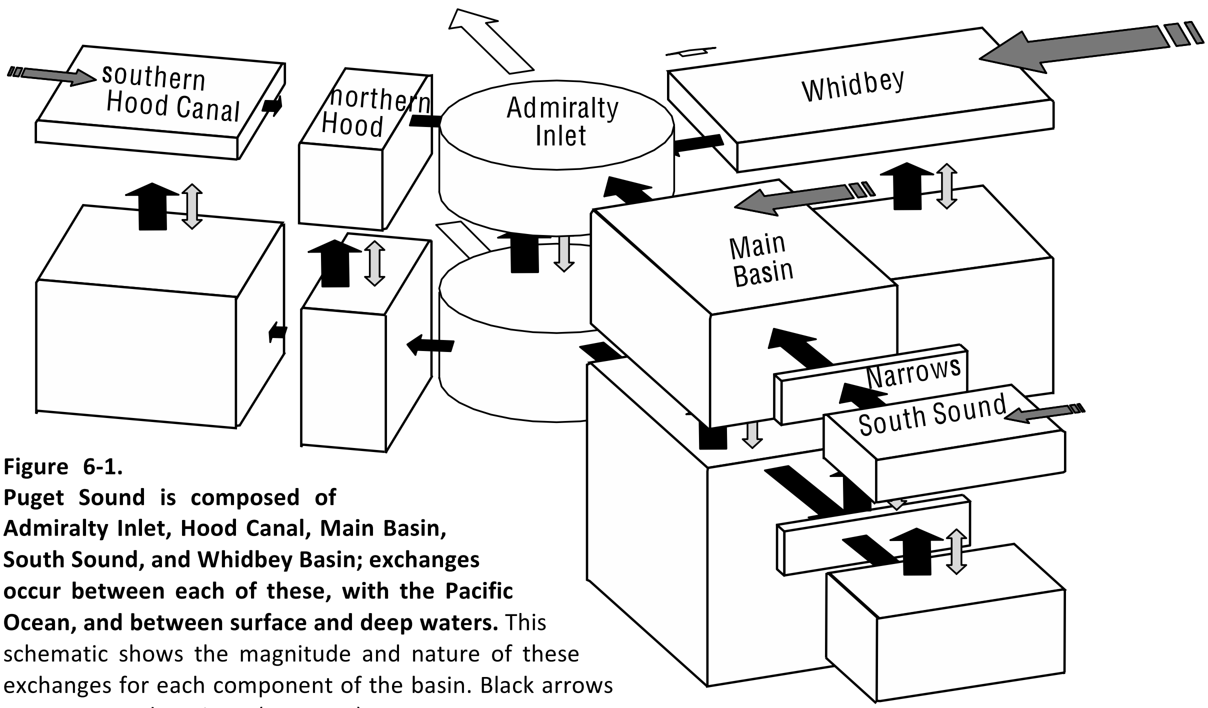

Figure 6-1.
Puget Sound is composed of Admiralty Inlet, Hood Canal, Main Basin, South Sound, and Whidbey Basin; exchanges occur between each of these, with the Pacific Ocean, and between surface and deep waters. This schematic shows the magnitude and nature of these exchanges for each component of the basin. Black arrows represent advection (currents), two-way grey arrows represent mixing, dark grey arrows with dashed ends represent river inputs and white arrows are outlets to the Strait of Juan de Fuca. Boxes have been scaled to show relative volumes. Similarly, arrows have been scaled to show the relative transports with each category. Rivers are proportional on a log scale. The Admiralty Inlet mixing arrow is shown at 50%. *Figure Source: Babson et al. 2006.*[4] *Copyright © La Societe Canadienne de Meterologie et d'Oceanographie reprinted by permission of Taylor & Francis Ltd, www.tandfonline.com on behalf of La Societe Canadienne de Meterologie et d'Oceanographie.*

Coastal Upwelling

UPWELLING ***The effect of climate change on coastal upwelling is currently unknown.*** Upwelling, which occurs along the outer coast of Washington, delivers cold, nutrient-rich water to the ocean surface. These waters affect Puget Sound waters via the exchange through the Strait of Juan de Fuca. Upwelling occurs when northerly winds (from the north) blow along the outer coast of Washington, typically between April and September. These winds push surface water offshore, which is then replaced by deeper water that rises, or "upwells" to the surface. Upwelling affects a wide range of ecological processes, contributing to the productive marine food web of the Pacific Northwest.

- *Upwelling has been hypothesized to increase with warming.* The so-called "Bakun Hypothesis" suggests that upwelling-favorable winds will increase as the climate warms. The idea stems from the fact that land temperatures are expected to warm more rapidly than ocean temperatures. This increasing contrast between land and ocean could drive stronger and more consistent upwelling-favorable winds.[11] This hypothesis is controversial, and may be contradicted by recent projections showing no long-term change in upwelling (see below).

- *Historical increases in upwelling-favorable winds.* One study analyzed 22 observational studies investigating wind trends for records ranging up to 60 years in length. They concluded that studies have consistently found trends in winds that favor increased upwelling along the west coast of North America.[B,12]

- *Warm phases of both ENSO (El Niño) and the Pacific Decadal Oscillatin (PDO) are correlated with a delay and shortening of summer upwelling along the Pacific Northwest coast.* El Niño conditions are also associated with more intense winter downwelling (in which surface waters are driven down to greater depths) along the coast.[13] ENSO and PDO are not projected to change with warming (see Section 2).

- *Projections indicate ongoing variability, but no long-term change in upwelling-favorable winds.* One study evaluated 50-year trends (2000 to 2050) in upwelling favorable winds in the Pacific Northwest, using 23 global climate model projections and a moderate (A1B) greenhouse gas scenario. Model results ranged from a decline of about −40% to an increase of +60%, by 2030-2039 relative to the average for 1980-1989.[C,D,14] Other studies are consistent in finding no evidence for a change in upwelling-favorable winds.[15,16,17] Future trends in upwelling will likely depend on winds, both along the Washington coast and farther south along the U.S. West Coast, and on changes in large-scale atmospheric circulations.[18]

B 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.

C 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 more details.

D Based on 23 global climate model projections and a moderate (A1b) greenhouse gas scenario.

Additional resources for evaluating and addressing the effects of climate change on circulation in Puget Sound.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **NOAA Tides & Currents:** Central resource for information on observed trends in sea level. http://tidesandcurrents.noaa.gov/
- **NOAA Office for Coastal Management:** Provides technical information and support for managing coastal hazards. Tools and products include "Coastal County Snapshots", which allows users to develop customizable PDF fact sheets with information on a county's exposure and resilience to flooding; its dependence on the ocean for a healthy economy; and the benefits received from a county's wetlands. https://csc.noaa.gov/
- **Northwest Association of Networked Ocean Observing Systems:** NANOOS provides Pacific Northwest ocean observations, model estimates ranging from wave heights to ocean properties, forecasts, and a variety of decision-making tools including visualizations of beach erosion rates, tsunami maps, and information on water properties for use by shellfish growers. http://nvs.nanoos.org/
- **West Coast Ocean Data Portal:** A project of the West Coast Governors Alliance, the portal is intended to be a hub for ocean and coastal data, and includes information on Puget Sound. http://portal.westcoastoceans.org/
- **NOAA Climate Prediction Center:** Provides information on seasonal weather predictions and large-scale weather patterns such as El Niño. http://www.cpc.ncep.noaa.gov/
- **Joint Institute for the Study Atmosphere and Ocean PDO website:** Provides a brief overview, along with figures, links, and references on the Pacific Decadal Oscillation (PDO). http://research.jisao.washington.edu/pdo/

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12 Syeman, W.J. et al., 2014. Climate change and wind intensification in coastal upwelling ecosystems. *Science,* 345 (6192), 77-80, doi: 10.1126/science.1251635.

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14 Wang, M. et al., 2010. Climate projections for selected large marine ecosystems. J. *Marine Systems,* 79(3-4), 258-266.

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SECTION 7

How is Puget Sound's Water Quality Changing?

Puget Sound is projected to experience a continued increase in sea surface temperatures, and continued declines in pH and dissolved oxygen concentrations. These changes, which could affect marine ecosystems and the shellfish industry, will be affected by variations in coastal upwelling and circulation within Puget Sound. While it is currently not known how climate change will affect circulation and upwelling in the region, these processes will continue to fluctuate in response to natural climate variability. Impacts on marine ecosystems and shellfish farming generally point to increasing stress for fish and shellfish populations. Efforts to address Puget Sound's water quality are increasing, particularly in the areas of ocean acidification monitoring and implementation of risk reduction practices in the shellfish industry.

Climate Drivers of Change

DRIVERS ***Wind patterns, natural climate variability, and projected changes in temperature and precipitation can all affect water quality in Puget Sound.[A]***

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2]
- *Warming.* The salinity of Puget Sound's waters is tightly linked to freshwater inflows from streams. Increasing air temperatures will result in more precipitation falling as rain instead of snow, leading to more freshwater inflows into Puget Sound during winter months, and decreased freshwater inflows during summer. In addition, increasing air temperatures are expected to drive a continued increase in water temperatures, increasing the likelihood of harmful algal blooms (see Section 3).
- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[3] These changes would lead to a further increase in winter streamflow.
- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent

[A] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describes the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

among models, and trends are generally much smaller than natural year-to-year variability.[2] The projected decrease in summer precipitation could accentuate the temperature-driven decrease in summer streamflow.

- *Wind patterns are not projected to change*. There are no projected changes for wind speed or the strength of low pressure systems in the region (see Section 2). Wind patterns affect upwelling, mixing, and currents within Puget Sound, all of which have an influence on water quality.

- *Although long-term changes in climate will likely influence currents and mixing in Puget Sound, natural climate variability is also expected to remain an important driver of regional circulation.* Natural variability in both weather patterns and ocean conditions will continue to affect water quality in Puget Sound. It is not known how variability might change with warming.

Circulation and Water Quality in Puget Sound

CIRCULATION **Puget Sound's water quality is strongly affected by changes in coastal upwelling and circulation.** Currents and mixing within Puget Sound, the rate of exchange through the Strait of Juan de Fuca, and the frequency and intensity of upwelling along Washington's coast all affect the water quality of Puget Sound*.*

- *Seasonal upwelling along the Washington Coast affects water properties within Puget Sound*. Coastal upwelling (see Section 6) brings nutrient-rich (nitrate, phosphate, silicate) water into the Strait of Juan de Fuca and Puget Sound. These nutrients promote phytoplankton blooms and biological productivity. Upwelled waters are also low in oxygen and high in CO_2, which can stress fish and be harmful to calcifying species (e.g., shellfish). Seasonal upwelling is also a major driver of changes in salinity, oxygen, and nutrients in Puget Sound.[4]

- *Seasonal and year-to-year variations in freshwater inflows and air temperature affect Puget Sound water quality.* Freshwater inputs from rivers and local surface air temperatures vary seasonally and from year-to-year. The salinity of Puget Sound's waters is strongly related to surface freshwater inflows from rivers, while the temperature of Puget Sound's surface waters is strongly related to surface air temperatures and regional weather patterns that determine the strength and direction of winds.[5] Variations in river input alter the circulation and the density stratification[B] of Puget Sound (see Section 6). Stratification affects water quality via its impact on mixing between surface and deep water. Greater stratification, for example due to increased freshwater inflows, results in an increased risk of low oxygen in deeper waters ("hypoxia"), and can alter the timing of spring blooms (causing a possible mismatch with the timing needs of larval fish species).[6]

[B] "Stratification" occurs when the water column has varying density levels. Stratified water has less dense water at the surface and the densest water at the bottom. For more on stratification, see Section 6.

- *We do not know how climate change will affect Puget Sound circulation.* Projected changes in upwelling, El Niño/La Niña (or ENSO, the El Niño Southern Oscillation), and the Pacific Decadal Oscillation (PDO) are ambiguous (see Section 2). Although there is high confidence in the projected warming and in the associated shifts in freshwater input (earlier snowmelt, higher winter streamflow, and lower summer streamflow; see Section 3), it is not known how these will compare to other factors affecting circulation (see Section 6).

Warming Water in Puget Sound

WARMING WATER ***Surface and subsurface water temperatures in Puget Sound and the Northeast Pacific Ocean are warming and could alter the marine ecosystem in Puget Sound.*** Puget Sound water temperatures are influenced by regional effects and via inflows from the Northeast Pacific Ocean. Warmer water holds less oxygen than colder water. Increased water temperatures can also increase the likelihood of harmful algal blooms (HABs). Warmer and low-oxygen conditions stress some cold-water fish and shellfish species that are commercially important to the region.

- *Water temperatures are rising in Puget Sound.* Water temperature increases ranged from +0.8 to +1.6 °F from 1950 to 2009 for stations located at Admiralty Inlet, Point Jefferson, and in Hood Canal.[C,7]

- *Water temperatures are rising in the Northeast Pacific Ocean.* Northeast Pacific coastal sea surface temperature has increased by about +0.9 to +1.8°F over the past century (1900-2012)[8] and subsurface temperatures (~300-1300 ft. depth) have increased by +0.45 to +1.1°F from 1956 to 2006.[D,9]

- *Coastal ocean surface temperatures are projected to rise.* 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).[E,F,10] This long-term trend will be obscured by short-term (up to several decades) variability resulting from coastal upwelling and climate variability such as ENSO and PDO.

- *Long-term trends in surface air temperature may be affected by natural variability.* Natural climate variability has a strong influence on trends: one previous study estimated that about half of the observed increase in air temperature in the

C Trends are statistically significant at the 90% confidence level, based on a seasonal Kendall test.

D Trends are statistically significant at the 95% confidence level, based on a student t-test.

E Projected change in sea surface temperature for model grid points near the coast between 46° and 49°N. Based on an ensemble of 10 global model projections and a moderate (A1B) greenhouse gas scenario.

F 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.

northern hemisphere (1900-1990) is a result of random natural variability (see Section 2).[11]

Harmful Algal Blooms

HARMFUL ALGAL BLOOMS ***Climate change may increase the magnitude and frequency of Harmful Algal Blooms (HABs).*** Often called "red tides," harmful algal blooms are a public health concern due to the toxins subsequently found in shellfish, and also have negative consequences for ecosystems. The dinoflagellate (a type of microscopic marine organism) *Alexandrium catenella* is often responsible for harmful algal blooms in Puget Sound. *A. catenella* generally blooms in July through November, and blooms are often associated with warm surface water and air temperature, low streamflow, weak winds, and small tidal variability.[12] While there is research on the influence of climate change and other anthropogenic influences on harmful algal blooms throughout the world,[13] and a growing body of research on *A. catenella* within Puget Sound, more research is needed to understand the effects of climate change on other harmful algae species that are found in the region.

- *Climate change may increase growth rates of harmful algal species*. Small increases in growth are projected for *A. catenella* throughout Puget Sound as conditions (e.g., temperature, salinity) become more favorable (Figure 7-1).[G,14]

- *Increasing water temperature is projected to expand the window of opportunity for harmful algal blooms.* By the end of the century (2070-2099, relative to 1970-1999), the number of days with favorable conditions (i.e., the "window of opportunity") for harmful blooms of *A. catenella* in Puget Sound is projected to increase by an average of +13 days, and may begin up to 2 months earlier and persist up to 1 month later compared to present conditions. However, if sea surface temperatures in Puget Sound increase past a threshold that exceeds the temperature range for *A. catenella* blooms, the window of opportunity in Puget Sound may then decline.[H,I,15]

- *Ocean acidification may increase the toxicity of some harmful algal blooms*. The interaction of high carbon dioxide concentration projected under ocean acidification and silicate limitation[J] increases the toxicity of the diatom *Pseudo-nitzschia*

G Climate data from 2 global climate models (CCSM3 and ECHAM5) from CMIP3 under the SRES A1b greenhouse gas scenario for 1969-2069 compared to historical conditions in 1970-1999. Ocean model simulations conducted using Modeling the Salish Sea (MoSSea).

H Based on an ensemble of 20 global climate models and the moderate (A1b) greenhouse gas scenario (from Mote and Salathé 2010) for the 2020s, 2040s, and 2080s representing averages for 2010-2039, 2030-2059, 2070-2099.

I The harmful algal bloom window of opportunity declined at a temperature increase of +2.2°F. Temperature increases between +0.9°F and +2.2°F were not tested.

J Biological productivity is frequently controlled by the availability of the least abundant nutrient. "Silicate limitation" refers to conditions in which productivity is limited by a lack of silicate (SiO3), an important nutrient for certain classes of marine organisms.

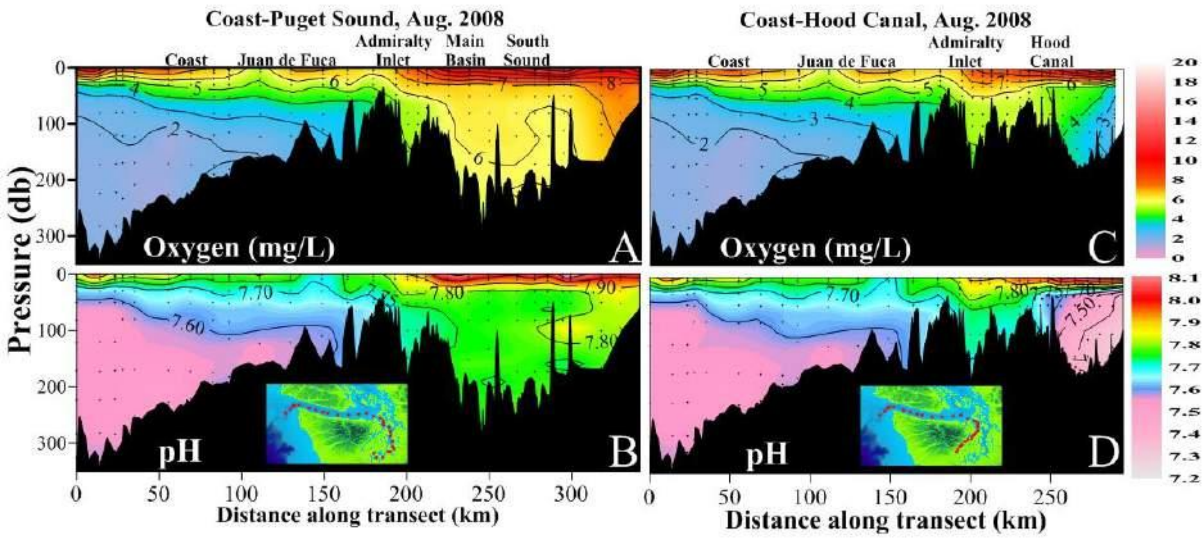

Figure 7-1. Observations from August, 2008: Oxygen and pH are lowest in the deep waters of the Strait of Juan de Fuca and Hood Canal. These figures show the dissolved oxygen concentration (top) and pH (bottom) as a function of depth in the water column (y-axis goes from 0 to 350 m, or about 1150 ft., below the water surface). The inset maps show the paths followed for each transect. The left-hand column shows the results of one transect, which goes from the Pacific Ocean at the entrance to the Straight of Juan de Fuca, to the southern end of Puget Sound. The right-hand column shows the results for a transect that ends in Hood Canal. The height of the sea floor is shown in black, and common landmarks are labeled at the top of the figure (for example, note how shallow the water column is at Admiralty Inlet). Black dots represent measurement locations. *Figure Source: Modified from the original presented in Feely et al. 2010,[24] courtesy of NOAA Pacific Marine Environmental Laboratory.*

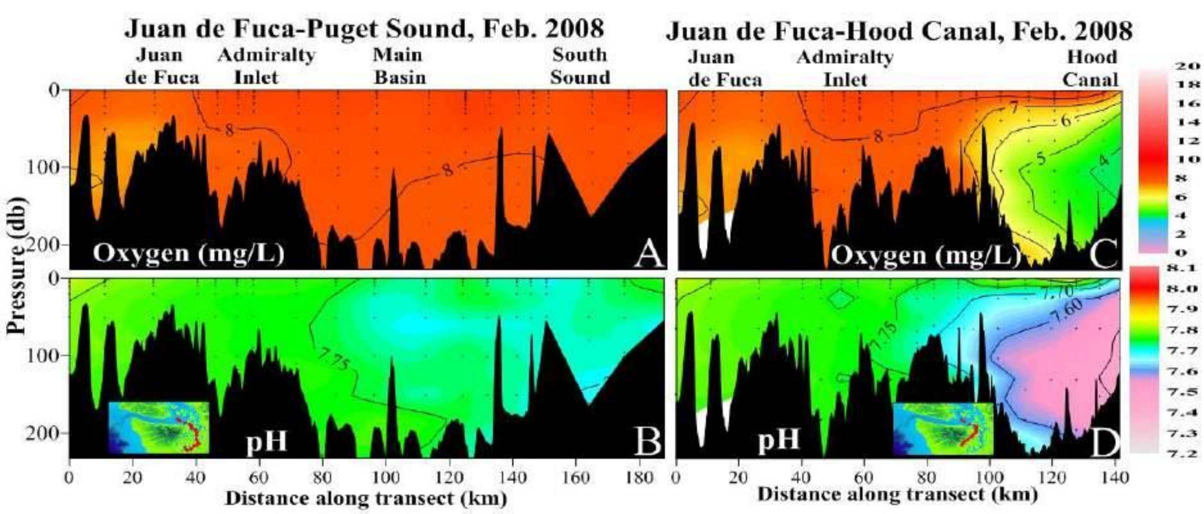

Figure 7-2. Observations from February, 2008: Oxygen and pH fairly uniform, except in the interior of Hood Canal, where there is a zone of low pH and low oxygen. The figure is identical to Figure 7-1, with one exception: the transects do not extend all of the way out to the Pacific Ocean but instead stop at the Strait of Juan de Fuca (see map insets). *Figure Source: Modified from the original presented in Feely et al. 2010,[24] courtesy of NOAA Pacific Marine Environmental Laboratory.*

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fraudulenta, which is another harmful algae species in Puget Sound.[K,16] Although silicate is not currently a limiting nutrient in the majority of Puget Sound, observations suggest that it is declining in abundance relative to nitrogen concentrations,[17] and projections indicate increases in Puget Sound nitrogen levels (see below).[18] This suggests that Puget Sound conditions may shift from nitrogen- to silicate-limited conditions in the future. Combined with projected acidification of Puget Sound's waters, this could result in increased toxicity of *Pseudo-nitzschia blooms*.

- *Increases in harmful algal bloom events represent a threat to human and marine health and commercial fisheries.* Shellfish closures and fish deaths damage Washington's shellfish industry, valued at ~$108 million per year.[L,14]

Ocean Acidification

OCEAN ACIDIFICATION ***Ocean acidification is increasing, and is projected to continue to increase, with consequences for Puget Sound's marine ecosystems and shellfish industry.*** The chemistry of the ocean along the Washington coast has changed due to the absorption of excess CO_2 from the atmosphere. Ocean acidification occurs when the pH of the ocean decreases (acidity increases) due to the uptake of CO_2 from the atmosphere.[M] Conditions vary by location and from season to season (Figures 7-1 and 7-2), but appear to have already reached levels that can affect some species (see Section 11).[19]

- *Ocean acidification is increasing.* 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 (since about 1750)[20] and by −0.027 from 1991 to 2006.[21]

- *Ocean acidification will continue to increase.* The pH of Washington's coastal waters is projected to continue to decrease due to increases in global ocean acidity: pH is projected to decline by −0.14 to −0.32 by 2100 (relative to 1986-2005; corresponding to an increase in the hydrogen ion concentration of +38 to +109%).[M,N,22] The patterns of low pH observed in Puget Sound are largely a result of natural processes: mixing, circulation, biology. By the time the atmospheric CO_2

K Determined from laboratory experiments with pCO_2 levels of 200 ppm (preindustrial), 360 ppm (modern day), and 765 ppm (projected for 2100) and silicate levels of 8.4 ppm (pre-industrial), 8.2 ppm (modern day), and 7.9 ppm (projected for 2100).

L Based on 2008 and 2009 data from the Pacific Coast Shellfish Growers Association.

M Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Average global ocean surface pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines a liquid's acidity) and is projected to fall to 7.8-7.9 by 2100. The term "ocean acidification" refers to this shift in pH towards the acidic end of the pH scale.

N Projections are a particular class of global climate models called "Earth System Models". The 12 models used in this study model the carbon cycle, and can therefore provide estimates of ocean-atmosphere CO_2 fluxes. 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.

concentration has doubled, ocean acidification could account for 49-82% of the pH decrease in the deep waters of Hood Canal.[23,24] The CO_2 concentration is projected to double by about 2050 for a high greenhouse gas scenario (RCP 8.5), or after 2100 for a low scenario (RCP 4.5, see Section 1). This long-term trend will be modified by short-term variability due to upwelling, nutrient inputs, and other factors.[23,24,25]

- *Other factors influence the pH of marine waters.* For instance, ocean acidification accounts for 24-49% of the total increase in dissolved inorganic carbon[O] in the deep waters of Hood Canal relative to estimated pre-industrial values. The remaining trend is a result of increased biological productivity in response to human or natural nutrient inputs. [24] Natural drivers of acidification include variability in upwelling and river runoff; additional human influences include nutrient runoff (e.g., from fertilizers) and built structures that alter currents.

- *Research on ocean acidification in Puget Sound is limited by a lack of observations*. The lack of high-quality, long-term, carbon time-series measurements in Puget Sound makes it hard to directly determine the increase in anthropogenic CO_2 in the region.[24] Refer to the *"Climate Risk Reduction"* subsection below (page 7-9) for more information about ongoing ocean acidification monitoring efforts in Puget Sound and the Pacific Northwest.

Dissolved Oxygen Concentrations in Puget Sound

DISSOLVED OXYGEN ***Dissolved oxygen levels are declining and are expected to continue to decline due to both climatic and non-climate factors.*** Oxygen concentrations in Puget Sound are affected by warming, changes in the northeast Pacific Ocean, freshwater inflows, and by human and natural sources of nutrients. Low oxygen levels (below 5 mg/L) can stress fish species, and extreme low oxygen events (hypoxia, below 2 mg/L) have caused fish kills in areas of Puget Sound such as Hood Canal.[26]

- *Dissolved oxygen concentrations in the Northeast Pacific are declining.* From 1960 to 2009, May through September dissolved oxygen concentrations have declined by -1.15 ± 0.35 mg/L (a decline of roughly −25%) at a depth of 500-650 ft. off the central Oregon coast.[P,27] Over the period 1956-2006, dissolved oxygen concentrations at Ocean Station Papa (50N, 145W) declined by about −22%, on average, for waters between about 300 and 1300 ft. in depth.[D,9]

- *Dissolved oxygen concentrations are declining in the Strait of Georgia, just north of Puget Sound.* Oxygen concentrations at depth have declined by −0.56 to −1.6 mg/L in May-June from 1971 to 2009 (a decline of roughly –13% to −29%), primarily due

O Dissolved Inorganic Carbon, or DIC, refers to the concentration of carbon stemming from CO_2 dissolution in water. When CO_2 dissolves in seawater, it forms a buffer solution composed of carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) ions.

P The uncertainty in the trend corresponds to the 95% confidence limits.

to coastal upwelling of water with low dissolved oxygen levels.[Q,28] If this trend continues, parts of the Strait of Georgia could occasionally become hypoxic as early as 2042, though this depends on the strength of mixing between surface and deep waters.

- *Observations of Puget Sound dissolved oxygen concentrations are too short to estimate trends.* Observations of dissolved oxygen concentrations that include measurements extending from the surface to the bottom of Puget Sound date back to 1999. Although the observations show that coastal upwelling has a strong influence on dissolved oxygen concentrations, the record is not sufficiently long to distinguish a long-term trend from natural variability.[4] Combined data sources between 1950 and 2009, however, suggest consistent decreases in dissolved oxygen in the Strait of Juan de Fuca, Admiralty Inlet and Hood Canal, which implies that the change may be driven by North Pacific Ocean waters entering Puget Sound.[7]

- *Observed trends in dissolved oxygen are influenced by natural variability, data availability, and geographic variations within Puget Sound.* Observations from different times and locations reflect a combination of local influences, distinct patterns of natural variability, data availability, and possible measurement biases. These factors can all have an influence on individual trend estimates.

- *Puget Sound oxygen concentrations are projected to decrease as a result of increased air temperatures, declining oxygen concentrations in the Northeast Pacific, and increasing nutrient inputs due to human activities.*[R] Model simulations estimate that nutrient runoff due to human activities (for example, fertilizers) causes over –0.2 mg/L in cumulative dissolved oxygen depletion compared to natural conditions in Puget Sound. Increasing nutrient runoff due to human activities is not a consequence of climate change. Models project that by 2070 (2065-2069, relative to 1999-2008) dissolved oxygen could decrease by more than –1 mg/L in the Strait of Juan de Fuca and dissolved oxygen could decline by more than –0.6 mg/L in Central Puget Sound and Hood Canal.[S,29] It is not known what proportion of this change is due to warming.

Nutrient Concentrations in Puget Sound

NUTRIENTS ***Puget Sound nutrient levels are projected to increase due to non-climatic factors: climate change has not been identified as a dominant factor affecting nutrient concentrations in Puget Sound***. Increased nutrient levels within Puget Sound enhance biological growth and productivity near the surface and lead to oxygen loss through respiration and decomposition in deeper water. Nutrient inputs are projected to continue to increase with projected population growth. Nitrogen in particular is naturally occurring in rivers and streams, and has also increased as a result of population growth and human activities.[29,30] Although climate could indirectly influence nutrient

[Q] Trends are statistically significant at the 95% confidence level.

concentrations, current studies do not quantify this effect.

- *Although observations of Puget Sound nitrate and phosphate levels show concentrations that are increasing, the records are too short to quantify the effect of warming.*[4,31] Observational records are not of sufficient length to reliably distinguish long-term trends due to climate change from natural variability or other human influences. For example, measurements from 1999-2014 show that the observed increase in nitrate and phosphate concentrations in Puget Sound's surface waters have not been accompanied by a parallel change in silicate concentrations. This suggests that the recent increase is due to a human impact on nutrient fluxes (e.g., changes in land use and development), and is not related to climate change.[17,18]

- *The Northeast Pacific Ocean is the largest source of nutrients for the Strait of Juan de Fuca and Puget Sound.* There are four physical factors governing nutrient concentrations in Puget Sound: the rate of exchange with Pacific Ocean waters, the intensity of upwelling, the magnitude of freshwater inflows, and tidal effects on mixing. Total nitrogen inputs from the Pacific Ocean are ~7-8 times greater than the combined inputs from sewage, runoff, and the atmosphere.[32]

- *Puget Sound nitrogen levels are projected to increase in the future due to projected changes in land use (e.g., development patterns, agriculture, etc.) and are not a consequence of climate change.* Relative to the 2006 baseline, nitrogen concentrations in rivers are projected to increase by +7% by 2020 (2015-2024), +14% by 2040 (2035-2044) and +51% by 2070 (2065-2069).[S,29]

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Shellfish growers, government agencies, and organizations are preparing for the effects of ocean acidification in Puget Sound.*** These groups are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

- *The Washington Ocean Acidification Center* works with scientific researchers, policymakers, industry, and other stakeholders to provide a scientific basis for strategies and policies to address the effects of ocean acidification. The Center is hosted at the University of Washington and was established in 2013 by the Washington State Legislature based on a recommendation from the Blue Ribbon Panel on Ocean Acidification. http://environment.uw.edu/research/major-initiatives/ocean-acidification/washington-ocean-acidification-center/

R Increased nutrient levels within Puget Sound enhance biological productivity near the surface and lead to oxygen loss through respiration. Respiration is essentially the opposite of photosynthesis: it is the process of breaking down organic material in order to release energy. This is typically accompanied by an intake of oxygen and the release of carbon dioxide (CO_2).

S Projection is based on a single global climate model simulation (ECHAM5) and a moderate (A1B) greenhouse gas scenario. The global model projection was dynamically downscaled using a regional climate model.

- *Increased monitoring of ocean acidification in Puget Sound and Washington State's coastal waters.* After confirming a link between acidified waters and the survival of oyster larvae, the Pacific Coast Shellfish Growers Association (PCSGA) established a monitoring network at hatcheries and other locations designed to provide real-time information on the pH of coastal and Puget Sound waters. The effort has now expanded to form the California Current Acidification Network (C-CAN), and involves coordination among partners including individual counties, the U.S. Integrated Ocean Observing System, and others. The C-CAN effort is designed to both directly monitor ocean chemistry and develop predictive and impact models linking low pH events to both the climate drivers and the economic consequences they entail.[33]

- *Changing practices at shellfish hatcheries.* Many hatcheries are now developing water treatment systems that can adjust the chemistry of waters that they draw in to their growing tanks. For example, Taylor Shellfish Hatchery in Puget Sound has installed buffering systems that improve water chemistry issues caused by low carbonate ion concentration. These systems pump carbonate ions, a form of inorganic carbon essential for shell formation, back into the water used to grow shellfish, improving shell development. Since these approaches may not be sufficient to guard against future decreases in pH, shellfish growers are also exploring long-term strategies for adaptation. For example, selective breeding, a practice used to grow shellfish resilient to ocean acidification, is now a common practice in commercial hatcheries. While these stocks were not selected for genetic resistance to ocean acidification, the stocks have been grown in the coastal waters of the Pacific Northwest for several generations and may have formed natural resistance to ocean acidification.[33]

Additional resources for evaluating and addressing the effects of climate change on water quality in Puget Sound.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **The Washington Ocean Acidification Center** conducts research, education and outreach on ocean acidification in Washington State. Created in 2013, the Center engages with researchers, policymakers, and industry to advance the scientific understanding of ocean acidification and inform efforts to respond to its effects. http://environment.uw.edu/research/major-initiatives/ocean-acidification/washington-ocean-acidification-center/
- **Northwest Association of Networked Ocean Observing Systems.** NANOOS provides Pacific Northwest ocean observations, model estimates ranging from wave heights to ocean properties, forecasts, and a variety of decision-making tools including visualizations of beach erosion rates, tsunami maps, and information on water properties for use by shellfish growers. http://nvs.nanoos.org/
- **Washington Department of Ecology, Environmental Assessment Program**. Provides monitoring data and assessments of Washington's streams, rivers, lakes, marine waters, sediments and groundwater. http://www.ecy.wa.gov/programs/eap/index.html
- **West Coast Ocean Data Portal.** A project of the West Coast Governors Alliance, the portal is intended to be a hub for ocean and coastal data, and includes information on Puget Sound. http://portal.westcoastoceans.org/
- **NOAA Pacific Marine Environmental Laboratory.** Provides information, research and data relating to Pacific Northwest climate, marine ecosystems and coastal and ocean processes, including ocean acidification. www.pmel.noaa.gov

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SECTION 8

How Will Climate Change Affect Agriculture?

Agriculture in the Puget Sound region is projected to experience a lengthening of the growing season, shifts in crop production, increasing water supply challenges, changing risks from pests, increasing winter flood risk, and an increasing risk of saltwater intrusion. While these changes will leave some crops and locations more vulnerable than others, Puget Sound's agricultural system as a whole is expected to be able to adapt to these changes. Impacts on Puget Sound agriculture will vary by production type but generally point to increasing suitability of some crops (e.g., grapes) and declining suitability of others (e.g., berries). In addition, increasing flood risk is likely to damage farm infrastructure, and rising sea levels coupled with increased flooding could negatively affect crops, prevent planting, and affect water quality, especially near the coast. Efforts to address agricultural impacts are increasing, particularly in the areas of flood risk reduction and water management.

Climate Drivers of Change

CLIMATE DRIVERS ***Increasing air temperatures, decreasing summer precipitation, shifting types of winter precipitation, CO_2 fertilization, and sea level rise are all projected to affect agriculture in the Puget Sound region.***[A]

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2] Increasing air temperatures will result in a longer growing season, but may also lead to decreased summer water availability, increased winter flood risk (see Section 3),[3,4] and an increased prevalence of pests.
- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[5] This could lead to increased damage and flood risk to farms, particularly those located in floodplains.
- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year

[A] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

variability.[2] Declining precipitation in summer would exacerbate temperature-driven declines in summer water availability.

- *CO_2 concentrations will continue to increase.* Increasing levels of atmospheric CO_2 may result in increased productivity in some crops (referred to as "CO_2 fertilization"). In the near term, if sufficient water is available, these benefits can outweigh the negative effects of warming. Invasive species may benefit as well; some as a result may gain a competitive advantage over native species and crops.[6,7]

- *Nearly all scenarios project a rise in sea level.* Sea level rise is projected for all locations except Neah Bay, where a decline in sea level cannot be ruled out due to the rapid rates of uplift in that area.[8,9,10] Sea level rise is likely to render existing dikes insufficient to prevent flooding of agricultural lands in cultivated Puget Sound deltas.[11] Higher sea level may also affect the ability to drain farmland in these floodplains.[12]

Crops

CROPS ***Projections are imited to a small selection of species and locations, and do not include the combined effects of changing crops, predators, and other factors.*** To date, very little research has been conducted that is specific to Puget Sound agriculture. Only one of the following examples discusses Puget Sound-specific agriculture, and the remaining examples reflect a general understanding of crop requirements, and do not exclusively address Puget Sound-specific conditions and crops, which could shift as a result of climate change.[B]

CROPS ***Increasing carbon dioxide (CO_2) concentrations and increasing air temperatures are expected to cause production increases in some crops grown in the Puget Sound region.***

- *Increasing air temperatures could increase the number of grape varieties best suited to growing in Washington's temperate regions, including the Puget Sound region.[13]* The warmer climate projected west of the Cascades would make it easier to grow grapes in areas that are currently unsuitable due to low growing season temperatures.[14] Projections suggest that the Puget Sound lowlands may become newly suitable for viticulture by 2050 (2041-2060), under both a low and a high greenhouse gas scenario (Figure 8-1).[C,D,15]

B 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.

C 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.

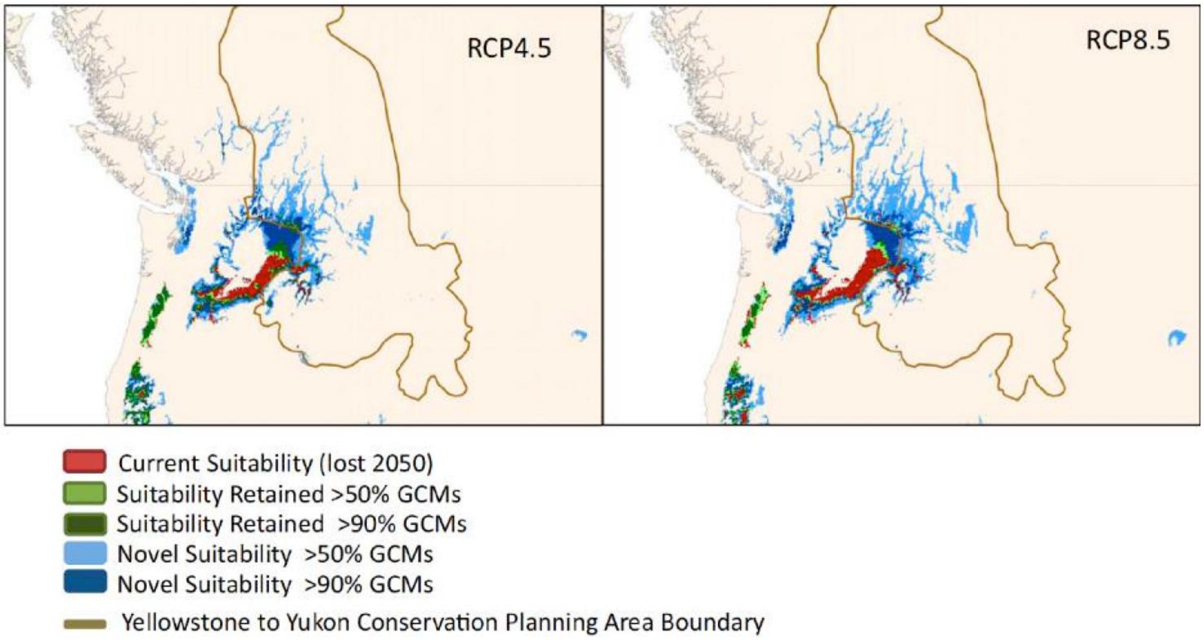

Figure 8-1. New areas becoming suitable for cultivating wine grapes. Projected changes in areas of climatic suitability for grapes for 2050 (2041-2060, relative to 1971-2000), under a low (RCP 4.5, left) and high (RCP 8.5, right) greenhouse gas scenario (see Section 1). Area suitable for viticulture is projected to increase from ~1.7 million acres to >+ 22 million acres under RCP 4.5 and to >+ 29 million acres under RCP 8.5 (increasing by a factor of 13 and 19, respectively). Results for both greenhouse gas scenarios indicate that the lowlands of Puget Sound will become newly suitable for grape production. *Figure source: Hannah et al. 2013* [D,15]

CROPS ***Increasing air temperatures and increasing water stress are expected to cause production declines in some crops grown in the Puget Sound region.***

- *Increasing air temperatures may negatively affect the production of some berries and tree fruit due to an insufficient chilling period – winter periods with low air temperatures necessary for fruiting and flowering.*[16,17] Extended periods between 32 °F and 45 °F are ideal for raspberry chilling, and warm air temperatures during winter may result in lower yields.[18]

- *Projected declines in summer water availability may adversely affect tuber production and quality.* Although not focused on the Puget Sound region, one study found that tuber production in Benton County, WA decreased by –8% to –17% in response to relatively modest decreases in irrigation.[19]

[D] The study defined the current climate by using a reference period from 1971-2000 and all parameters used were monthly or annual means. Future global climatologies, representing monthly 20-year normals for 2041-2060, were downscaled from 17 global climate model simulations (see Section 1), based on the RCP 4.5 and RCP 8.5 greenhouse gas scenarios.

CROPS ***Increased CO_2 concentrations are projected to reduce nutritional quality of forage and pasture, and can reduce the digestibility of forage.***[E,6] Experiments indicate that CO_2 fertilization will result in reduced nutritional value in forage and pasture land. For instance, up to a −14% reduction in forage digestibility for livestock was observed in response to a doubling of CO_2.[20]

Water Resources Impacts

WATER RESOURCES ***Elevated sea levels and declines in summer water availability could increase the risk of saltwater intrusion into Puget Sound groundwater; reduced summer water availability could also result in water supply challenges.*** Limited summer water supply can lead to an increase in groundwater extraction. When extraction outpaces recharge, the risk of saltwater intrusion grows.[21]

- *Several coastal regions of Washington have documented cases of saltwater intrusion*.[21] The most widespread occurrences of saltwater intrusion have been documented on San Juan and Island Counties.[22] Although climate change will likely increase the risk of saltwater intrusion, there are no published projections that quantify the anticipated change.

- *As water availability declines, it could be increasingly challenging to supply water to all consumers.* Projected increases in air temperatures and declines in summer precipitation could reduce summer water availability in the region (see Section 3). Increasing water scarcity could result in increased conflict over water rights.

WATER RESOURCES ***Increasing flood risk may negatively affect Puget Sound farms, a significant proportion of which lie in susceptible valleys and floodplains.*** For example, farms in the Snoqualmie Valley Agriculture Production District are already very vulnerable to flooding, and have experienced several major floods since 1990.[23]

- *Rising sea levels could inundate farmland in the Skagit River delta, adversely affecting crops already in the ground and preventing planting.*[11] On the Swinomish Reservation in southwestern Skagit County, sea level rise (see Section 4) could inundate over 1,100 acres of reservation land, including the only agricultural lands in the Reservation.[F,24] Sea level rise is also likely to increase inundation risk and slow drainage of cropland elsewhere in Skagit County.[12]

E When yield is increased (e.g., as a result of CO_2 fertilization) without a concurrent increase in nitrogen supply, protein levels (and thus quality) of the plant are reduced. If nitrogen levels are adjusted based on increasing yields, the issue of reduced plant quality is eliminated. Therefore, it is likely that this is a manageable agricultural concern.

F This study incorporated approximate local sea level rise in in the Puget Sound by applying the contributions of regional atmospheric dynamics and vertical land movement to the average of 18 IPCC global model projections of sea level rise. These estimates range from very low, 8 cm (3 inches), by 2050 to very high, 128 cm (50 inches), by 2100.

- *Floods allow pollution from roads, including oil and hazardous material, to wash into rivers and streams.* During a flood, these pollutants can settle on dry soils, which can negatively affect crops and livestock.[25]
- *The majority of the crop and pastureland in Skagit County is in the floodplain-delta area and is vulnerable to repeated flooding*. Increased peak river flows (see Section 3) and sea level rise (see Section 4) are projected to substantially increase flood risk for agriculture in these floodplains. Flower (tulips) and vegetable crops (including seed crops) are especially vulnerable to floods, as they may still be in the ground during fall floods, or may need to be planted in spring, before spring floods have receded.[23]
- *Increasing flood risk is likely to result in direct damage to farm infrastructure.*[25,26] An analysis evaluating the expected annual flood damages of a Skagit River flood estimated that farm buildings will incur just under $1.5 million dollars worth of damage annually.[G,26] The total value of existing at risk farm property (structures and contents) in the Skagit River basin is estimated at a little more than $86 million.[H,26]

Agricultural Pests

PESTS ***Increasing air temperatures are associated with changes in the geographic distribution of insect pests, spring arrival dates, and life-cycle durations.*** Although specific projections of changes in Puget Sound agricultural pests are not currently available, studies have identified links between pests and air temperature. However, making generalizations about how pathogens will respond to climate change is difficult because responses are likely to be species- and host-specific.

- *Increasing winter air temperatures will likely drive a mixture of increases and decreases in the damages caused by pests.* As geographic ranges for agricultural pests shift, some new pests will arrive in the region, while others will no longer be suited to the new climate. Some pests will survive winters when they previously had not, and longer growing seasons may allow for more successful reproductive cycles within a given year, resulting in exponentially faster population growth. Conversely, some pests that have historically emerged in tandem with specific crop life stages (e.g., flowering) may no longer emerge at the correct time, resulting in a decrease in economic damage.[27,28,29]

[G] A Monte-Carlo analysis of flood damages was conducted using the HEC-FDA model (Flood Damage Analysis), which considers uncertainties related to hydraulics, hydrology, levee performance, and economics. Expected annual damages for the lower floodplain is based on the current 500-year flood event.

[H] Value of damageable property is based on October 2012 prices, and is based on the current 500-year flood event.

Livestock

LIVESTOCK ***Livestock production may be adversely affected by increasing air temperatures and flood risk.***

- *Heat stress may lead to reduced milk production in dairy cattle, due to the high metabolic costs of lactation.*[30,31,32] Beef cattle are generally considered to be less vulnerable to heat stress, however, they do display similar physiological responses to heat stress as dairy cattle.[31,33] While the effects of heat stress on milk production are not negligible, they are small: nationally, climate change is projected to reduce dairy production by –6.3% by the 2080s.[32]

- *Livestock production may be adversely affected by increased flooding.* While livestock may be managed in emergency conditions for a few days, flood emergency operations typically cannot be sustained for more than one to two weeks.[23] One King County dairy farmer stated that he was unable to milk 47 dairy cows for over 50 hours during flooding of the farm's milking parlor. As a result, the cows became sick and the milk could no longer be sold.[34]

Capacity for Accommodating Climate Change

CAPACITY ***Agriculture is expected to be very adaptable to changing circumstances, although some crops and locations are more vulnerable than others.***

- *Farming and ranching are inherently flexible.* Agricultural production already involves adapting to changing weather and climate conditions. This flexibility will facilitate adaptation to climate change.

- *Agriculture in the Puget Sound region is very diverse.* This will likely facilitate adaptation, as some crops fare better than others.

- *Shifts in irrigation and improved management practices could outpace climate-related effects.* For instance, the pace of recent changes in livestock production – in response to changes in management and breeding – is much larger than existing projections of climate-related changes.[32] Although increased competition for water is likely to become a key challenge, shifts from dryland (non-irrigated) to irrigation could reduce the impact of declining in summer water availability on Puget Sound crops.

- *Western Washington agriculture is likely less vulnerable than central and eastern Washington.* Greater water availability, access to urban markets, and the milder climate of coastal Washington will likely make it easier for agriculture to adapt in this region.

- *While the agricultural system in western Washington is expected to be able to adapt to climate-related effects, individual farms in the region may be unable to adopt new* *management practices or switch crop varieties.* For example, transitioning to new crops can require substantial investments in time and money. Wine grapes and apples, for instance, require years to establish and begin generating revenue.

- *Some subsidies and conservation programs could inhibit adaptation.* Some policies and regulations – including crop subsidies, disaster assistance, conservation programs, environmental regulations, and certain tax policies – may reduce the incentive for adaptation.

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Many communities, organizations, tribes, and government and state agencies are working to adapt agricultural systems in the region to the potential effects of climate change.*** Examples include:

- *Puyallup Tribe of Indians vulnerability assessment and adaptation plan.* This assessment and plan will address priority issues within the following sectors: agriculture and first foods[I]; water resources; human health; ecosystems and habitats; species; forests; oceans and shorelines; traditional lifestyles; and infrastructure.

- *King County 2015 Farm Pad Program.* King County offers technical assistance and logistical support for the construction of farm pads in the Snoqualmie Valley Agricultural Production District. Farm pads are elevated areas where livestock, farm machinery and other agricultural equipment and supplies can be stored safely during a flood. Properly designed farm pads and other elevated flood refuges can help mitigate flood damages to farming operations. http://www.kingcounty.gov/environment/water-and-land/flooding/farm-pad.aspx

- *Ensuring adequate water supply for fish and farms.* King County Water and Land Resources and Wastewater Treatment Divisions (WLRD, WTD) will work with water purveyors and the U.S. Army Corp of Engineers to help ensure minimum viable river flows for fish and agriculture during low flow seasons, and will work with water purveyors and farmers to expand water conservation efforts and use of reclaimed water.

- *King County Agricultural Drainage Assistance Program (ADAP).* ADAP helps agricultural property owners improve drainage of agricultural lands by providing technical and financial assistance. http://www.kingcounty.gov/environment/waterandland/stormwater/agricultural-drainage-assistance.aspx

I “First foods” includes salmon, wild game, roots, berries, and clean water.

Additional resources for evaluating and addressing the effects of climate change on agriculture in Puget Sound.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **U.S. Department of Agriculture (USDA) Climate Change Adaptation Plan.** This plan presents strategies and actions to address the effects of climate change on key USDA mission areas including agricultural production, food security, rural development, and forestry and natural resources conservation. http://www.usda.gov/oce/climate_change/adaptation/adaptation_plan.htm

- **The Future of Farming, a strategic plan for Washington agriculture.** This plan was developed in 2008 by the Washington State Department of Agriculture, and includes detailed recommendations and proposals for potential future agricultural actions within the state. http://agr.wa.gov/fof/

- **Regional Earth System Modeling Project (BioEarth).** This project improves the understanding of the interactions between carbon, nitrogen, in the Pacific Northwest, in the context of global change, to inform decision makers' strategies regarding natural and agricultural resource management. http://bioearth.wsu.edu/

- **Climate Friendly Farming (CFF).** Established by Washington State University's Center for Sustaining Agriculture and Natural Resources, CFF aims to better understand carbon sequestration and greenhouse gas emissions from agricultural systems and to establish long-term agricultural research projects that are focused on improving resiliency of agriculture to a changing climate. http://csanr.wsu.edu/program-areas/climate-friendly-farming/

- **Watershed Integrated Systems Dynamics Modeling (WISDM).** This program aims to improve understanding of interactions between water resources, water quality, climate change, and human behavior in agricultural and urban environments in the Columbia River Basin, including exploring how primary water users can be involved in the research process to develop scientifically sound and economically feasible public policy. http://wisdm.wsu.edu/

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SECTION 9

How Will Climate Change Affect Terrestrial Ecosystems?

Terrestrial ecosystems in the Puget Sound region are projected to experience a continued shift in the geographic distribution of species, changes forest growth and productivity, increasing fire activity, and changing risks from insects, diseases, and invasive species. These changes have significant implications for ecosystem composition and species interactions. Changes are projected to be most pronounced at high elevations, where increasing air temperatures and declining snowpack can degrade habitat quality for some species but benefit others via a longer snow-free season and increased biological productivity. Many of the changes expected for Puget Sound forests are likely to be driven by increases in the frequency and intensity of disturbances such as fire, insect outbreaks, and disease. Efforts to address impacts on terrestrial ecosystems in the region are increasing, particularly in the area of adaption planning, where many local organizations, agencies, and tribes have already begun to engage in planning and collaboration between scientists, managers, and stakeholders.

Climate Drivers of Change

Projected changes in the Puget Sound region's[A] terrestrial environment are driven by increasing air temperature, reduced snow accumulation, and declining summer precipitation.

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2,3] Warming, along with reduced snowpack, will result in a longer growing season and an earlier onset spring growth. Declining snowpack will also drive a decline in summer water availability, with consequences for soils, streams, and groundwater.[4,5,6] Finally, the associated shift to earlier peak streamflows could negatively affect floodplain wetlands.[7]

- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year variability.[2] Projected decreases in summer precipitation will exacerbate the temperature-induced shift from snow accumulation to rain.

[A] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

Changes in Timing of Biological Events

Climate change could alter the timing (or "phenology") of some biological events.

- *A lack of sufficiently cold air temperatures may delay leaf emergence.* Studies of Douglas-fir in western Washington and Oregon[B] have found that warmer air temperatures may result in earlier spring growth initiation,[8] but that rising winter air temperatures could lead to delayed leaf emergence due to an unfulfilled winter chill requirement.[9] One study documented irregular leaf timing in plants with a winter chilling requirement (including Douglas-fir) that received no to low levels of chilling.[10]

Changes in the Geographic Distribution of Species

Climate change is projected to alter species' geographic distributions. Some species may be unable to move fast enough to keep pace with shifting climates, which may result in local extinctions. Both range shifts and local extinctions are likely to lead to changes in the composition of biological communities in the Puget Sound region. Because species will respond individualistically, effects should be considered on a case-by-case basis. For many species, the effects of land-use and fragmentation may act as a more serious stressor than climate change. Regional examples include:

- *Wolverine (Gulo gulo) habitat is projected to decline*. One study, modeling snow distribution[C,D], predicted that while contiguous areas of spring snow cover would shrink and fragment, large areas of wolverine habitat (>400 mi^2) would persist in north-central Washington (Figure 9-1).[11] Another study found that climate change could result in a significant decline in wolverine distributions across the western three-quarters of Washington.[12] Wolverines are also projected to undergo a significant shift to higher elevations in Western Washington.[E,12]

- *Northern Spotted Owl (Strix occidentalis caurina) habitat may decline*. The primary threat to northern spotted owls is a lack of old-growth forest, primarily as a consequence of historical logging practices. Climate change may put these habitats

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B 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.

C Distribution of snow cover was modeled using a downscaled ensemble climate model. The ensemble model was based on the arithmetic mean of 10 global climate models under a single greenhouse gas scenario, A1B.

D Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate-related effects. 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.

E Data for the mammal species' current ranges were obtained from the Washington State Gap Analysis Project. Future climate and ecological data (all provided by the Oregon State MC1 model) were based on two global climate models, including the high-sensitivity MIROC 3.2 medres and the intermediate-sensitivity Hadley CM 3. The mid-level A1B, and a high-level A2 CO_2 greenhouse gas scenarios prepared by the IPCC were used in this analysis.

at risk as a result of projected increases in wildfire. In addition, one study examining the effects of climate change and management practices on northern spotted owl habitat in coastal Washington found that climate change may result in vegetation shifts away from types that are typically associated with high quality spotted owl habitat, with many outer coastal watersheds having a <20% probability of maintaining current levels of high quality owl habitat by the end of the century.[B,F,13]

- *Garry Oak (Quercus garryana) habitat may increase or decrease.* One set of model projections showed a significant contraction of the range of Oregon white oak / Garry oak on the west side of the Cascades and an expansion on the east side of the Cascades by the end of the century. This shift is a result of increasing air temperatures projected west of the Cascades.[G,14] However, another study found that climate suitability for Garry oak is generally projected to increase across Washington, Oregon, and British Columbia.[B,15]

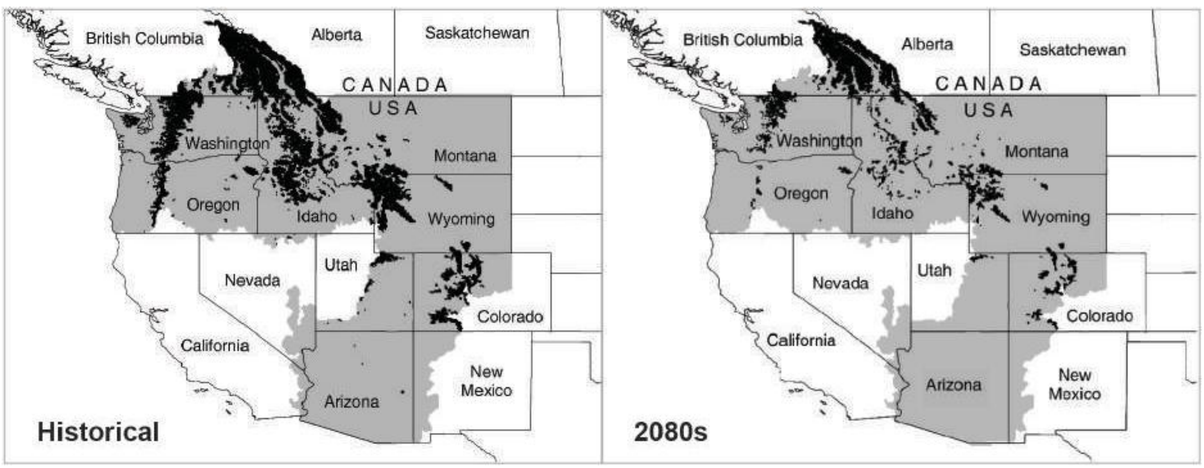

Figure 9-1. Declining Wolverine habitat with increasing temperatures. Maps show the extent of snowcover historically (1916-2006, left) and simulated for the 2080s (2070-2099, right) for a moderate (A1B) greenhouse gas scenario. The study area is shown in gray, and snow cover is black. The authors classified each point as wolverine habitat if snow depth exceeded 13 cm (about 5 inches) through 15 May. *Figure Source: McKelvey et al. 2011.[C,11] Reproduced with permission.*

F MC2 Dynamic Global Vegetation Models were run using different GCM projections. Global climate models were from the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset and were run under the Intergovernmental Panel on Climate Change Special Report on greenhouse gas scenario A2.

G Species distributions were simulated under present climate using observed data (1951–80, 30-year mean) and under future climate (2090–99, 10-year mean) using scenarios generated by three general circulation models—HADCM2, CGCM1, and CSIRO.

- *Increasing air temperatures and decreasing summer precipitation are projected to reduce the climatic range of bird species in the region.* While specific estimates for the Puget Sound region are not available, projections for Washington State indicate that the current climatic ranges of 113 bird species may decline by −50% or more (relative to 1971-2000) by the 2080s.[B,H] Bird species with projected climate range declines include, but are not limited to: the bald eagle, black oystercatcher, black-bellied plover, western grebe, trumpeter swan, rhinoceros auklet, and the gray-crowned-rosy-finch.[16]

- *Increasing air temperatures may result in increased tree growth at high elevations,[17] as well as local tree expansion into subalpine meadows.* One study projects that suitable conditions for subalpine and tundra vegetation could decline by the end of the 21st century with warming on the Olympic Peninsula.[I,18] Montane meadows in the North Cascades may also decrease in extent as reduced snowpack and longer growing seasons allow trees to establish in meadow areas.[17,19]

- *Climate change may lead to prairie expansion in the Puget Sound region.* Increases in summer water stress will negatively affect less drought tolerant trees and species adjacent to prairies, potentially enabling prairie ecosystems to expand.[20] Increases in winter precipitation may also lead to an increase in the area of wetland prairies in south Puget Sound.[20] Further research is needed on how exotic prairie species in the Puget Sound region will respond to climate change.

Forests

Climate change is projected to affect the distribution and productivity of Puget Sound forests. Changes are driven by increasing air temperatures, reductions in snowpack, and declining summer water availability.

- *The geographic distribution of forests is projected to change.* Increasing air temperatures and drier summer conditions are likely to reduce the area of climatically suitable habitat for Douglas-fir[21] in lower elevations of the Puget Sound region, specifically in the south Puget Sound and southern Olympic Mountains, by the end of the 2060s.[23] Across the entire Pacific Northwest, western hemlock, whitebark pine, and western redcedar may expand their ranges under climate change by the end of the century.[J] The occupied area of climatically suitable habitat

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H Spatially downscaled (5-min resolution) climate grids for 2010-2039, 2040-2069, and 2070-2099 were obtained from the International Center for Tropical Agriculture (CIAT) for combinations of 3 greenhouse gas scenarios (A2, A1B, B2) and 9 general circulation models. Results shown used a high greenhouse gas scenario (A2).

I Projections for the MC1 vegetation model incorporated two greenhouse gas scenarios: A2 and B1, and three global climate models: CSIRO, MIROC, Hadley. Projections were generated for 2040-2060, and 2070-2099.

J These projections do not account for the deleterious effects of forest pests, which could potentially affect distributions of tree species.

for ponderosa pine is projected to decline by the end of the century.[K,22]

- *Declining snowpack is projected to result in increased growth.* In the high elevations of the Olympic and Cascade ranges, tree establishment and growth is limited by the amount of snowpack and the duration of the snow season.[19,24] Increasing air temperatures will result in lower snowpack levels and earlier snowmelt. This will allow for an earlier start to the growing season and increased productivity in high elevation forests.[19,24]

- *Decreased water availability will cause further summer water stress.* Forests that are currently water stressed in summer are likely to experience more severe or longer duration water stress in the future.[2,19,23] Increased water stress is likely to result in decreased tree growth and declining forest productivity,[I] in particular for the northeastern forests of the Olympic Peninsula.[24] These declines in water availability will decrease fuel moisture, and will likely increase fire risk in these forests,[23] which in turn, could increase susceptibility to pine beetle outbreaks.[25]

- *The balance between increases in the growing season and decreased summer water availability will differ from place to place.* North Cascade forests will experience a longer growing season but less water available to support ecosystems. The southwest Olympic Peninsula will experience a longer growing season with sufficient moisture levels to support increased growth, while the northeast Olympic Peninsula will experience a longer growing season with drier summer conditions.[26] Projections are not currently available for central Cascade forests. The net effect of these shifts depends on the extent of summer drying in each location. [19,23]

Wildfire

WILDFIRE ***Climate change is expected to increase fire activity in the Puget Sound region, even though the area is not thought to have been fire prone historically.***[L,23,27] Increasing air temperatures and drier conditions are the primary mechanisms leading to projected increases in area burned for Washington State.[23]

- *Past fires have been large but rare in the Puget Sound region.* Fire history west of the Cascades is defined by infrequent, large, stand-replacing fires[M] occurring every 200 to 500 years.[28,29,30] 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 one million acres on the Olympic Peninsula, and between three and ten million acres in western

K This study extended through 2100 and used projections from the Canadian global circulation model with a high greenhouse gas scenario (A2) and a baseline climate period between 1950-1975.

L Statistical models of area burned were not run for the Coast Ranges/Olympic Mountains and Puget Trough / Willamette valley because there were too few observations from which to draw a statistical relationship.[23]

M A "stand-replacing fire" refers to a fire in which most of the forest is killed.

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Washington.[31] 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.[31,32,33]

- *Area burned is projected to increase.* Two different studies estimate that the annual area burned for Northwest forests west of the Cascade crest could more than double, on average, by 2070-2099 compared to 1971-2000.[N,23,O,34] However, the models used to project fire risk west of the Cascades are limited in their ability to capture the rare combination of conditions associated with wildfires in the region. Further research is needed to clarify the mechanisms of changing fire risk and severity in the Puget Sound region.

WILDFIRE ***Projected increases in wildfires in the western Cascades may negatively affect the ability of terrestrial ecosystems to store carbon.*** It is not known if increased ecosystem productivity resulting from longer growing seasons and increased carbon dioxide (CO_2) concentrations will offset carbon losses from wildfires.[N,27,35,36]

- *Carbon storage is projected to decline.* Fire risk is projected to increase for the maritime forests west of the Cascades. These forests could possibly lose up to –46% of ecosystem carbon stocks (1.2 billion metric tons of carbon) by the end of the century. Fire suppression was incorporated in model simulations but was shown to be unable to mitigate these fire-induced carbon emissions.[N,34] Another study projects that by the 2040s the mean live biomass (Mg C/ha) in the western Cascades will decrease by –24% to –37% by the 2040s (2030-2059).[P,27]

Insects and Disease

Insect and disease outbreaks are projected to change in prevalence and location, as forests become more susceptible due to climate stressors (e.g., increasing water stress), and areas climatically suitable for outbreaks shift. However, making generalizations about how pathogens will respond to climate change is difficult because responses are likely to be species- and host-specific.

- *Some diseases and pathogens could become more prevalent, while others may not.* Projected increases in air temperature and declines in summer water availability will likely decrease the effect of sudden oak death, *Dothistroma* needle blight, Swiss

N Based on a statistical model linking wildfire area burned with climate conditions. Projections are based on ten global climate model projections for a low (B1) and a moderate (A1B) greenhouse gas scenario.

O Changes from historical (1971-200) to future (2070-2099) modeled using MC1 vegetation model projections based on three global climate models (CSIRO-Mk3, Hadley CM3, and MIROC 2.3 medres) under a high (A2) greenhouse gas scenario.

P Climate variables and area burned were projected based on the ensemble of 20 general circulation models archived for the IPCC AR4 with two SRES greenhouse gas scenarios: a low (B1) and moderate (A1B) greenhouse gas scenario. These projected changes were relative to the "historical" time period which was classified as the "presettlement" period, ranging from late 1500s – 1910.

needle cast (Figure 9-2), and white pine blister rust on forest communities in the Puget Sound region. Some tree species affected by these forest diseases include Douglas-fir, Pacific madrone, and white pine. Conversely, warming and declines in summer water availability will likely increase the impact that *Armillaria* root disease and some canker pathogens have on forest communities in the Puget Sound region.[37] *Armillaria* root disease and canker pathogens affect conifer and hardwood trees in the Puget Sound region.

- *Bark beetles are projected to become less prevalent in the Cascade and Olympic ranges.* While current air temperatures in areas of the Olympic Mountains and western white pine forests of the Cascade Mountains are suitable for bark beetles, modeled results suggest that increasing air temperatures may lead to shifts in the areas of suitability for bark beetles to higher elevation forests in the Cascade and Olympic ranges.[Q,23]

Figure 9-2. Douglas-fir needles showing the effect of Swiss needle cast (*Phaeocryptopus gaeumannii*) infection. *Figure source: USDA Forest Service https://en.wikipedia.org/wiki/Phaeocryptopus_gaeumannii*

Q In this study, historical (1970–1999) air temperatures were used to predict current adaptive seasonality of bark beetles. Future (2070–2099) air temperature suitability was calculated for two future climate scenarios (ECHAM5 and HADCM, A1B SRES scenario).

Invasive Species

Climate change will affect the establishment, distribution, and impact of current and potential invasive and non-native species.[38] However, it is difficult to make generalizations regarding these species because responses will be based on species-specific climatic tolerances.[19]

- *Non-native species not currently established in the Puget Sound region may be able to colonize the region if climatic conditions fall within their thermally optimum ranges.* Cold air temperature constraints, which may have previously prevented invasive establishment at higher-elevations, will be reduced, potentially leading to increased non-native species establishment in those regions.[38] More research is needed to understand how specific invasive and non-native species within the Puget Sound region will respond to climate change, and which new species will emerge as invasive.

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Many communities, government agencies, organizations, and tribes are preparing for the effects of climate change on Puget Sound's terrestrial ecosystems.*** Examples include:

- *Science-management collaborations have been established to develop adaptation strategies for addressing climate change effects on forests in western Washington.* For example, the North Cascadia Adaptation Partnership is a 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. More information is available at http://adaptationpartners.org/ncap, which includes the Climate Change Adaptation Library.

- *A guidebook has been developed to assist with developing adaptation options for national forests, including those in Washington.* "Responding to Climate Change in National Forests: A Guidebook for Developing Adaptation Options" includes both strategies and approaches to strategy development.[39] http://www.fs.fed.us/pnw/pubs/pnw_gtr855.pdf

- *Climate adaptation strategies have been or are being developed for specific national forests and national parks.* Developed by bringing numerous stakeholders together with scientists, these strategies include a climate change vulnerability assessment as well as a list of options identified for federal agencies working to incorporate climate change into planning.
  - Adapting to Climate Change at Olympic National Forest and Olympic National Park[18] http://www.fs.fed.us/pnw/pubs/pnw_gtr844.pdf

- Climate Change Vulnerability and Adaptation in the North Cascades Region, Washington[19] http://www.fs.fed.us/pnw/pubs/pnw_gtr892.pdf

- *The Climate Change Adaptation Library for the Western United States* is derived from climate change vulnerability assessments conducted by Adaptation Partners[R]. Adaptation options are intended to inform sustainable management of natural resources, reduce the negative effects of climate change, transition ecosystems to a warmer climate, and help integrate climate change in natural resource management, planning, and business operations of federal land management agencies. http://adaptationpartners.org/library.php

- *The Pacific Northwest Tribal Climate Change Network* fosters communication between tribes, agencies, and other entities about climate change policies, programs, and research needs pertaining to tribes and climate change. More information is available at http://tribalclimate.uoregon.edu/network/.

- *Many Puget Sound area tribes have already begun to engage in adaptation planning.*

  - *Stillaguamish Tribe Vulnerability Assessment.* The Stillaguamish Tribe is currently conducting a comprehensive climate change vulnerability assessment of target species and habitats within the Stillaguamish Watershed.

  - *Vulnerability assessment and adaptation plan: Jamestown S'Klallam Tribe*. The climate vulnerability assessment and adaptation plan identified key tribal resources, expected climate-related effects, and created adaptation strategies for each resource.[40]

  - *Swinomish Indian Tribal Community Climate Change Initiative.* This project led to the development of two reports: an impact assessment technical report,[41] and a community action plan[42] that included suggestions for adaptation strategies. The Swinomish Indian Tribal Community are currently implementing the following: a regulatory code review with a focus on shoreline/sensitive areas to address issues raised in the assessment and action plan; a reservation wide program to reduce risk of wildfire; and a North Reservation coastal protection plant which focuses on the 1,100 low lying acres on the Reservation most vulnerable to flood risk.

  - *Port Gamble S'Klallam Tribe Vulnerability Assessment and Web-Based Adaptation Tool.* The Port Gamble S'Klallam Tribe is currently conducting a climate change vulnerability assessment and is also developing a web-based "Tribal Government Adaptation Planning Tool" capable of rapid climate

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[R] "Adaptation Partners" is a science management partnership, led by the U.S. Forest Service and other federal agencies, focused on climate change adaptation in the western United States. Adaptation efforts are intended to inform sustainable management of natural resources, reduce the negative effects of climate change, transition ecosystems to a warmer climate, and help integrate climate change in natural resource management and operations: http://adaptationpartners.org/index.php exposure. The Tribe also plans to develop an adaptation plan that will be used to address economic and resilience concerns of the Tribe.

- *The Nooksack Indian Tribe has commenced a large climate change project that addresses glacier ablation, altered river hydrology, changes in sediment dynamics, and increasing stream temperatures.* A climate change impacts analysis, vulnerability assessment, and an adaptation plan for salmon habitat restoration are in preparation.

- *Quinault Treaty Area Climate Vulnerability Assessment.* An assessment will evaluate potential risks to natural resources of economic and cultural importance.

- *The Puyallup Tribe vulnerability assessment and adaptation plan.* This assessment and subsequent adaptation plan will addresses priority issues within planning areas and sectors such as: Ecosystems, Species, Habitats (including hunting & gathering areas); Water Resources; Agriculture & First Foods; Traditional Lifestyles; Forests; Oceans and Shorelines; Human Health; and Infrastructure and the Built Environment.

Additional resources for evaluating and addressing the effects of climate change on terrestrial ecosystems in Puget Sound.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **AdaptWest** is a climate adaptation conservation planning database for Western North America. It offers a spatial database and synthesis of methods for conservation planning aimed at enhancing resilience and adaptation potential of natural systems under climate change. http://adaptwest.databasin.org/
- **Climate and hydrologic scenarios.** The Climate Impacts Group provides downscaled daily historical data implemented at a spatial resolution of 1/16th degree (~30 km^2) and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for 297 specific streamflow locations throughout the western U.S. including 18 locations the Puget Sound region.[45,46,47] http://cig.uw.edu, http://warm.atmos.washington.edu/2860, http://cig.uw.edu/cig/data/wus.shtml
- **Climate and hydrologic scenarios for the Western U.S.** (2015 dataset) This dataset provides future projections of daily climate and hydrology at a spatial resolution of about 4 miles, using new statistical downscaling methods and the new climate projections included in IPCC 2013.[3,43,44] http://climate.nkn.uidaho.edu/IntegratedScenarios/index.php
- **Climate Change Sensitivity Database**, produced by the University of Washington and partners, summarizes the results of an assessment of the inherent climate-change sensitivities of species and habitats of concern throughout the Pacific Northwest. http://climatechangesensitivity.org/
- **Data Basin** is a science-based mapping and analysis platform that aggregates, describes, and shares datasets, maps, and galleries of information of relevance to forest and disturbance change in the Pacific Northwest. http://databasin.org/
- **The Washington Wildlife Habitat Connectivity Working Group** (WHCWG) is a large collaborative effort to identify opportunities for maintaining and restoring landscape connectivity in Washington. Increasing connectivity is a key recommendation of the *Washington State Integrated Climate Change Response Strategy*. WHCWG products offer tools for implementing this recommendation. More information is available at: http://waconnected.org.
- **Climate Adaptation Handbook.** The Washington Department of Fish & Wildlife (WDFW) is developing a *Climate Adaptation Handbook* designed to provide practical, hands on guidance for integrating climate considerations into WDFW activities.
- **Climate Change Adaptation Library.** Adaptation Partners[R] has developed a library that synthesizes climate change vulnerabilities and adaptation options for land management agencies. http://adaptationpartners.org/library.php

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SECTION 10

How Will Climate Change Affect Freshwater Ecosystems?

Freshwater ecosystems in the Puget Sound region are projected to experience a continued increase in water temperatures, a shift to earlier peak streamflows, and declining snowmelt. These changes have widespread implications for ecosystem composition and aquatic species. Changes are expected to be most pronounced in mid-elevation basins that have historically received a mix of rain and snow during the winter. Increasing stream temperatures, increasing winter streamflow, and declining summer streamflow are projected to affect salmon growth and survival across many life stages and habitats, particularly for populations where juvenile development occurs in freshwater streams. Wetland ecosystems are projected to decline in both extent and number as a result of decreasing water availability in summer. Efforts to address impacts on freshwater ecosystems are increasing, and many local organizations, agencies, and tribes have already begun to develop adaptation strategies and plans.

Climate Drivers of Change

Projected changes in the Puget Sound region's[A] freshwater environment are driven by increasing air temperature, reduced snow accumulation, and declining summer precipitation.

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2,3] Warming will cause more precipitation to fall as rain instead of snow. The resulting decrease in summer water availability can have negative consequences for freshwater wetlands. Increasing water temperatures could prove stressful for several freshwater organisms, including salmon and some amphibians.

- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[4] Along with temperature-induced increases in winter flood risk, higher flood

[A] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

flows can be harmful to certain fish populations.

- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year variability.[2] Projected decreases in summer precipitation would exacerbate the temperature-driven decrease in summer streamflow.

Warming Streams, Changing Flow

STREAMFLOW ***Projected decreases in summer streamflow, and increases in water temperature, winter streamflow, and winter flood risk (see Section 3) will affect the freshwater ecosystems in the Puget Sound region.***

- *Stream temperatures are projected to increase substantially during the 21st century.* In the Puget Sound region, stream temperatures are projected to increase by +4.0°F to +4.5°F by the 2080s (2070-2099, relative to 1970-1999).[B,5] As streams warm, suitable temperature conditions for many aquatic species are projected to shift upstream (see Section 3). Smaller shifts may occur along relatively steep streams with high temperature gradients, and larger shifts along relatively flat streams with gentle temperature gradients.[C,6]

- *Increasing winter streamflow*. Total winter streamflow for Puget Sound basin is projected to increase by +40% to +49% on average by the 2080s (2070-2099, relative to 1970-1999).[D,E,7]

- *Declining summer streamflow*. Total summer streamflow for Puget Sound basin is projected to decrease by −32% to −40% on average by the 2080s (2070-2099, relative to 1970-1999).[D,7]

- *Multiple factors combine to drive large increases in flood risk.* The highest river flows are expected 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 greenhouse gas scenario (see Section 3).[D,F,7] These increases are compounded by

B Based on a composite of ten global climate model projections for a moderate (A1B) greenhouse gas scenario.

C Based on mountain streams in central Idaho and a warming of 3.6°F under a low greenhouse gas scenario.

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

E 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.

F Projected changes in streamflow were calculated for 12 Puget Sound watersheds. Listed in clock-wise order, starting at the US-Canadian border, they are: the Nooksack, Samish, Skagit, Stillaguamish, Snohomish, Cedar, Green, Nisqually, Puyallup, Skokomish, Dungeness, and Elwha Rivers.

projected increases in both heavy rainfall events (see Section 2) and sea level affecting the coasts (see Section 4).

STREAMFLOW ***Streamflow is projected to change the most in watersheds that are strongly influenced by both rain and snow.*** These "mixed-rain-and-snow" basins, currently found on the north Olympic Peninsula and at middle elevations in the Cascades (see Section 3, Figure 3-1), are projected to experience large increases in winter flows and flooding, and more severe declines in summer low flows. Higher-elevation "snow dominant" basins are projected to completely disappear from the Puget Sound region by the 2080s, while many mixed-rain-and-snow watersheds transition into rain-dominated basins (see Section 3).[7]

Salmonids

SALMONIDS ***Many Pacific salmonid populations are projected to be harmed by warming stream temperatures, increasing winter peak flows, and decreasing summer low flows.*** These changes could affect growth and survival across many life stages and habitats,[8] particularly for salmonid populations for which juvenile development occurs in freshwater streams (e.g., steelhead, stream-type Chinook salmon, sockeye salmon, and Coho salmon).[9] Some species and sub-populations may remain relatively unharmed by climate change or may have access to cold water "refugia" within their normal range, affording them some protection from increased water temperatures elsewhere. Population diversity may also provide a buffer for species decline, as populations that are more adapted to warm conditions survive and reproduce in greater numbers. Estuarine influences on Pacific salmon in Puget Sound are discussed in Section 11.

- *Increasing stream temperatures are projected to thermally stress adult salmon and charr.* Some salmonid species and populations that rely on freshwater habitat (e.g., adult spawning migrations and juvenile rearing) during summertime may be affected by increasing summer stream temperatures.[10] Projections indicate that Puget Sound rivers will more frequently exceed thermal tolerances for adult salmon (64°F) and charr (54°F).[G,11] By the 2080s (2070-2099), the number of river miles with August stream temperatures in excess of these thermal tolerances is projected to increase by 1,016 and 2,826 miles, respectively.[B,5] One study examining 37 Puget Sound stream monitoring stations found that 12 streams currently experience weekly average stream temperatures in excess of 64°F.[G,11] By the 2080s (relative to 1970-1999), these 12 streams are projected to experience an increase in the frequency and duration of stream temperatures above the 64°F threshold, ranging from an average annual increase of +0 to +7.5 weeks.[H,9] Optimal water temperature

[G] In this report we use regulatory thresholds listed in EPA (2007),[11] which defines 12°C (54°F) and 17.5°C (64°F) as the criteria for protecting adult charr 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 weekly August temperatures.

[H] Based on an average of 10 global model projections and a moderate (A1B) greenhouse gas scenario.

ranges for Pacific salmon are species-, life-stage-, and size-dependent, so individual responses to warming streams will vary.

- *Warm stream temperatures can delay or prevent salmon migration.* Previous studies have shown that thermal barriers can block migration, but also that salmon can adapt the pace of their migration to take advantage of times with lower water temperatures.[12] For example, a modeling study of sockeye salmon in the Okanagan River[I] found that warmer temperatures routinely lead to delays in upstream migration.[13]

- *Increasing stream temperatures may lead to increased growth in juvenile salmonids in western Washington.* One study projects that by the mid-21st century (relative to a 2010 baseline), juvenile salmonid growth will increase in many western Washington streams as a result of increasing water temperatures. In the Skagit River, Chinook salmon and steelhead are both projected to experience weight increases of more than +15% by 2050 (relative to 2010). The projected increase in juvenile growth was not uniform across all sites evaluated in the study. Growth was projected to decrease in streams that currently experience warm summer water temperatures, and increase in streams with cooler summer water temperatures. For example, some sites in the lower Columbia River Basin and northern California are projected to experience decreases in salmonid growth in response to warming.[14]

- *High stream temperatures increase the susceptibility of salmonids to certain diseases.* Increasing stream temperatures can alter the geographic ranges of pathogens and thermally stress aquatic species, reducing their ability to mount an effective immune response against the disease or pathogen.[15] One example is the death of more than 33,000 adult salmon (mainly fall-run Chinook) and steelhead in California's Klamath River in September of 2002 as a result of an outbreak of *Ichthyophthirius multifiliis*[J] and columnaris disease[K]. The outbreak occurred during a period of warm water temperatures, low flows, and high fish densities, which likely contributed to disease transmission.[16] Additional research is needed to accurately quantify the effect of climate change on the complex interactions among hosts, pathogens, and disease vectors.[L,17]

- *Increasing water temperatures and altered streamflow regimes could lead to species introductions and alter predator-prey relationships, negatively affecting salmonid*

I 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.

J Commonly known as "ich", *Ichthyophthirius multifiliis* is a common disease affecting freshwater fish. This is a highly contagious disease, which can spread rapidly through a population. Outbreaks can be especially severe when fish are crowded, for example due to low streamflow.

K A disease caused by *Flexibacter colummaris* bacterium, which infects both coldwater and warmwater fishes. The disease can result in significant population losses, and outbreaks can be especially severe in regions with warm water temperatures.

L "Vector" refers to the agent that carries and transfers an infective agent from one organism to another.

populations. Increasing water temperatures and decreasing summer streamflow may favor the spread of warm-adapted invasive fish, which compete with or prey on native salmonid species.[18,19,20] This could exacerbate the effect of native predators on resident populations. For example, a study based in the Columbia River projected that a 4°F increase in summer water temperature would increase consumption of salmon by northern pikeminnows (*Ptychocheilus* oregonensis, a native predator of juvenile salmon) by +26% to +31%.[M,21] Additionally, these shifts resulting from climate change could intensify the effect that non-native predators are currently exerting on native populations.[18] The same study in the Columbia River found that a 2°F increase in annual river temperatures near the Bonneville Dam could result in a +4% to +6% increase in per capita consumption of salmonids by walleye and smallmouth bass, both non-native species which prey upon native salmonid species.[M]

- *Cold-water streams at high elevations may provide refuge for cold-water fish species, such as bull trout and cutthroat trout.* Although a comparable study has not been conducted in Puget Sound, one study found that cold-water refugia remain abundant in the Northern Rocky Mountains. Specifically, while the length of cold-water habitat in the Northern Rockies (water temperature <51.8 °F) is projected to decline between −33% and −61% (relative to 1970-1999), 68 bull trout stream refuges[N] and 1,425 cutthroat trout stream refuges are projected to remain by the 2040s (by the 2080s the projected number of stream refuges drops to 33 and 917 for bull trout and cutthroat trout, respectively).[O,22,23]

- *Decreasing summertime streamflows are projected to reduce the habitat, health, and survival of Pacific salmon.* For some species, the amount and quality of spawning habitat may decline due to projected reductions in summer flows.[9,24] Rearing habitat for juveniles may also be reduced, as the number of pools and small side channels that act as thermal shelters decline. Along with with higher water temperatures (lower flows are more susceptible to warming), these changes could lead to increased competition for resources and a greater vulnerability to predators.[9,25] Reduced flows during migration periods may result in timing shifts or reduced migration success.[26] In addition, fish densities in streams will increase as flow is reduced, increasing the probability of infection.[27]

[M] This is similar to the warming projected by the 2080s, relative to 1970-1999, for a moderate (A1B) greenhouse gas scenario (see Section 3).

[N] Cold-water habitats that will be able to withstand the effects of climate change while still supporting fish populations.

[O] Based on >25,000 stream kilometers in the Northern Rocky Mountains and a fish probability of occupancy of >90% determined by species-specific criteria. Summer flow projections are based on 10 global climate models, assessed for the 2040s and 2080s (2030-2059 and 2070-2099 relative to 1970-1999) for the A1B greenhouse gas scenario. Average August stream projections were obtained from the NorWeST stream temperature statistical model, and an ensemble of 10 global climate models and the moderate (A1B) greenhouse gas scenario[5] for the same future time periods, but compared to 1993-2011.

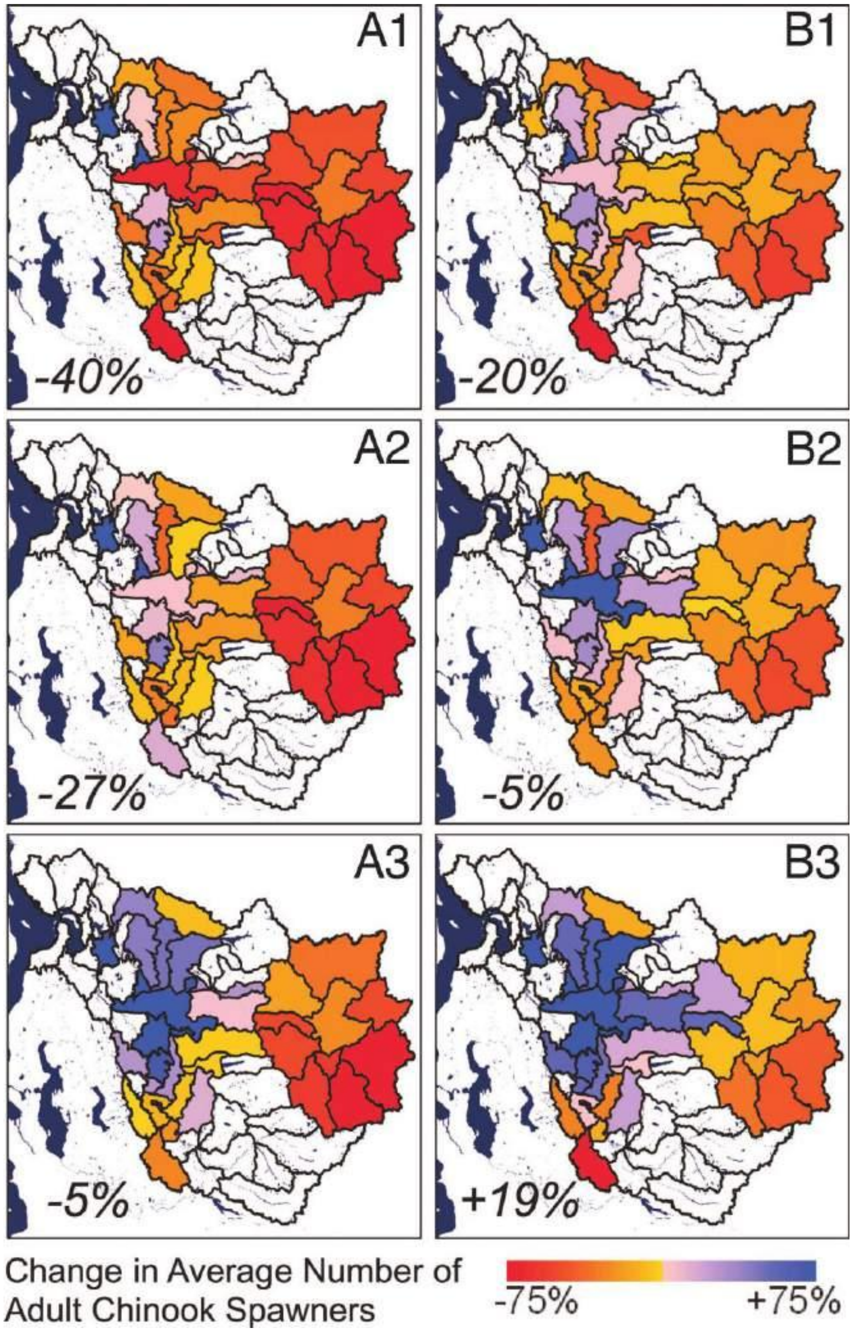

Figure 10-1. Declining salmon populations, mixed benefits of restoration. Projected change in spawning Chinook salmon abundance for the Snohomish River Basin in 2050 relative to 2000. Results are shown for three future land-use scenarios (top: current land-use; middle: moderate restoration; bottom: full restoration) and two climate model projections (left: GFDL R30; right: HadCM2), both based on a high (A2) greenhouse gas scenario. The basin-wide total change in spawning Chinook salmon abundance is in the lower left corner of each map. *Figure source: Battin et al. 2007*.[36]

- *Projected shifts towards earlier springtime snowmelt and increasing summer water temperatures may negatively affect the success of smolt*[P] *migration*. In snow-influenced streams the timing of seaward migration in salmon has evolved to align with peak flows in spring. The projected shift to earlier peak flows, along with warming streams, could potentially advance smolt migration timing.[9] Some salmon have adapted migration timing earlier in the year to align with historical shifts in flow timing. For example, populations of Chinook salmon in the Salmon River Basin in Idaho have been observed to advance their migration timing in response to shifts in environmental cues.[I,28] While the advance in migration timing may enhance upstream survival, these shifts may have negative consequences for survival in estuary or coastal regions.[29]

- *Salmonids have advanced migration timing to align with favorable freshwater conditions occurring earlier in the year.* For example, sockeye salmon (*Oncorhynchus nerka*) migration up the Columbia River has shifted 10.3 days earlier from 1949 to 2010. Researchers hypothesize that the 4.7°F rise in mean July water temperatures over that same time period (due to the combined effects of reservoir management, land use change, and warming) have resulted in a genetic selection for earlier migration timing.[30]

- *Flooding may increase egg and fry mortality, reduce return rates, and reduce the availability of slow-water habitat.* High flows can scour the streambed and remove or crush salmon eggs.[10,31,32,33] In the Skagit River, egg survival is largely driven by flood magnitudes during incubation, with large floods reducing survival.[34] Flooding also temporarily reduces the extent of slow-water habitat in rivers, potentially washing juvenile salmonids downstream prematurely.[35] For instance, large floods have been observed to reduce Chinook salmon returns to the Skagit River.[Q,8] Similarly, flooding is projected to inhibit incubation and migration life stages for steelhead in the western Cascades,[R,24] and reduce salmon habitat and productivity in the Snohomish River (Figure 10-1).[S,36]

- *Increasing sediment loads may reduce egg survival.* Sediment loads in rivers reduce oxygen availability to eggs, can physically damage eggs,[37] and could mobilize contaminants in some locations.[38] Projected increases in winter floods (see Section 3) and winter sediment loads (see Section 5) could result in

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P A juvenile salmon approaching the time of seaward migration. During this developmental stage camouflage bars are lost and physiological shifts enable them to survive the transition from freshwater to saltwater.

Q Based on annual maximum peak discharge data from the U.S. Geological Survey stream gauge near Concrete, Washington.

R Steelhead exposure estimated based on comparison of duration, intensity, and timing of temperatures and flows between historical (1970-1999) and projected (2030-2059) conditions. Based on Elsner et al. (2010) climate projections under the A1B greenhouse gas scenario (IPCC 2007).

S Global climate projections used from GFDL R30 and HADCM3 under the SRES A2 greenhouse gas scenario for 2025 and 2050 compared to 2001. The global climate models were downscaled using the Wiley quantile mapping method to 11 locations near the Snohomish River basin.

increased sediment deposition,[T,39] potentially reducing egg survival further.

- *Although declining snowpack may lead to increased winter streamflow variability (i.e., more extreme peak and low flows within each season), no study has specifically quantified the change.* Increased winter flow variability is associated with decreased population growth in Chinook salmon.[40]

- *Population diversity within a species may improve salmon resilience.* Individual sub-populations of a species have diverse characteristics and adaptations. The diversity among sub-populations helps stabilize and sustain the overall population size.[41] As climate conditions fluctuate, certain sub-populations will thrive more than others, which often reduces the overall change. For instance, variability in sockeye salmon returns to Bristol Bay would be more than twice as high if there was only a single population, instead of hundreds of diverse sub-populations.[U,42] This population diversity, known as the "portfolio effect", is critical for maintaining resilience for current and future climate-related effects.[41]

Lake Temperatures

LAKES ***Warming of lakes may alter the timing of critical biological events, such as the spring plankton bloom.*** The spring plankton bloom, which supports the food web in lakes, occurs after the onset of thermal stratification.[V] The onset of stratification has been shown to occur earlier in the season with increasing water temperature. For example, the water temperature in March to June in the upper 33 feet of Lake Washington increased by +2.5°F between 1962 and 2002.[43] This warming has resulted in earlier water column stratification and an earlier spring phytoplankton bloom. The onset of stratification in Lake Washington occurred 21 days earlier in 2002 compared to 1962, and the spring phytoplankton bloom advanced 27 days over that period.[43]

- *The timing of many predator-prey interactions will continue to overlap, while others will be altered.* The timing of peak abundance of *Keratella* (a microscopic "rotiver") and its phytoplankton food source have both shifted 21 days earlier between 1962 and 1995 in Lake Washington, closely tracking changes in the timing of onset of stratification.[43] In contrast, the timing of peak abundance of the water flea *Daphnia pulicaria* has not shifted to match that of its phytoplankton food source, contributing

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T Both the patterns of sediment deposition and the types of sediment that are deposited depend on complex relationships between the local geology, streamflow patterns, and characteristics of the stream channel. Although changes in the water cycle will undoubtedly affect sediment patterns, additional research is needed to understand how sediment deposition may change over time.

U Interannual variability of sockeye salmon returns calculated for each of the major rivers in Bristol Bay, Alaska, determined from visual counts since 1956 and compared to variability in total returns to Bristol Bay.

V Stratification is the division of the water column into sections based on water temperature. In Lake Washington, thermal stratification generally occurs from April to November when a warm water layer (upper 33 feet) overlays a cool deep layer. Stratification prevents large vertical mixing so nutrients remain in the warm upper layer, facilitating phytoplankton blooms.

to a recent population decline of *D. pulicaria*.[43] *D. pulicaria* is the keystone herbivore in Lake Washington and is an important link in food chain.

Wetland Ecosystems

WETLANDS ***The area of freshwater wetlands is projected to decline with increases in air temperature and changes in precipitation.*** Freshwater wetlands are threatened by declining snowpack and summer precipitation, and increasing evaporation, all of which contribute to the decline in water availability, especially at high elevations.

- *Montane wetlands are projected to be highly sensitive to climate change.* Snowmelt is an important determinant of montane wetland extent and water level. The extent of montane wetlands is projected to decline due to both the reduction in winter snowpack and earlier spring melt. As a result, the frequency, magnitude, and duration of wetland drying in the summer are projected to increase. These changes are projected to be greatest for ponds that dry late in the year or only in years with low water availability (i.e., intermediate hydroperiod ponds). However, there is limited research on the distribution of montane wetlands or their physical, chemical, and biological dynamics, making future projections difficult and uncertain.[44]

- *Sea level rise is projected to change the area of freshwater wetlands located near the coast* (see Section 11)*.* Sea level rise is projected to alter coastal inland freshwater marsh between −29% and 0%, and freshwater swamp between −33% and +3% by 2100 (relative to 1980-1999).[W,45]

WETLANDS ***Amphibians are threatened by the loss of wetland habitat due to projected shifts in temperature and precipitation regimes*** *(Figure 10-2).* Wetland amphibians are excepted to be highly sensitive to climate change,[X,46] but the species- and population-specific influence of climate change is uncertain and more research is needed to improve future projections.

- *Increased wetland temperatures may increase mortality rates.* Amphibians are cold-blooded, and thus particularly sensitive to temperature. Effects of increased temperature and amphibian desiccation will vary among species and populations. Some populations may be able to adapt to temperature changes, while others will become too warm or too dry, resulting in increased mortality, reduced growth, or other negative effects.[44,47,48]

- *Many amphibian species are projected to experience geographical shifts in latitude*

W Using a projected 27 in. (69 cm, about the middle of the range projected for 2100) increase in global sea level by 2100 relative to 1980-1999 under the A1B maximum greenhouse gas scenario (IPCC 2001), the Sea Level Affecting Marshes Model (SLAMM 5.0) was applied to 10 sites within Puget Sound and one site along the Oregon and Washington coast.

X Projected climate data for 2001- 2100 for 10 global climate models from CMIP3 under the B2 SRES and A2 greenhouse gas scenarios compared to data from 1961-1990 for 50 x 50 km grids of the western hemisphere.

and elevation ranges. These range shifts may result in range expansions or range contractions, depending on species' dispersal capacities and migration barriers.[46]

- *Reductions in water permanence, alterations in seasonal water levels, and decreases in water availability are projected to negatively affect wetland amphibians due to habitat loss and increased desiccation stress.* More frequent drying of wetlands is projected to harm amphibians and invertebrates that require multiple years of permanent water to complete metamorphosis.[44,49] Additionally, climate change may cause mismatches of the timing of peak predator and prey abundances, altering food web dynamics in ways that may negatively affect amphibians.[44]

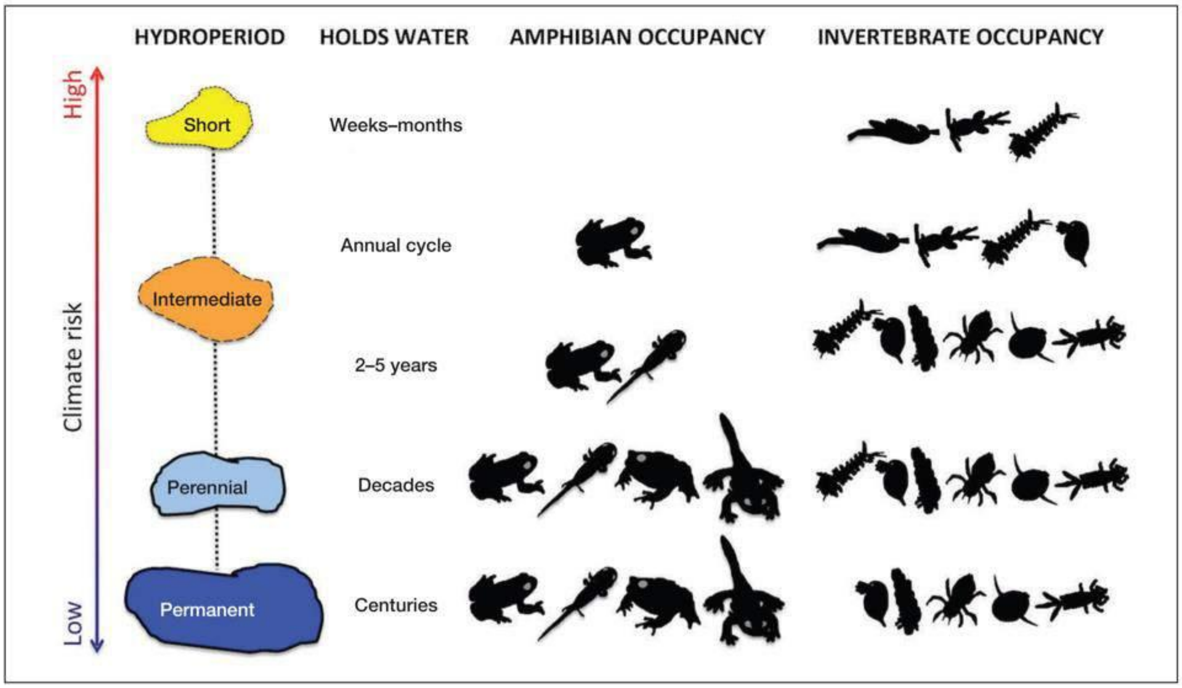

Figure 10-2. Ephemeral wetlands are at much higher risk than permanent freshwater wetlands. The above figure shows the species occupancy across a range of wetland types, each with a different likelihood of experiencing a temporary dry period (i.e., "hydroperiod"). This figure does not address the risk to organisms associated with shifts of hydroperiods (e.g., amphibians that require several years of permanent water to complete metamorphosis will likely experience increased larval mortality as a result of more frequent pond drying events). Organism icons represent dominant species in each wetland pond type, including (from left to right): Cascades frog, long-toed salamander, western toad, Northwestern salamander, mosquito larva, cladoceran, caddisfly larva, dragonfly larva, beetle, and mayfly larva. The short and intermediate hydroperiods also include icons for fairy shrimp and copepods. *Figure source: Ryan et al. 2014.*[Y,44] *Reproduced with permission.*

Y Republished with permission of Ecological Society of America, from [Amphibians in the climate vise: loss and restoration of resilience of montane wetland ecosystems in the western US, Ryan, M.E., Palen, W.J., Adams, M.J., Rochefort, R.M., volume 12, issue 4, 2014]; permission conveyed through Copyright Clearance Center, Inc.

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Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Various communities, government agencies, and organizations are planning for the effects of climate change on freshwater species and ecosystems in the Puget Sound region.*** Examples include:

- *The North Cascadia Adaptation Partnership (NCAP) is a science-management collaboration focused on climate change adaptation strategies in U.S. Forests and National Parks,[50] including the Mount Baker-Snoqualmie National Forest, Okanogan-Wenatchee National Forest, Mount Rainer National Park, and North Cascades Complex National Park.* Fish and fish habitat are one of the four focus sectors of NCAP for which adaptation strategies and tactics were developed based on three impact pathways. These impact pathways include increasing stream peak flows, decreasing low flows, and warming stream temperatures. For instance, adaptation strategies for mitigating the effects of increasing peak flows include restoring spawning habitat and removing migration barriers in order to enhance habitat resilience. http://www.northcascadia.org/

- The Swinomish Climate Change Initiative was a two-year project to identify vulnerability of the Swinomish Indian Tribal Community to climate change effects and prioritize planning areas in order to create an action plan. The Initiative was based on the 2007 Proclamation of the Swinomish Indian Senate to respond to climate change challenges. An Impact Assessment Technical Report[51] and a Climate Adaptation Action Plan[52] were published from the Initiative. The decline and degradation of upland wetland habitat, water quality, and streamflow were identified as medium-high freshwater risks. Adaptation strategies included in-stream and riparian enhancement. http://www.swinomish-nsn.gov/climate_change/climate_main.html

- *The Washington State Integrative Climate Change Response Strategy*[53] developed a framework to aid decision-makers in state, tribal, and local governments; public and private organizations; and businesses prepare for climate-related effects on natural resources and economy. Climate change effects on freshwater streams included warming temperatures and lower summer streamflows. Adaptation strategies included managing freshwater withdrawals to maintain and restore streamflows and lake levels, restoring riparian zones, reconnecting rivers and floodplains, and taking early action to control non-native invasive species.

- *The Forest Service Aquatic Guidebook* (forthcoming) builds on existing approaches to adaptation planning and surveys of U.S. Forest Service aquatic habitat managers and scientists in the PNW to develop a resource-specific guide for: 1) synthesizing information about climate effects to assess the sensitivity of aquatic habitats to climate change, 2) evaluating the resource's climate change-related adaptive capacity, 3) identifying priority planning areas, goals and actions related to preparing for climate change, and 4) developing measures of resilience to track progress and update plans over time.

Additional resources for evaluating and addressing the effects of climate change on freshwater ecosystems in Puget Sound.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **Climate Change Sensitivity Database**. Produced by the University of Washington and partners, this database summarizes the results of an assessment of the inherent climate-change sensitivities of species and habitats of concern throughout the Pacific Northwest.
  http://climatechangesensitivity.org/

- **Climate Shield.** Geospatial data on potential cold-water refuge streams for native Cutthroat Trout and Bull Trout in the Pacific Northwest.
  http://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html

- **NorWeST.** Historical and projected future stream temperature data and geospatial map outputs from a regional stream temperature model for the Pacific Northwest and other parts of the Western U.S.
  http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

- **Western U.S. Streamflow Metrics.** Modeled flow metrics for streams in the Western U.S. for historical and future climate change scenarios. Data available for the Pacific Northwest, which includes the Puget Sound catchment.
  http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml

- **USGS Water Watch.** Map of current streamflow compared to historical flow for Washington.
  http://waterwatch.usgs.gov/?m=real&r=wa

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SECTION 11

How Will Climate Change Affect Marine Ecosystems in Puget Sound?

Coastal and marine ecosystems in Puget Sound are projected to experience continued increases in sea surface temperatures, sea level rise, and ocean acidification. These changes are expected to have implications throughout Puget Sound's marine food web affecting organisms at the bottom (e.g., phytoplankton and marine plants) and at the top (e.g., salmon and marine mammals) of the food chain. Increasing sea surface temperatures are projected to negatively affect salmon populations, increase the magnitude and frequency of harmful algal blooms, and may increase growth rates in eelgrass beds. Sea level rise is projected to increase the area of some coastal habitats (e.g., tidal flats and salt marshes), and decrease the area covered by other habitats (e.g., estuarine beach, tidal swamp). Ocean acidification will likely harm many estuarine species, especially shellfish and other organisms that form calcium-based shells. Efforts to address climate-related effects on marine ecosystems are increasing, particularly with respect to ocean acidification and ocean monitoring.

Climate Drivers of Change

CLIMATE DRIVERS ***Estuarine species and ecosystems in Puget Sound[A] are projected to face changes in sea level, sea surface temperature, and ocean acidification during the 21st century.***

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2] Increasing air temperatures will likely cause sea surface temperatures to increase, leading to higher growth rates, increased risk of harmful algal blooms, and impaired health and habitat quality for certain species.

- *Nearly all scenarios project a rise in sea level.* Sea level rise is projected for all locations except Neah Bay, where a decline in sea level cannot be ruled out due to the rapid rates of uplift in that area (see Section 4).[3,4,5] Rising seas will inundate more land, altering the geographic area of many coastal habitats.

[A] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

- *Ocean water will become more acidic*[B] *as excess atmospheric carbon dioxide (CO_2) is absorbed by the oceans.*[6] Ocean acidification will make it more difficult for marine organisms to create shells and skeletons, potentially disrupting an important food source for many important fish species in Puget Sound and the northeast Pacific.[C,7]

Tidal Wetlands

TIDAL WETLANDS ***The area of tidal wetlands is projected to change during the 21st century.*** The actual changes (i.e., expansion or decline) will depend on wetland type, the rate of sea level rise, amount of sedimentation, and availability of landward buffers into which to migrate.

- *Sea level rise is projected to expand the area of some tidal wetlands but reduce the area of others.* An analysis of coastal areas in Puget Sound found that rising seas are projected to increase the area[D] of salt marsh by +260% (range: +49% to +4300%, depending on location), and result in +70 times more transitional marsh[E] (range: increasing by a factor of 16 to 378) by 2100, relative to 2000, for a mid-range sea level rise projection.[F,G,8] Sea level rise is also projected to change tidal flat area by +240%, on average (range: −81% to an increase from 0 to 236 acres), reduce estuarine beach area by −79% (range: −96% to −34%), reduce brackish marsh by −57% (range: −84% to −1%), change the area covered by tidal swamp by −77% (range: −97% to 0%), and change tidal freshwater marsh area by −24% (range: −85% to +3%).[8]

- *Sea level rise is projected to alter the composition of many existing coastal wetland areas.* By 2100, 52% of brackish marsh in Puget Sound, southwestern Washington, and northwest Oregon is projected to convert to tidal flat, salt marsh, and

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B Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Global ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines a liquid's acidity) and is projected to fall to 7.8-7.9 by 2100. The term "ocean acidification" refers to this shift in pH towards the acidic end of the pH scale.

C Many marine organisms produce shells from the dissolved carbonate ions in seawater. As ocean waters become more acidic, the "aragonite saturation state" (the absolute carbonate ion concentration) decreases, making it more difficult to create and maintain "calcareous" (calcium carbonate) shells.

D Baseline habitat coverage areas were based on National Weather Inventory (NWI) photo dates, ranging between 1972 and 2000. The NWI photo date serves as the starting point for a SLAMM simulation.

E "Transitional marsh" refers to an intertidal shrub marsh: regularly flooded by tides, but not fully converted into a saltmarsh. In contrast with the sea grasses typical of salt marshes, transitional marshes are usually populated by broad-leaved deciduous trees.

F The large increase in area covered by transitional marshes is a consequence of the relatively small amount of area occupied by this habitat historically (only 138 acres in the entire study domain) and by the conversion of dry land to wetland as a result of sea level rise.

G Results are for based on a projected 27 in. (69 cm, about the middle of the range projected for 2100, relative to 1980-1999) increase in global sea level. The Sea Level Affecting Marshes Model (SLAMM 5.0) was applied to 10 sites within Puget Sound. The numbers in the text give the total change across all of Puget Sound, plus the range among the 10 sites.

transitional scrub-shrub, while 2% of undeveloped dry land is projected to be inundated, eroded, and converted to wetland or other coastal land cover.[G,8]

- *Projected changes in the timing and magnitude of peak and low streamflows could alter sediment delivery to tidal wetlands.* Adequate sediment delivery and sedimentation is vital for tidal wetlands, which can persist if increases in surface elevation proceed at a rate comparable to sea level rise.[9] Although sediment supplied from rivers is projected to increase, it is not known what proportion of sediments will be deposited in estuaries in the future, nor whether this increase might be sufficient to keep pace with sea level rise (see Section 5).

Eelgrass

EELGRASS ***Eelgrass may be resilient to climate change, and the area of eelgrass may expand in the short-term due to warming and sea level rise.*** Eelgrass beds are a key Puget Sound ecosystem, providing food and shelter for a wide variety of estuarine life, including salmon and crabs. Eelgrass area may expand with warming and sea level rise if thermal thresholds are not exceeded and its expansion is not limited by migration barriers. Eelgrass is generally resilient to, and has recovered from, disturbances such as disease and climate anomalies.[H,10]

- *Eelgrass growth rates may increase with warming, provided that thermal thresholds are not exceeded.* As sea surface temperature increases, eelgrass growth may increase up to a threshold temperature of about 77°F, as long as water clarity does not decline.[I,11,12] For instance, the highest observed summer growth rates for eelgrass in Sequim Bay tend to correspond with the warm sea surface temperatures associated with El Niño climatic conditions.[J,11] Once sea surface temperatures exceed the optimal range for eelgrass, growth may begin to decline.

- *Eelgrass area may increase with sea level rise as long as landward migration is not blocked.* For instance, eelgrass productivity and spatial area are projected to increase in Padilla Bay under moderate rates of sea level rise through the 21st century.[K,13] In Padilla Bay, eelgrass area is projected to increase because there is a landward buffer of mudflat into which the eelgrass is projected to migrate. However, under high sea level rise scenarios, eelgrass in Padilla Bay is projected to reach the limit of this buffer and the total area is expected to begin to decline as it is submerged.[13]

H Summarized from the literature.

I Based on laboratory experiments that measured dissolved oxygen changes in glass jars filled with sea water and three to four 3.94 inch-long (10 cm) eelgrass leaf sections at various temperatures.

J Based on the Oceanic Niño Index (ONI), which is defined by sea surface temperature anomalies from a long-term average in the Niño 3.4 region.

K Based on IPCC 2007 AR4 low, mid, and high greenhouse gas scenarios and a mid and high sea level rise scenario from Rahmstorf (2007) based on IPPC 2001. Eelgrass changes were modeled using a Spatial Relative Elevation Model.

Salmon

SALMON ***Pacific salmon populations are likely to be affected by changes in the temperature and salinity of ocean waters, ocean acidification, and upwelling.*** Climate change effects are different depending on the life stage (adult, juvenile) and time spent in the ocean. Climate change is also expected to significantly affect Pacific salmon in their freshwater life history stages (see Section 10).

- *Increasing sea surface temperatures may cause a small decline in Pacific salmon survival.* A +1.8°F increase in sea surface temperature (similar to the warming projected for the northeast Pacific by the 2040s, see Section 7), could result in a −1% to −4% decline in the survival of salmon species ranging from northern California to southeast Alaska.[L,14] Warm phases of the Pacific Decadal Oscillation (PDO, see Section 6), which are associated with warmer-than-usual Washington coastal ocean waters, tend to be associated with low Coho salmon fisheries landings[M] in Washington, Oregon, and California. Although not focused solely in Puget Sound, one study found that the percent change in average catch of southeast Alaskan pink salmon[N] declined by −37.2% in 1947, the start of a cool phase (negative) PDO (see Section 6), and increased by +242.2% in 1977, the start of a warm phase (positive) PDO.[15] Among other environmental factors, Chinook salmon return rates to the Skagit River are lower when sea surface temperatures are above normal in the 3rd year of ocean residency;[O] the opposite is true when sea surface temperatures are below normal.[P,16]

- *Stronger upwelling is associated with increased salmon productivity.* Although it is not known how upwelling may change with warming (see Section 6), changes in upwelling associated with PDO cycles are known to significantly affect salmon populations.[15] A study evaluating the effect of coastal upwelling on the growth of juvenile Coho salmon (*Oncorhynchus kisutch*) off the coast of Washington and Oregon found that earlier summer upwelling was associated with higher rates of survival between 1981 and 1985.[17] A similar study found increased Coho salmon survival during strong upwelling years.[18]

- *Ocean acidification could directly affect salmon via lower growth rates, altered olfactory preferences, and a reduced anti-predator response.* Juvenile pink salmon begin migration to the ocean shortly after hatching, and are the smallest salmon

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L A lagged model of survival was developed for two salmon stocks included in the analysis: the Columbia Upriver Brights and the Oregon Coastal, to evaluate if survival was related to local conditions. This model uses ENSO conditions in the tropical Pacific between May and June to predict PDO conditions for the following June, and then links PDO conditions to local sea surface temperatures which could potentially affect Chinook salmon survival in the short-term.

M Fisheries "landings" refers to the total weight of fish that are caught and brought on land.

N Mean catch levels were estimated from intervention models fitted to the data and incorporating a 1-yr lag for the pink salmon stock.

O Chinook salmon spend an average of three to four years in the ocean.

P Sea surface temperature and sea level pressure from COADS data between 48-57°N and 122-137°W from October to the following September for coastal and inland passage areas. The upwelling mean index was taken from four coastal sites in Washington and British Columbia.

species arriving in saltwater.[19,20] Small body size at the time of ocean arrival increases the vulnerability of this species to the effects of ocean acidification. One laboratory experiment found that projected increases in ocean acidity could reduce early seawater survival in pink salmon by reducing metabolic rate,[Q] growth, and appetite. Additionally, increases in CO_2 concentration may impair the sense of smell in pink salmon, limiting their ability to detect and avoid predators.[21]

- *Ocean acidification could indirectly affect salmon via changes in food availability, but the effects are projected to be minimal.* One study, using a model of the Puget Sound food web, found that the majority of impacts on fisheries stemmed from direct effects of ocean acidification, primarily by inhibiting the formation of calciferous shells. The effects on salmon populations were found to be minimal because these species can rely on alternative sources of food that are not directly affected by acidification.[22]

Estuarine Primary Productivity[R]

PRIMARY PRODUCTIVITY ***Estuarine primary productivity may be affected by changes in nutrient inputs, carbon dioxide levels, and sea surface temperature.*** Primary producers in Puget Sound include phytoplankton, macroalgae, kelps, seagrasses, and wetland plants. Climate-related effects on primary productivity remain uncertain.

- *Increases in marine carbon dioxide levels may increase growth and productivity of estuarine eelgrass and bull kelp*. In laboratory experiments, elevated carbon dioxide levels resulted in increased growth and productivity for eelgrass and bull kelp at carbon dioxide concentrations up to 2.5 times higher than ambient levels, after which productivity began to decline.[S,23]

Harmful Algal Blooms

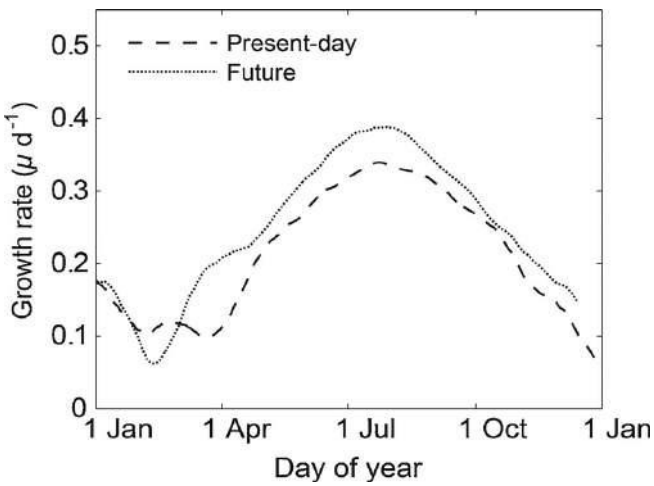
HARMFUL ALGAL BLOOMS ***Climate change may increase the magnitude and frequency of harmful algal blooms (HABs).*** Often called "red tides," HABs are a public health concern due to the toxins subsequently found in shellfish, and also have negative consequences for ecosystems. Climate change is projected to increase growth rates of harmful algal species,[24] and increasing sea surface temperature is projected to expand the "window of opportunity" when such blooms can occur.[25] In addition, ocean acidification may increase the toxicity of some harmful algal blooms (see Section 7 for more details).[26]

Q "Metabolic Rate" refers to the level of energy expenditure in a specific period of time.

R "Primary Productivity" refers to the total rate of biological production (growth, reproduction, etc.) in an ecosystem.

S 28 to 30 eelgrass shoots were collected from Sequim, Washington, planted in plastic pots, and placed in 130 L tanks filled with seawater. Sea water was then enriched with CO_2 at levels 1x, 1.25x, 1.75x, and 2.0x ambient CO_2 levels. Plants were grown for 10 and 7 days in two different trials.

Figure 11-1. Longer season of elevated risk for Harmful Algal Blooms in Puget Sound. Daily mean growth rates of *Alexandrium* are higher in the future, and the growth rates begin to increase about 30 days earlier in spring as a result of increasing sea surface temperatures. When *Alexandrium* growth rates are high enough HABs can form, so higher growth rates earlier and later in the year could lead to a longer HAB season. The plot shows the daily mean growth rate of *Alexandrium* for present day (1988, dashed-line) and under future conditions projected (2047, dotted-line). The projection is based on a single global climate model (CCSM3) and a moderate (A1B) greenhouse gas scenario. Growth rate is averaged over the Puget Sound Basin and both lines are smoothed with a 31-day running mean. *Figure source: Moore et al. 2015.*[T,24] *Reproduced with permission.*



Ocean Acidification

OCEAN ACIDIFICATION ***Ocean acidification will likely harm many estuarine species, especially shellfish and other organisms that form calcium-based shells.*** Ocean acidification is projected to increase the frequency, magnitude, and duration of periods of harmful pH conditions in Puget Sound (see Section 7). Limited field studies have been conducted on the impacts of ocean acidification on estuarine species in Puget Sound; however, experimental studies in the region and throughout the world have demonstrated potential effects of increased ocean acidification.

- *Ocean acidification is projected to reduce shell formation and increase shell dissolution.* Ocean acidification makes it more difficult for calcifying organisms (e.g., oysters, clams, mussels, pteropods, and crabs) to produce and maintain their shells and skeletons.[7,27] For instance, the shell formation of larval stages of calcifying invertebrates may take more energy to produce.[U,7] One experiment showed that shell dissolution of the pteropod *Limacina helicina* occurred under acidity levels that occasionally occur in Puget Sound and are projected to occur more frequently in the future (Figure 11-2).[V,28] Globally, ocean acidification is projected to result in a −40%

T Reprinted from Harmful Algae, 10(5), Moore, S.K., Manuta, N.J., Salathé Jr., E. P. Past trends and future scenarios for environmental conditions favoring the accumulation of paralytic shellfish toxins in Puget Sound shellfish, 521-529, 2011, with permission from Elsevier.

U Saturation state is the absolute carbonate ion concentration, while pH is the ratio of dissolved CO_2 concentration to carbonate ions.

V Shell dissolution was measured after one week of exposure to sea water with saturation state $\Omega_a \approx 1.59$, $\Omega_a \approx 1.17$, $\Omega_a \approx 0.56$, and $\Omega_a \approx 0.28$ under starvation conditions. Shell dissolution was determined based on transparency/opaqueness, transparency/brownness, scarred structures, corrosion, and number of perforations.

reduction in the rate at which molluscs (e.g., mussels and oysters) form shells, a −17% decline in mollusc growth, and a −34% decline in mollusc survival by the end of the century.[W,29]

- *Ocean acidification is projected to reduce the effectiveness of other marine biomaterials*. For instance, ocean acidification is projected to weaken and reduce the extensibility (i.e., capability of being extended) of the filaments that attach mussels to hard substrates.[X,30] Mussels require strong, extensible filaments to remain secure during disturbances, such as from storms and waves.

- *Fish and other organisms that depend on shelled organisms may decline if they are unable to switch to alternate food sources.* Ocean acidification impacts on shellfish and plankton are projected to result in a −10% to −18% decline in the abundance of commercially important groundfish on the U.S. west coast by 2028 (relative to 2009), including English sole, arrowtooth flounder, and yellowtail rockfish, owing to the loss of shelled prey items from their diet.[31] However, predators may be able to switch food sources and avoid the effects of ocean acidification.[Y,32]

- *Increasing water temperatures may modulate the responses of shelled organisms to ocean acidification.* One study evaluating the effect of ocean acidification and water temperature on shell growth in the blue mussel (*Mytilus galloprovincialis*) found these effects to be tightly coupled. The study found that while waters with a high

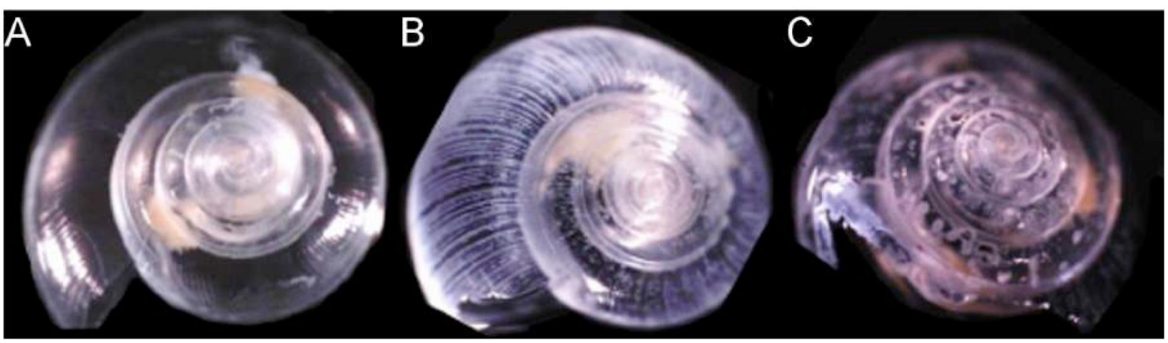


Figure 11-2. Ocean acidification is projected to reduce shell formation and increase shell dissolution in pteropods. Pictures of pteropod (sea snail) shells in aragonite saturation state levels of (A) 1.59 (current summer suface conditions), (B) 0.56 (current surface conditions during upwelling), and (C) 0.28 (projected future surface conditions during upwelling) showing corrosion and shell perforations. Pteropods are an important prey species in the Puget Sound marine food web. *Figure Source Busch et al. 2014*.[28]

W Based on a meta-analysis of many different studies: Results were included from any research that measured a biological response to a decline in pH (increase in acidity) of –0.5 or less. By 2100 (relative to 1986-2005), ocean acidification is projected to result in a decline in pH of –0.14 to –0.32 (see Section 7).

X Individual byssal threads of *Mytilus trossulus* (1.57-1.97 inches shell length) broke at lower forces as water ρCO_2 ranged from 300-15,000 μatm in flow-through experimental chambers with sea water at controlled pH measurements.

Y The food web model used was developed for the central basin of Puget Sound using the Ecopath with Ecosim software version 5.1.

CO_2 concentration[Z] reduced mussel growth at 57.2 °F, the reduced growth effect tapered with warming up to 68 °F. This study demonstrates how a moderate level of sea surface warming can offset some of the negative effects of ocean acidification for shelled organisms.[33]

Species-Specific Responses

SPECIES-SPECIFIC RESPONSES ***Some estuarine species may benefit from climate change, while others will not.*** Particular changes are dependent on species-specific responses to the interaction of physical and biological processes. Additional research is needed to quantify the impacts on a wider variety of species and climate scenarios.

- *Dungeness crab populations in Hood Canal may increase or decrease under future climate change.* Increases in sea surface temperatures are projected to increase juvenile survival, leading to increases in Dungeness crab population size.[AA,34] However, other factors, such as ocean acidification and decreases in dissolved oxygen (see Section 7), may counterbalance the positive influence of sea surface temperature. Sea level rise could also reduce the area of estuarine and nearshore habitats, potentially leading to declines in the Dungeness crab fishery.[35] More research is needed to clarify potential responses of Dungeness crabs to climate change.

- *Salmon are a vital food source for southern resident killer whales* (*Orcinus orca*). If salmon populations decline, this could negatively affect Orcas.[36] To date, very little research has examined the effects of climate change on whale populations in Puget Sound.

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Various communities, government agencies, tribes, and organizations are planning for the effects of climate change on estuarine species and ecosystems in Puget Sound.***

- *The Washington Ocean Acidification Center* works with scientific researchers, policymakers, industry, and other stakeholders to provide a scientific basis for strategies and policies to address the effects of ocean acidification. The Center is hosted at the University of Washington and was established in 2013 by the Washington State Legislature based on a recommendation from the Blue Ribbon

Z 1200 µatm $CO_{2(atm)}$

AA Based on linked watershed-marine models that estimate the influence of land use and climate change on watershed discharge, nutrients, marine water quality, and population available for harvest. Climate change impacts for 2035-2045 from five global climate models under the moderate (A1B), high (A2), and low (B1) greenhouse gas scenarios compared to 2005-2007.

Panel on Ocean Acidification. http://environment.uw.edu/research/major-initiatives/ocean-acidification/washington-ocean-acidification-center/

- *The Swinomish Climate Change Initiative* was a two year project to identify vulnerability of the Swinomish Indian Tribal Community to climate change impacts and prioritize planning areas in order to create an action plan. The Initiative was based on the 2007 Proclamation of the Swinomish Indian Senate to respond to climate change challenges. An Impact Assessment Technical Report[37] and a Climate Adaptation Action Plan[38] were published from the Initiative. Coastal impacts included inundation from sea level rise and storm surges. http://www.swinomish-nsn.gov/climate_change/climate_main.html

- *The Swinomish Tribe is studying how coastal climate change will affect traditional foods, cultural sites, and tribal community health and well-being.* This project, funded by an EPA grant awarded 2014, will develop a model showing projected coastal erosions due to sea level rise, storm surge, and wave energy on the shores of the Swinomish Reservation through 2100. Additionally, the Tribe will map the vulnerability of Swinomish coastal ecosystem habitats of first foods[BB] and culturally significant sites; create educational and outreach tools for Swinomish community members and coastal Salish communities; and assess research results and develop adaptive strategies. http://1.usa.gov/1Wm3HdR

- *The Washington State Integrative Climate Change Response Strategy*[39] developed a framework to aid decision-makers in state, tribal, and local governments, public and private organizations, and businesses prepare for climate change impacts on natural resources and economy. Climate change effects on marine species and ecosystems included sea level rise and ocean acidification. Adaptation strategies included restoring tidal wetlands and replacing hard shoreline armoring with green or soft alternatives.

- *The Jamestown S'Klallam Tribe Climate Vulnerability Assessment and Adaptation Plan*[40] identified climate change impacts on tribal resources and developed adaptation strategies for each resource. The Adaptation Plan identified sea level rise, coastal flooding, and ocean acidification as key threats. Resource areas of high priority included salmon, clams, oysters, and shellfish biotoxins. Strategies for reducing stressors on salmon resources included habitat restoration and the reduction of stressors such as urbanization and pollution.

[BB] "First foods" includes salmon, wild game, roots, berries, and clean water.

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Section 12
How Will Climate Change Affect the Built Environment?

Puget Sound's built environment – transportation, wastewater and water conveyance, urban centers, and energy systems – is projected to be affected by a continued rise in sea level, more intense heavy rains, more and hotter heat waves, and increased wildfire activity. These changes have significant implications for infrastructure, are likely to cause transportation closures, delays, or detours, and will be most pronounced for facilities and transportation lines located in or near coastal and low-lying areas. Some benefits may also be realized, including the potential for fewer snow-related road closures. Coastal infrastructure is likely to experience more problems with saltwater intrusion, corrosion, flooding, and inundation as a result of sea level rise. In addition, aviation, bus, and rail services located in or near current floodplains are likely to experience increases in the number of delays due to projected increases in heavy rainfall and river flooding. Many communities, agencies, and organizations are in the initial stages of assessing impacts and developing response plans; some are currently implementing adaptive responses.

Climate Drivers of Change

DRIVERS ***Most climate change effects are likely to increase the potential for damage to infrastructure and service disruptions (unplanned transportation closures, delays, or detours) in the Puget Sound region,[A] although some risks may decrease.*** Existing studies on infrastructure impacts in the Puget Sound region have primarily focused on transportation infrastructure and coastal infrastructure (particularly as it relates to sea level rise). In general:

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2] Warmer conditions can lead to reduced snowpack, and more frequent and intense flood events (see Section 3), heat waves, mudslides, erosion (see Section 5), and wildfire.

- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain

[A] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

events.[3] Changes in extreme events are more likely to damage infrastructure than changes in average conditions.[4,5,6,7]

- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year variability.[2]

- *Nearly all scenarios project a rise in sea level.* Sea level rise is projected for all locations except Neah Bay, where a decline in sea level cannot be ruled out due to the rapid rates of uplift in that area.[8,9,10] Higher seas would result in greater risk of storm surge, saltwater intrusion, and permanent inundation of low-lying areas.

- *Some climate-related changes may lead to decreased risk or otherwise create benefits.* For example, increasing spring and fall air temperatures may extend the construction season, possibly improving cost efficiencies. Lower winter snowpack and increasing winter air temperatures will likely decrease the frequency of snow-related closures on mountain highways.[4,5,6] The benefits of reduced snow closures may be offset by an increase in landslides as a result of rain events on slopes not protected by snow, and because of an increase in the intensity of heavy precipitation events.[6]

- *Understanding the specific nature of climate-related changes on infrastructure often requires detailed, locally specific studies.* Similar types of infrastructure can have very different responses to climate change, depending on location, age, and specifics of design, maintenance, and operation.[4,6] For example, while a small amount (+3 inches) of sea level rise may have important effects on flooding and stormwater management in Olympia, sea level rise impacts on Washington State-owned coastal transportation infrastructure do not begin to emerge until much higher amounts (>+2 feet) of sea level rise occur.

- *New infrastructure and ongoing improvements to existing infrastructure generally increase resilience to climate impacts, although the resilience of individual pieces of infrastructure can be affected by vulnerabilities in other parts of the system.*[6,11] Infrastructure updates such as seismic retrofits, fish passage improvements, culvert replacement, and drilled shaft bridges generally make infrastructure more resilient to the effects of climate change.[6,11] Additionally, fish passage improvements and culvert replacement can improve salmon migration and increase habitat connectivity for wildlife. For example, large culverts with sufficient vertical clearance (> 8 feet) provide connectivity options for deer moving under roads.[12] While such updates can increase resilience to the effects of climate change, vulnerabilities in related parts of the system can affect that resilience. For example, while the majority of Washington State Department of Transportation's (WSDOT) newer bridges were found to be resistant to the effects of climate change, including up to +4 feet of sea level rise in some cases, use of those bridges may be affected by more frequent flooding or inundation of low-lying roads leading to bridges.[6]

Sea Level Rise

SEA LEVEL RISE ***Coastal wastewater and stormwater collection systems are likely to experience more problems with saltwater intrusion, corrosion, flooding, and inundation.***

- *Sea level rise is projected to temporarily or permanently inundate three or more King County Wastewater Treatment Division facilities as early as 2050,* depending on the combined effects of different sea level rise projections and the return frequency of specific storm sizes.[B,13] The County has also identified 20 facilities that are at risk of saltwater inflow into the conveyance system (pipes and pumps taking wastewater to and from the plant) by 2050, due to sea level rise, high tides, and storm surge.[14] This additional inflow can increase the volume of wastewater that has to be conveyed and treated, shortening equipment lifespan, and increasing treatment costs.[15] King County estimates the current cost of treating saltwater already entering the system[C] during high tides to be $0.5 to $1.0 million annually.[D]

- *City of Olympia.* Modest amounts of sea level rise (as little as +3 inches, below the low end of the range projected for 2050) increases the likelihood that saltwater will enter the city's combined sewer system and be conveyed to the Lacey, Olympia, Tumwater, and Thurston County (LOTT) wastewater plant for treatment, potentially increasing operating costs.[16]

SEA LEVEL RISE ***Port operations and infrastructure, including access to port facilities, are likely to be affected by sea level rise and increased coastal flooding.[17,18]*** Climate-related effects in other parts of the world[E] may also affect Washington's marine trades, although little is known about the specific nature and potential size of those impacts on port business.[4,17]

- *Direct sea level rise impacts on Port of Seattle facilities.* Direct sea level rise impacts include increased storm surge damage to port facilities and more saltwater corrosion in docks and other infrastructure (e.g., piles, pile caps, and beams) exposed more frequently to saltwater as a result of higher tidal and storm surge

B Periodic or permanent inundation of the Division's three lowest facilities occurs as early as 2050 with +1.8 feet (22 inches) of sea level rise and a +2.3 foot storm surge, currently considered a 50% chance (once every 2 years) storm surge event. As many as 14 facilities would be periodically or permanently inundated by 2100 with +4.17 feet of sea level rise (currently near the high-end of projections for Puget Sound) and a +3.2 foot storm surge (annual storm surge event with a 1% chance of occurring).

C Sources for saltwater intrusion are leaky gates, overflow weirs, groundwater infiltration, and local sewer connections. Intrusion already occurs during high tides in the industrial area along the Duwamish Waterway, the downtown Seattle waterfront, and the Salmon Bay area near the Ballard Locks.[15]

D This cost estimate is specifically for saltwater treatment at the West Point Treatment Plant and does not include the cost of repairing and replacing damaged equipment. King County estimates that 3 to 6 million gallons of salt water enters the system each day, totaling about 1 to 2 billion gallons each year.[15]

E Reduced sea ice in Alaska and the Arctic is likely to extend the shipping season and create new opportunities for shipping, although it is unknown at this time if, when, and how these changes could affect Washington's ports. Climate impacts on trading partners in Asia may also affect traffic in and out of Washington's shipping ports, although it is not known how traffic would be affected specifically.

reach. Sea level rise will also make it more difficult to drain stormwater from port facilities.[17] Projected increases in extreme precipitation (see Section 2) would exacerbate this problem.

- *Effect on low-lying areas serving Port of Seattle facilities.* Low-lying rail yards and roads serving the Port of Seattle are vulnerable to permanent inundation if sea level rise is +3 feet or greater. Lower amounts of sea level rise would likely result in more frequent temporary flooding of low-lying rail yards and roads. These impacts may affect the movement of goods in and out of port facilities regardless of how the Port of Seattle adapts its own infrastructure.[18]

SEA LEVEL RISE ***Sea level rise poses risks for transportation systems.***[6,19] In many cases, areas most likely to be affected by climate change are areas already experiencing problems or on "watch lists," such as bridges or roads that are being undercut by fast moving waters ("scour critical" transportation infrastructure) or chronic environmental deficiency sites.[F,6]

- *Sound Transit.* Sea level rise has the potential to affect Sound Transit's north Sounder rail alignment and the Edmonds and Mukilteo facilities. Sea level rise of +50 inches (currently near the high end of projections for 2100, see Section 4) or more could result in permanent inundation of rail track and facilities in Edmonds and Mukilteo. Sea level rise under +50 inches would not permanently inundate the track or facilities, but would expose more of the north Sounder rail alignment to higher high tides, temporary flooding, saltwater corrosion, and storm surge.[19]

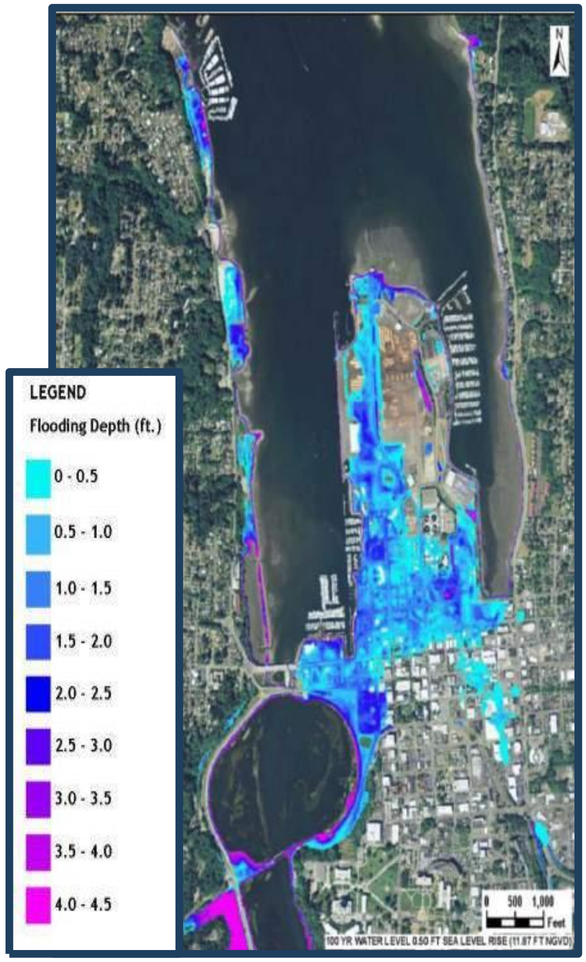

Figure 12-1. Increased flooding in Olympia. The map shows the projected area and depth of flooding in the City of Olympia during a 100-year flood event with +6 inches of sea level rise (near the low end of the range projected for 2050). The projected depth of flood waters ranges from less than 6 inches to 4.5 feet, as indicated by the map colors. *Figure source: Simpson 2012*[16]

F Chronic environmental deficiencies (CED) are locations along the state highway system where recent, frequent, and chronic maintenance repairs to the state transportation system are causing impacts on fish and fish habitat.

- *Washington State Department of Transportation*. Examples cited in WSDOT's assessment:[6] A +2 foot sea level rise could result in more logjams collecting on bridge piers of US 2 as they move down the Skykomish River, increasing the risk for damage to the bridge. Additionally, on and off-ramps in low-lying coastal areas are susceptible to flooding associated with sea level rise. For example, the flooding that occasionally occurs on the off and on-ramps of I-5 near McAllister Creek is likely to be made worse by sea level rise.[6]

- *City of Seattle.* Sea level rise may affect urban public transit routes and freight rail lines in some low-lying areas. An analysis evaluating sea level rise in the City of Seattle found that +2 feet of sea level rise would affect 8.2% of bus routes (0.04% of total lineal feet of bus routes) and 0.18% of freight rail throughout Seattle, while +5 feet of sea level rise would affect 20.5% (0.18% of total lineal feet of bus routes) of bus routes and 9.6% of freight rail lines.[G,20] Transit south of downtown in the Duwamish River basin is most vulnerable to the effects of sea level rise.[20]

- *Jamestown S'Klallam Tribe.* Moderate and high severity sea level rise scenarios project flooding on Highway 101 near Discovery Bay. While the near term potential for these floods is low, they could lead to the inability to access Highway 101 for 12-24 hours following extreme storms. The highway serves a critical function for the Tribe as it is the main access route for goods and services from the Tribe to other counties.[H]

SEA LEVEL RISE ***Low-lying urban and commercial infrastructure is likely to experience more frequent flooding or permanent inundation due to sea level rise.***

- *City of Olympia.* A small amount of sea level rise greatly increases the probability of flooding in downtown Olympia, potentially affecting public infrastructure, high-density development, and the City's historic district (Figure 12-1).[16,21] For example, a +3-inch rise in sea level makes it impractical to use common emergency response measures (sand bags and sealing catch basins) to control flooding associated with the 1-in-10 year (10% annual chance) flood event.[16] A +6-inch rise in sea level shifts the probability of occurrence for the 100-year flood event in Olympia from a 1% to a 5.5% annual chance event.[16]

G This assessment is based on 2014 data. Subsequent transit route changes may alter the conclusions of this report.

H Three representative scenarios were selected for mapping, a "Low Severity" scenario with a mean water level of +0.8 feet above the current sea level (projected to occur between 2025 and 2045), a "Moderate Severity" scenario with a mean water level of +2.0 feet above current sea level (projected to occur between 2055 and 2090), and a "High Severity" scenario with a mean water level of +5.1 feet above the current sea level, which may occur by the end of the century.

Floods and Extreme Precipitation

FLOODS ***Projected increases in extreme precipitation and river flooding increase the risk of aviation, bus, and rail service interruptions and damage to infrastructure located in or near current floodplains.*** In coastal drainages that flow to Puget Sound, sea level rise can exacerbate river flooding.[I] More extreme precipitation events can increase drainage problems and lead to more localized flooding.

- *The effect of floods and extreme precipitation events on highway, aviation, bus and rail operations could increase operation and maintenance costs, increase the potential for infrastructure damage, result in more frequent service delays, cancellations, and re-routes, and strand migrating salmon populations.*
  - *Sound Transit.* The Sounder, ST Express, Link, and Customer Facilities, specifically those located in Kent, Tukwila, and Sumner Stations are services that will potentially be affected by increasing risk of river floods. Areas with the greatest potential for flood impacts include: (1) the Link's crossing of the Duwamish River, and (2) Link's traction power substation at South 133rd Street and at 112th Street and East Marginal Way, which will potentially be affected by flooding in the Duwamish and Green rivers.[19]
  - *Washington State Department of Transportation.* Highways adjacent to rivers are expected to experience more frequent flooding due to more precipitation falling as rain, and are therefore likely to see an increase in temporary road closures.[6]
  - *The King County International Airport/Boeing Field*. Boeing Field is located in the Duwamish River floodplain near sea level, and is likely to be affected by more frequent and larger rain events, which could increase the number of standing water issues.[22]
  - *Seattle City Light*. The electric utility could experience delays in access and power restoration after storms because of heavy precipitation and standing water that reduces access to distribution infrastructure.
- *Larger flood events can reduce the effectiveness of existing levees and tide gates.* Flood flows in the Skagit basin are expected to more frequently exceed the design capacity of many of the basin's current dikes and levees, which are designed to the current 30-year return interval. Sea level rise is also expected to reduce the effectiveness of tide gates for draining low-lying cropland in the Skagit Valley.[23]
- *The ability of dams to mitigate increasing flood risk may be limited in some areas.* Initial research for the Skagit basin suggests that reducing community vulnerability to increasing flood risk will be more effective if those efforts focus primarily on

[I] Higher sea level can increase the extent and depth of flooding by making it harder for flood waters in rivers and streams to drain to the ocean or Puget Sound. Because of this, even modest river flooding could produce larger flood impacts in the lower portion of a river basin in the future relative to today's flood events.

improving management of the floodplain rather than on increasing flood storage in headwater dams (e.g., Ross Dam, Upper Baker Dam).[J,23] This is because most of the streamflows causing the increased flood risk originate *below* the headwater dams.

- *Climate change increases the risk of flooding in Green River communities.* By the 2080s, streamflow volume for the 100-year (1%) flood event in the Green River, as measured at Auburn, could increase by +15% to +76% relative to historical (1970-1999) climate for a moderate greenhouse gas scenario.[K,L,24] At the upper end of this range, the probability of today's 1-in-500 year (0.2% annual chance) flood event on the Green River increases to a 1-in-100 year (1% annual chance) flood event.[25] Recent research suggests that most of the projected increase in flood risk can be mitigated by flood control operations at Howard Hanson dam.[26] Inundation mapping of the current 500-year flood event by the U.S. Army Corps of Engineers estimates flood depths of 0-15 feet under different future scenarios following levee overtopping in the Kent-Auburn area.[M] Flooding in this area has widespread consequences; affecting residential and commercial properties, local roads, access to SR 167, and rail services in the area. Climate change is projected to increase the risk of these impacts.[25]

- *More sediment and flood debris in coastal rivers could adversely affect port and ferry facilities, as well as increasing flood risk in rivers.* Increased river flooding and reduced snow and ice cover in mountain watersheds are projected to increase the amount of sediment and flood debris carried by coastal rivers (see Section 5).[23] As a result, more frequent dredging near port facilities and ferry terminals in Puget Sound is likely to be needed.[17] Damage to port facilities and ferry terminals is also possible due to the potential for more flood debris.

- *Residential housing areas located in floodplains or adjacent to rivers are at risk from erosion and flooding.* For example, the Sauk-Suiattle Indian Reservation is situated in the channel migration zone of the Sauk River and could suffer significant infrastructure damage if higher flood flows cause the river to migrate into the inhabited areas of the reservation.[27]

- *Flooded roadways can affect salmon species in the Puget Sound region.* Floods enable

J Results are based an integrated daily time step reservoir operations model built for the Skagit River Basin. The model simulated current operating policies for historical streamflow conditions and for projected flow for the 2040s and 2080s associated with five global climate model simulations, driven by the moderate A1B greenhouse gas scenario.

K 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.

L This range was based on 20 global climate models and a moderate (A1B) greenhouse gas scenario. Data from the Pacific Northwest (PNW) Hydroclimate Scenarios Project website (http://warm.atmos.washington.edu/2860/).

M See "Potential Inundation, Shown as Simulated Water Depth, in Kent for a Peak Flow at Auburn Gage of 25,000 cubic feet Per Second" map produced by the U.S. Army Corps of Engineers to view the upper range of projected 500-year flood events. Map available at: http://www.nws.usace.army.mil/Missions/CivilWorks/LocksandDams/HowardHansonDam/GreenRiverFloodRiskMaps.aspx salmon to exit stream channels and take more direct routes to reach natal spawning grounds. While flooded roadways may initially provide some salmon with a more direct path to spawning sites, receding floodwaters can strand and kill salmon before they are able to spawn.

- *Increases in extreme high precipitation and river flooding could expose aquatic organisms to chemical pollutants from increasing urban runoff.* Premature mortality of Coho salmon spawning in restored habitats in the Puget Sound region have been attributed to a phenomenon known to as Coho pre-spawn mortality (PSM).[28] PSM occurs when adult Coho salmon are exposed to chemical pollutants from urban runoff, and typically results in death within a few hours.[28,29] Egg retention[N] is frequently observed in females that died of PSM.[28] Projected increases in extreme high precipitation could result in increased runoff,[30] and exposure to chemical pollutants from urban runoff.

Wildfire

WILDFIRE ***Increased wildfire risk west of the Cascades may affect energy transmission within the Puget Sound region***. Projected increases in area burned by wildfire (see Section 9) could cause damage and interruption of power generation facilities and transmission and distribution infrastructure. Even when wildfires do not directly threaten infrastructure, generation and transmission can be interrupted if transmission lines are de-energized because of smoke or safety concerns. [31]

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Many Washington communities, government agencies, and organizations are preparing for the effects of climate change on infrastructure.*** Most are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

- *State, county, and local agencies are taking steps to increase the resilience of publically-owned transportation infrastructure and services.*

  WSDOT

  - *Considering climate change and weather events in project-level environmental review.* WSDOT is integrating the results of its statewide vulnerability assessment[6] into the environmental review of proposed projects. WSDOT has published specific guidance on how to consider climate in project-level

[N] Female Coho salmon that did not spawn (deposit eggs) prior to death from PSM.

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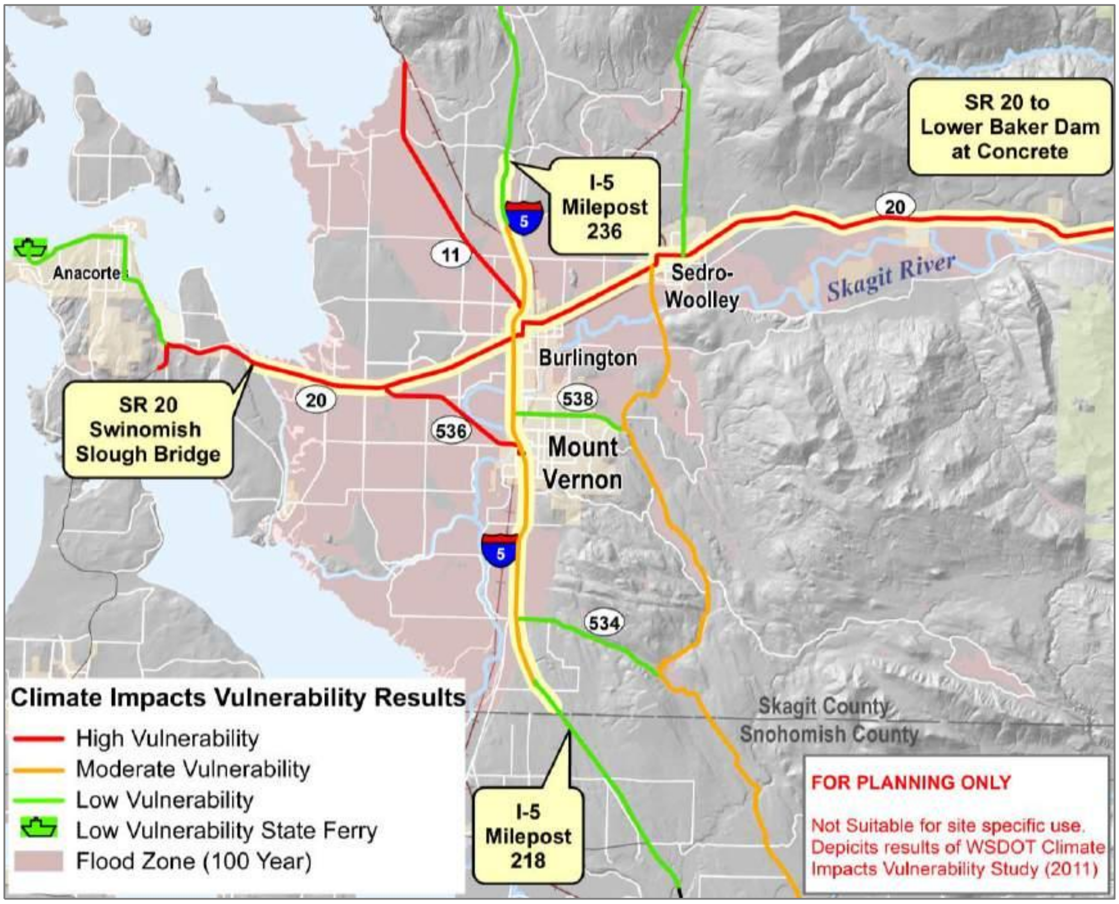

Figure 12-2. Evaluating the vulnerability of Washington State's transportation infrastructure to extreme flooding. Study area for WSDOT's Preparing Interstate and State Routes in the Skagit River Basin pilot project, funded by the Federal Highway Administration. Red lines highlight routes that are highly vulnerable to the impacts of climate change, while orange and green lines highlight routes of successively lower vulnerability. Low vulnerability classifies roads that will remain open, but may result in reduced capacity, or no impact. Moderate vulnerability classifies roads that will experience temporary closures (no more than 60 days). High vulnerability classifies roads that experience closures for more than 60 days for any one event. *Figure source: WSDOT.*[33]

environmental review under NEPA and SEPA.[0] As a result, more than a dozen project documents contain information about the relationship of the proposed project to a changing climate. For example, the Mukilteo Multimodal Ferry Terminal (MMFT) environmental impact statement evaluated impacts of sea level rise and increased storm intensity. With assistance from the Puget Sound Regional Council, WSDOT developed maps showing a 2- and 4-foot sea level rise in the Mukilteo project area. WSDOT then evaluated the potential for project design measures to withstand the projected sea level rise and increased storm intensity.[32]

0 The National Environmental Policy Act (NEPA) and State Environmental Policy Act (SEPA) were both written to promote the enhancement of valuable environmental resources. Both require environmental impacts assessments to better document and understand the impacts of proposed projects.

- *Long-term planning for corridor improvements.* WSDOT's strategic plan requires all plans to document how climate change and extreme weather vulnerability are considered. Recent studies for US 2, SR 516, and SR 520 discuss the level of climate risk, emergency response and hazard reduction strategies, and options for increasing resilience.

- *Preparing interstate and state routes in the Skagit River basin for climate change.* WSDOT recently completed a project which developed site-specific adaptation options to improve the resilience of Interstate 5 and state routes in the Skagit basin (Figure 12-2). For example, in response to Skagit River flooding on North SR 9 WSDOT highlighted two options that will reduce flood concerns for this route and will improve transportation infrastructure resilience to future flood events: (1) develop a new road alignment out of the floodway, and (2) raise the road in existing alignment.[33] This work complements flood hazard reduction strategies proposed by the U.S. Army Corps and Skagit County.

- *Partnering with others to share tools and results.* WSDOT is working with local governments and state agencies to share information on how to complete a qualitative assessment of transportation infrastructure vulnerability to climate change. Specifically, WSDOT is working with the Department of Commerce to share data and develop tools for local governments to better integrate transportation planning into comprehensive city and county plan updates.[34]

<u>*King County*</u>

- *Building floating docks and gangways that are able to accommodate several feet of sea level rise.* In 2010, King County Marine Division replaced the existing dock and gangway in West Seattle used by the Water Taxi (owned and operated by WSDOT) with a new floating dock and gangway, which is able to handle rising sea levels.[22]

- *Levee improvements and flood-risk reduction activities.* King County formed a new Flood Control District in 2007 to increase county capacity for addressing regional flood risks due to a variety of factors, one of which was climate change. The creation of the new District resulted in a ten-fold increase in local funding[P] for flood risk reduction efforts. Accomplishments in 2014 include mapping of channel migration hazards along the Cedar River, completing a critical levee extension project, implementing five projects that raised structures in flood zones, and purchasing forty-two acres of floodplain on the Tolt, Snoqualmie, Cedar, and White rivers (including 20 acres in Pierce County). Public ownership of this land and removal of structures will reduce

[P] Funding for the Flood Control District comes from a county-wide property levy of 10 cents per $1,000 assessed value. This amounts to $40 per year on a $400,000 home. The levy raises roughly $36 million a year. http://www.kingcountyfloodcontrol.org/

flood risks and preclude development in these flood prone areas.[11]

- *Widening bridge spans and increasing the resilience of roads.* As of 2012, King County had replaced 15 short span bridges with wider span structures and 42 small culverts with large box culverts. These changes will increase resilience of bridges and roads to major flooding. In many cases these wider structures also allow for the movement of a variety of wildlife along the river's edge during normal flows and elevated flood events thereby protecting wildlife connectivity between critical habitats.[11] King County's Road Services Division[Q] will incorporate information about changes in future flooding, storm size and frequency, and landslide risk projections into roads maintenance and preservation programs and projects.[22]

<u>Sound Transit</u>

- *Assessing the vulnerability of the Sound Transit system to the effects of climate change.* The Sound Transit Climate Risk Reduction Project assessed the vulnerability of Sound Transit assets and services to climate change while creating a process and a model for transit agencies across the United States. The analysis found that while climate change exacerbates many existing issues such as sea level rise, extreme precipitation events, heat stress, mudslides, and river flooding, Sound Transit already possesses some degree of climate resilience and capacity to address climate impacts, both of which will be further enhanced by integrating climate considerations into decision making.[19]

<u>National Parks and Forests</u>

- *The National Parks Service and Forest Service are incorporating climate change into transportation plans and infrastructure maintenance and development activities.* The National Parks Service 20-year National Long-Range Transportation Plan incorporates the effects of climate change in the transportation planning process, and will be updated at least every 5 years.[35,36] Mount Baker-Snoqualmie National Forest (MBSNF) engineers are replacing failing bridges and culverts, and disconnecting roads from waterways to mitigate impacts on aquatic ecosystems. However, limited funding and staff impede current efforts to upgrade infrastructure to current standards, and therefore future costs for upgrades to accommodate projected hydrological shifts (see Section 3) poses a barrier to adaptation.[36] Additionally, MBSNF engineers are adapting road management to the effects of climate change by reducing the size of the road system in the national forest; this includes closing, decommissioning, or converting roads to non-vehicular modes of transportation.[36] Road decommissioning is an expensive process. To date, MBSNF has decommissioned more than 130 miles of roads

[Q] King County's Road Services Division maintains roads, bridges, culverts, and other related infrastructure in unincorporated King County.[22]

(~5% of the total road miles within MBSNF), with each decommissioned mile costing between $40,000-$100,000.[37]

- *Local public utilities are working to incorporate the effects of climate change into siting and design procedures, and to protect facilities from current flood risks.*

    - *Incorporating sea level rise into the Wastewater Treatment Division facility siting and design procedure.* A 2008 study evaluating the effects of sea level rise on King County's Wastewater Treatment Division facilities recommended that sea level rise should be incorporated in planning for major asset rehabilitation or conveyance planning that involves the facilities included in the analysis.[13] Since the release of the report King County has modified the conveyance system and outfalls of the Wastewater Treatment Division facilities to reduce or eliminate seawater intrusions, even during high tide. [15,22] Additional preparations for limiting saltwater intrusion include installing flap gates, raising weirs, and other similar controls.[22]

    - *Protecting Water Treatment Division facilities in floodplains from flood risk.* The King County Wastewater Treatment Division has reviewed all of its facilities within the Federal Emergency Management Agency's (FEMA) 100-year floodplains and is identifying steps to ensure all facilities are protected from current flood risks.[22]

    - *The redesigned Anacortes Water Treatment Plant reduces the potential for flooding.* 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.[21]

    - *Increasing capacity to manage extreme high precipitation events in Seattle.* Seattle Public Utilities' RainWatch system[R] provides operators and decision-makers with 1-hour precipitation forecasts and 1- to 48-hour rain accumulation totals that can be used to manage extreme high precipitation risks at the neighborhood- or basin-scale in real-time.

    - *Increasing capacity to manage storm-related power outages.* Seattle City Light's WindWatch tool provides operators with real time wind speed forecasts and alerts up to three days in advance of major storms. This can be used to better prepare crews and equipment for power restoration work following storms.

    - *Considering sea level rise in facilities master planning.* Seattle City Light is reviewing a facility in the Duwamish River basin for potential flooding

[R] See http://www.atmos.washington.edu/SPU/

impacts associated with sea level rise and storm surge.

- *Urban centers are planning for sea level rise.*
    - *Planning for sea level rise in the City of Olympia.* In an effort to reduce flood risk in association with sea level rise, the City of Olympia conducted GIS mapping of projected inundation zones, incorporated sea level rise considerations into the City's Comprehensive Plan and Shoreline Management Plan, and develops annual work plans to address adopted goals and priorities, key information needs, improve emergency response protocols, and survey and identify shorelines, structure elevations, and sewer basins that are vulnerable to flooding.[38]
    - *Planning for sea level rise at the Port of Bellingham.* 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.[39]
    - *Evaluating the robustness of the Seattle sea wall design to sea level rise.* An evaluation of sea level rise impacts on design considerations for the new Seattle sea wall found that the current sea wall height would be able to accommodate +50 inches of sea level rise and a +3 foot storm surge (a 100-year event surge).[S] As a result, the City determined that it was not necessary to build a higher structure to accommodate sea level rise over the next 100 years.[T]
- *Tribes are working to identify climate hazards affecting their communities and infrastructure.*
    - *Adaptation planning for multiple climate-related hazards: the Swinomish Indian Tribal Community.* The Swinomish Indian Tribal Community is implementing adaptation recommendations developed in 2010. This includes revisions to shoreline codes, development of a detailed coastal protection plan for the most vulnerable 1,100 low-lying acres on the north end of the Reservation, development of a Reservation-wide wildfire risk reduction program, and development of a system of community health indicators to measure knowledge of and impacts of climate change within the Tribal community.[40]
    - *Vulnerability assessment and adaptation plan: Jamestown S'Klallam Tribe*. The climate vulnerability assessment and adaptation plan identified key tribal resources, the expected impacts from climate change, and created adaptation strategies for each resource. Moderate and high severity sea level rise scenarios project potential flooding on Highway 101 near Discovery Bay,

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S The Mean Higher High Water, which is the average of the highest daily tide at a place over a 19-year period.

T See http://sdotblog.seattle.gov/2013/01/23/sea-level-and-the-seawall/ for more details.

preventing the Tribe's access to the highway for 12-24 hours. The adaptation plan recommends that the Tribe work with Washington Department of Transportation to discuss raising the vulnerable infrastructure, especially in conjunction with future repairs.[41]

- *In addition to previous examples, there are a number of efforts that are currently underway that will help increase regional resilience to climate change.* Final results of these efforts will be included in updated editions of this report.

  - *Efforts to increase climate resilience for infrastructure in the Puget Sound region are underway:* in the City of Tacoma (climate change vulnerability assessment), City of Seattle (adaptation plan), Seattle City Light (vulnerability assessment and adaptation plan), King County Wastewater Treatment Division (impact assessment), WSDOT (landslide mitigation), Hood Canal Coordinating Council (adaptation plan), North Olympic Peninsula Resource Conservation and Development Organization (risk assessment and adaptation plan), and the Puyallup Tribe (vulnerability assessment and adaptation plan). Additionally, climate resilience benefits are expected from programs that incorporate climate-related changes in risk – as well as current risks – in the prioritization and design of project implementation. For example, programs like Floodplains by Design, which was created to promote the reduction of flood risks and floodplain ecosystem recovery while maintaining or improving agricultural production, water quality, and open space.

Additional resources for evaluating and addressing the effects of climate change on agriculture in Puget Sound.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **National Climate Assessment | Infrastructure:** The National Climate Assessment summarizes the impacts of climate change on the United States (addressing national and regional issues) now and in the future. The infrastructure section addresses sea level rise, extreme precipitation events, and extreme heat: http://nca2014.globalchange.gov/highlights/report-findings/infrastructure

- **Federal Highway Administration (FHWA) | Climate Change:** FHWA is partnering with both state and local transportation agencies to increase the resilience of the transportation system to the impacts of climate change. Resources discussing how the FHWA is increasing resilience of federal transportation systems is available on the following FHWA website: http://www.fhwa.dot.gov/environment/climate_change/

- **U.S. Department of Energy | Infrastructure:** The Partnership for Energy Sector Climate Resilience is an initiative to enhance U.S. energy security by improving the resilience of energy infrastructure to extreme weather and climate-related changes: http://energy.gov/epsa/partnership-energy-sector-climate-resilience

- **EPA | Infrastructure:** The Environmental Protection Agency (EPA) is working with partners to provide the knowledge and tools to ensure that investments made in water infrastructure are moving towards a sustainable future: http://water.epa.gov/infrastructure/
  EPA's Climate Ready Water Utilities (CRWU) resources provides water utility managers with tools, training, and technical assistance needed to adapt to climate change: http://www2.epa.gov/crwu

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SECTION 13
How Will Climate Change Affect Human Health?

Climate change could affect human health in the Puget Sound region via the direct effects of more intense heat waves and higher flood risk, and via the indirect effects of increasing wildfire severity, declining summer water supply, shifting infectious disease dynamics, and declining air quality. Projected changes in climate are likely to have widespread implications for Puget Sound's population, and a disproportionate effect on its most vulnerable residents (i.e., over age 65, children, homeless). Projected increases in the frequency and intensity of extreme heat events are expected to increase hospitalizations due to heat stress, and have the potential to reduce air quality. Increasing fire risk could affect human health via smoke exposure and increased occupational hazards for emergency responders. Washington's state and local governments are in the early stages of identifying how climate change may affect human health and public health infrastructure.

Climate Drivers of Change

Climate change is expected to exacerbate existing public health challenges by altering the frequency, duration, or intensity of climate-related hazards to which Puget Sound[A] communities are exposed.[1,2] In some cases (e.g., disease vectors), climate change may also lead to the introduction of new risks, and subsequently, new diseases.

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[3,4] Warming is expected to affect health via more intense and more frequent heat waves,[1] increased winter flood risk, decreased summer water supply, increased wildfire risk, lower air quality, and shifts in the types and distribution of vectors that transmit infectious and fungal diseases (Figure 13-1).

- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[5] This would increase the risk of flooding and associated health risks.

- *Most models are consistent in projecting a substantial decline in summer precipitation.*

[A] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describe the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

Projected changes in other seasons and for annual precipitation are not consistent among models, and trends are generally much smaller than natural year-to-year variability.[4] Declining summer water availability may result in reduced water quality for some locations.[6]

- *The climate-related effects on human health will disproportionally affect vulnerable populations.* Vulnerable populations include those over age 65, children, poor and socially isolated individuals, homeless, the mentally ill, outdoor laborers, and those with underlying health problems.

- *Very few studies have evaluated the climate-related effects on human health within the Puget Sound region.*[7] A small number of heat-related health outcome studies have provided a glimpse of the region-specific human health effects likely to be experienced in the Puget Sound region as a result of climate change. The remaining examples in this section reflect a general understanding of climate-related health effects, and do not exclusively address projected responses for the Puget Sound region.

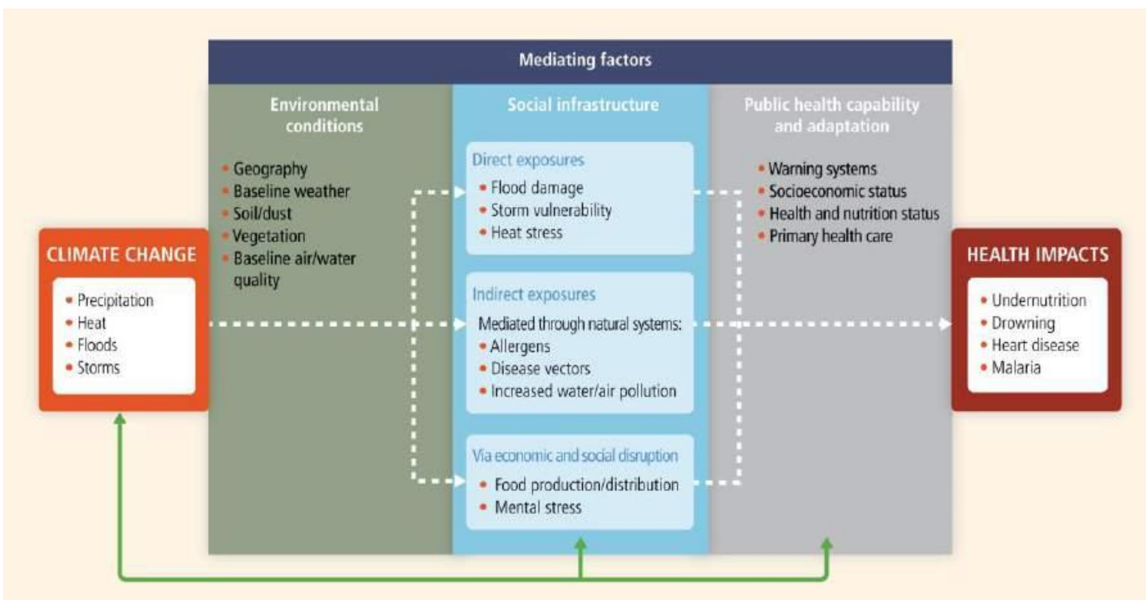

Figure 13-1. Conceptually, there are three primary ways that climate change affects health: directly through climate and weather; indirectly through natural systems that are influenced by climate; and indirectly via effects on economic and social well-being. Health effects occur when climate change influences a region's baseline environmental conditions (green box) creating new or differing exposure pathways (blue box). These effects can be further modified by factors such as the public health system's existing infrastructure and adaptive capacity (gray box). Green arrows show how some of these factors may be affected by one another. *Figure Source: IPCC (2013).*[8]

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Direct Pathways

DIRECT **Changes in the frequency, intensity, or duration of extreme weather events directly affect health outcomes.**

- *The frequency, duration and intensity of extreme heat is expected to increase in Washington State*. Heat-health exposure studies focused on Puget Sound counties have identified the warmest 1% of historical days (approximately 97°F, or 36°C, Humidex),[B,C,D] as the threshold at which significant adverse health outcomes occur.[9,10,11,12] Figure 13-2 illustrates the relationship between mortality rates and increasing humidex for 1980-2010. Climate models project that extreme heat events will become more frequent and more intense, while extreme cold events will become less frequent (see Section 2).

- *Mortality, hospitalizations, and emergency medical service call rates significantly increase on an extreme heat day compared to a non-heat day.* A King County study found that, for all ages, extreme heat (Humidex > 97°F) elevated the risk of: all-cause (+10%), circulatory (+9%), cerebro-vascular (+40%) and accident-related (+19%) mortality;[11] chronic kidney failure (+57%), acute kidney failure (+68%) and natural heat-related exposure (+244%) causes of hospital admissions;[10] and emer-gency medical service call volume by +16% on an extreme heat day compared to a non-heat day.[E,13]

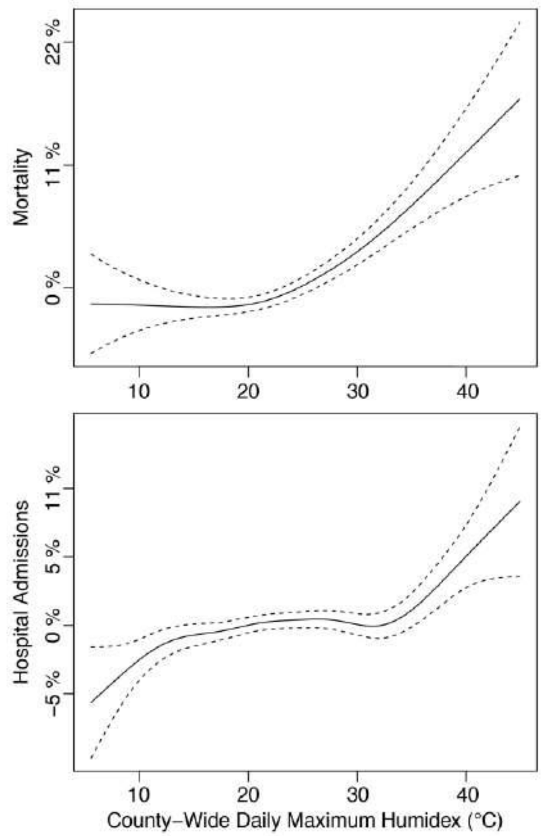

Figure 13-2. Strong link between heat stress and health outcomes in King County, Washington. The figures show the change in mortality (top) and hospital admissions (bottom) as a function of humidex. In both plots, the black line shows the fitted relationship (cubic spline) based on the observed data (analyzed for 1980-2010), and the dashed lines show the 95% confidence limits. On the graph, any value over zero represents an increase. *Figure Source: Isaksen et al. 2014.*[12]

B Humidex is an index that measures the combined effects of air temperature and humidity on the human body. For example, the threshold humidex of 97°F (36°C) could correspond to an air temperature of 90°F and a humidity of 35%, or to an air temperature of about 80°F at 80% humidity.

C Each study used a different time period for the analysis, all within the range of 1970-2010.

D The air temperature thresholds used to define extreme heat vary by location. Studies focused on Puget Sound counties define the threshold around 97°F (36.0°C) humidex.

E The analyses were based on the following time frames: 1980-2006 & 1980-2010 for the mortality studies; 1990-2010 for the hospitalization analysis; and 2007-2012 for the emergency medical services analysis.

Table 13-1. Heat-vulnerable population health estimates observed and predicted for Puget Sound communities.

Variable	Location	Observed Change
Age		
0-4 & 5-14	King County	Historical +14% and +7% increase, respectively, for all-causes of emergency medical service calls on extreme heat days.[F]
65+	King, Pierce Snohomish County	Historical +10% increase in mortality on extreme heat days[F,9]; Projected annual excess heat-related mortality[G] ranged from +64 to +200 for 2025, depending on the greenhouse gas scenario.[H,I,9]
65-84	King County	Historical +6% increase in mortality on extreme heat days.[F,11]
85+	King County	Historical +18% increase in mortality and 8% in hospital admissions on extreme heat days.[F,10,11]
85+	King, Pierce Snohomish County	Projected 2.3–8.0 (2025) and 4.0–22.3 times higher (2045) mortality for low compared to high warming scenarios.[I,J,12]
Underlying Health Conditions		
Diabetes	King County	Historical 78% increase in diabetic-related mortality on an extreme heat day,[F] 45-64 year old age group; 8% increase in diabetic-related emergency medical service calls, all-ages [11,E]
Acute Kidney Failure	King County	Historical 76% increase in acute kidney failure hospitalizations on an extreme heat day,[F] 45-64 year old age group[10]
Chronic Kidney Failure	King County	Historical 99% increase in chronic kidney failure hospitalizations on an extreme heat day,[F] 45-64 year old age group[10]
Outdoor Occupation		
	Washington State	78.5% of all heat-related injury workers' compensation claims in the State of Washington occur as a result of working outdoors. The construction sector experienced the highest rate of HRI at 12.1 per 100,000 FTE. [14]

[F] Heat events were defined as one or more consecutive days where the humidex was above the 99th percentile humidex threshold calculated for a historical period (1970-2006). [9]

[G] Excess deaths are the number of expected deaths above the baseline number of deaths. The baseline number of deaths was calculated between 1980-2006.[9]

[H] This study included King, Pierce, and Snohomish Counties. Projected change in mortality for those over age 65, relative to a base period of 1980-2006.

[I] Projections are based on the average of two global climate models and two greenhouse gas scenarios: the PCM1 model run with a low (B1) greenhouse gas scenario and the HADCM1 model run with a moderate (A1B) greenhouse gas scenario. Population was held constant at the level projected for year 2025.

[J] This study included the greater Seattle area. Projected change in mortality was estimated relative to a base period of 2002-2006.

- *Certain populations are more vulnerable to extreme heat*, resulting in increased risk of mortality, hospitalization, and emergency medical service utilization (Table 13-1).

- *Projected reductions in the frequency and severity of winter cold snaps may not be closely tied to health benefits.* Most studies are consistent in projecting a smaller decrease in cold-related mortality than the increase projected for heat-related deaths. One reason for this is that wintertime mortality is primarily associated with the seasonal effects of cold weather (e.g., influenza), and is not strongly affected by the frequency or severity of daily extremes. Recent studies have found evidence that the number of cold deaths is unlikely to change with warming.[15,16]

- *Flooding is a health concern for Puget Sound residents.* Flood waters present direct, short-term physical threats to health. In addition, floods can indirectly affect health by conveying biological and chemical agents to drinking, storm, and recreational waters; and by establishing favorable conditions for mold growth.[1,17] Risk of illness increases as individuals and communities are exposed to pathogens through contact with contaminated waters and/or mold-filled dwellings.

    - *Future increases in the severity of heavy rainfall and flooding, and sea-level rise, may exacerbate these health risks.* Heavy rainfall events are projected to become more intense (see Section 2). On average in the Northwest,[K] the intensity of the heaviest 24-hour rain events is projected to increase by +22% by the 2080s (2070-2099 relative to 1970-1999, see Section 2).[L,M,18] Rising air temperatures are also projected to result in a shift from snow-dominant to rain-dominant watersheds, thereby increasing peak river flows during flood events (see Section 3). These changes are projected to result in more severe flooding in middle and low-elevation basins (see Section 3). Additionally, sea-level rise (see Section 4) could affect Puget Sound in a variety of important ways including increasing the potential for higher tidal/storm surge and associated coastal flooding.

    - *Flooding is rarely related to mortality in Washington State.* Since 1995, nationwide, there have been 1,455 deaths attributed directly to floodwaters, but only 14 have occurred in Washington State.[19]

[K] 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.

[L] The study evaluated 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). Projected changes in intensity were evaluated for latitudes ranging from 40 to 49N.

[M] 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.

- *Other health effects of flooding: learning from Katrina.* Research is lacking regarding the long-term, indirect effects from flooding in the Puget Sound region and Washington State. Although there are many important differences relative to what can be expected in the Puget Sound region, a lot has been learned about health effects from Hurricane Katrina.
    - Following the storm, illnesses accounted for 67% of all reports of post-hurricane injuries and illnesses, while injuries accounted for 32%, and chemical exposure accounted for less than 1% of the total.[20] After floodwaters receded, 46% of the homes had visible mold growth[N,21], and the average outdoor spore concentration in flooded areas was twice the concentration in non-flooded areas.[20] Upper respiratory and lower respiratory symptoms increased by +54% and +27% in children and adolescent patients, respectively, compared to before the flooding occurred.[22]

Indirect Pathways

Climate change is likely to have indirect effects on health outcomes through the modification of natural systems and social dynamics.

INDIRECT ***Projected increases in wildfire activity could affect respiratory health, income, and entail heightened occupational hazards for emergency responders.*** Wildfire emissions can have acute or long-term health effects for those exposed. Health can be affected through exposure to air pollutants, stress from loss of property or belongings, or as an occupationally-related injury/exposure while wildfire fighting. As with other effects, there is a lack of analyzed Puget Sound region and Washington State-specific wildfire-associated health impact data.

- *Wildfire risk is projected to increase.* Two different studies estimate that the annual area burned for Northwest forests west of the Cascade crest could more than double, on average, by 2070-2099 compared to 1971-2000.[O,23,P,24]

- *Wildfire smoke has been linked to increased hospitalizations.* Smoke from the 2012 wildfires in Chelan and Kittitas counties contributed to an additional 350 hospitalizations in those counties for respiratory conditions and 3,400 student absences from school.[Q]

[N] Because of its cooler and drier climate, Puget Sound would likely to have less mold growth under the same conditions.

[O] Based on a statistical model linking wildfire area burned with climate conditions. Projections are based on ten global climate model projections for a low (B1) and a moderate (A1B) greenhouse gas scenario.

[P] Changes from historical (1971-200) to future (2070-2099) modeled using MC1 vegetation model projections based on three global climate models (CSIRO-Mk3, Hadley CM3, and MIROC 2.3 medres) under a high (A2) greenhouse gas scenario.

[Q] Glen Patrick, Manager of the Environmental Epidemiology, Washington State Dept. of Health, personal communication.

- *The economic cost of smoke exposure can be high.* A California-based study looked at quantifying all health-related costs of wildfire smoke exposure from the California Station Fire of 2009. They estimated the costs from wood smoke-related illness at $9.50 per exposed person per day, however, total costs, which included defensive actions taken to avoid exposure to smoke, were considerable higher at $84.42 per exposed person per day.[25] Although wildfire risk is expected to rise, no study has quantified the implications for smoke exposure.

- *Occupational health risks* associated with wildland firefighting include reduced lung function, increased upper and lower respiratory symptoms, injuries, and related mortality.[26]

INDIRECT ***Reductions in summer water supply can negatively affect health.*** Increasing air temperatures, less rainfall in summer, reductions in snowpack, and more frequent episodes of low streamflow (see Section 2 & 3) – these are all projected to further limit summer water supply, which may negatively affect water quality in some locations.[6] Health can be affected through exposure to compromised drinking and recreational water sources.[1] Mental health effects also increase as droughts persist.[27] As with wintertime flooding, few studies have analyzed regionally-specific drought-health impact data.

- *With less water available, contaminants in both surface and well waters become more concentrated.* Municipal water quality is unlikely to be affected, since water from these systems is purified. In contrast, private water systems that rely on shallow wells (less than 50-100 feet deep), those that are already at risk for seawater intrusion, or those with low productivity (less than 10 gallons/minute) are more vulnerable during drought conditions.[28,29] Consumers are at an increased risk for bacterial and/or chemical (e.g., nitrates) exposures associated with drinking and bathing in these waters.

INDIRECT ***Climate change could alter patterns of infectious disease.*** Few studies have analyzed region-specific relationships between climate and infectious diseases. However, there is evidence linking various pathogens and exposure pathways to anticipated changes in climate. The following are examples of the pathways by which climate change could affect diseases, exposure, and the resulting health outcomes.

- *Vector-borne example: West Nile Virus.* There are approximately 65 mosquito species capable of carrying West Nile Virus (WNV), 27 have been detected in Washington State.[30] Increasing air temperatures and changes in precipitation patterns may affect vector (e.g., mosquito, tick, flea, etc.) distribution, habitat, and population growth. Changes in vector prevalence may increase the incidence of existing or emerging diseases.[31] It is not known to what extent climate played a role in the emergence of WNV in 1999 along the east coast of the United States and the ensuing westward spread throughout North America.

- *Food-borne example: Vibrio parahaemolyticus and Vibrio vulnificus. Vibrio parahaemolyticus* (Vp) and *Vibrio vulnificus* (Vv) are strains of bacteria that can cause illness in humans consuming raw or undercooked shellfish (specifically oysters).[32] *Vv* was first detected in sediment from Willapa Bay, Washington in 1984.[33] 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. Increasing sea-surface temperatures increase the spread of these bacteria strains.[34]

- *Water-borne example: Cryptosporidiosis. Cryptosporidium parvum* and *Cryptosporidium hominis* are the parasites that cause Cryptosporidiosis, a diarrheal disease affecting humans and animals. Transmission of occurs when environmentally resilient cysts (oocysts) are ingested. These environmentally resilient cysts, or oocysts, are found in most surface waters, and the concentration of these cysts is positively associated with increased rainfall and peak river flow (see Sections 2 & 3).[35] Because these cysts are extremely chlorine resistant, recreational waters are a particular risk for transmission.[36]

- *Emerging pathogens example: Cryptococcosis.* Cryptococcosis is a rare infection caused by inhalation of spores from *Cryptococcus gattii*, a tropical and subtropical fungus found on eucalyptus trees. The infection can affect the lungs, brain, and/or spinal cord, as well as other parts of the body. Warmer, drier summers may have contributed to the establishment of *C. gattii* in British Columbia[37,38] and the subsequent emergence in the Puget Sound region.[39]

INDIRECT ***Warming increases the risk of Harmful Algal Blooms (HABs) and as a result, shellfish poisoning.*** During HAB events, the algae *Alexandrium catenella* produces neurotoxins. Consuming shellfish contaminated with these toxins can result in paralytic shellfish poisoning. This poisoning is distinct from the illness associated with consuming naturally-occurring pathogenic bacteria such as *Vibrio parahaemolyticus* and *Vibrio vulnificus* (discussed above). Climate change is projected to increase the risk of HAB events and lengthen the season over which the can take place (see Section 7).

INDIRECT ***Increasing air temperatures, longer heat waves, and decreasing summer precipitation (see Section 2) all have the potential to alter ambient ground-level ozone and fine particle levels (<2.5 micrometers), affecting respiratory and cardiovascular health outcomes.*** Dry conditions and wildfire activity can also lead to short-term increases in particulate air pollution.

- *Increased ground-level ozone, possible increases in particulates.* Higher summer air temperatures are expected to lead to the production of more ground-level ozone, particularly in urban areas. This could slow air quality improvements made in recent decades in urban areas.[9] Heat waves are often associated with air stagnation, which can cause fine particulate matter ($PM_{2.5}$) to accumulate.[40]

- *Increased deaths due to ozone.* Projections of future ground-level ozone concentrations combined with population growth in the Greater Seattle area are estimated to increase the attributable number of excess deaths[G] during the summer months from 69 per year (95% range: 35–102 per year) in 1997-2006 to +132 per year (95% range: 68–195 per year) by mid-century.[R,9]

- *Increased deaths due to particulates.* Projections of future $PM_{2.5}$ concentrations, combined with population growth in Washington State, are projected to cause +139 more deaths per year (95% CI 52–226) by mid-century compared to 2001.[R,41]

INDIRECT ***Changing air temperature and pollution affect aeroallergen levels.*** The relationship between climate change, aeroallergen levels and adverse health outcomes has not been studied in the Puget Sound region.

- *Increasing production of allergens.* Earlier start dates and longer pollen seasons have been detected for some ragweed species[42], while total pollen production and biomass, per plant, has increased significantly with rising CO_2 levels.[43] Similarly, studies have found that birch trees are more allergenic during episodes of higher air temperatures. [44]

- *Ozone exacerbates allergy symptoms.* Ground-level ozone, which is projected to increase (see above) enhances allergic responses in susceptible individuals.[45]

Mental Health

MENTAL HEALTH ***Climate change could affect mental health outcomes both directly and indirectly.*** Direct psychological effects would result from the emotional and psychological stress related to a particular extreme weather event, while indirect effects would be associated with perceived threats to emotional well-being and concern regarding the uncertainty of future risks.[46]

- *Research on the effect of climate-related events on mental health in Washington State is lacking.* Possible mental health effects of climate change include: post-traumatic stress disorder and unhealthy coping mechanisms (e.g., increased alcohol or tobacco use, poor dietary habits); non-trauma related anxiety and depression related to feelings of losing control over a situation, or uncertainty about the future; and grief the loss, or potential loss, of culturally important resources, traditions, or places.[1,46,47] These effects would disproportionally affect vulnerable populations and individuals with pre-existing mental conditions.[46]

- *Hot conditions have been linked to mental health deaths.* In King County, mental health disorder-related mortality increased +43% on extreme heat days relative to non-heat days for the 65-84 year-old age group (1980-2010).[11]

[R] The study domain was the Greater Seattle area. Projected changes in mortality are relative to a base period of 1990-1999. Projections based on MM5/CMAQ model run with the high (A2) greenhouse gas scenario. Population levels were held constant at year 2025.

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Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Washington's state and local governments are in the early stages of identifying how climate change may affect human health and public health infrastructure.***

- *Washington State Department of Health:* In October 2014 the Washington State Department of Health began developing a set of climate and health indicators. Currently, there are 15 indicators in five categories: health, environment, human vulnerability, mitigation, and adaptation. The set will be used as an adaptation tool to help the agency raise public awareness about the linkages between climate and health, track changes in trends over time, and develop materials that local health jurisdictions can use for communicating to the public and writing adaptation plans. The project has already helped identify areas where surveillance needs to be improved and where the agency may be able to collaborate with new partners to collect data. It is anticipated that the indicators will be finalized by December 2015 and hosted on Washington's Environmental Public Health Tracking data portal (the Washington Tracking Network) by March 2016. http://www.doh.wa.gov/DataandStatisticalReports/EnvironmentalHealth/WashingtonTrackingNetworkWTN

- *Public Health Seattle/King County:* King County is partnering with the University of Washington's Department of Environmental and Occupational Health Sciences to identify and plan for the effects of climate change on human health, including synthesizing data on the effects of changing air temperatures on illness and death in King County. They have also recently updated their King County Strategic Climate Action Plan. The plan is a five-year blueprint for County action to confront climate change, integrating climate change into all areas of County operations and its work in the community. By 2020 the King County public health sector aims to implement a data surveillance system to monitor and report the human effects of climate change, conduct community and stakeholder engagement, and establish systems to detect and respond to current and emerging health threats. http://your.kingcounty.gov/dnrp/climate/documents/2015_King_County_SCAP-Full_Plan.pdf

- *Clark County Public Health:* As part of Clark County's Comprehensive Growth Management Plan revision process, Clark County Public Health produced and included a health element - *Growing Healthier* that addressed climate change effects in their county. Though not a Puget Sound County, the background reports are good examples of incorporating climate change and public health science to support policy recommendations. http://www.clark.wa.gov/public-health/community/growing_healthy/documents/ClimateLitReviewandCCFINAL_32912.pdf

- *Thurston County Public Health and Social Services:* Thurston County Public Health and Social Services received a one-year demonstration grant from the National Association of County and City Health Officials to assess local capacity to address public health effects from climate change and to increase awareness. Educational materials were created to inform the conversation. These materials can be found online and include a white paper and several PowerPoint presentations. http://www.co.thurston.wa.us/health/admin/initiatives/climatechange.html

- *EpiTRENDS: A monthly online illness trend publication produced by the Washington State Department of Health.* The Washington State Department of Health has developed this website as a means of disseminating information and monitoring emerging health issues over time. http://www.doh.wa.gov/DataandStatisticalReports/DiseasesandChronicCondition/CommunicableDiseaseSurveillanceData/EpiTRENDS

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APPENDIX A

Hydrologic Projections From the Integrated Scenarios dataset

There are two principal datasets that are often used to evaluate hydrologic projections for Puget Sound and the greater Pacific Northwest:

- ***Integrated Scenarios for the Future Northwest Environment.*** The current set of projections, developed by Mote et al. in 2015,[1] which stem from the newer 2013 IPCC report,[2] and
- ***The Pacific Northwest Hydroclimate Scenarios Project.*** A previous set of projections, developed by Hamlet et al. in 2010,[3] which are based on the climate projections used in the IPCC's 2007 report.[4]

Although newer, the hydrologic projections from the "Integrated Scenarios" dataset appear to contain biases, especially in mountainous areas. Specifically, the simulations assume winter temperatures that appear to be too cold at high elevations. This has a large impact on model simulations of snow accumulation and melt, which in turn has implications for streamflow. In addition, this dataset is currently being further refined through calibration – these refinements may partially alleviate the issues associated with the temperature bias.

In looking at projections from the Integrated Scenarios dataset, we found that projected changes in snow-influenced basins were large compared to expectations. For example, for the Nooksack River Basin, the projected increase in the 100-year peak flow event is +71 to +102%,[A,B,1] on average for the Integrated Scenarios dataset, as compared with +27%,[C,3] on average, for the Hamlet et al. dataset. Differences between the two datasets appear to be greatest for streamflow extremes.

Since there were concerns about the hydrologic projections obtained from the Integrated Scenarios dataset, most of the projections included in Section 3 stemmed from the Hamlet et al. dataset. For comparison, this appendix includes a summary of hydrologic projections from the Integrated Scenarios dataset.

[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 more details.

[B] Projected change is for ten global climate models, averaged over the Puget Sound region. Scenarios include a low (RCP 4.5) to a high (RCP 8.5) greenhouse gas scenario.

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

Table A-1. Projected changes in hydrology, for comparison with projections included in Section 3.

Variable	*Projected Long-term Change*
Snow	
Snowpack	Declines • Declines projected for all greenhouse gas scenarios; specific amount depends on the amount of greenhouse gases emitted.[A] • Projected change in April 1st snowpack,[D] on average for Puget Sound:[A,1] 2050s (2040-2069, relative to 1970-1999): low emissions (RCP 4.5): −45% (range: −53 to −32%) high emissions (RCP 8.5): −53% (range: −66 to −37%) 2080s (2070-2099, relative to 1970-1999): low emissions (RCP 4.5): −56% (range: −65 to −50%) high emissions (RCP 8.5): −74% (range: −85 to −59%)
Streamflow	
Annual	Small changes projected. Some models project increases while other project decreases. • Change in annual runoff, on average for Puget Sound:[A,1] 2050s (2040-2069, relative to 1970-1999): low emissions (RCP 4.5): 0% (range: −5 to +12%) high emissions (RCP 8.5): −1% (range: −10 to +12%) 2080s (2070-2099, relative to 1970-1999): low emissions (RCP 4.5): +1% (range: −8 to +8%) high emissions (RCP 8.5): −2% (range: −12 to +2%)
Winter	All scenarios project an increase in winter streamflow. • Change in Winter (Oct-Mar) runoff, on average for the Puget Sound region:[A,1] 2050s (2040-2069, relative to 1970-1999): low emissions (RCP 4.5): +26% (range: +17 to +38%) high emissions (RCP 8.5): +34% (range: +20 to +55%)

[D] These numbers indicate 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 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).

Variable	*Projected Long-term Change*
	2080s (2070-2099, relative to 1970-1999): low emissions (RCP 4.5): +40% (range: +20 to +56%) high emissions (RCP 8.5): +60% (range: +43 to +77%)
Summer	All scenarios project a decrease in summer streamflow. • Change in Summer (Apr-Sep) runoff, on average for the Puget Sound region:[A,1] 2050s (2040-2069, relative to 1970-1999): low emissions (RCP 4.5): −15% (range: −20 to −7%) high emissions (RCP 8.5): −18% (range: −26 to −8%) 2080s (2070-2099, relative to 1970-1999): low emissions (RCP 4.5): −19% (range: −25 to −9%) high emissions (RCP 8.5): −29% (range: −41 to −20%)
Streamflow timing	Peak streamflows are projected to occur earlier in many snowmelt-influenced rivers in the Puget Sound region. • Change in the timing of peak streamflow for 12 Puget Sound watersheds for the 2080s (2070-2099, relative to 1970-1999).[E,F] Average change for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario:[A,1] Nooksack R.: −21 days (RCP 4.5), −28 days (RCP 8.5) Samish R.: −6 days (RCP 4.5), −7 days (RCP 8.5) Skagit R.: −21 days (RCP 4.5), −33 days (RCP 8.5) Stillaguamish R.: −19 days (RCP 4.5), −24 days (RCP 8.5) Snohomish R.: −23 days (RCP 4.5), −30 days (RCP 8.5) Cedar R.: −21 days (RCP 4.5), −24 days (RCP 8.5) Green R.: −18 days (RCP 4.5), −20 days (RCP 8.5) Nisqually R.: −17 days (RCP 4.5), −19 days (RCP 8.5) Puyallup R.: −19 days (RCP 4.5), −26 days (RCP 8.5) Skokomish R.: −11 days (RCP 4.5), −14 days (RCP 8.5) Dungeness R.: −25 days (RCP 4.5), −40 days (RCP 8.5) Elwha R.: −28 days (RCP 4.5), −37 days (RCP 8.5)
Flooding	Increases projected for most scenarios. • Projected change in streamflow volume associated with the 100-year

[E] Projected changes in streamflow were calculated for 12 Puget Sound watersheds. Listed in clock-wise order, starting at the US-Canadian border, they are: the Nooksack, Samish, Skagit, Stillaguamish, Snohomish, Cedar, Green, Nisqually, Puyallup, Skokomish, Dungeness, and Elwha Rivers.

[F] Calculations are based on the change in streamflow "Center Timing" (CT). CT is defined as the day of the water year (starting on October 1st) when cumulative streamflow reaches half of its total annual volume.

Variable	*Projected Long-term Change*
	(1% annual probability) flood event for 12 Puget Sound watersheds, on average for the 2080s (2070-2099, relative to 1970-1999):[E] Average change for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario:[A,1] Nooksack R.: +71% (RCP 4.5), +102% (RCP 8.5) Samish R.: +56% (RCP 4.5), +60% (RCP 8.5) Skagit R.: +111% (RCP 4.5), +147% (RCP 8.5) Stillaguamish R.: +55% (RCP 4.5), +99% (RCP 8.5) Snohomish R.: +72% (RCP 4.5), +104% (RCP 8.5) Cedar R.: +44% (RCP 4.5), +84% (RCP 8.5) Green R.: +43% (RCP 4.5), +71% (RCP 8.5) Nisqually R.: +37% (RCP 4.5), +57% (RCP 8.5) Puyallup R.: +49% (RCP 4.5), +80% (RCP 8.5) Skokomish R.: +5% (RCP 4.5), +38% (RCP 8.5) Dungeness R.: +99% (RCP 4.5), +119% (RCP 8.5) Elwha R.: +81% (RCP 4.5), +94% (RCP 8.5)
Minimum flows	Decreased flow in all Puget Sound watersheds • Projected changes in summer minimum streamflow (7Q10)[G] for 12 Puget Sound watersheds, on average for the 2080s (2070-2099, relative to 1970-1999).[E] Average change for a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario:[A,1] Nooksack R.: −34% (RCP 4.5), −51% (RCP 8.5) Samish R.: −20% (RCP 4.5), −31% (RCP 8.5) Skagit R.: −46% (RCP 4.5), −71% (RCP 8.5) Stillaguamish R.: −40% (RCP 4.5), −53% (RCP 8.5) Snohomish R.: −39% (RCP 4.5), −53% (RCP 8.5) Cedar R.: −44% (RCP 4.5), −49% (RCP 8.5) Green R.: −42% (RCP 4.5), −48% (RCP 8.5) Nisqually R.: −38% (RCP 4.5), −47% (RCP 8.5) Puyallup R.: −32% (RCP 4.5), −47% (RCP 8.5) Skokomish R.: −42% (RCP 4.5), −61% (RCP 8.5) Dungeness R.: −52% (RCP 4.5), −74% (RCP 8.5) Elwha R.: −56% (RCP 4.5), −77% (RCP 8.5)

[G] The 7Q10 flow is the lowest 7-day average flow that occurs on average once every 10 years. 7Q10 flows are a common standard for defining low flow for the purpose of setting permit discharge limits.

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APPENDIX B

Maps of Climate and Hydrologic Change for Major Puget Sound Watersheds: Basin average projections

This appendix contains maps of historical and projected changes in climate and hydrology, averaged over the major watersheds in Puget Sound. As a complement to the watershed averages, Appendix C includes maps showing the full-resolution climate and hydrologic projections. Results are included for the following two datasets:

- ***Integrated Scenarios for the Future Northwest Environment.*** The current set of projections, developed by Mote et al. in 2015,[1] which stem from the newer 2013 IPCC report,[2] and

- ***The Pacific Northwest Hydroclimate Scenarios Project.*** A previous set of projections, developed by Hamlet et al. in 2010,[3] which are based on the climate projections used in the IPCC's 2007 report.[4]

The global climate model projections that form the basis of these two datasets stem from the current and previous generations of the Coupled Model Intercomparison Project ("CMIP", see Section 1). The previous projections originate from the CMIP3 archive, while the current projections come from the newer CMIP5 archive.[5,6] Each CMIP experiment is associated with a different set of greenhouse gas scenarios.[A] For simplicity, each figure is labeled with the CMIP experiment on which it is based ("CMIP3" or "CMIP5"), as well as the name(s) of the greenhouse gas scenarios that are the basis of the projections shown in each figure (e.g. "Moderate (A1B)", or "Low (RCP 4.5)").

Projections are included for the following climate and hydrologic variables:

Figures 1a, b:	Average Winter Temperature
Figures 2a, b:	Average Summer Temperature
Figures 3a, b:	Growing Degree Days
Figures 4a, b:	Extreme high daytime temperatures
Figures 5a, b:	Extreme low nighttime temperatures
Figures 6a, b:	Total Winter Precipitation
Figures 7a, b:	Total Summer Precipitation
Figures 8a, b:	Max 24-hour Precipitation
Figures 9a, b:	Summer Water Deficit
Figures 10a, b:	April 1st Snow Water Equivalent (SWE)
Figures 11a, b:	Annual Maximum Snow Water Equivalent (SWE)
Figures 12a, b:	Ratio of max SWE to Oct-Mar Precipitation

[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 more details.

Figures 13a, b:	Length of the Snow Season
Figures 14a, b:	Summer Runoff
Figures 15a, b:	Winter Runoff
Figures 16a, b:	Peak daily streamflow, 2-year Event
Figures 17a, b:	Peak daily streamflow, 10-year Event
Figures 18a, b:	Peak daily streamflow, 50-year Event
Figures 19a, b:	Peak daily streamflow, 100-year Event
Figures 20a, b:	Minimum 7-day streamflow, 2-year Event
Figures 21a, b:	Minimum 7-day streamflow, 10-year Event

Other maps and figures, for example showing averages over smaller sub-basins to each watershed, are available upon request.

1 Mote, P. W., Rupp, D. E., Abatzoglou, J. T., Hegewisch, K. C., Nijssen, B., Lettenmaier, D. P., Stumbaugh, M., Lee, S.-Y., & Bachelet, D., 2015. Integrated Scenarios for the Future Northwest Environment. Version if relevant. USGS ScienceBase. Data set accessed 2015-03-02 at https://www.sciencebase.gov/catalog/item/5006eb9de4b0abf7ce733f5c

2 (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

3 Hamlet, A.F. et al., 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. *Atmosphere-Ocean* 51(4): 392-415. doi: 10.1080/07055900.2013.819555

4 (IPCC) Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

5 Taylor, K. E. et al., 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485-498, doi:10.1175/BAMS-D-11-00094.1

6 Knutti, R. et al., 2013. Climate model genealogy: Generation CMIP5 and how we got there. *Geophys. Res. Lett*, *40*, 1194-1199, doi:10.1002/grl.50256

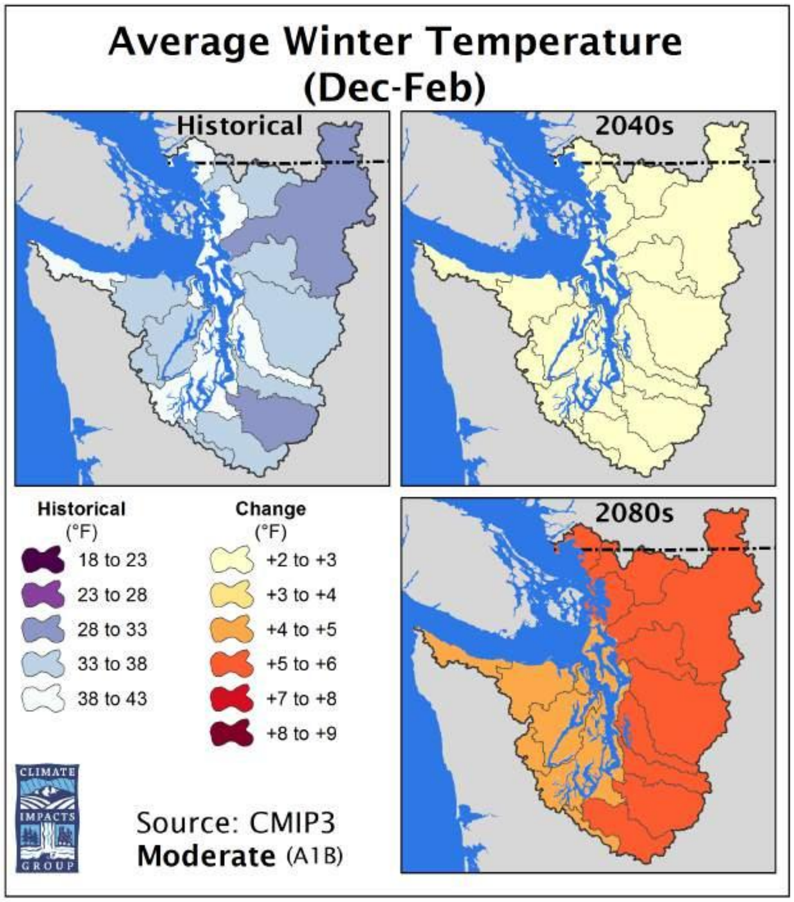

Figure 1a. Average Winter Temperature, previous projections. Maps show the historical and projected change in average winter (December–February) temperature, in °F. Maps compare watershed averages for historical conditions (1970-1999) and the projected change for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark blue shading on the historical map indicates areas with the lowest average winter temperature. Projected increases in average winter temperature are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

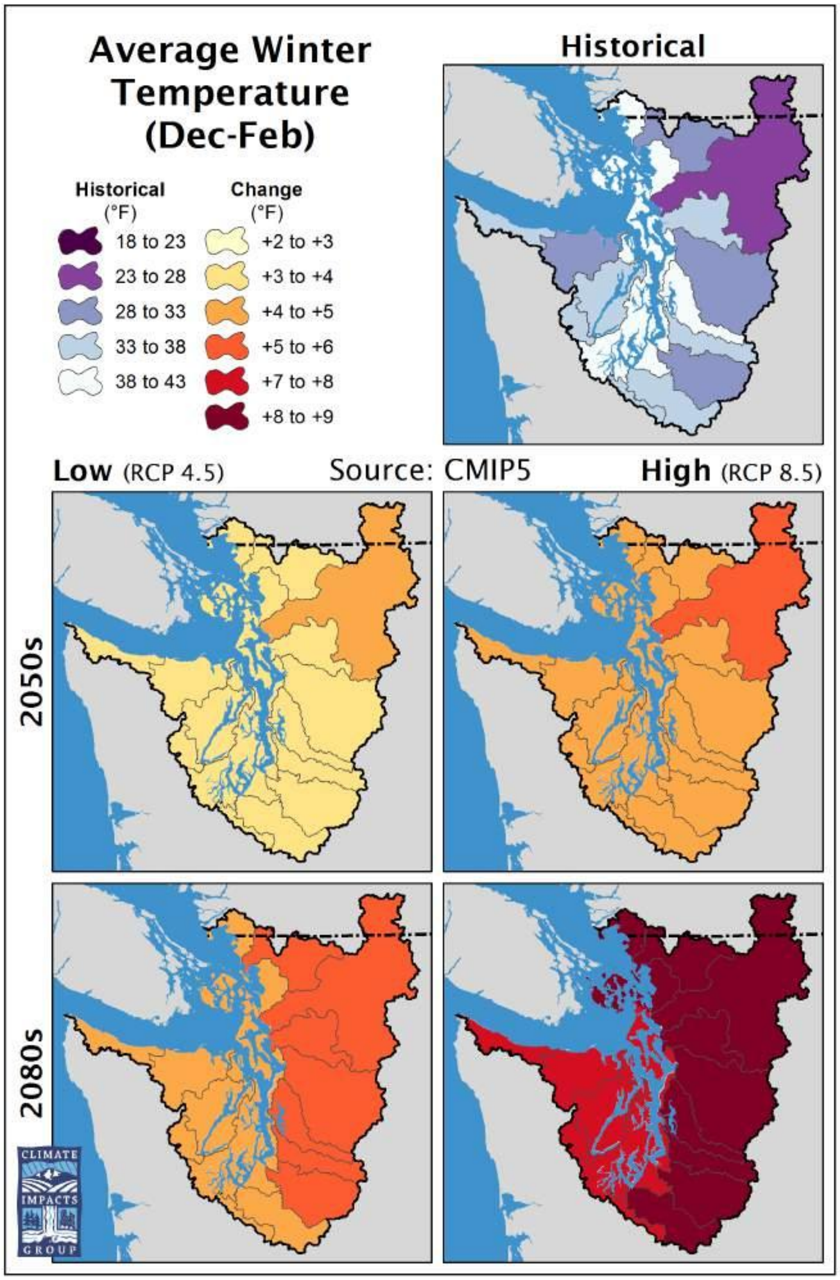

Figure 1b. Average Winter Temperature, newer projections. As in Figure 1a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

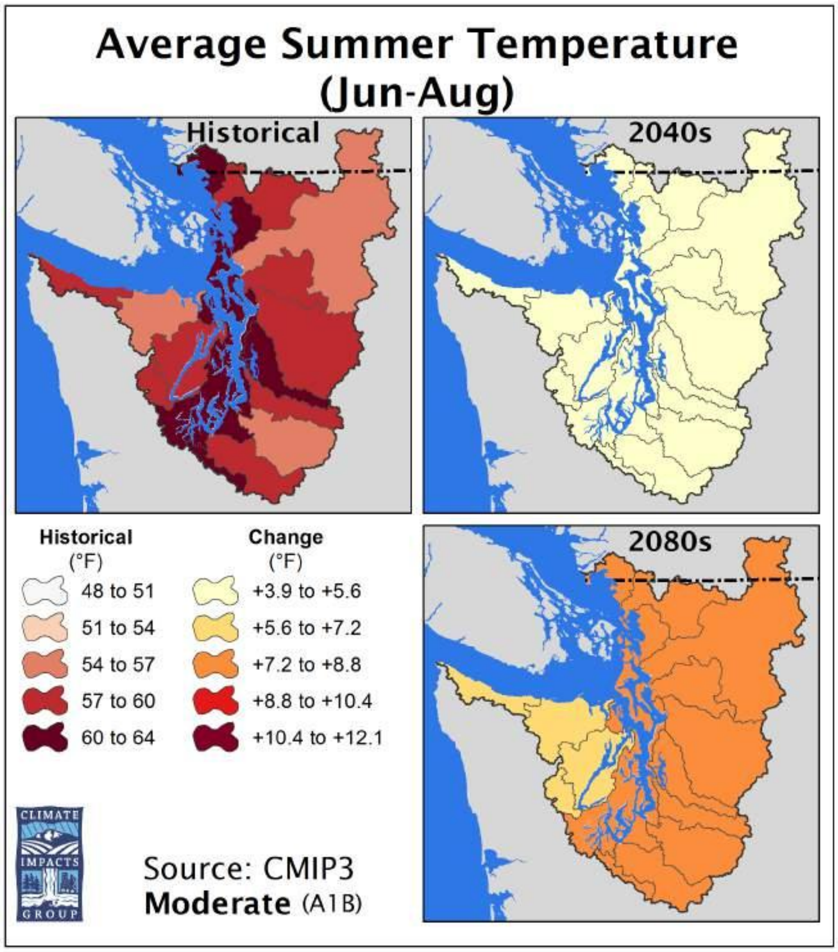

Figure 2a. Average Summer Temperature, previous projections. Maps show the historical and projected change in average summer (June–August) temperature, in °F. The figure compares watershed averages for historical conditions (1970-1999) and the projected change for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark red shading on the historical map indicates areas with the highest average summer temperature. Projected increases in average winter temperature are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007*[4] *report. Data source: Hamlet et al. 2013.*[3]

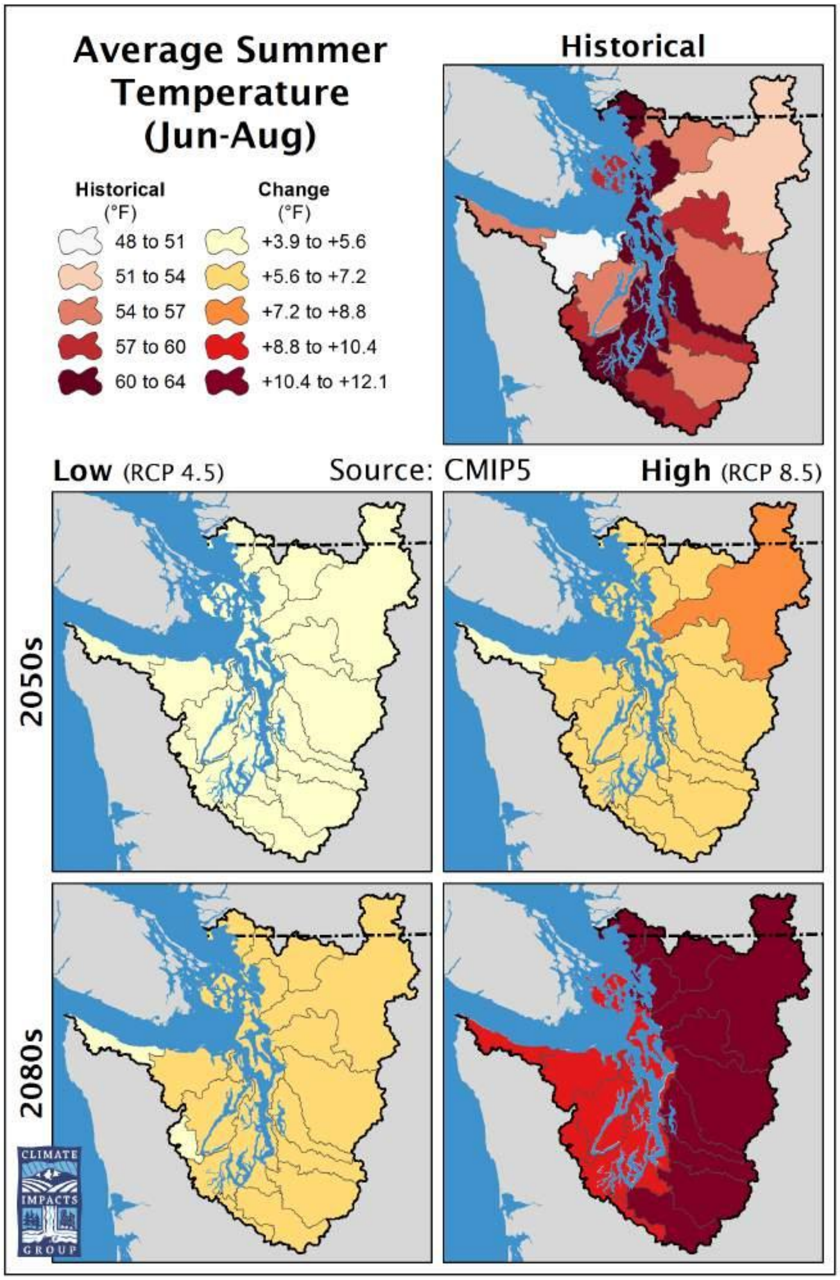

Figure 2b. Average Summer Temperature, newer projections. As in Figure 2a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

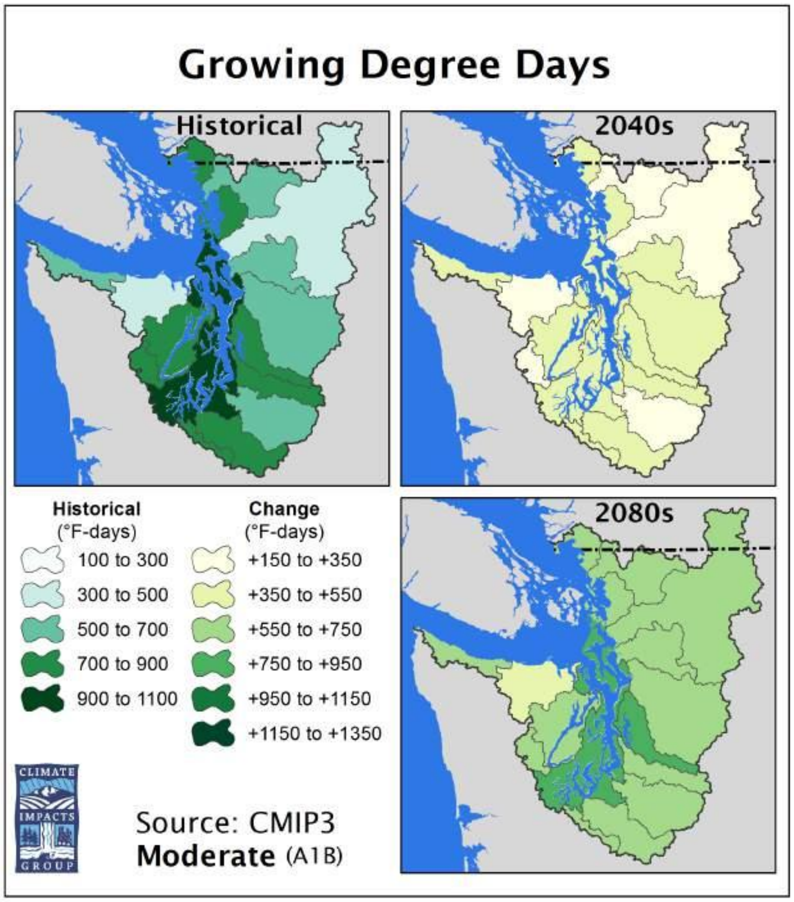

Figure 3a. Growing Degree Days, previous projections. Maps show the historical and projected growing degree days (GDD), a measure of heat accumulation in plants, which measures the cumulative seasonal warming above a base temperature of 50°F. The figure compares watershed averages for historical conditions (1970-1999) and the projected change for ten global models, all in units of °F-days. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas with the highest average GDD. Projected increases in growing degree days are depicted by the beige to dark green shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

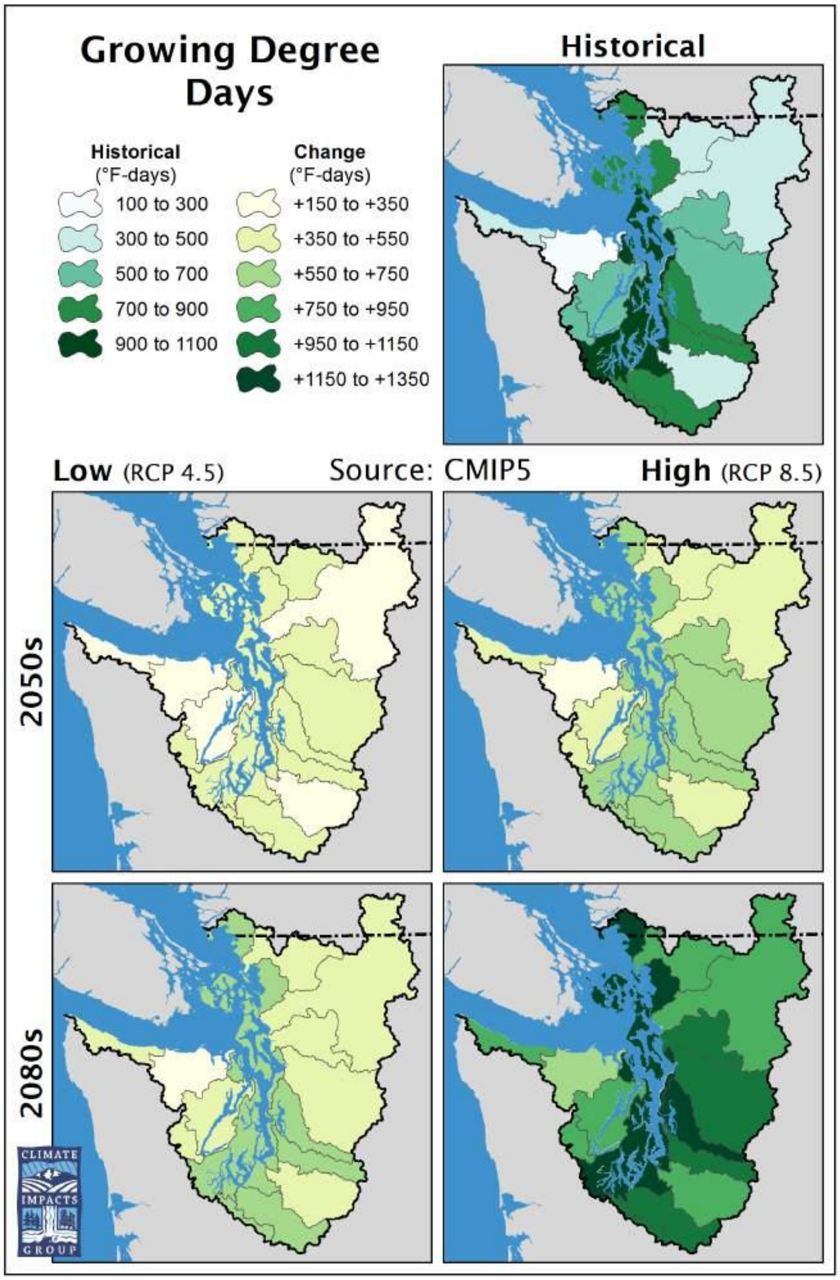

Figure 3b. Growing Degree Days, newer projections. As in Figure 3a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

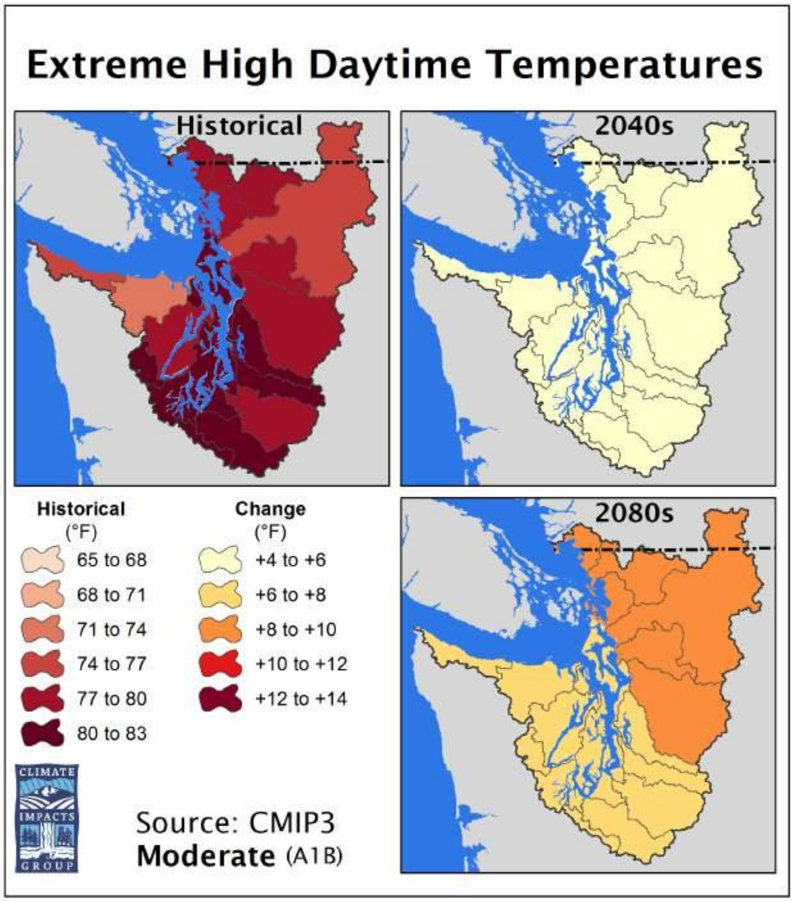

Figure 4a. Extreme high daytime temperatures, previous projections. Maps show the historical and projected change in extreme high daytime temperatures, in °F. The "extreme high" temperature is defined as the 95th percentile of daily maximum temperatures occurring in each year. The figure compares watershed averages for historical conditions (1970-1999) and the projected change for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark red shading on the historical map indicates areas with the warmest extreme high daytime temperatures. Projected increases in extreme high daytime temperatures are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

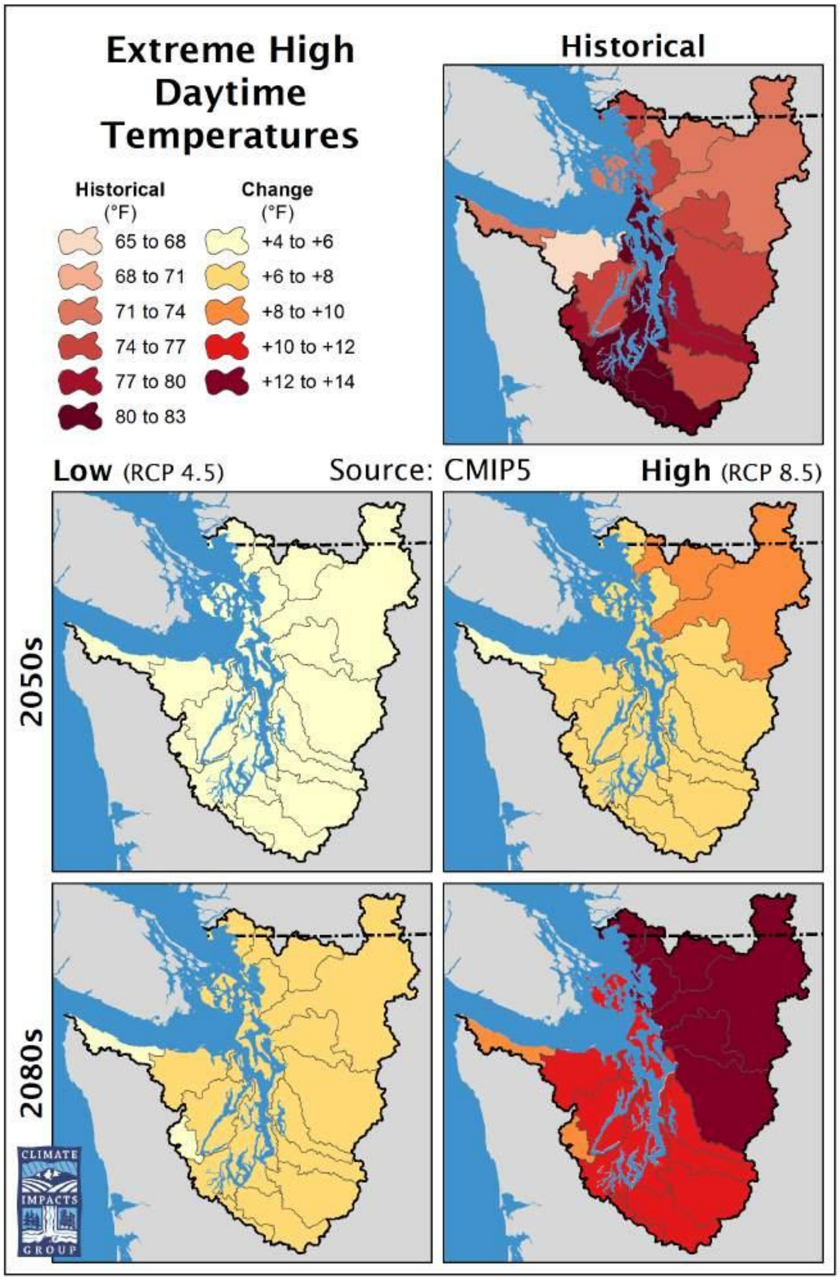

Figure 4b. Extreme high daytime temperatures, newer projections. As in Figure 4a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

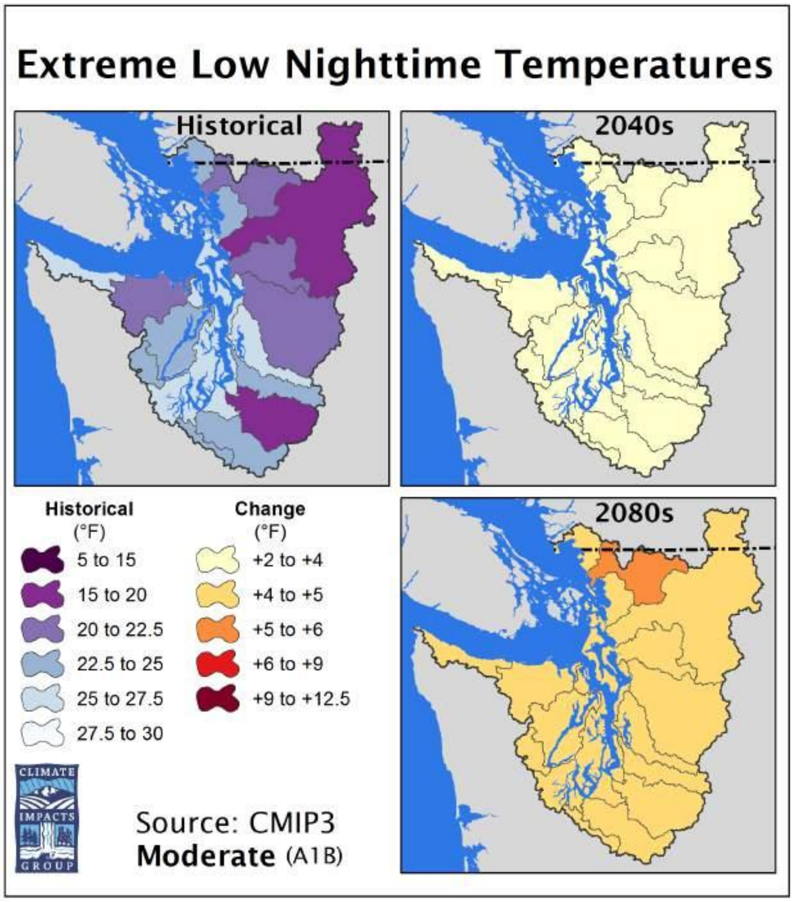

Figure 5a. Extreme low nighttime temperatures, previous projections. Maps show the historical and projected change in extreme low nighttime temperatures, in °F. The "extreme low" temperature is defined as the 5th percentile of daily minimum temperatures occurring in each year. The figure compares watershed averages for historical conditions (1970-1999) and the projected change for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark purple shading on the historical map indicates areas with the lowest extreme low nighttime temperatues. Projected increases in extreme low nighttime temperatures are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

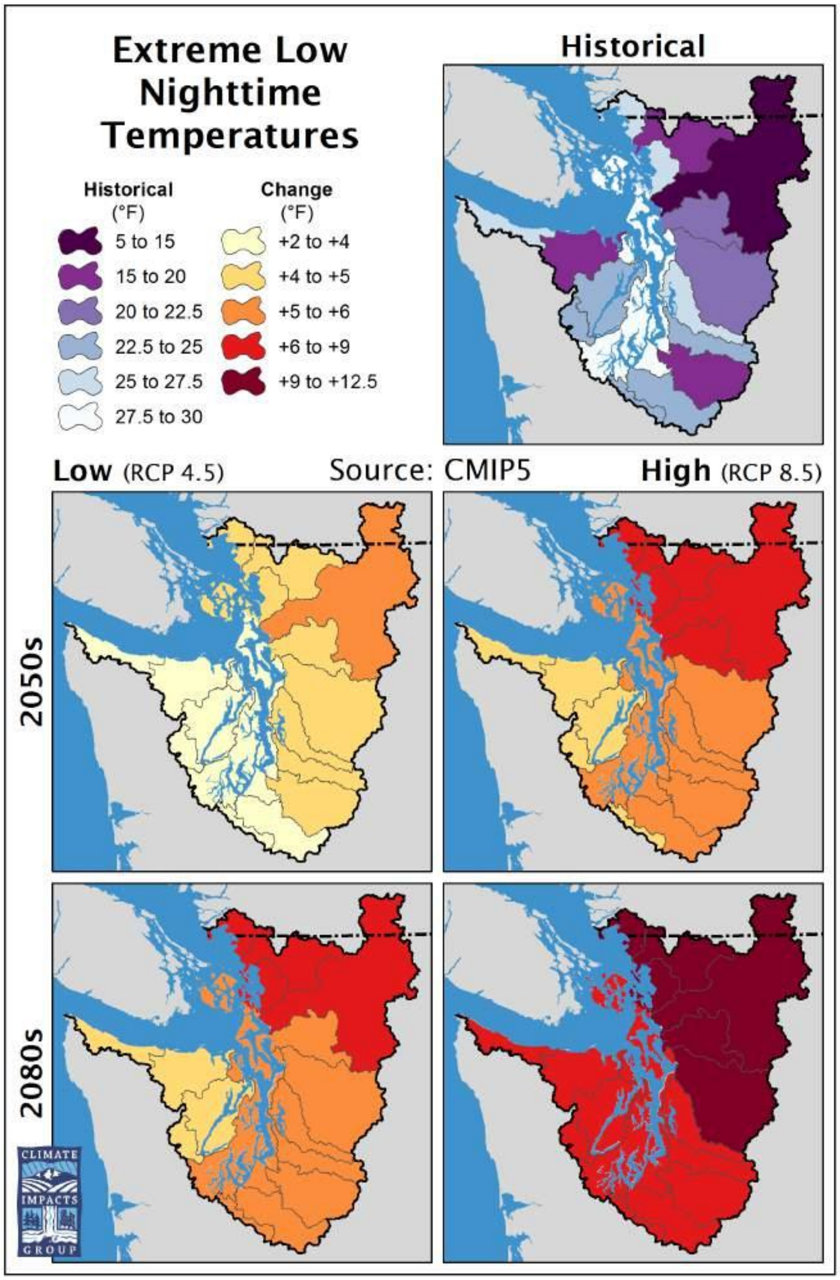

Figure 5b. Extreme low nighttime temperatures, newer projections. As in Figure 5a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

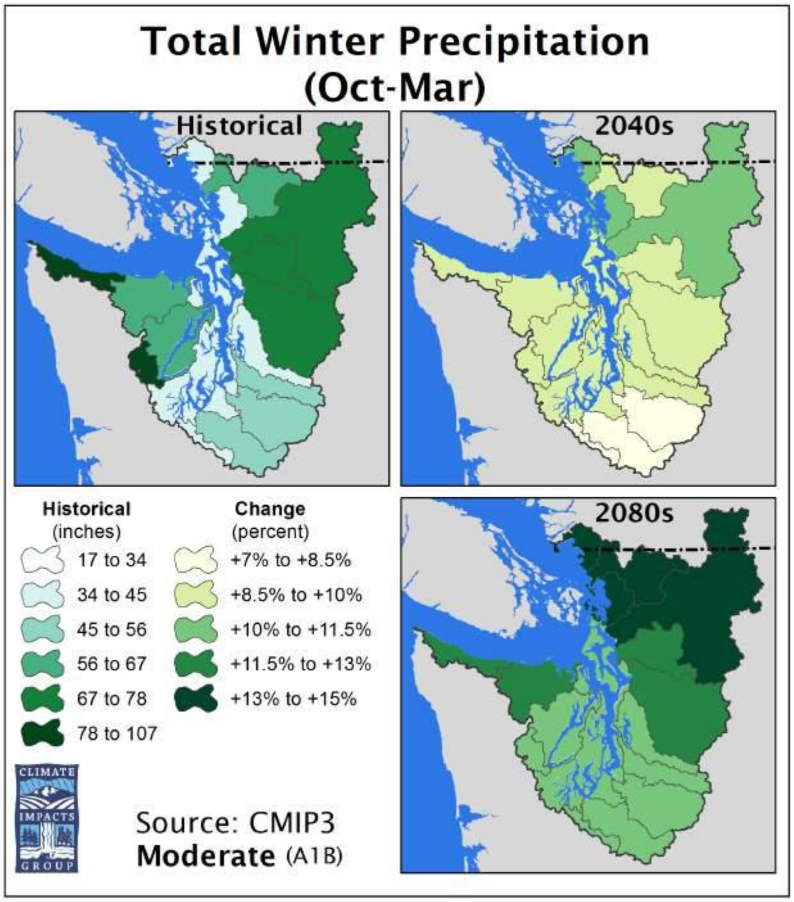

Figure 6a. Total winter precipitation, previous projections. Maps show the historical and projected total winter (October–March) precipitation. The figure compares watershed averages for historical conditions (1970-1999, in inches) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Dark green shading on the historical map indicates areas that have received highest levels of total winter precipitation in Puget Sound. Projected changes are depicted by the light to dark green shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

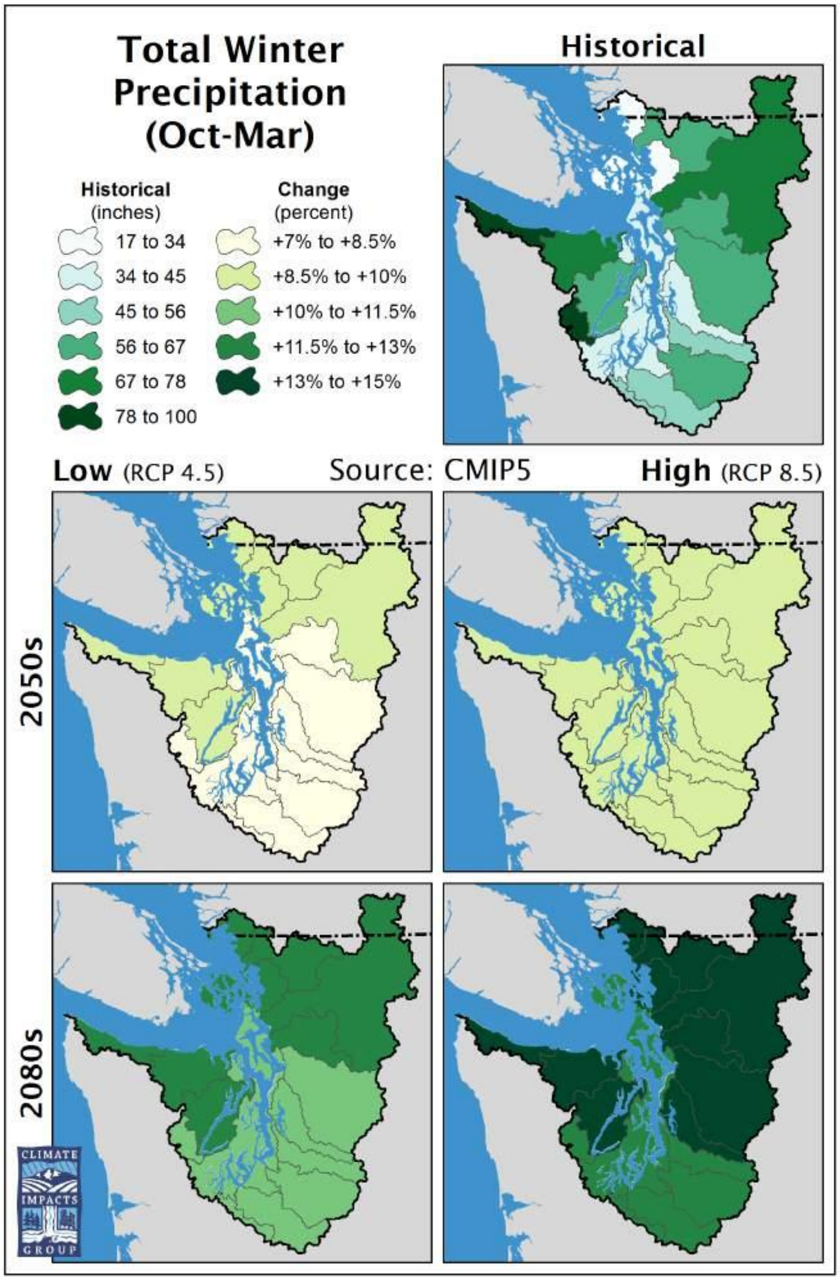

Figure 6b. Total winter precipitation, newer projections. As in Figure 6a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

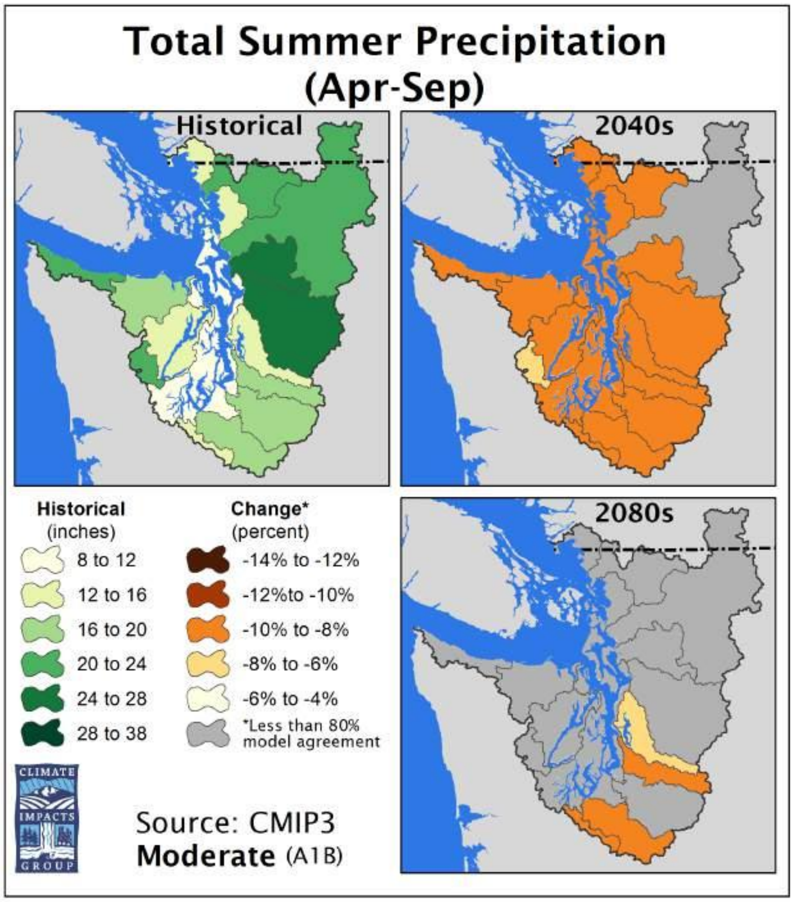

Figure 7a. Total summer precipitation, previous projections. Maps show the historical and projected total summer (April-September) precipitation. The figure compares watershed averages for historical conditions (1970-1999, in inches) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have received highest levels of summer precipitation in Puget Sound. Projected changes are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

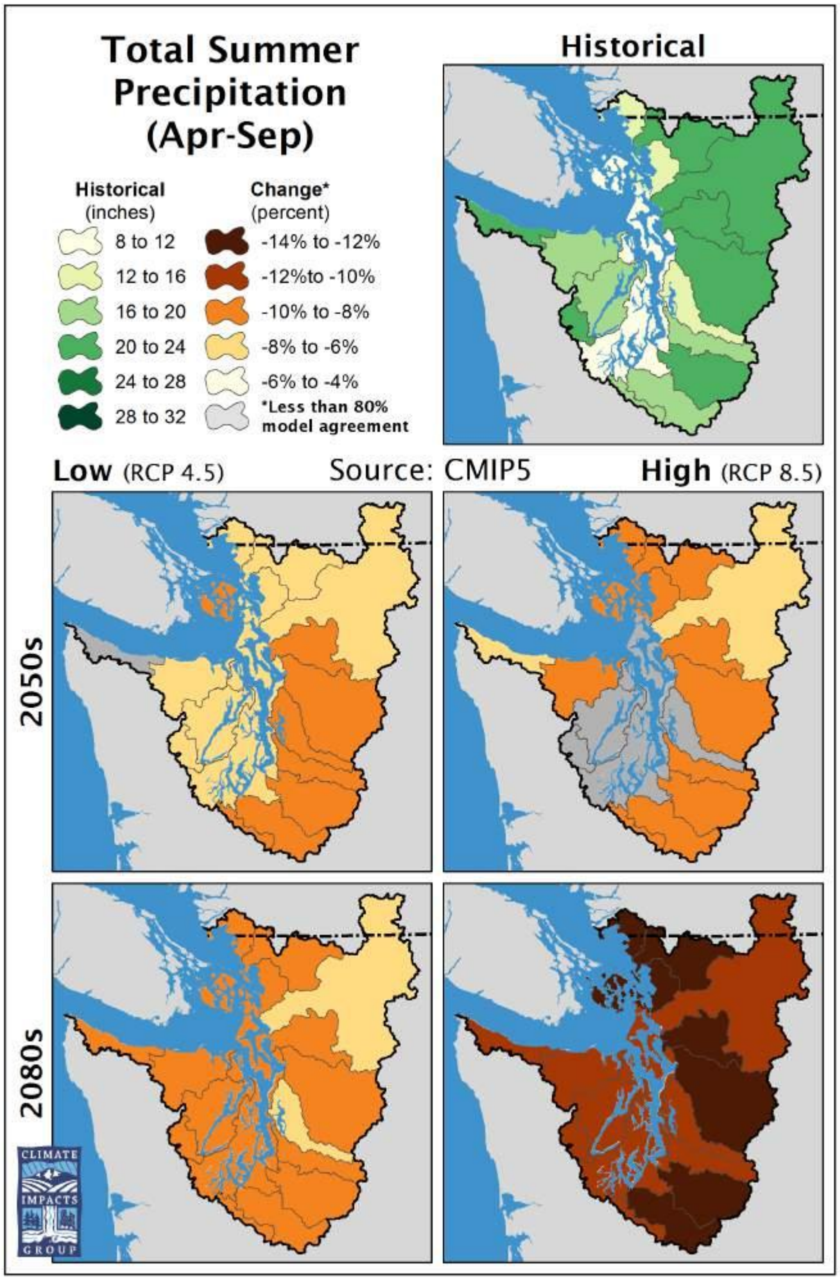

Figure 7b. Total summer precipitation, newer projections. As in Figure 7a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

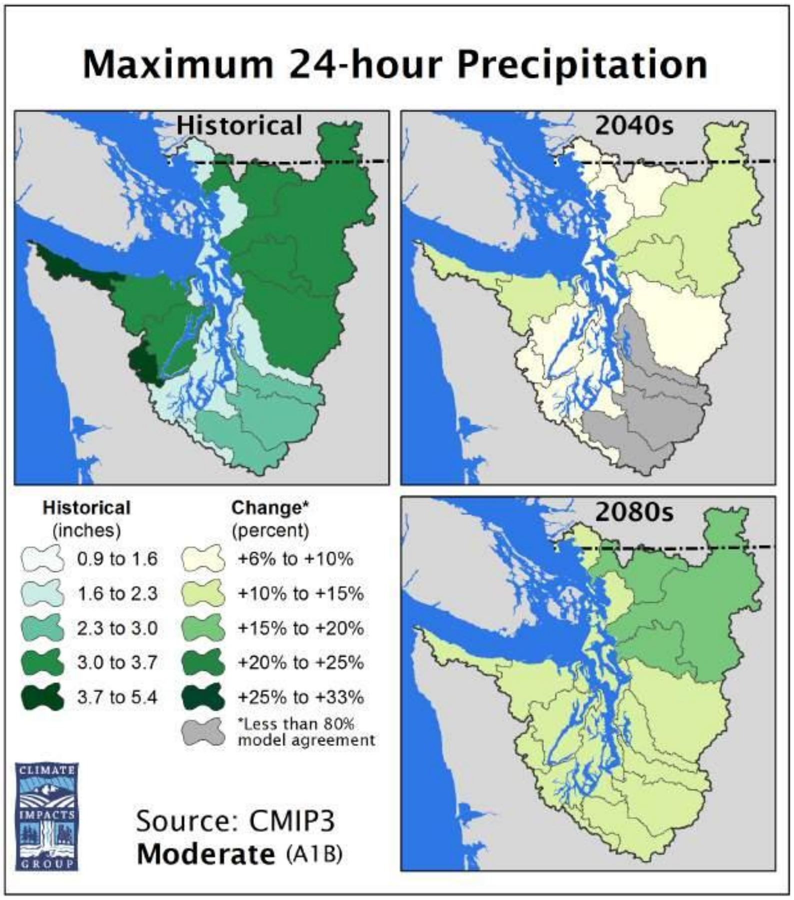

Figure 8a. Maximum 24-hour precipitation, previous projections. Maps show the maximum daily precipitation for Puget Sound watersheds. The figure compares watershed averages for historical conditions (1970-1999, in inches) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have received highest levels of maximum daily precipitation in Puget Sound. Projected changes are depicted by the light to dark green shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

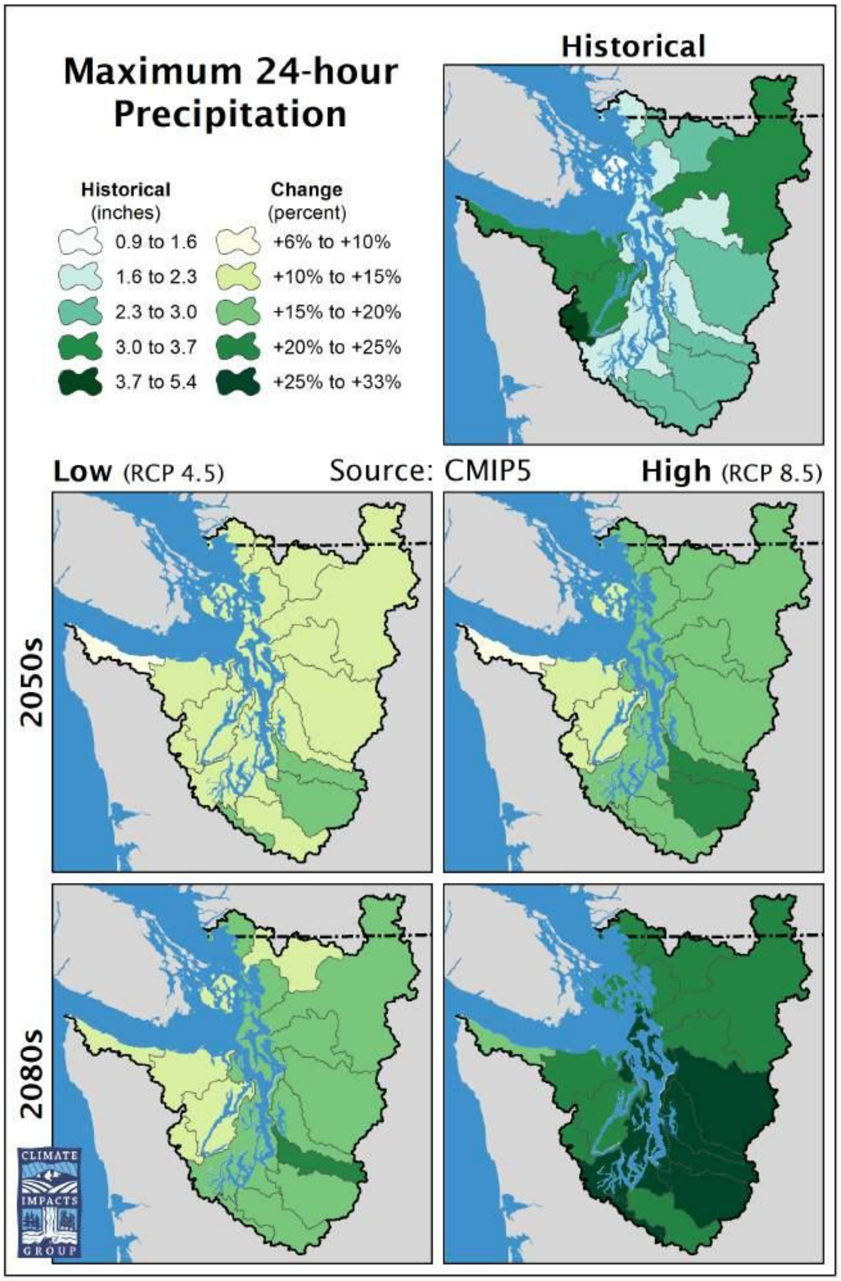

Figure 8b. Maximum 24-hour precipitation, newer projections. As in Figure 8a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

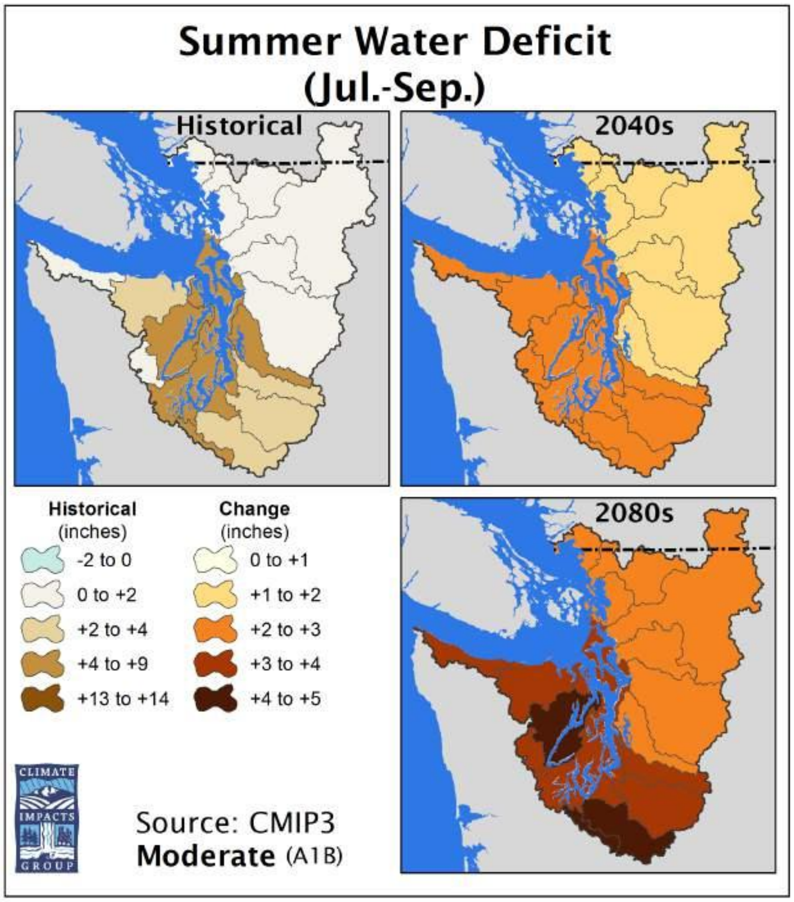

Figure 9a. Summer Water Deficit, previous projections. Maps show the historical and projected summer (July-September) water deficit, based on the amount of soil moisture available relative to atmospheric demand for water via evaporation, either from water bodies or vegetation. Maps compare watershed averages for historical conditions (1970-1999) and the projected change for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Teal shading indicates areas where water availability exceeds water demand. Light to dark brown shading indicates areas where a positive water deficit occurs, that is, regions where water demands exceed soil water availability. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

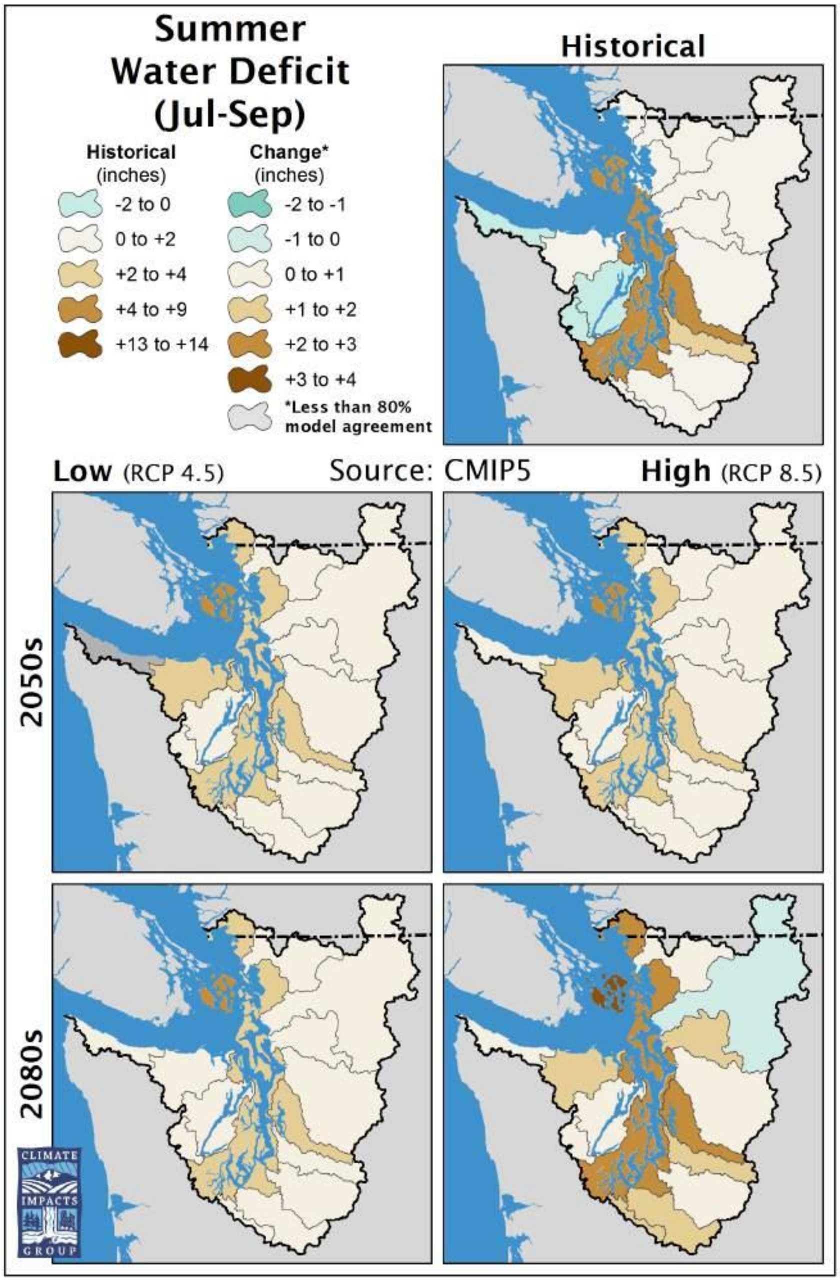

Figure 9b. Summer Water Deficit, newer projections. As in Figure 9a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

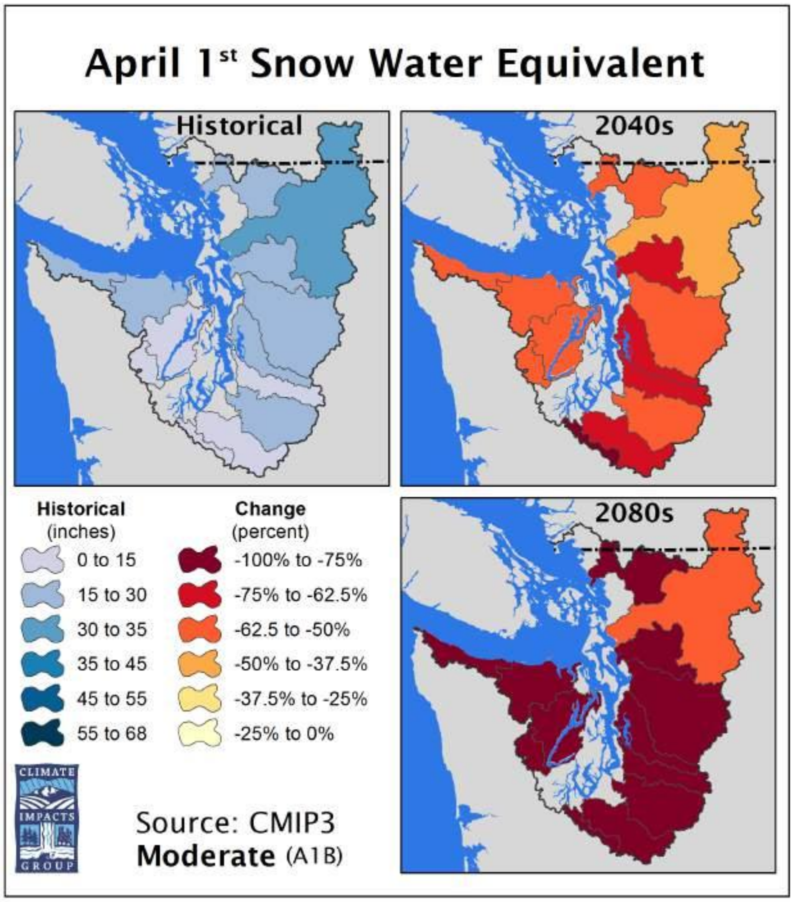

Figure 10a. April 1st Snow Water Equivalent, previous projections. Maps show the historical and projected April 1st snow water equivalent (SWE), a measure of the total amount of water contained in the snowpack. The figure compares watershed averages for historical conditions (1970-1999, in inches) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). 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 snow water equivalent in Puget Sound. Projected decreases in snow water equivelant are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

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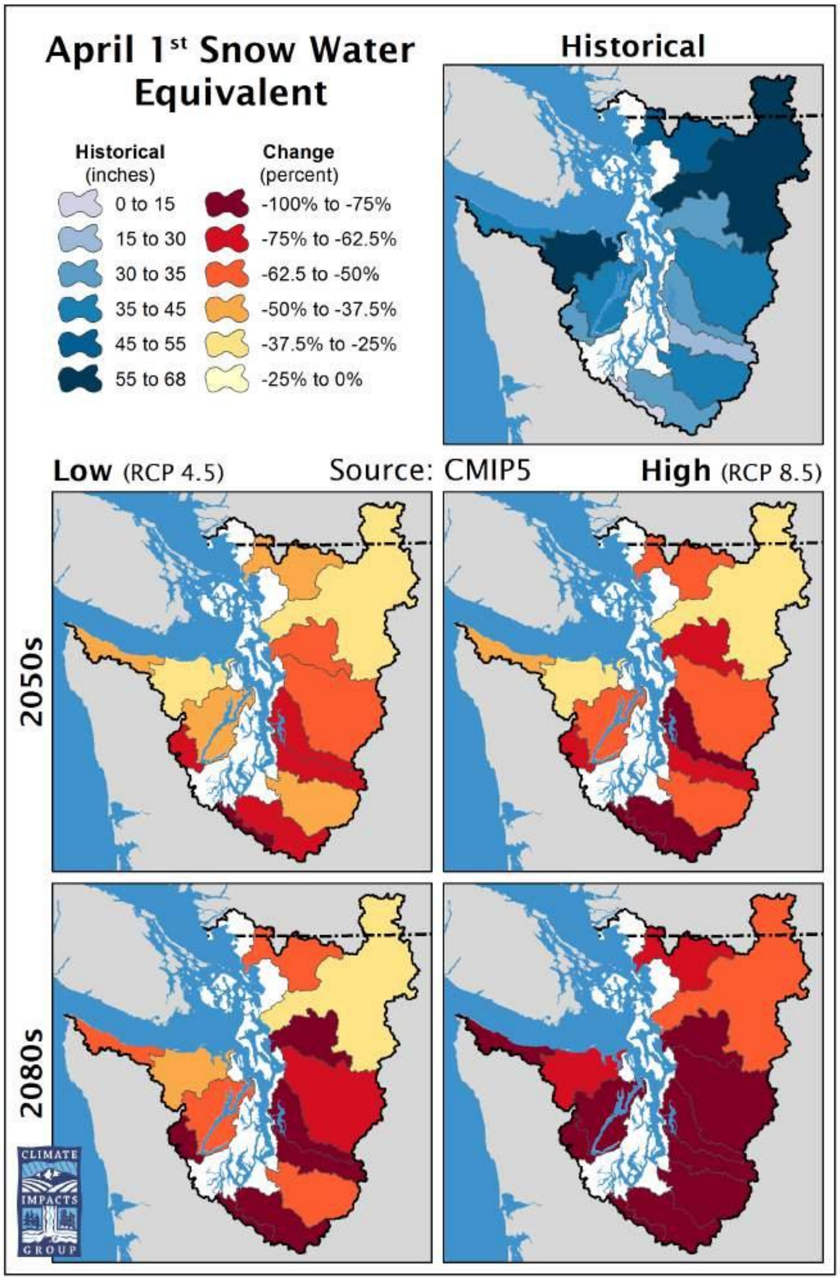

Figure 10b. April 1st Snow Water Equivalent, newer projections. As in Figure 10a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

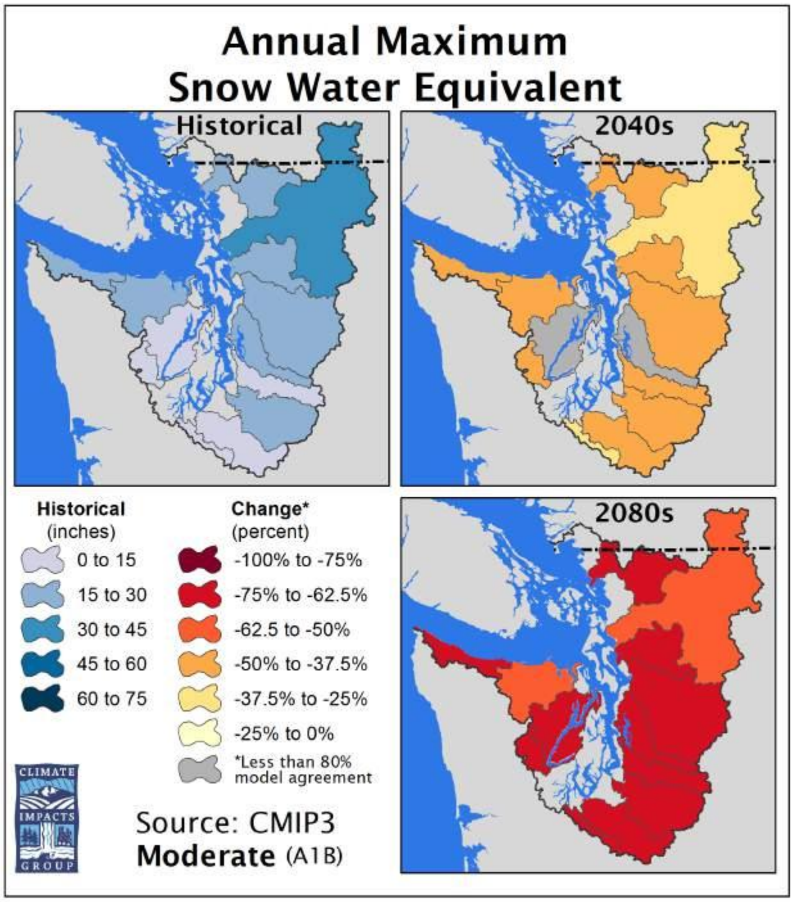

Figure 11a. Annual Maximum Snow Water Equivalent, previous projections. Maps show the historical and projected annual maximum snow water equivalent (SWE), a measure of the total amount of water contained in the snowpack. The figure compares watershed averages for historical conditions (1970-1999, in inches) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds with an average historical April 1st SWE of at least 0.4 inch, and for which at least 8 out of the 10 models agree on the direction of change. White to dark blue shading on the historical map indicates areas which received highest levels of April 1st snow water equivalent in Puget Sound. Projected decreases in snow water equivelant are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

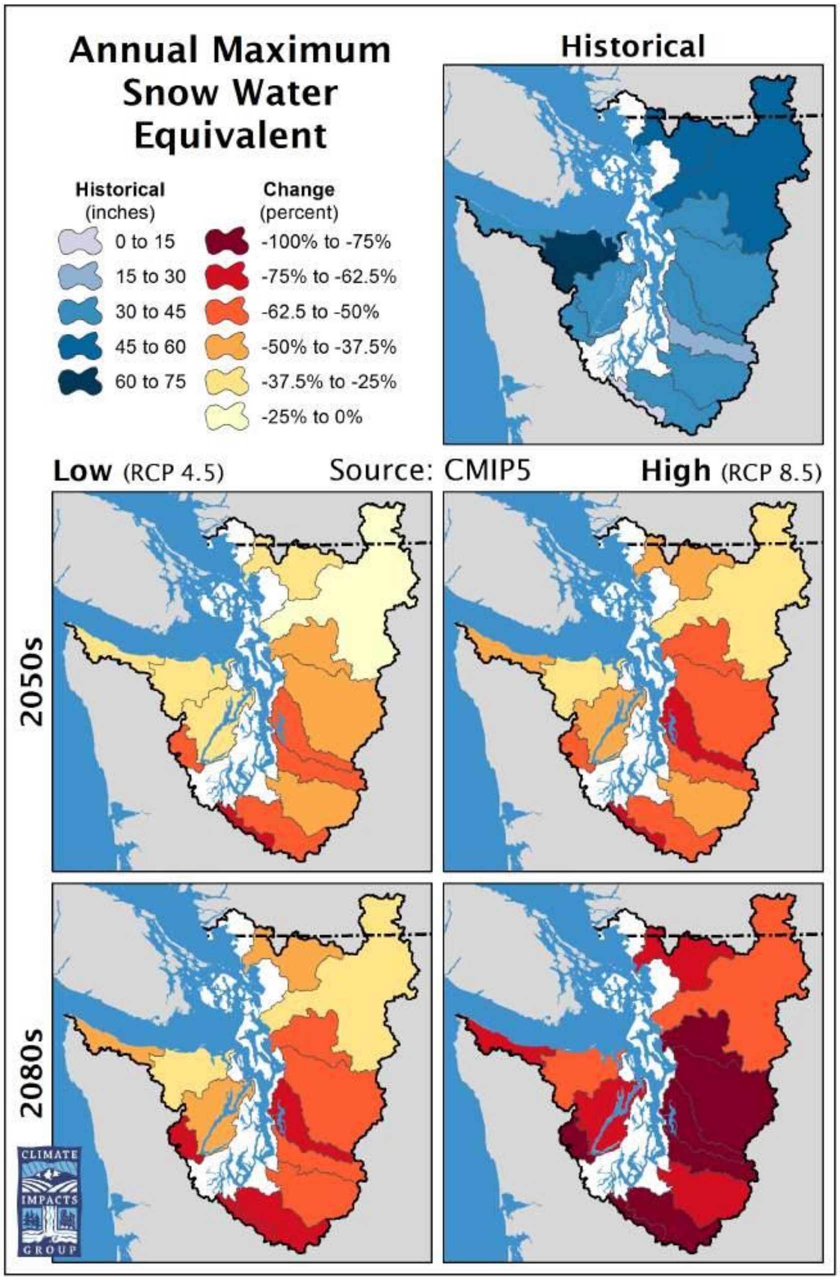

Figure 11b. Annual Maximum Snow Water Equivalent, newer projections. As in Figure 11a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

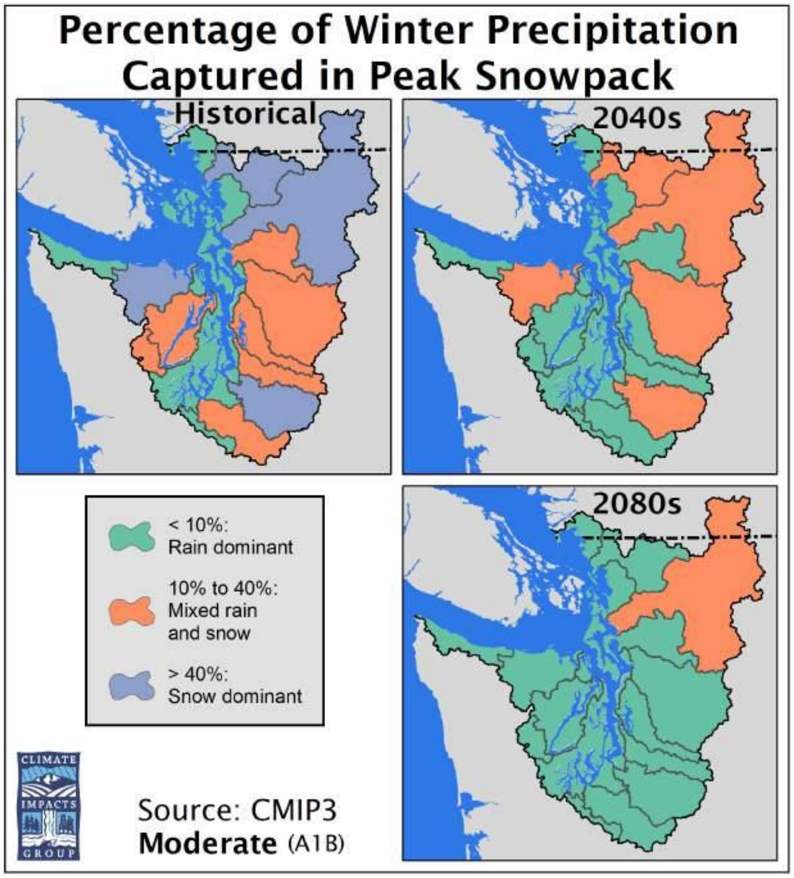

Figure 12a. Percentage of Winter Precipitation Captured in Peak Snowpack, previous projections. Maps show the historical and projected percentage of winter (October-March) precipitation that is retained in the annual maximum snow water equivalent (SWE). The figure compares watershed averages for historical conditions (1970-1999) to the conditions projected by the average of ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Green shading in the maps indicates *warm ("rain-dominant") watersheds*, which retain less than 10% of winter precipitation as snow. Blue indicates *cold ("snow-dominant") watersheds,* that is, cold basins that retain more than 40% of their winter precipitation as snow. The most sensitive basins to warming are the *watersheds that are near the current snowline ("mixed rain and snow")*, shown in red. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

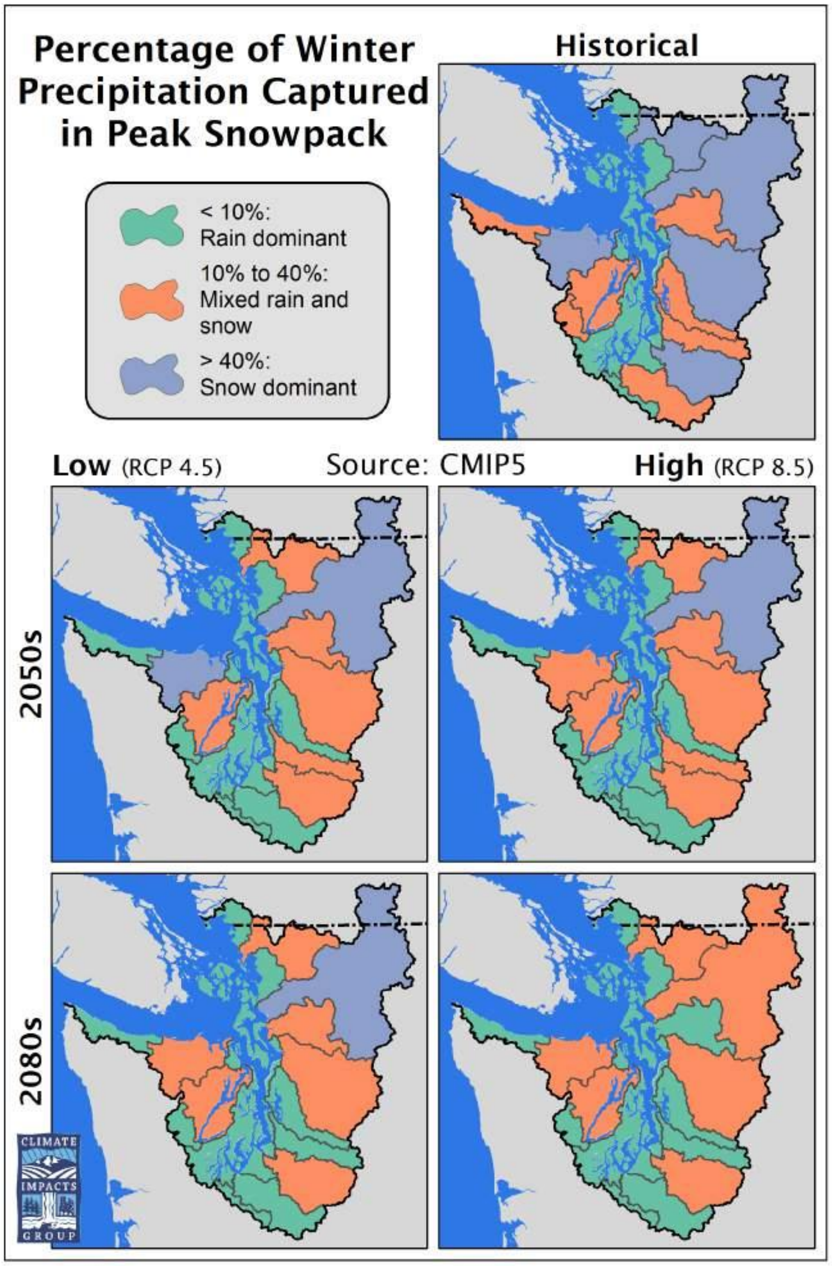

Figure 12b. Percentage of Winter Precipitation Captured in Peak Snowpack, newer projections. As in Figure 12a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

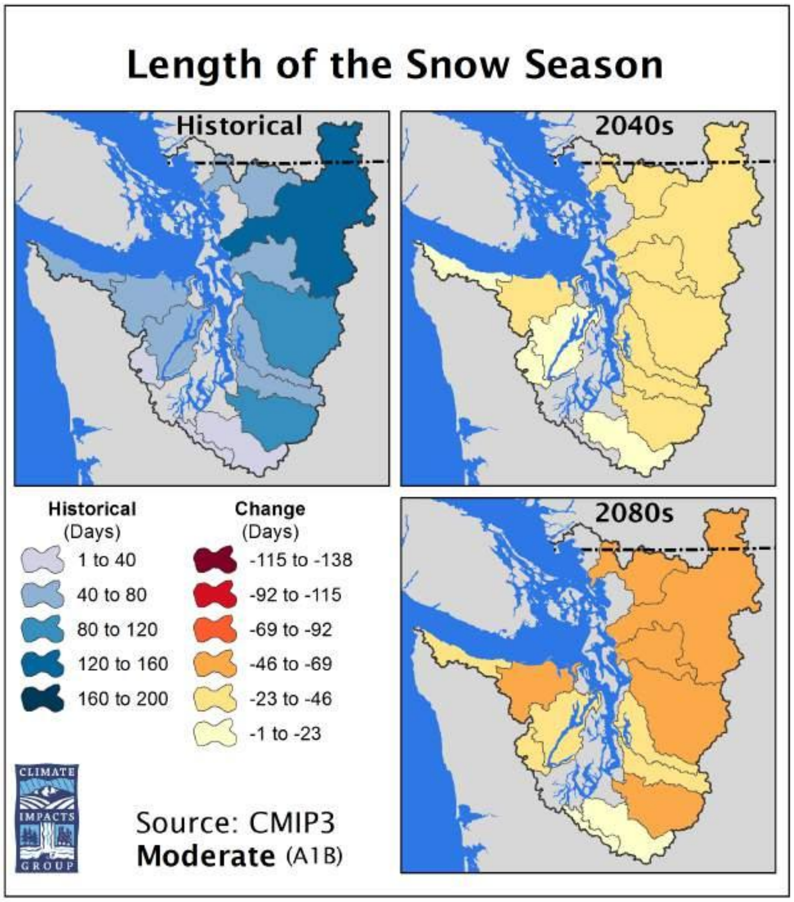

Figure 13a. Length of the Snow Season, previous projections. Maps show the historical and projected change in the length of the snow season, defined as the number of days between the date of 10% accumulation and 90% melt, relative to annual maximum snow water equivalent (see Figures 11a and 11b). The figure compares watershed averages for historical conditions (1970-1999, in inches) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds with an average historical April 1st SWE of at least 0.4 inch, and for which at least 8 out of the 10 models agree on the direction of change. White to dark blue shading on the historical map indicates areas which received highest levels of April 1st snow water equivalent in Puget Sound. Projected decreases in snow water equivelant are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

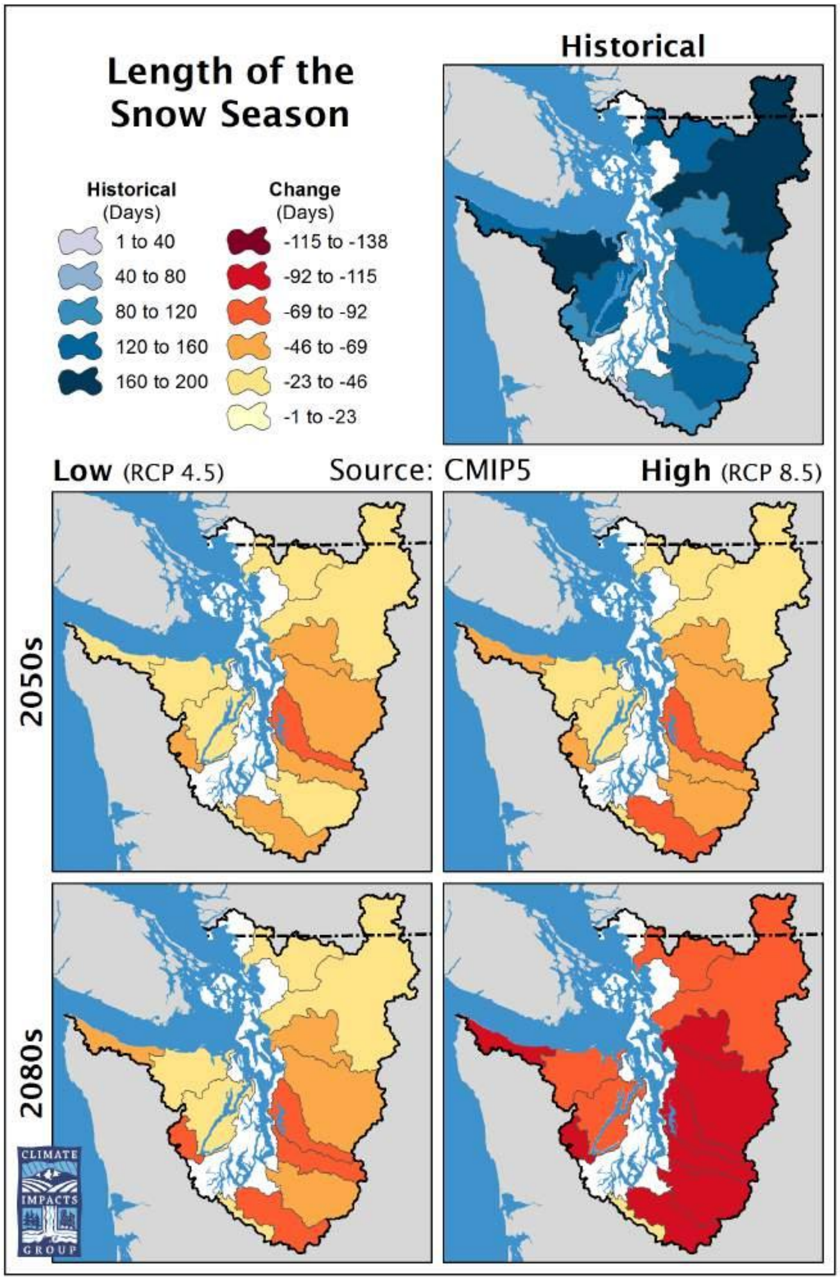

Figure 13b. Length of the Snow Season, newer projections. As in Figure 13a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

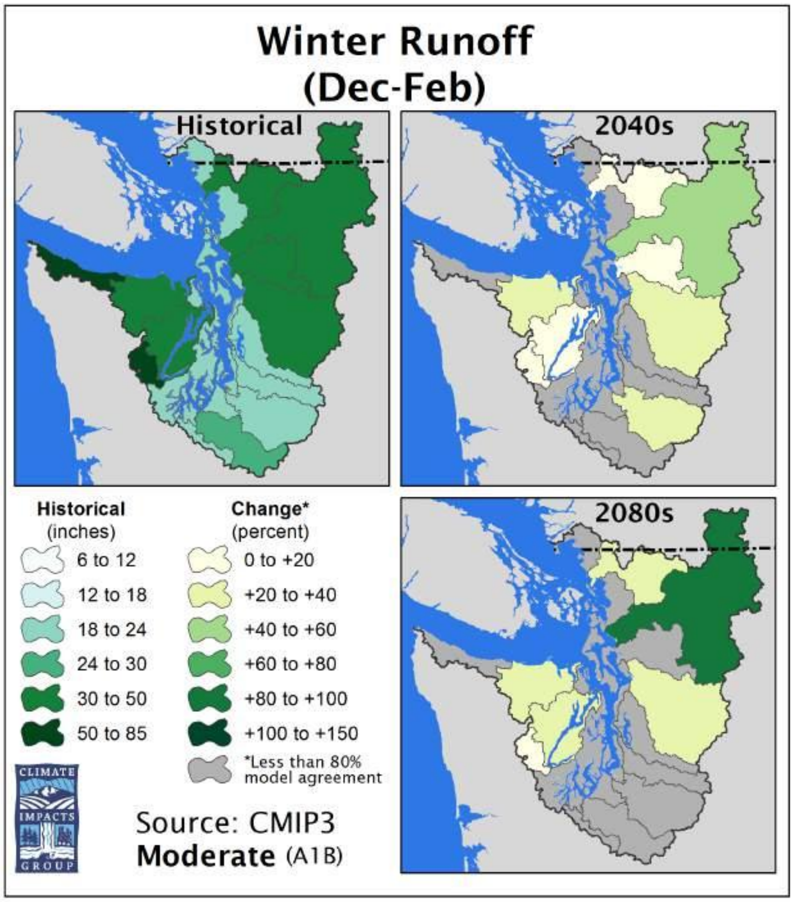

Figure 14a. Winter runoff, previous projections. Maps show the historical and projected total summer (December-February) runoff. This includes any overland water flows in addition to subsurface runoff in shallow groundwater. The figure compares watershed averages for historical conditions (1970-1999, in inches) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Dark green shading on the historical map indicates areas that have received highest levels of total winter precipitation in Puget Sound. Projected changes are depicted by the light to dark green shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007*[4] *report. Data source: Hamlet et al. 2013.*[3]

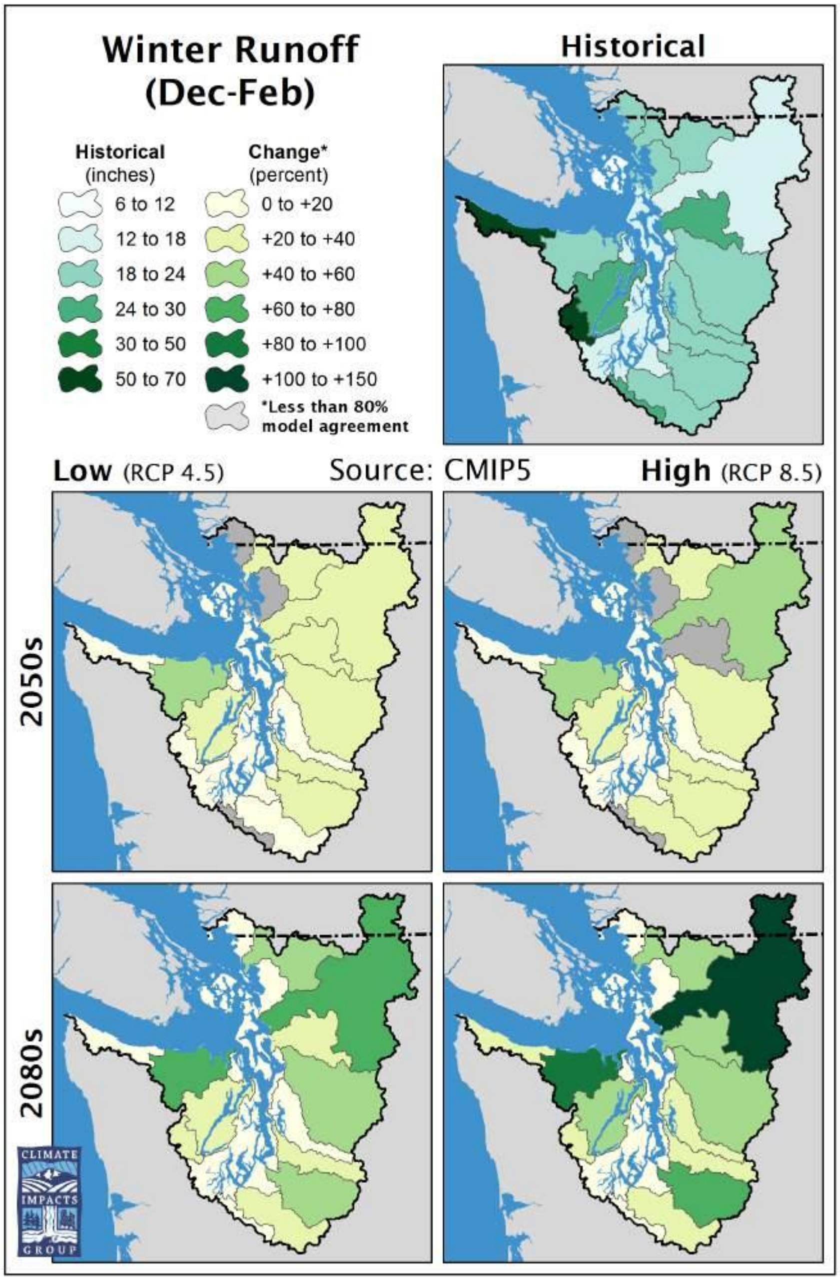

Figure 14b. Winter runoff, newer projections. As in Figure 14a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

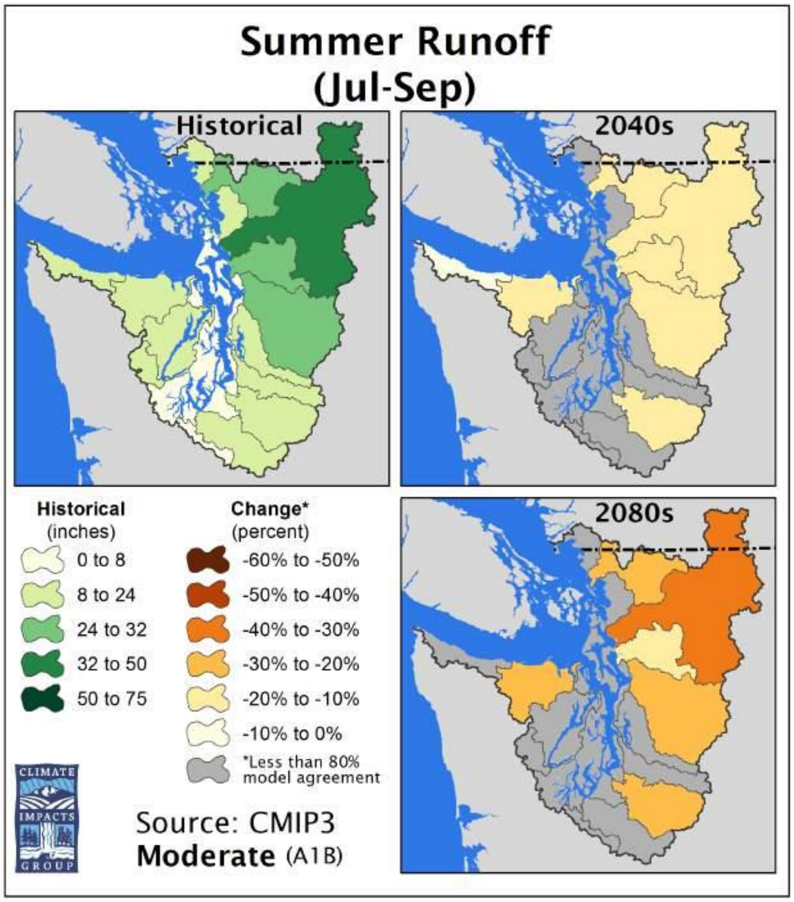

Figure 15a. Summer runoff, previous projections. Maps show the historical and projected total summer (July-September) runoff. This includes any overland water flows in addition to subsurface runoff in shallow groundwater. The figure compares watershed averages for historical conditions (1970-1999, in inches) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Dark green shading on the historical map indicates areas that have received highest streamflow in Puget Sound. Projected changes are depicted by the yellow to red shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

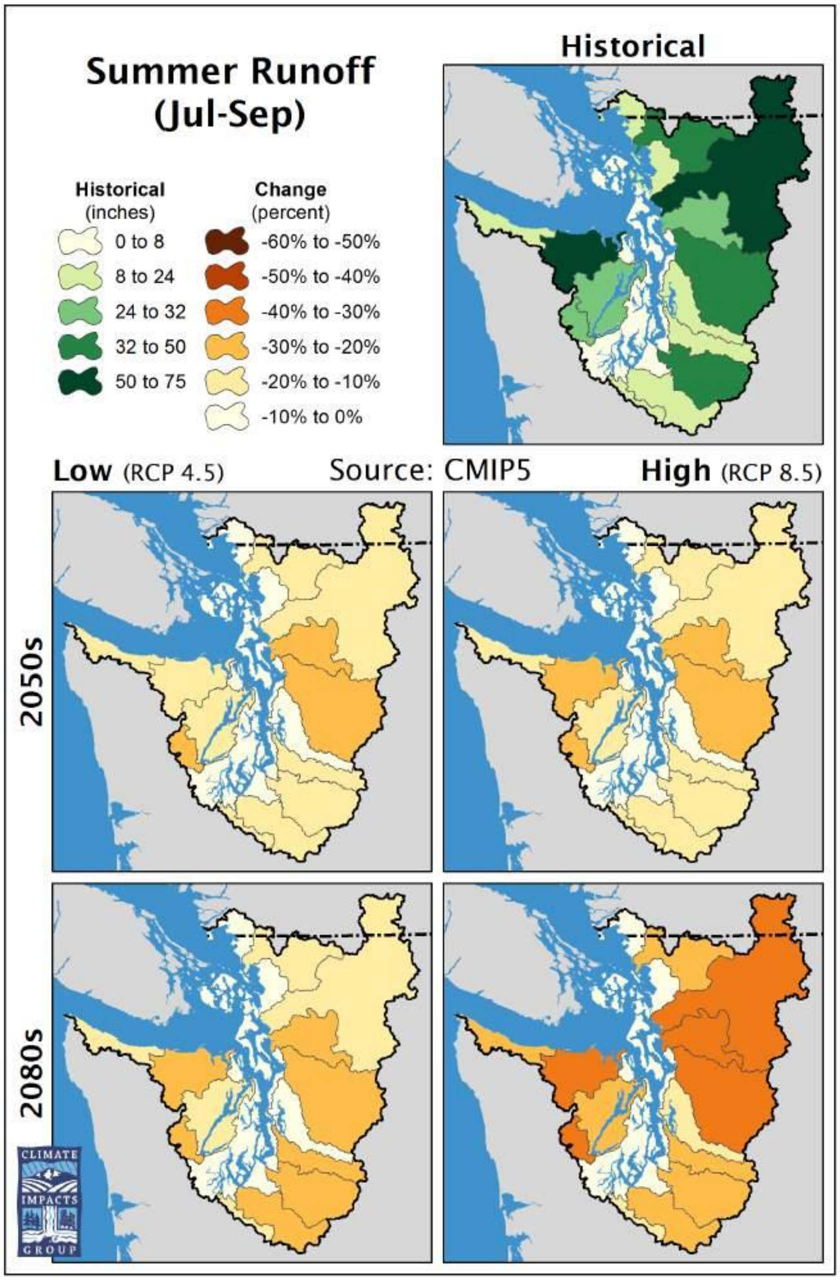

Figure 15b. Summer runoff, newer projections. As in Figure 15a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

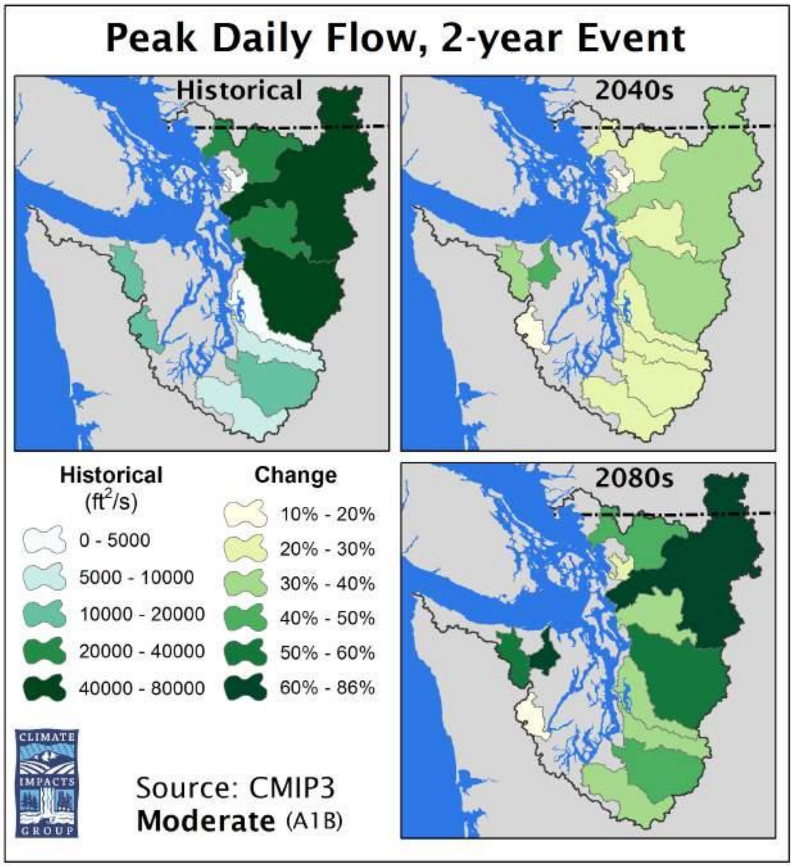

Figure 16a. Peak daily streamflow, 2-year event, previous projections. Maps show the historical and projected change in the peak daily streamflow volume with a 2-year return interval (50% annual chance of exceedance). Daily streamflow for each watershed was assessed at the mouth of each river. The figure includes a map of historical conditions (1970-1999, in ft^3/s) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have the greatest flows historically. Projected changes are depicted by the yellow to green shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

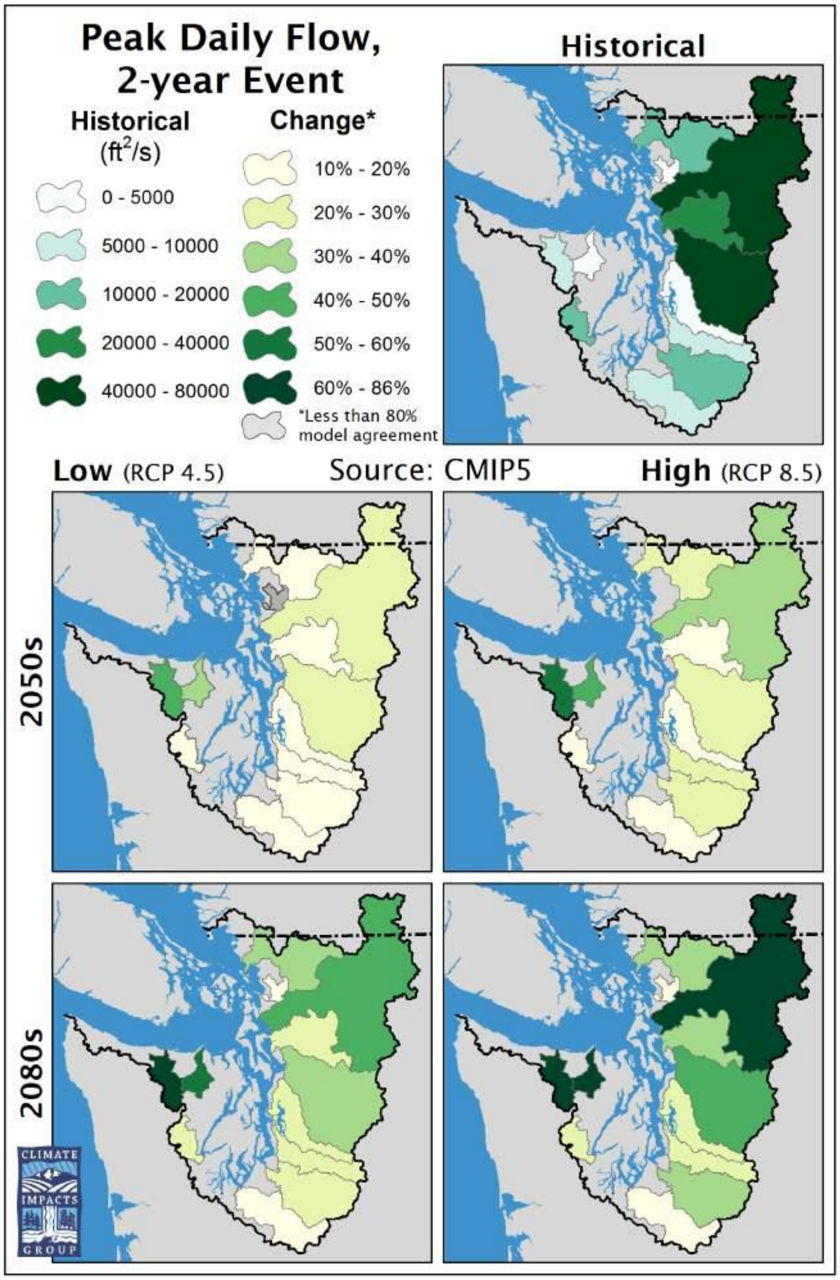

Figure 16b. Peak daily streamflow, 2-year event, newer projections. As in Figure 16a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

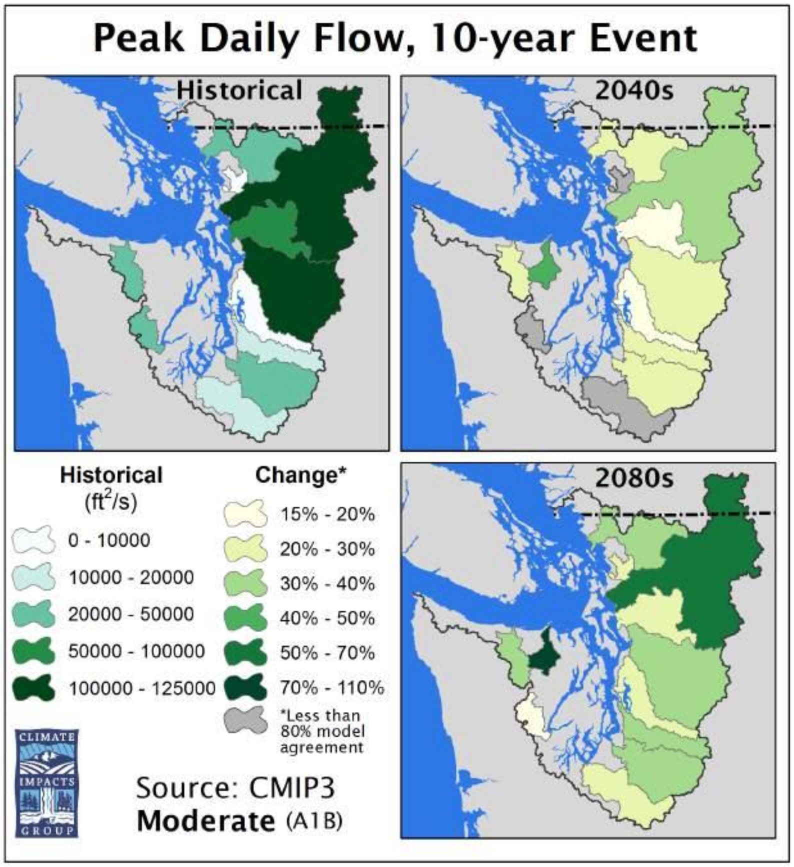

Figure 17a. Peak daily streamflow, 10-year event, previous projections. Maps show the historical and projected change in the peak daily streamflow volume with a 10-year return interval (10% annual chance of exceedance). Daily streamflow for each watershed was assessed at the mouth of each river. The figure includes a map of historical conditions (1970-1999, in ft^3/s) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have the greatest flows historically. Projected changes are depicted by the yellow to green shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

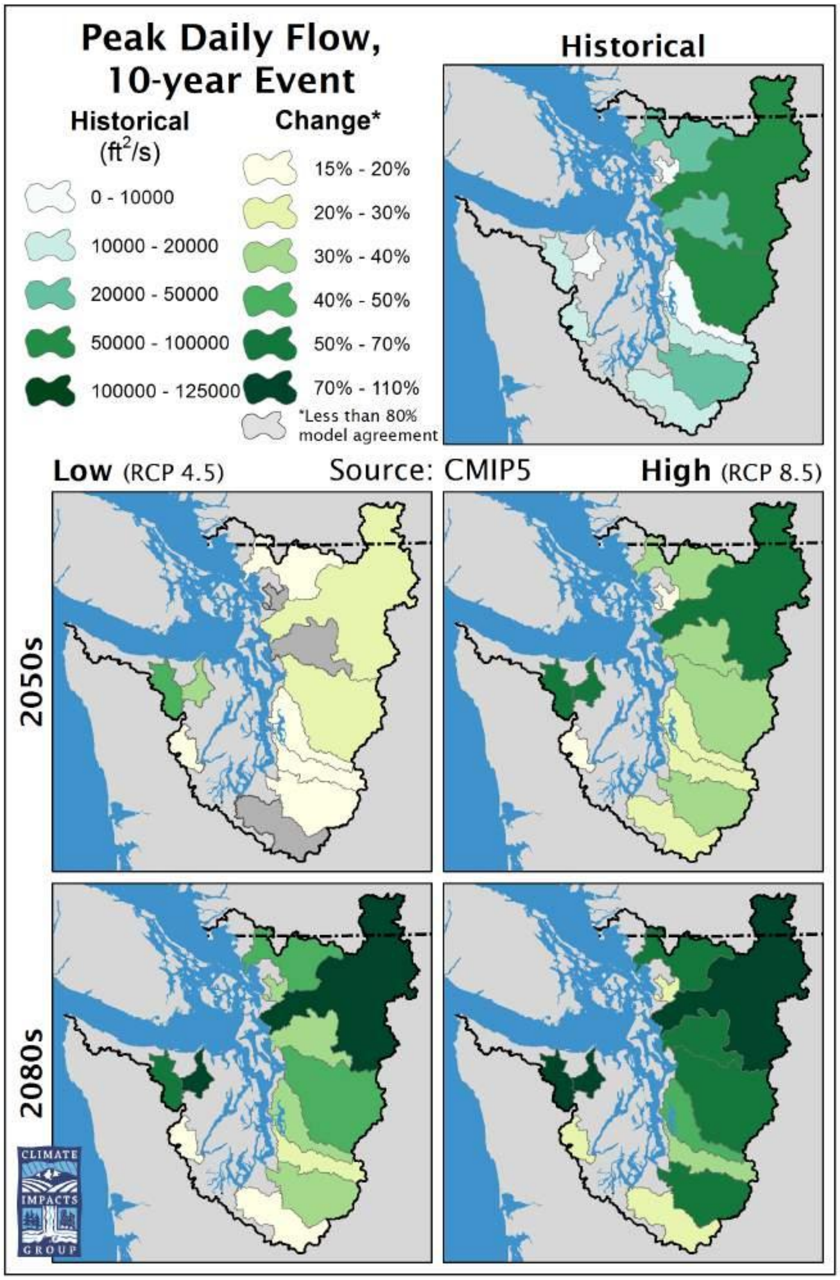

Figure 17b. Peak daily streamflow, 10-year event, newer projections. As in Figure 17a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

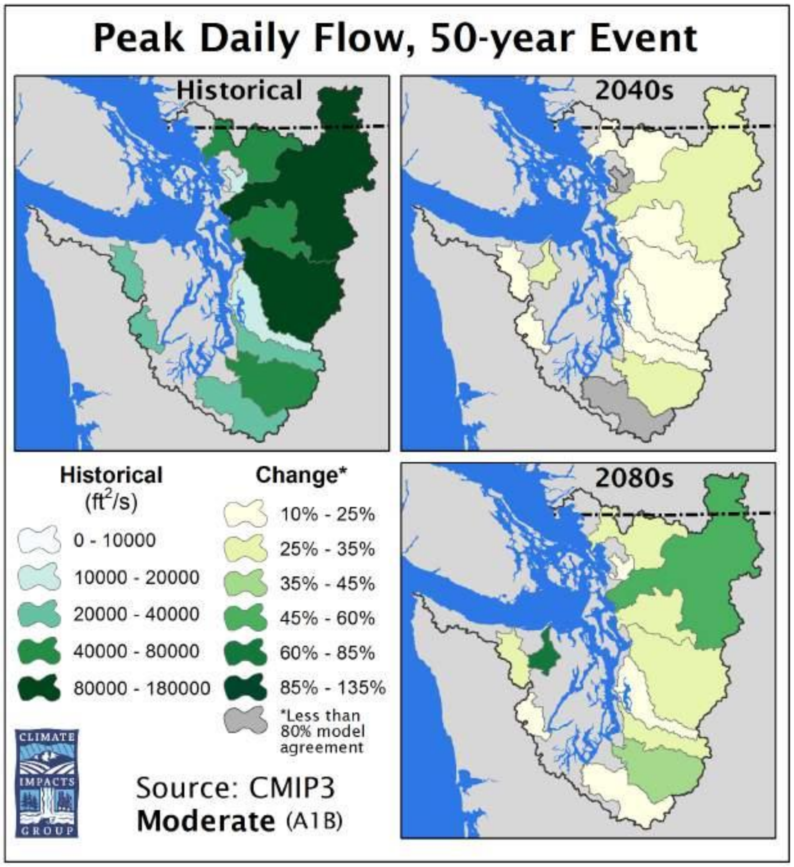

Figure 18a. Peak daily streamflow, 50-year event, previous projections. Maps show the historical and projected change in the peak daily streamflow volume with a 50-year return interval (2% annual chance of exceedance). Daily streamflow for each watershed was assessed at the mouth of each river. The figure includes a map of historical conditions (1970-1999, in ft^3/s) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have the greatest flows historically. Projected changes are depicted by the yellow to green shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

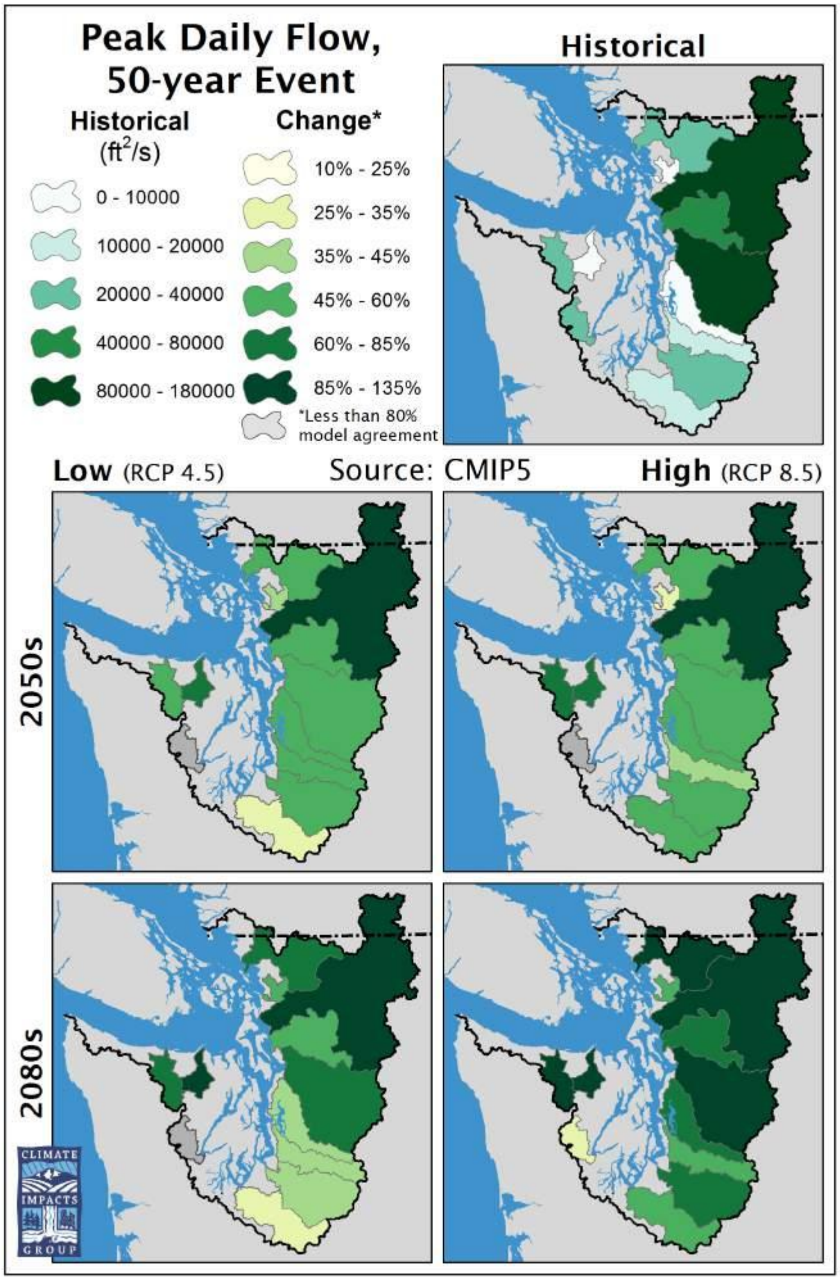

Figure 18b. Peak daily streamflow, 50-year event, newer projections. As in Figure 18a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

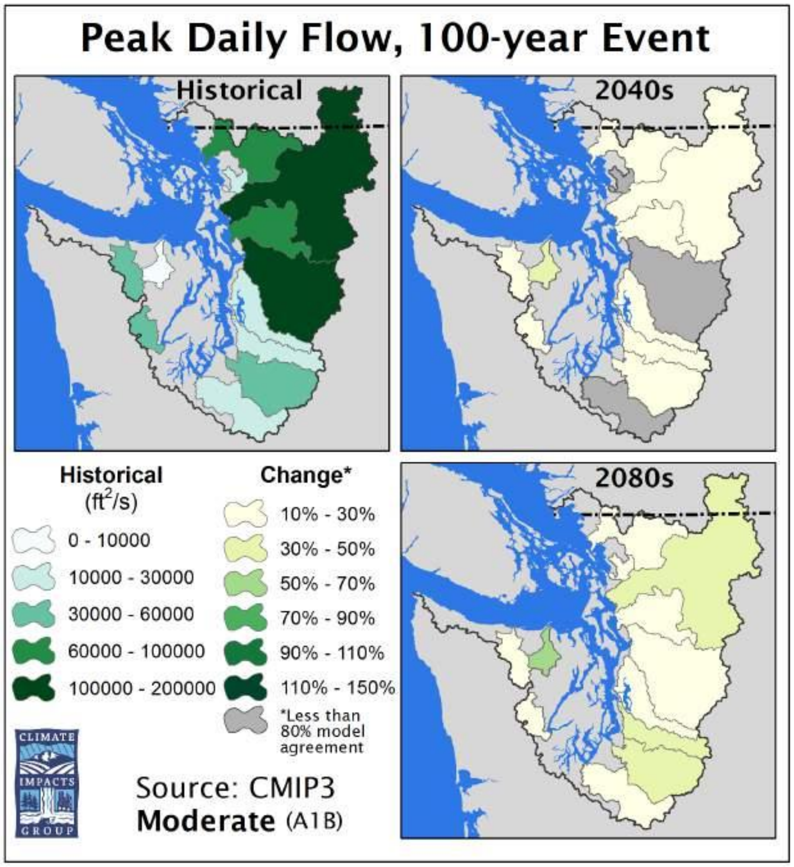

Figure 19a. Peak daily streamflow, 100-year event, previous projections. Maps show the historical and projected change in the peak daily streamflow volume with a 100-year return interval (1% annual chance of exceedance). Daily streamflow for each watershed was assessed at the mouth of each river. The figure includes a map of historical conditions (1970-1999, in ft^3/s) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have the greatest flows historically. Projected changes are depicted by the yellow to green shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007*[4] *report. Data source: Hamlet et al. 2013.*[3]

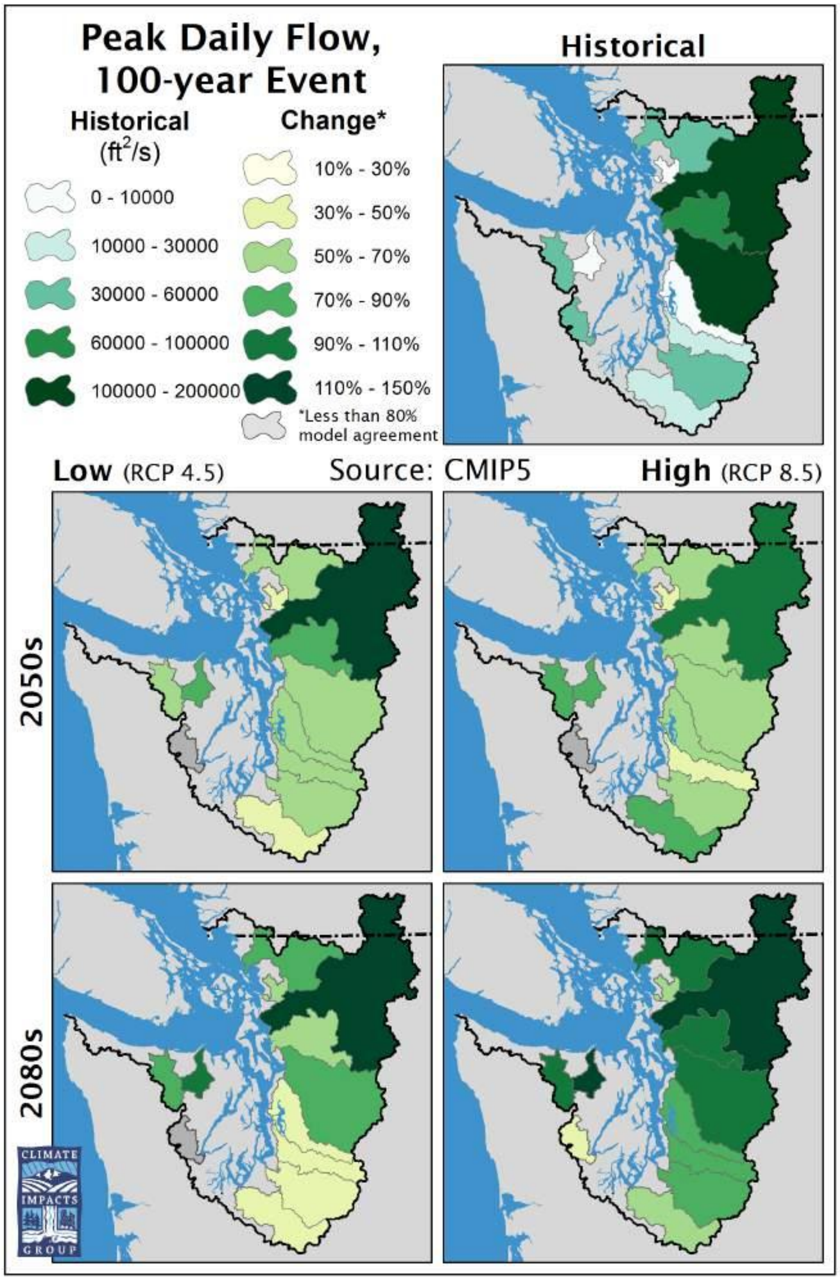

Figure 19b. Peak daily streamflow, 100-year event, newer projections. As in Figure 19a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

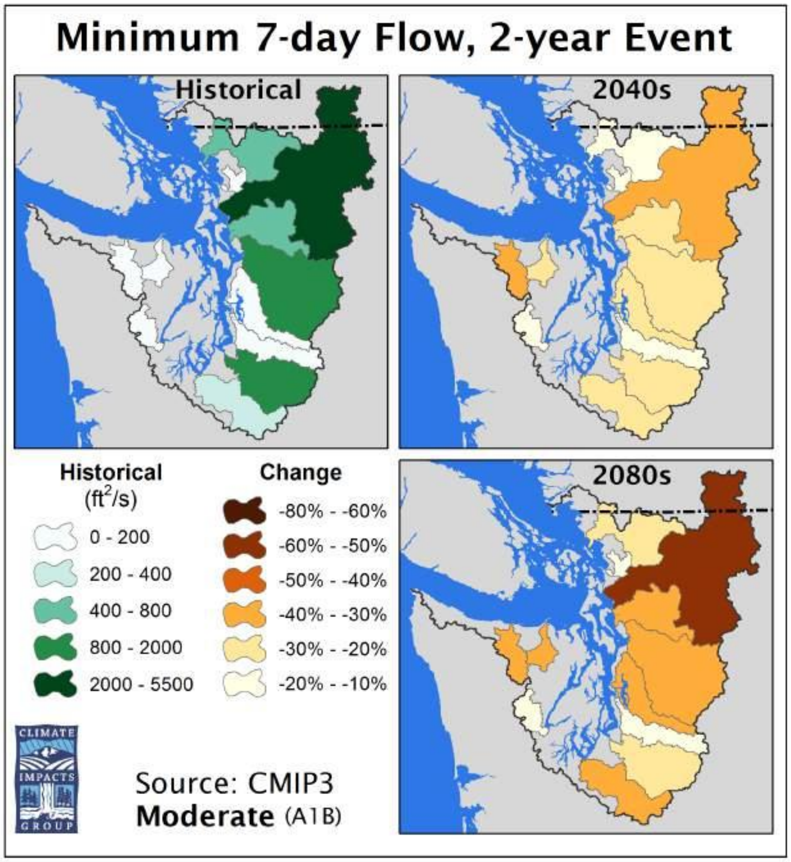

Figure 20a. Minimum 7-day streamflow, 2-year event, previous projections. Maps show the historical and projected change in the annual minimum 7-day streamflow volume with a 2-year return interval (50% annual chance of exceedance). Weekly (7-day) streamflow for each watershed was assessed at the mouth of each river. The figure includes a map of historical conditions (1970-1999, in ft^3/s) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have the greatest flows historically. Projected changes are depicted by the yellow to black shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

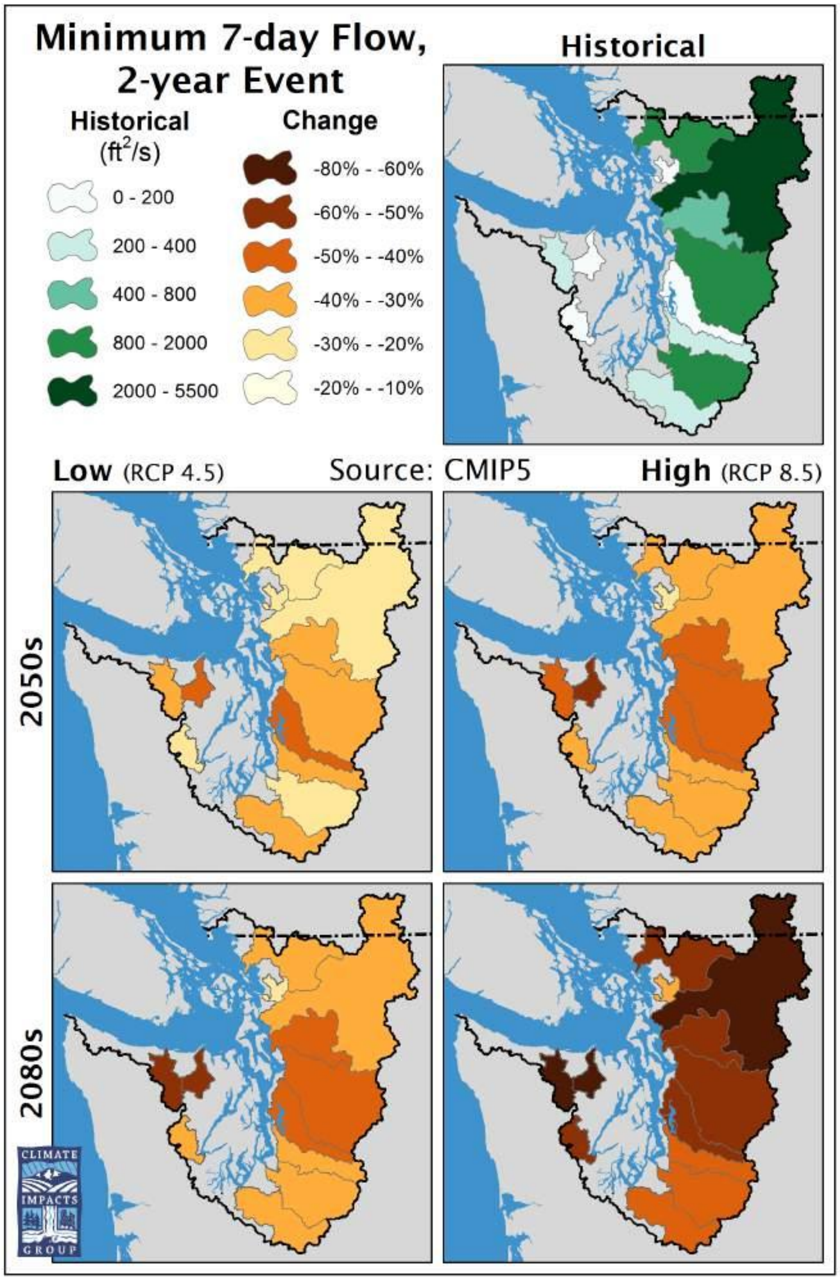

Figure 20b. Minimum 7-day streamflow, 2-year event, newer projections. As in Figure 20a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

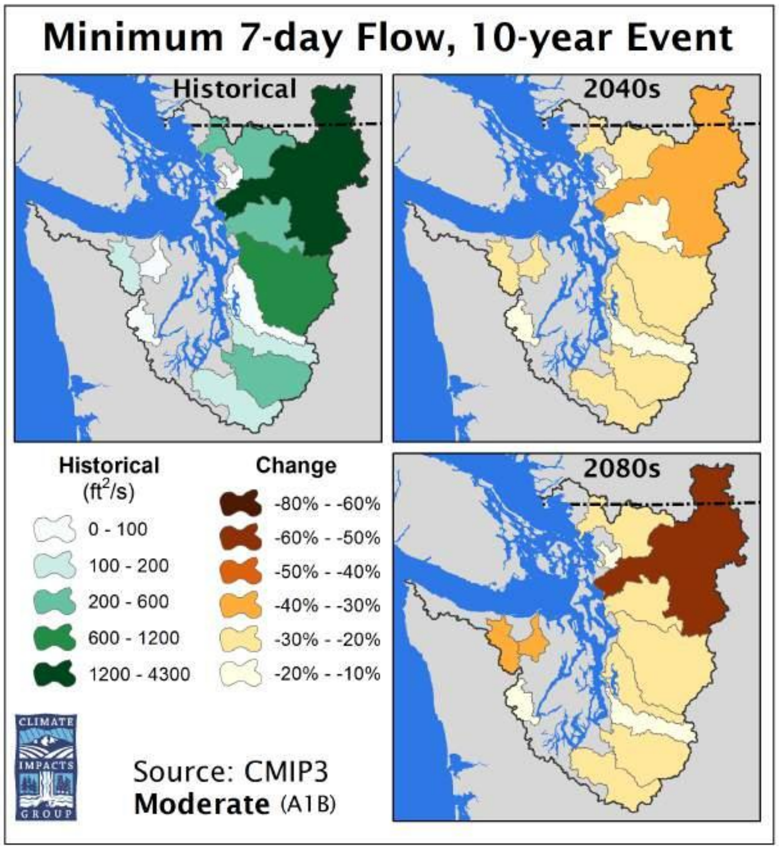

Figure 21a. Minimum 7-day streamflow, 10-year event, previous projections. Maps show the historical and projected change in the annual minimum 7-day streamflow volume with a 10-year return interval (10% annual chance of exceedance). Weekly (7-day) streamflow for each watershed was assessed at the mouth of each river. The figure includes a map of historical conditions (1970-1999, in ft^3/s) and the projected change (in percent) for ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have the greatest flows historically. Projected changes are depicted by the yellow to black shading. *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

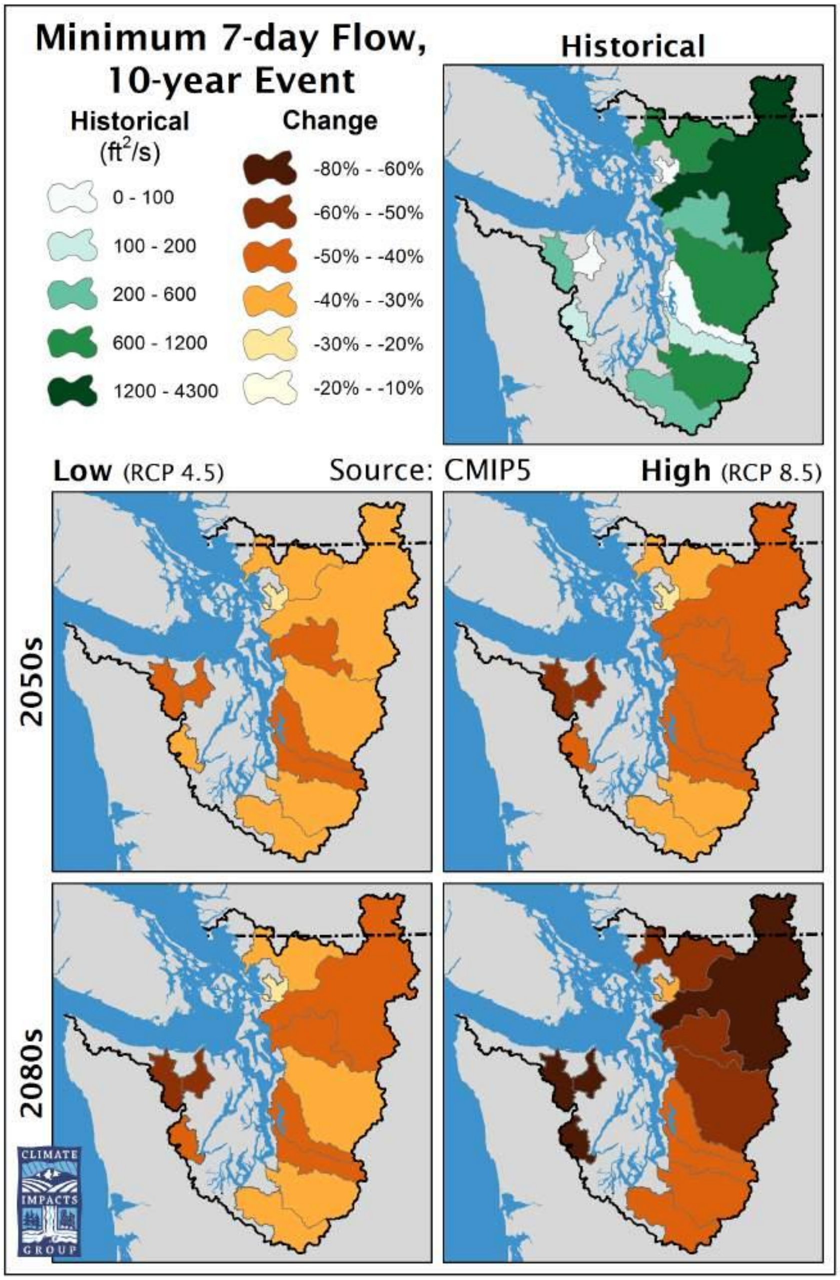

Figure 21b. Minimum 7-day streamflow, 10-year event, newer projections. As in Figure 21a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Robert Norheim, Climate Impacts Group, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

APPENDIX C

Maps of Climate and Hydrologic Change for Major Puget Sound Watersheds: Full-resolution projections

This appendix contains maps of historical and projected changes in climate and hydrology. Results are shown at the spatial resolution of the downscaled projections: 0.0625-degree (about 6 km). As a complement to these full-resolution projections, Appendix B includes maps showing the watershed-averages of the climate and hydrologic projections. Results are included for the following two datasets:

- ***Integrated Scenarios for the Future Northwest Environment.*** The current set of projections, developed by Mote et al. in 2015,[1] which stem from the newer 2013 IPCC report,[2] and

- ***The Pacific Northwest Hydroclimate Scenarios Project.*** A previous set of projections, developed by Hamlet et al. in 2010,[3] which are based on the climate projections used in the IPCC's 2007 report.[4]

The global climate model projections that form the basis of these two datasets stem from the current and previous generations of the Coupled Model Intercomparison Project ("CMIP", see Section 1). The previous projections originate from the CMIP3 archive, while the current projections come from the newer CMIP5 archive.[5,6] Each CMIP experiment is associated with a different set of greenhouse gas scenarios.[A] For simplicity, each figure is labeled with the CMIP experiment on which it is based ("CMIP3" or "CMIP5"), as well as the name(s) of the greenhouse gas scenarios that are the basis of the projections shown in each figure (e.g. "Moderate (A1B)", or "Low (RCP 4.5)").

Projections are included for the following climate and hydrologic variables:

Figures C-1a, b:	Average Winter Temperature
Figures C-2a, b:	Average Summer Temperature
Figures C-3a, b:	Growing Degree Days
Figures C-4a, b:	Extreme high daytime temperatures
Figures C-5a, b:	Extreme low nighttime temperatures
Figures C-6a, b:	Total Winter Precipitation
Figures C-7a, b:	Total Summer Precipitation
Figures C-8a, b:	Max 24-hour Precipitation
Figures C-9a, b:	Summer Water Deficit
Figures C-10a, b:	April 1st Snow Water Equivalent (SWE)
Figures C-11a, b:	Annual Maximum Snow Water Equivalent (SWE)

[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 more details.

Other maps and figures, for example showing averages over smaller sub-basins to each watershed, are available upon request.

1 Mote, P. W., Rupp, D. E., Abatzoglou, J. T., Hegewisch, K. C., Nijssen, B., Lettenmaier, D. P., Stumbaugh, M., Lee, S.-Y., & Bachelet, D., 2015. Integrated Scenarios for the Future Northwest Environment. Version if relevant. USGS ScienceBase. Data set accessed 2015-03-02 at https://www.sciencebase.gov/catalog/item/5006eb9de4b0abf7ce733f5c

2 (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

3 Hamlet, A.F. et al., 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. *Atmosphere-Ocean* 51(4): 392-415. doi: 10.1080/07055900.2013.819555

4 (IPCC) Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

5 Taylor, K. E. et al., 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485-498, doi:10.1175/BAMS-D-11-00094.1

6 Knutti, R. et al., 2013. Climate model genealogy: Generation CMIP5 and how we got there. *Geophys. Res. Lett*, *40*, 1194-1199, doi:10.1002/grl.50256

7 Environmental Protection Agency. 2007. *Biological evaluation of the revised Washington water quality standards*. US EPA, Seattle. http://www.ecy.wa.gov/programs/wq/swqs/WAbiolevalWQS-final.pdf

8 Isaak, D.J. et al., 2011. *NorWeST: An interagency stream temperature database and model for the Northwest United States*. U.S. Fish and Wildlife Service, Great Northern Landscape Conservation Cooperative Grant. Project website: www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

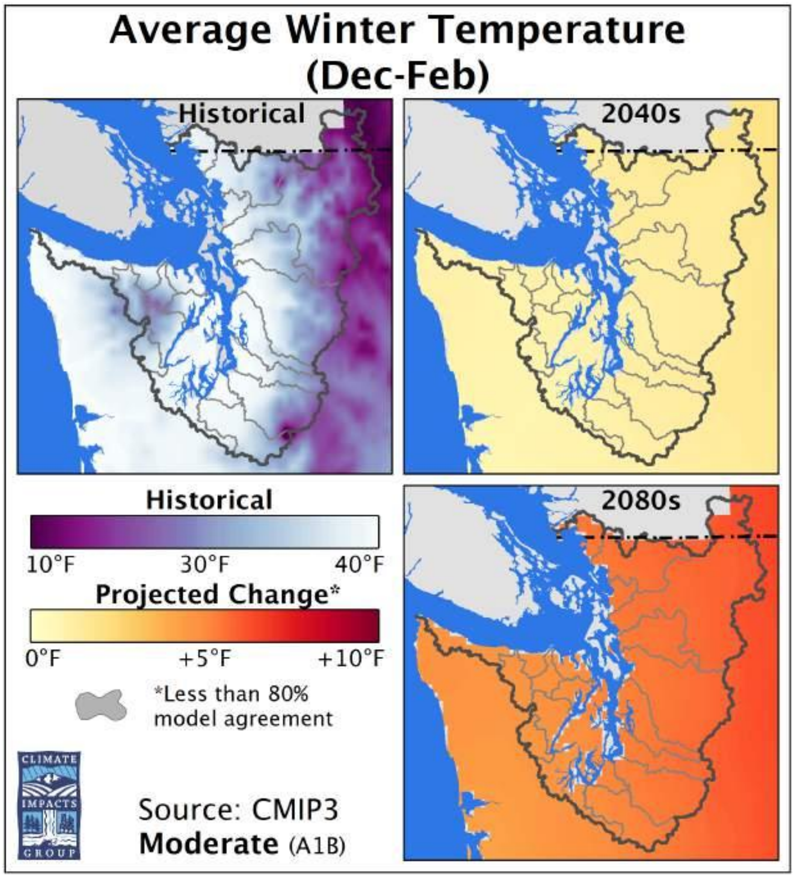

Figure C-1a. Average Winter Temperature, previous projections. Maps show the historical and projected change in average winter (December–February) temperature, in °F. Maps compare historical conditions (1970-1999) with the projected change for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for grid cells for which at least 8 out of the 10 models agree on the direction of change. Dark blue shading on the historical map indicates areas with the lowest average winter temperature. Projected increases in average winter temperature are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

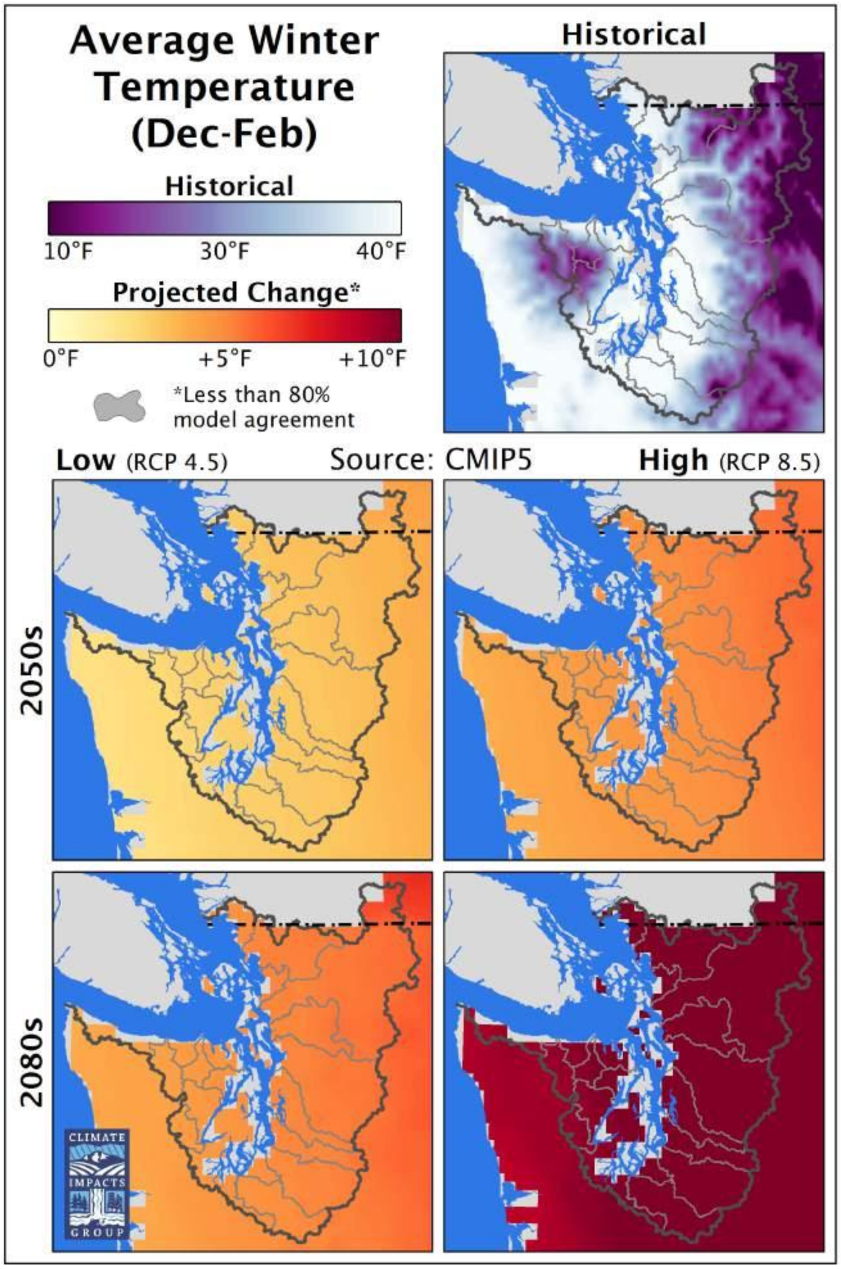

Figure C-1b. Average Winter Temperature, newer projections. As in Figure C-1a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

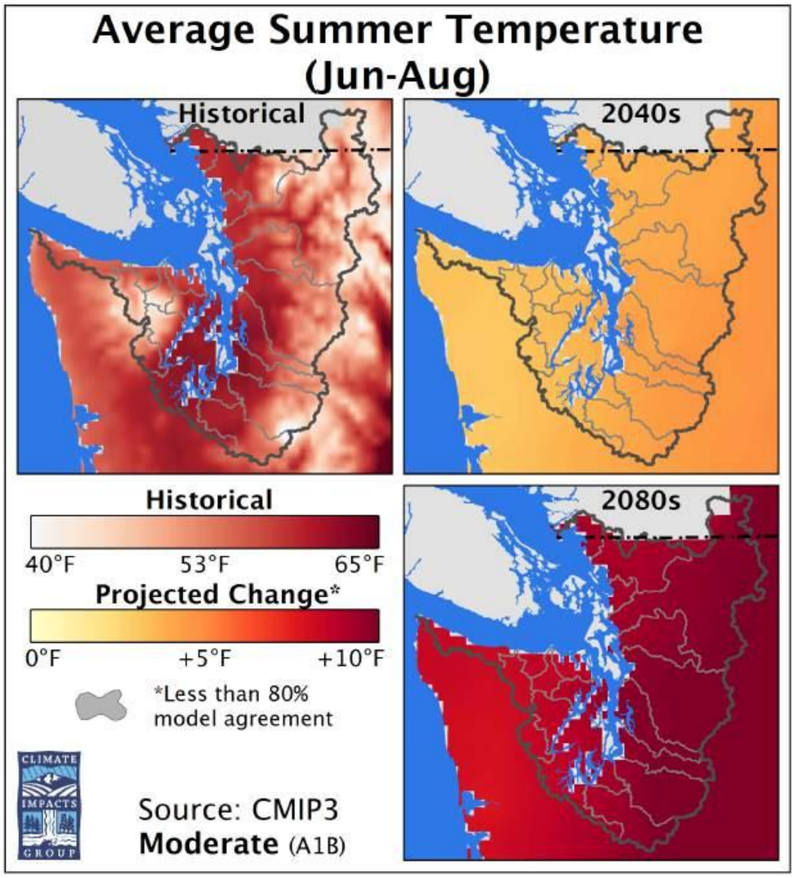

Figure C-2a. Average Summer Temperature, previous projections. Maps show the historical and projected change in average summer (June–August) temperature, in °F. The figure compares historical conditions (1970-1999) with the projected change for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for grid cells for which at least 8 out of the 10 models agree on the direction of change. Dark red shading on the historical map indicates areas with the highest average summer temperature. Projected increases in average winter temperature are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

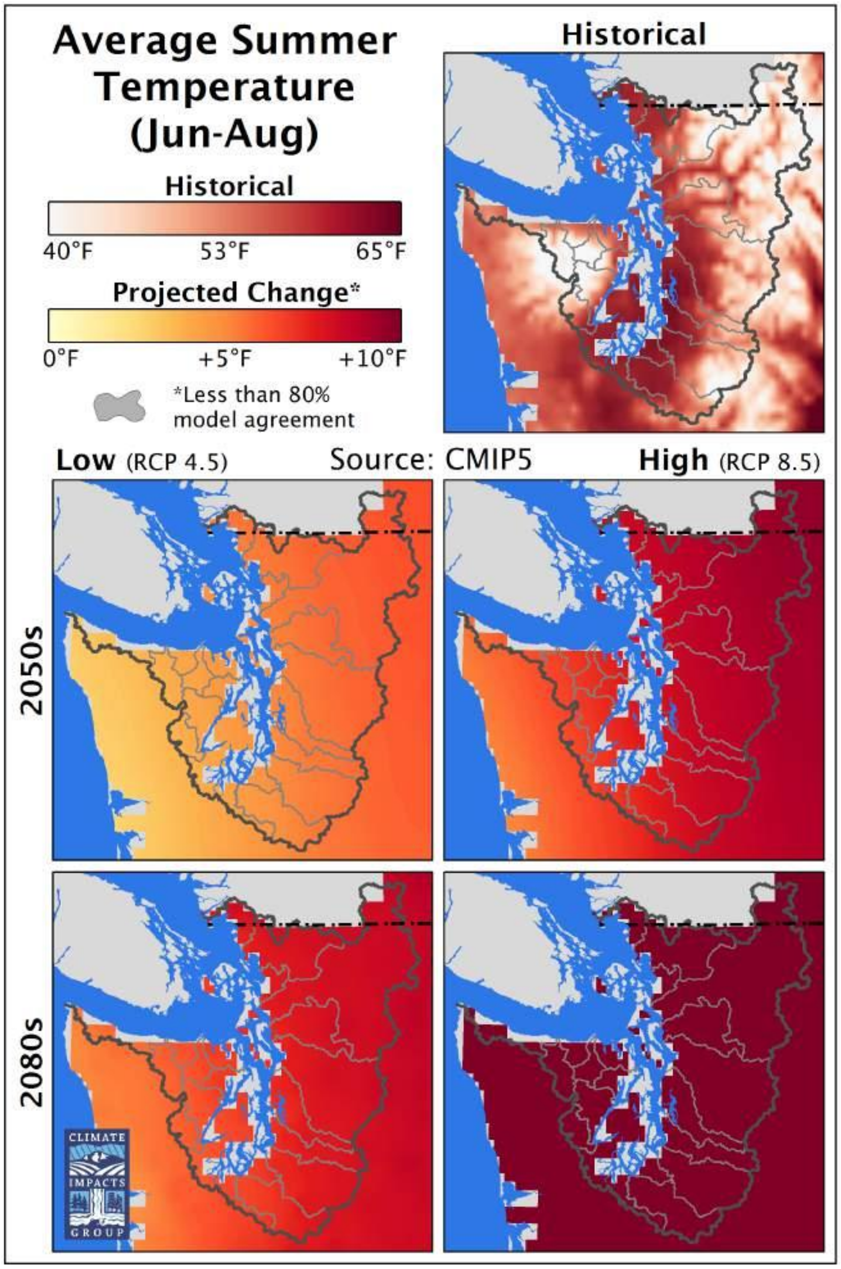

Figure C-2b. Average Summer Temperature, newer projections. As in Figure C-2a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

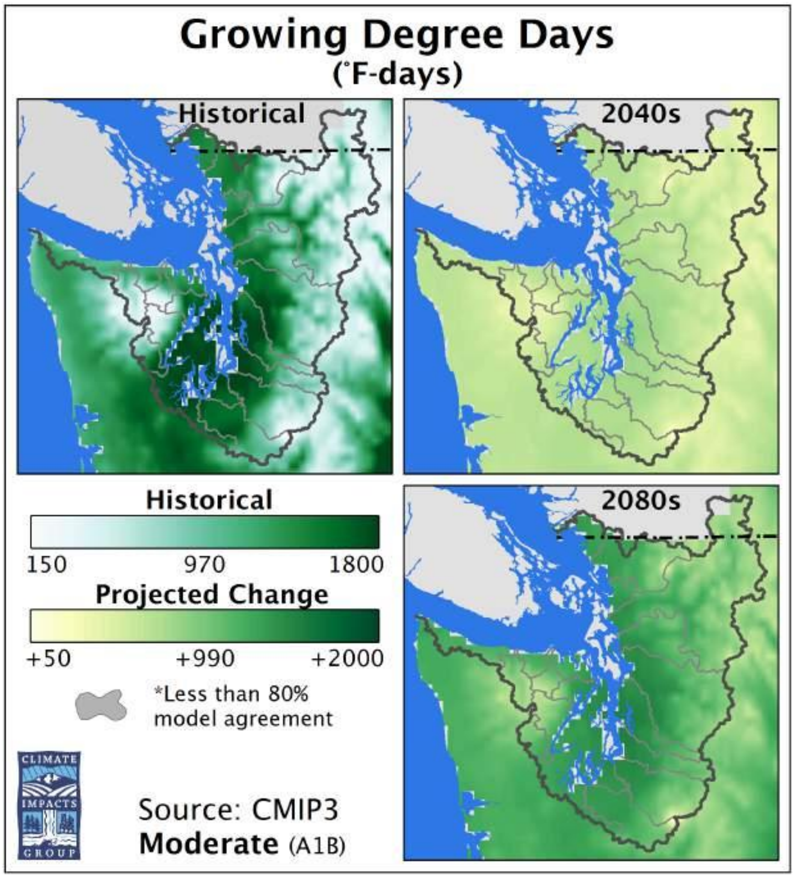

Figure C-3a. Growing Degree Days, previous projections. Maps show the historical and projected growing degree days (GDD), a measure of heat accumulation in plants, which measures the cumulative seasonal warming above a base temperature of 50°F. The figure compares historical conditions (1970-1999) with the projected change for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections, all in units of °F-days. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for grid cells for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas with the highest average GDD. Projected increases in growing degree days are depicted by the beige to dark green shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007*[4] *report. Data source: Hamlet et al. 2013.*[3]

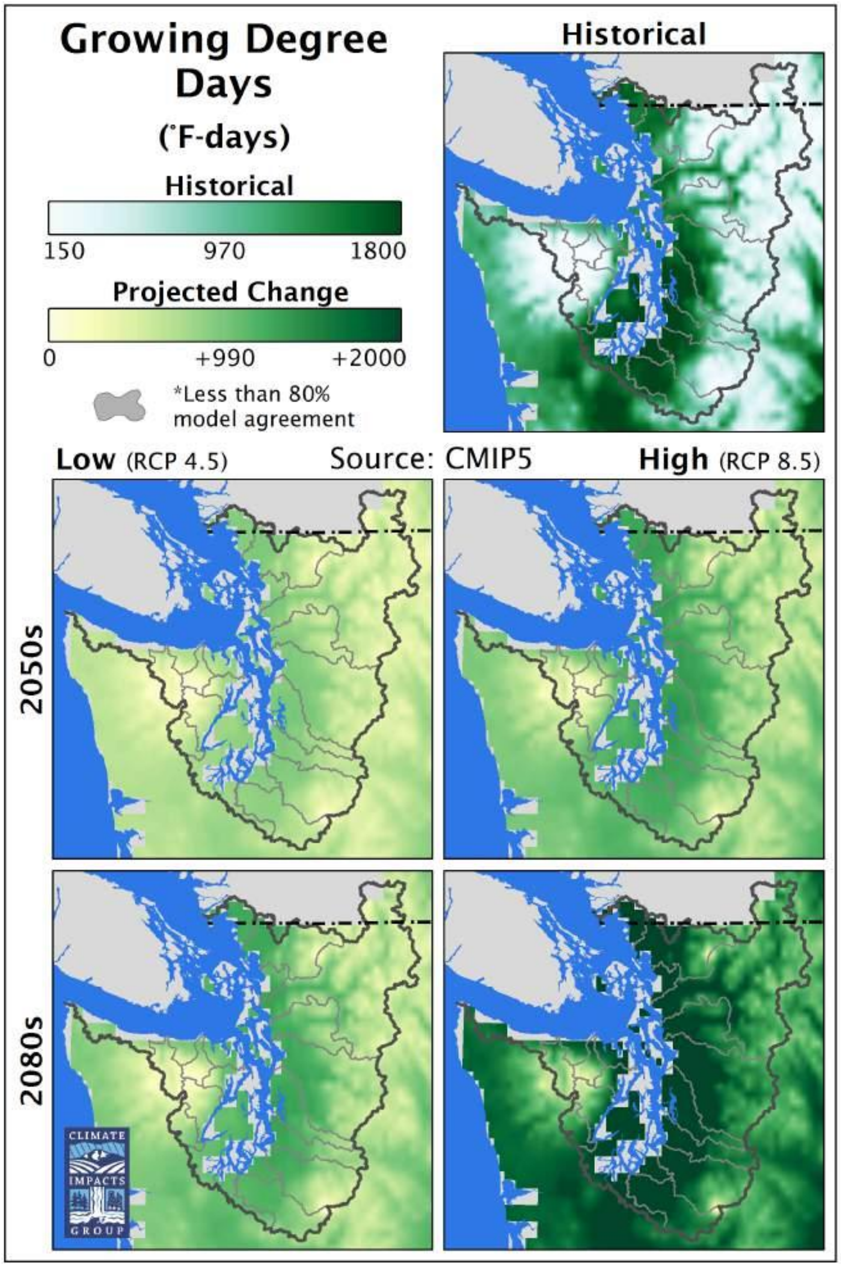

Figure C-3b. Growing Degree Days, newer projections. As in Figure C-3a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

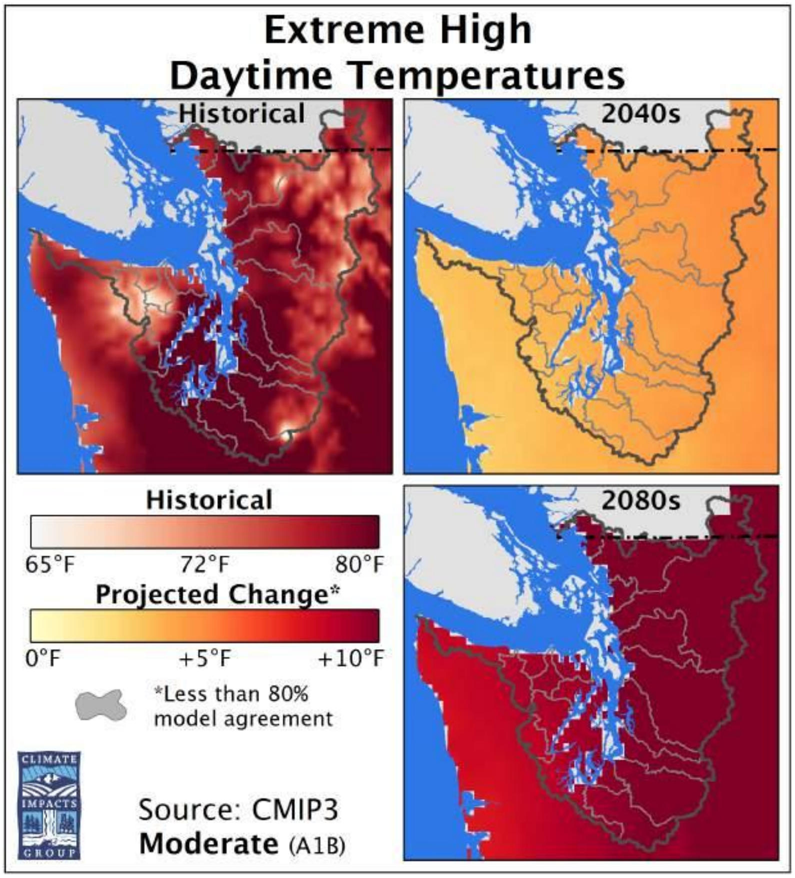

Figure C-4a. Extreme high daytime temperatures, previous projections. Maps show the historical and projected change in extreme high daytime temperatures, in °F. The "extreme high" temperature is defined as the 95th percentile of daily maximum temperatures occurring in each year. The figure compares historical conditions (1970-1999) with the projected change for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for grid cells for which at least 8 out of the 10 models agree on the direction of change. Dark red shading on the historical map indicates areas with the warmest extreme high daytime temperatures. Projected increases in extreme high daytime temperatures are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

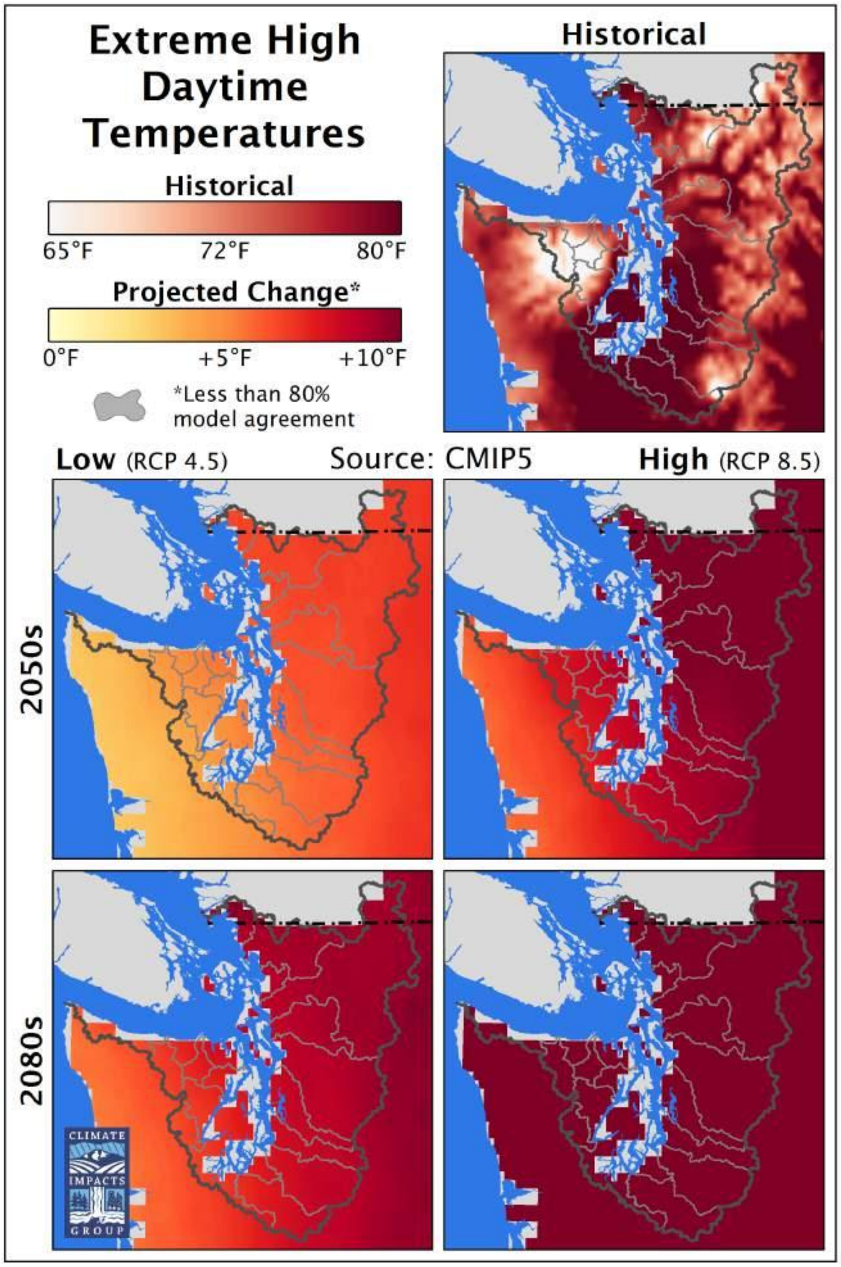

Figure C-4b. Extreme high daytime temperatures, newer projections. As in Figure C-4a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

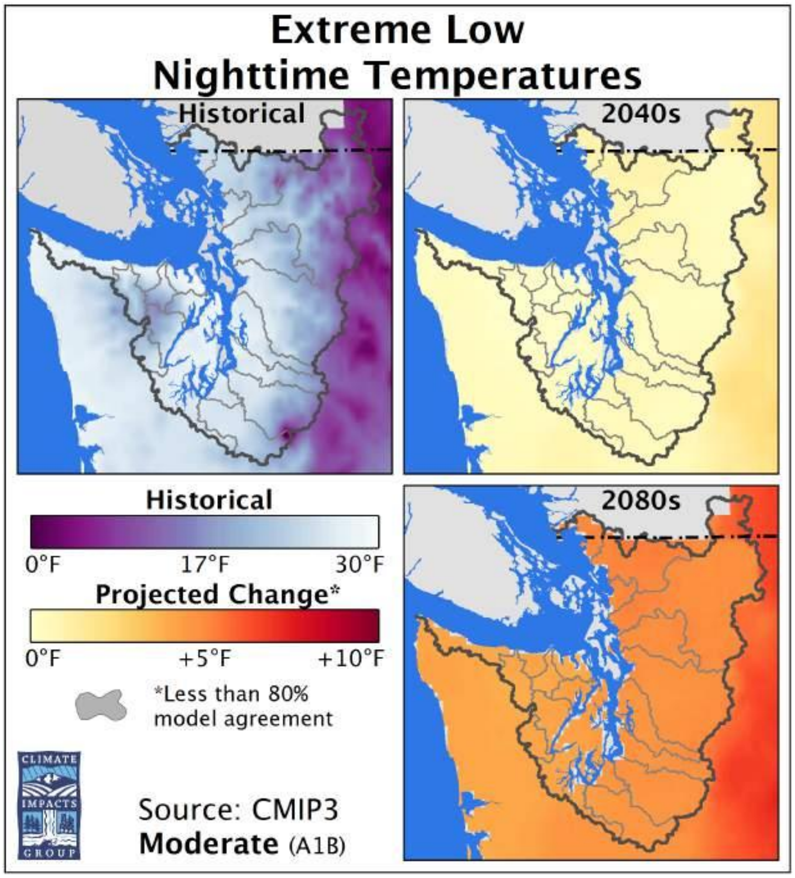

Figure C-5a. Extreme low nighttime temperatures, previous projections. Maps show the historical and projected change in extreme low nighttime temperatures, in °F. The "extreme low" temperature is defined as the 5th percentile of daily minimum temperatures occurring in each year. The figure compares historical conditions (1970-1999) with the projected change for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for grid cells for which at least 8 out of the 10 models agree on the direction of change. Dark purple shading on the historical map indicates areas with the lowest extreme low nighttime temperatues. Projected increases in extreme low nighttime temperatures are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007*[4] *report. Data source: Hamlet et al. 2013.*[3]

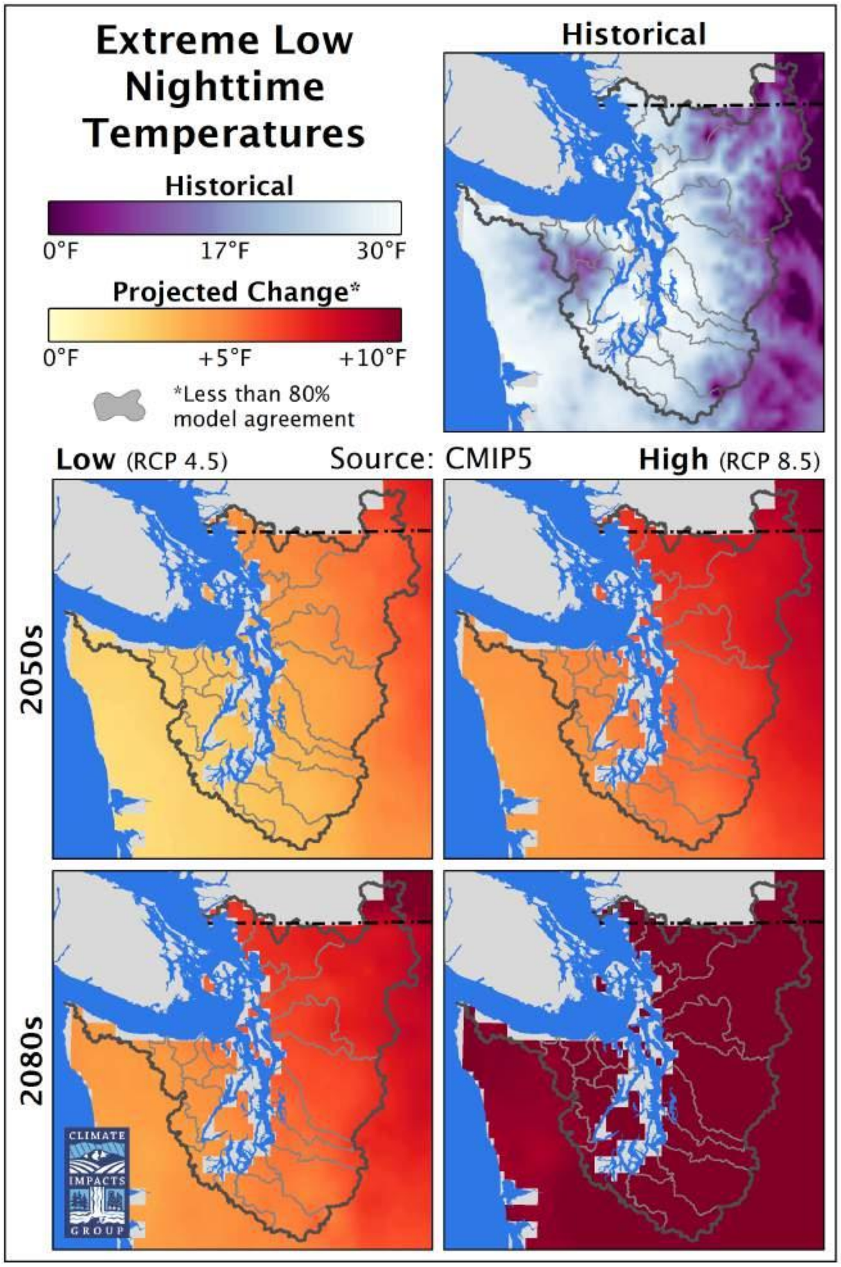

Figure C-5b. Extreme low nighttime temperatures, newer projections. As in Figure C-5a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

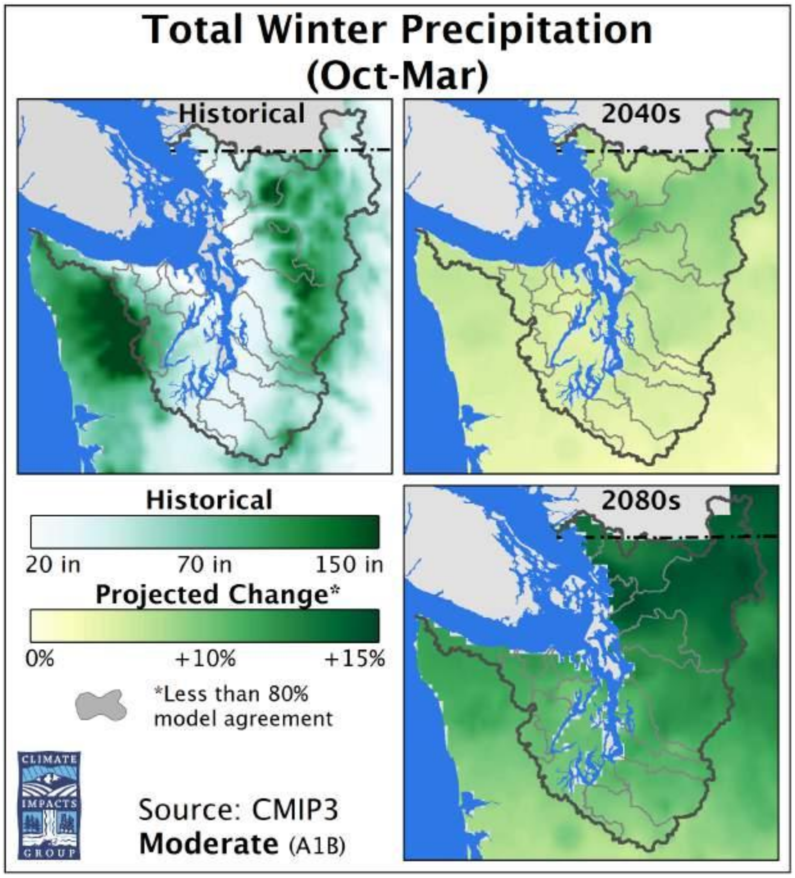

Figure C-6a. Total winter precipitation, previous projections. Maps show the historical and projected total winter (October–March) precipitation. The figure compares historical conditions (1970-1999, in inches) with the projected change (in percent) for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Dark green shading on the historical map indicates areas that have received highest levels of total winter precipitation in Puget Sound. Projected changes are depicted by the light to dark green shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

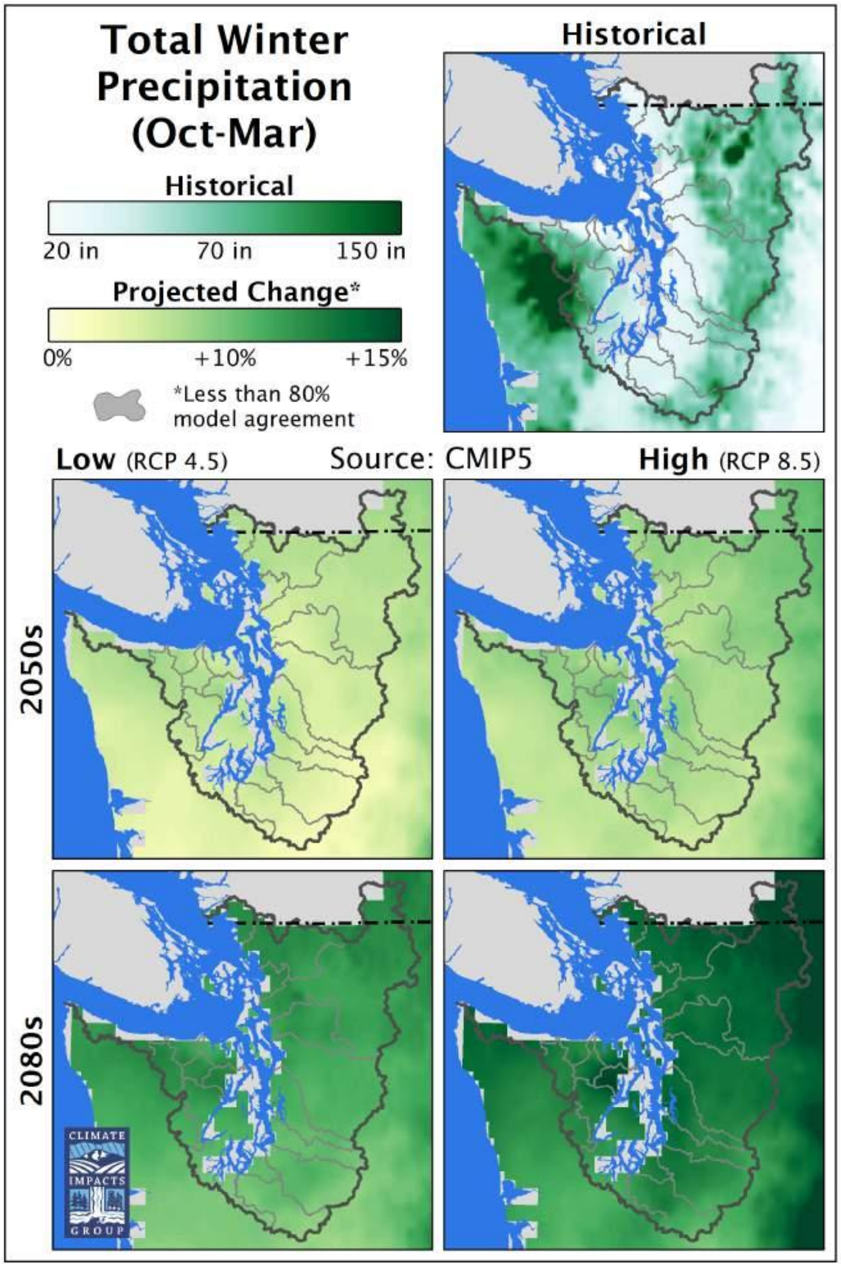

Figure C-6b. Total winter precipitation, newer projections. As in Figure C-6a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

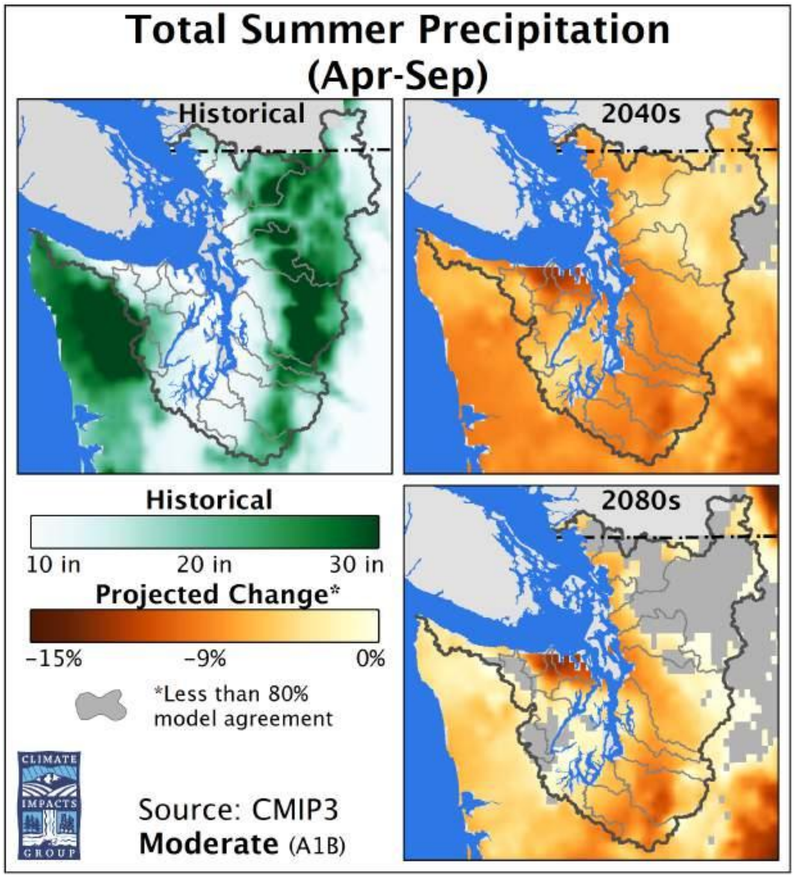

Figure C-7a. Total summer precipitation, previous projections. Maps show the historical and projected total summer (April-September) precipitation. The figure compares historical conditions (1970-1999, in inches) with the projected change (in percent) for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for grid cells for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have received highest levels of summer precipitation in Puget Sound. Projected changes are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

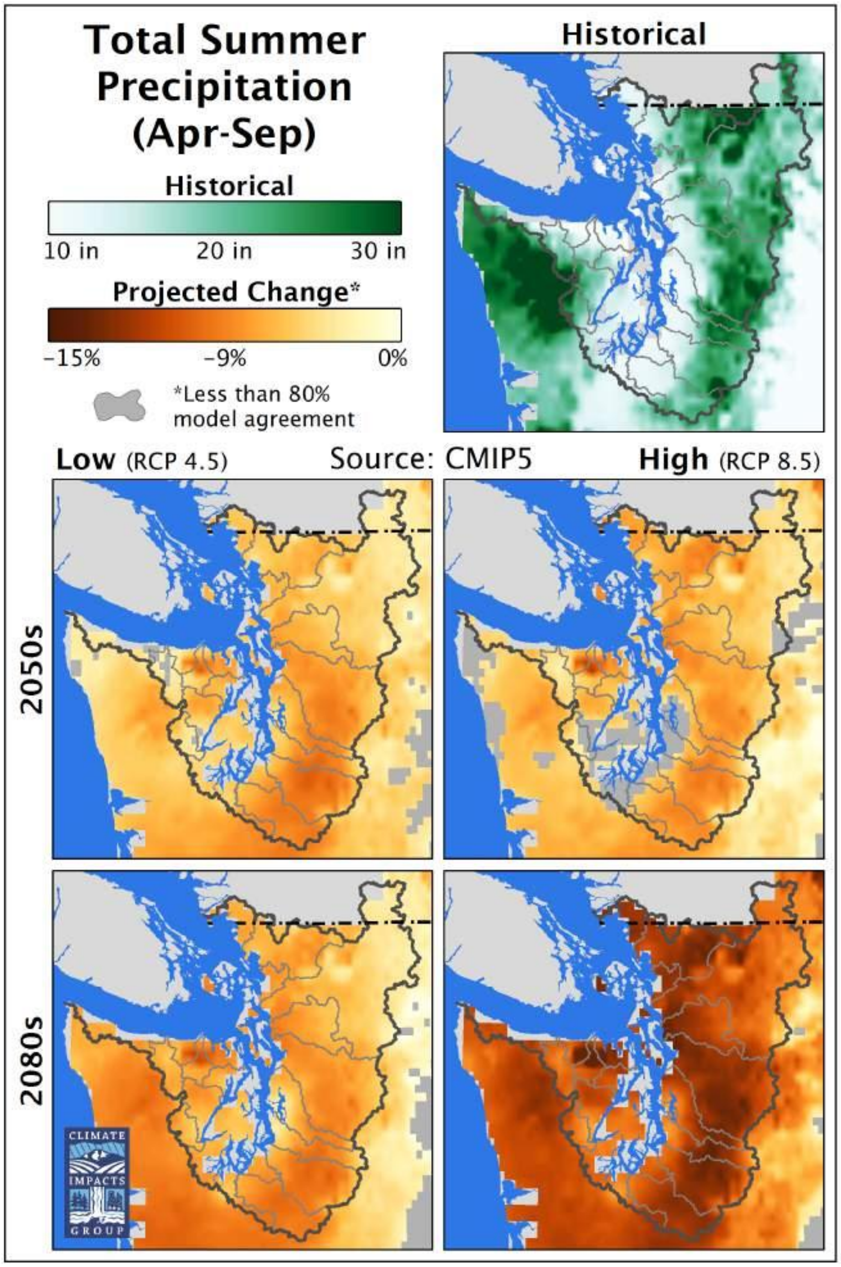

Figure C-7b. Total summer precipitation, newer projections. As in Figure C-7a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

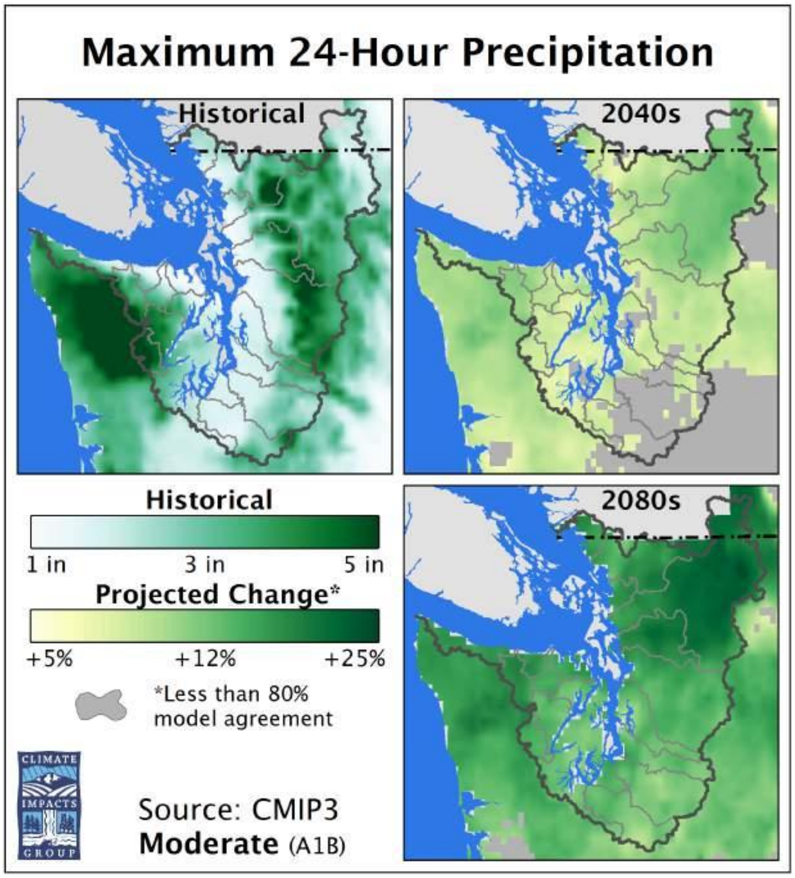

Figure C-8a. Maximum 24-hour precipitation, previous projections. Maps show the maximum daily precipitation for Puget Sound watersheds. The figure compares historical conditions (1970-1999, in inches) with the projected change (in percent) for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for grid cells for which at least 8 out of the 10 models agree on the direction of change. Dark green shading on the historical map indicates areas that have received highest levels of maximum daily precipitation in Puget Sound. Projected changes are depicted by the light to dark green shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

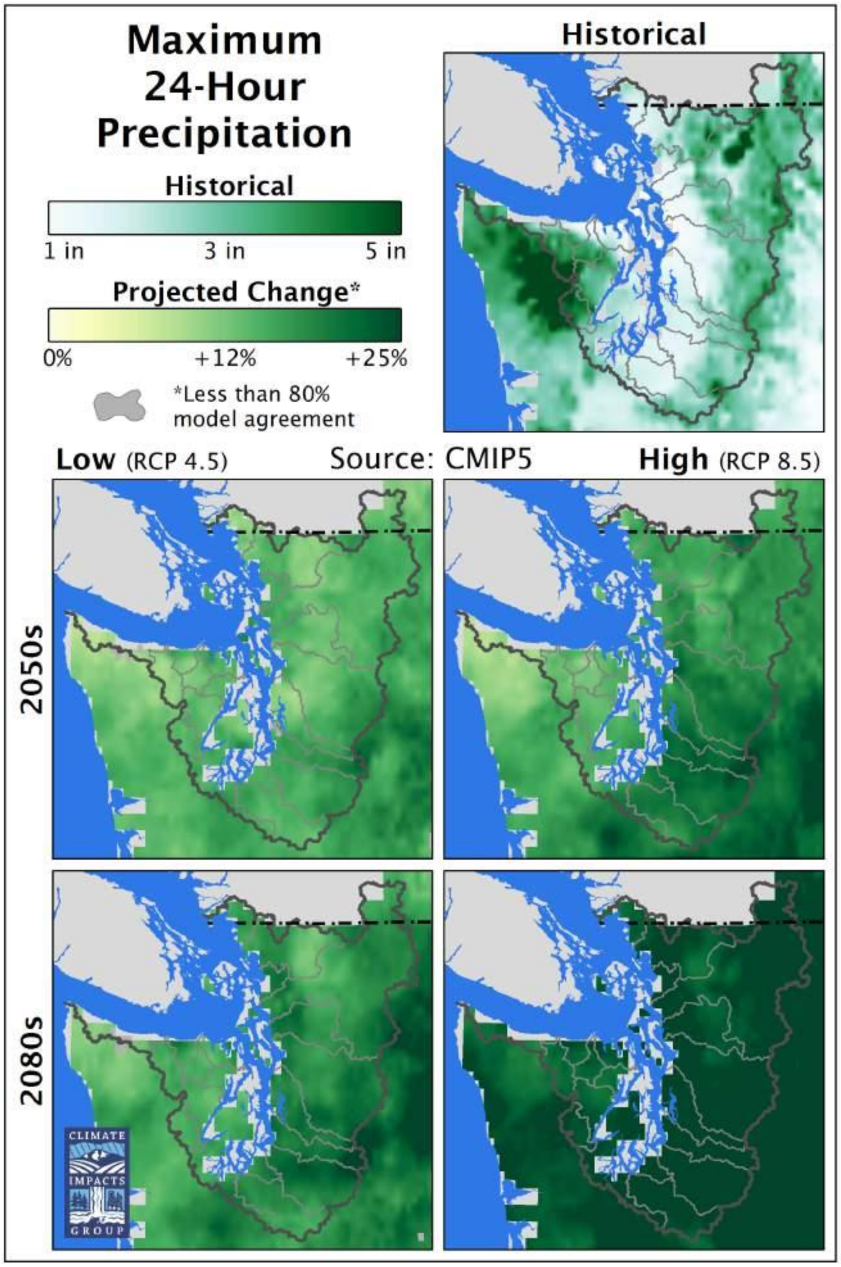

Figure C-8b. Maximum 24-hour precipitation, newer projections. As in Figure C-8a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

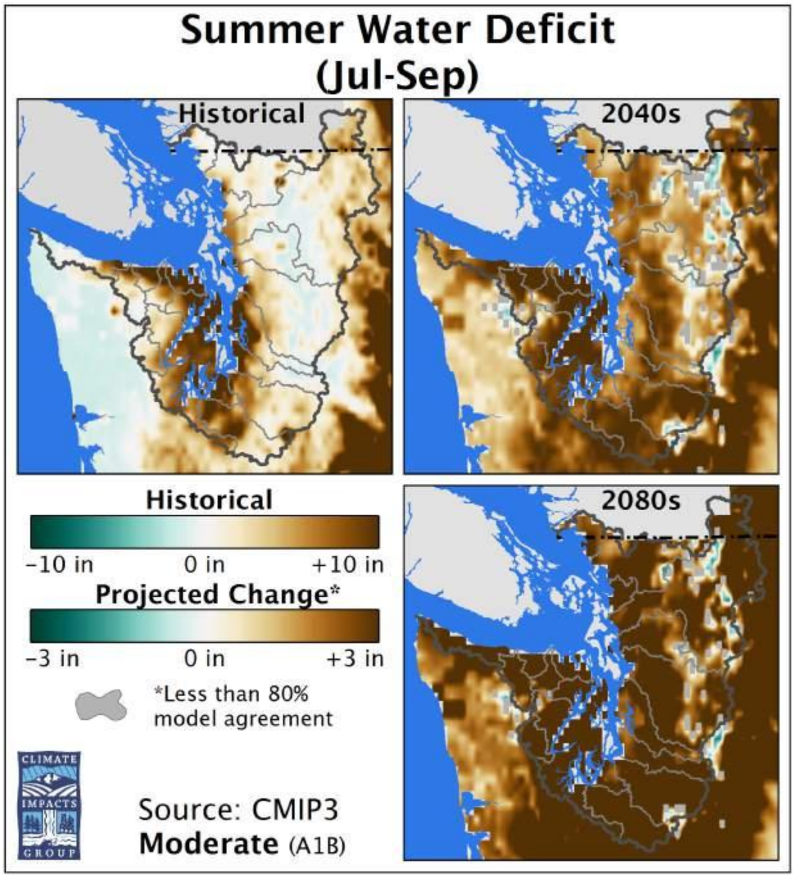

Figure C-9a. Summer Water Deficit, previous projections. Maps show the historical and projected summer (July-September) water deficit, based on the amount of soil moisture available relative to atmospheric demand for water via evaporation, either from water bodies or vegetation. Maps compare historical conditions (1970-1999) with the projected change for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for grid cells for which at least 8 out of the 10 models agree on the direction of change. Teal shading indicates areas where water availability exceeds water demand. Light to dark brown shading indicates areas where a positive water deficit occurs, that is, regions where water demands exceed soil water availability. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

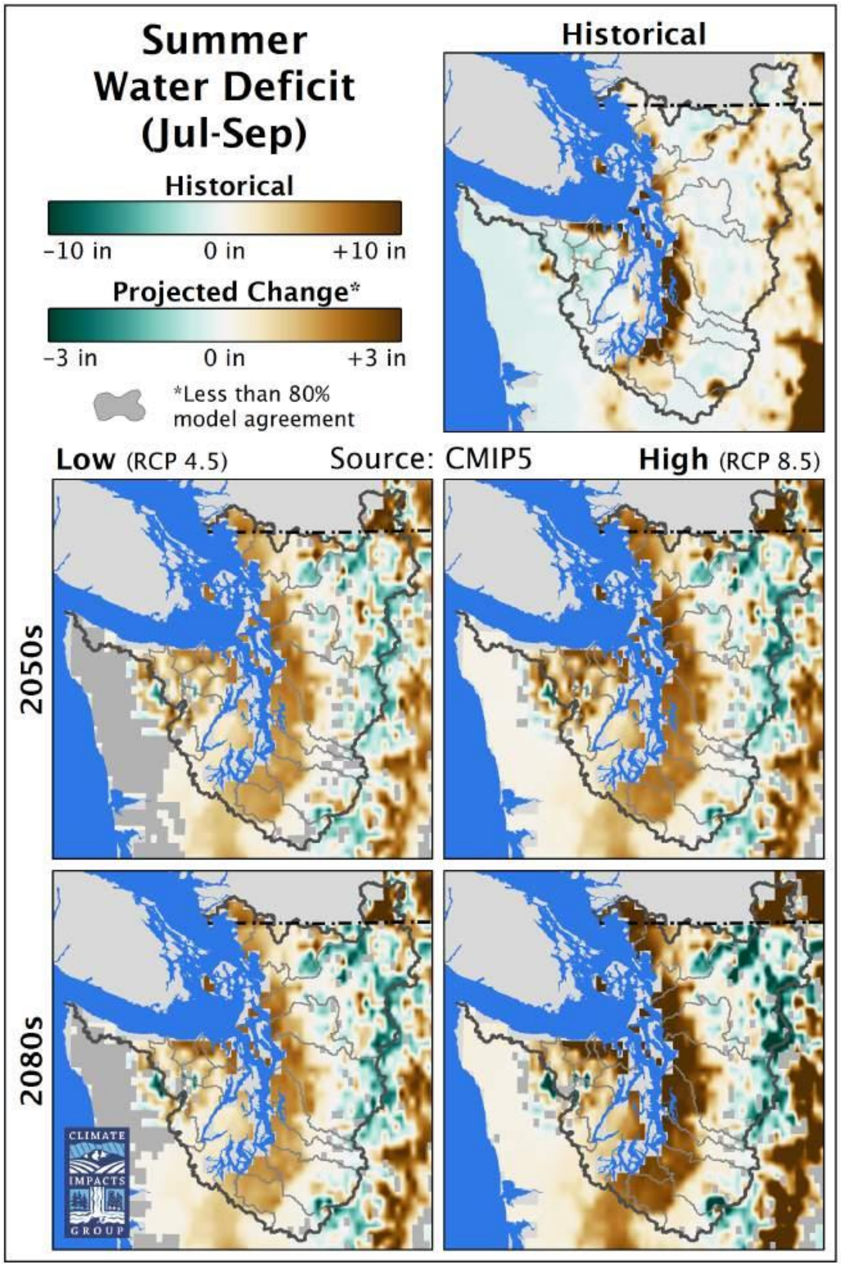

Figure C-9b. Summer Water Deficit, newer projections. As in Figure C-9a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

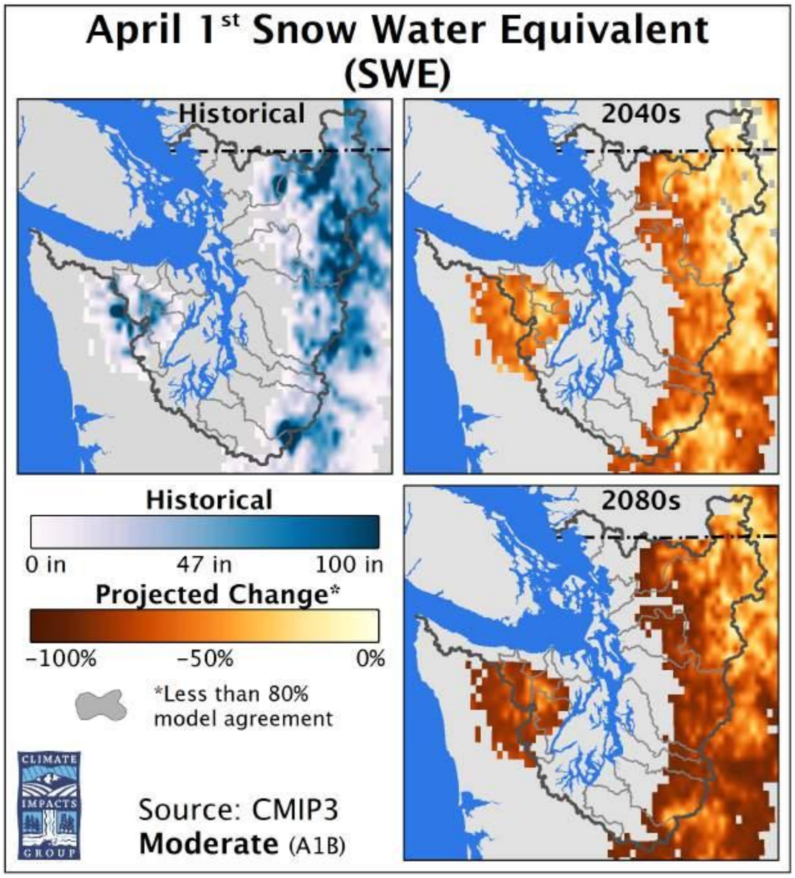

Figure C-10a. April 1st Snow Water Equivalent, previous projections. Maps show the historical and projected April 1st snow water equivalent (SWE), a measure of the total amount of water contained in the snowpack. The figure compares historical conditions (1970-1999, in inches) with the projected change (in percent) for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). 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 snow water equivalent in Puget Sound. Projected decreases in snow water equivelant are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

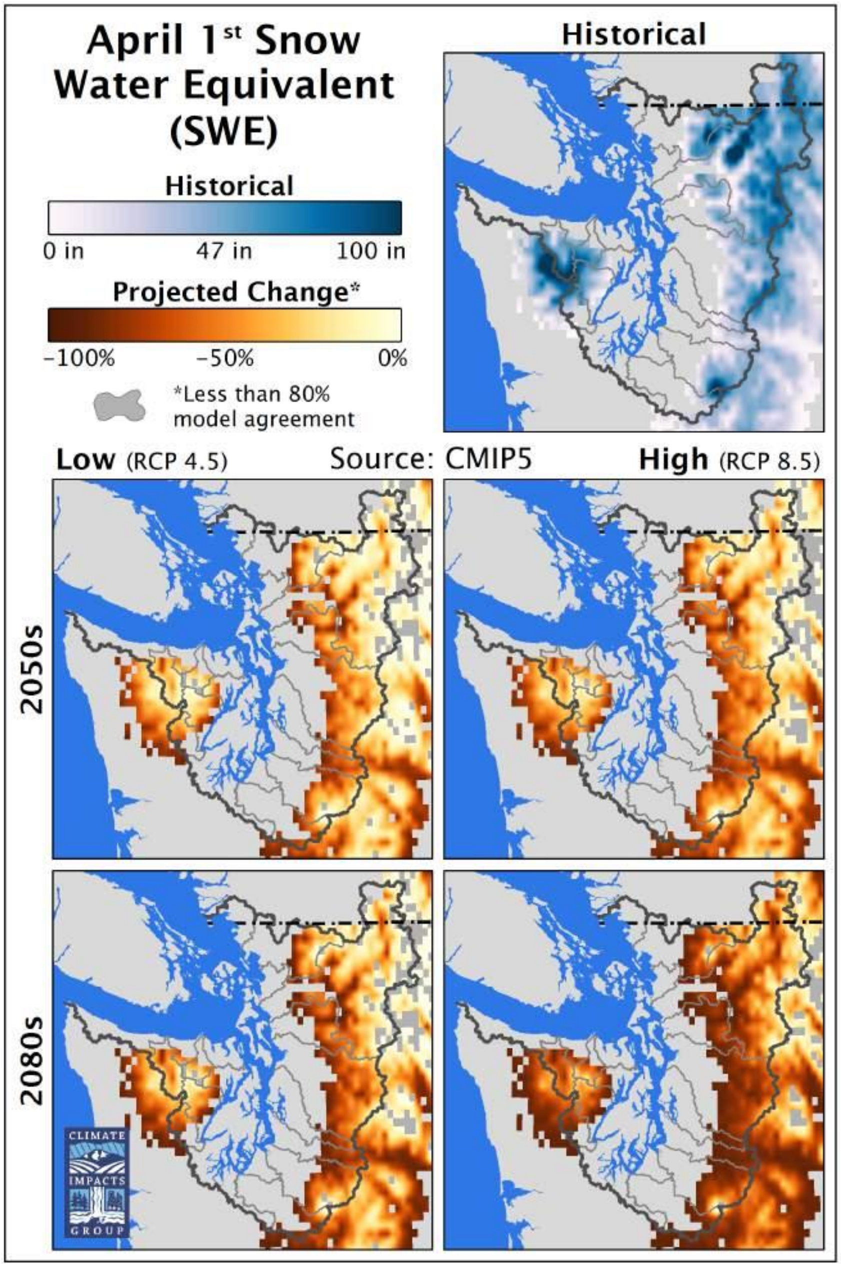

Figure C-10b. April 1st Snow Water Equivalent, newer projections. As in Figure C-10a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

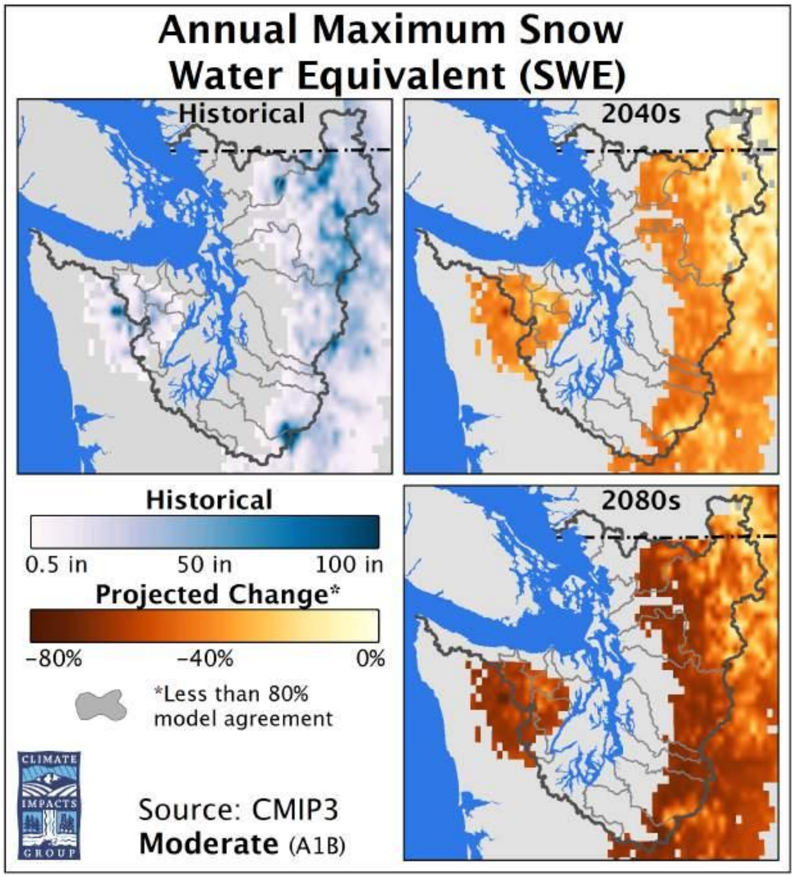

Figure C-11a. Annual Maximum Snow Water Equivalent, previous projections. Maps show the historical and projected annual maximum snow water equivalent (SWE), a measure of the total amount of water contained in the snowpack. The figure compares historical conditions (1970-1999, in inches) with the projected change (in percent) for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds with an average historical April 1st SWE of at least 0.4 inch, and for which at least 8 out of the 10 models agree on the direction of change. White to dark blue shading on the historical map indicates areas which received highest levels of April 1st snow water equivalent in Puget Sound. Projected decreases in snow water equivelant are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

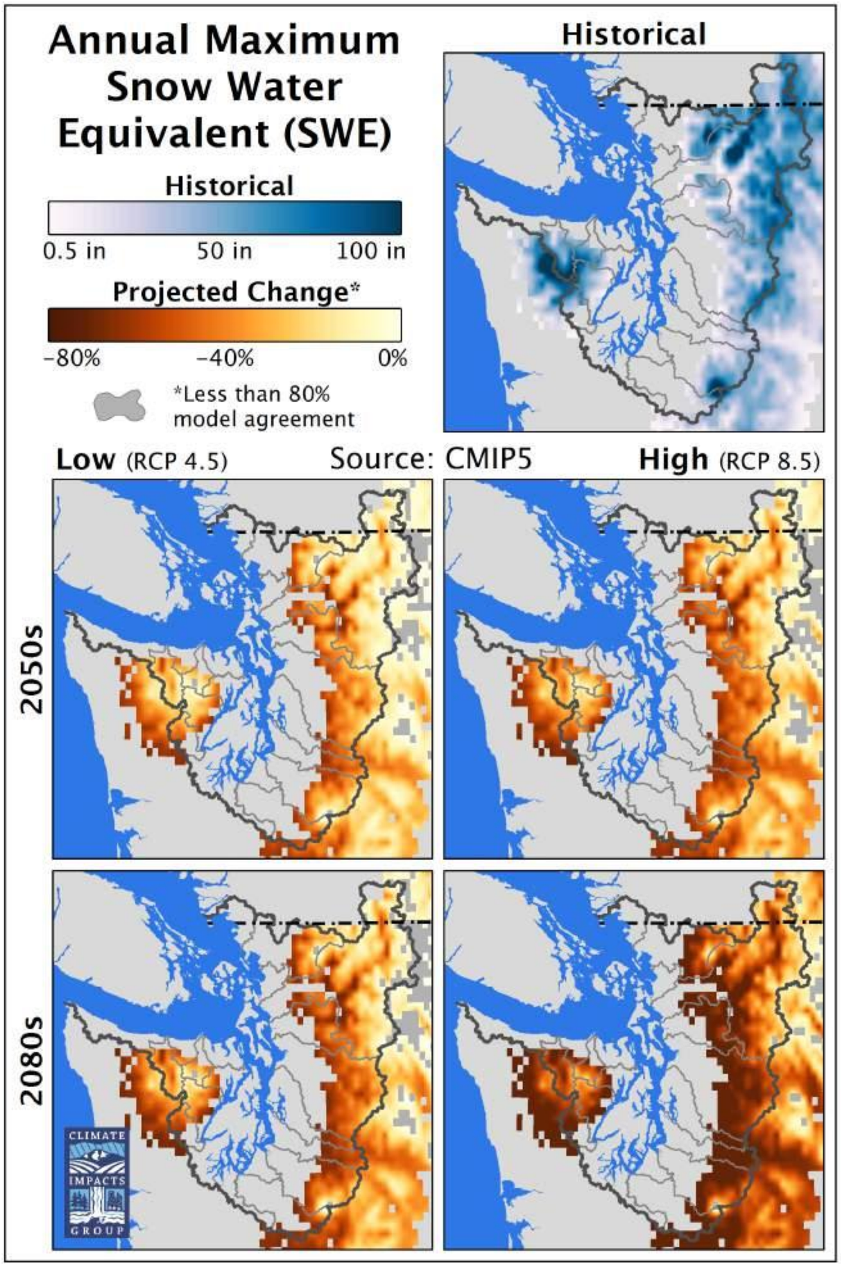

Figure C-11b. Annual Maximum Snow Water Equivalent, newer projections. As in Figure C-11a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013*[2] *report. Data source: Mote et al. 2015.*[1]

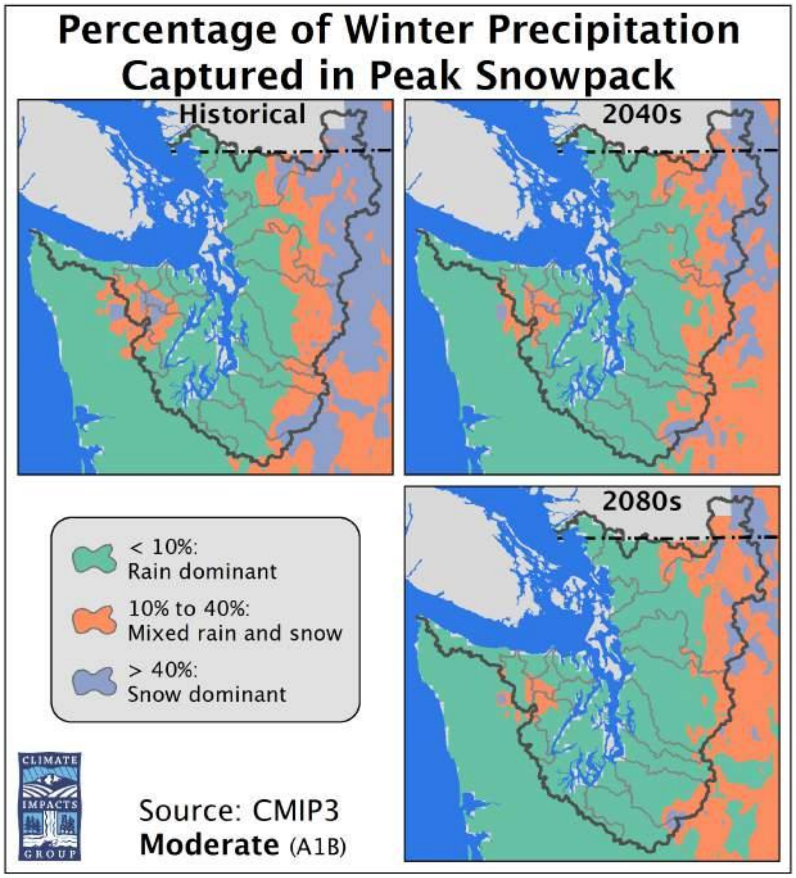

Figure C-12a. Percentage of Winter Precipitation Captured in Peak Snowpack, previous projections. Maps show the historical and projected percentage of winter (October-March) precipitation that is retained in the annual maximum snow water equivalent (SWE). The figure compares historical conditions (1970-1999) to the conditions projected by the average of ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Green shading in the maps indicates *warm ("rain-dominant") watersheds*, which retain less than 10% of winter precipitation as snow. Blue indicates *cold ("snow-dominant") watersheds,* that is, cold basins that retain more than 40% of their winter precipitation as snow. The most sensitive basins to warming are the *watersheds that are near the current snowline ("mixed rain and snow")*, shown in red. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

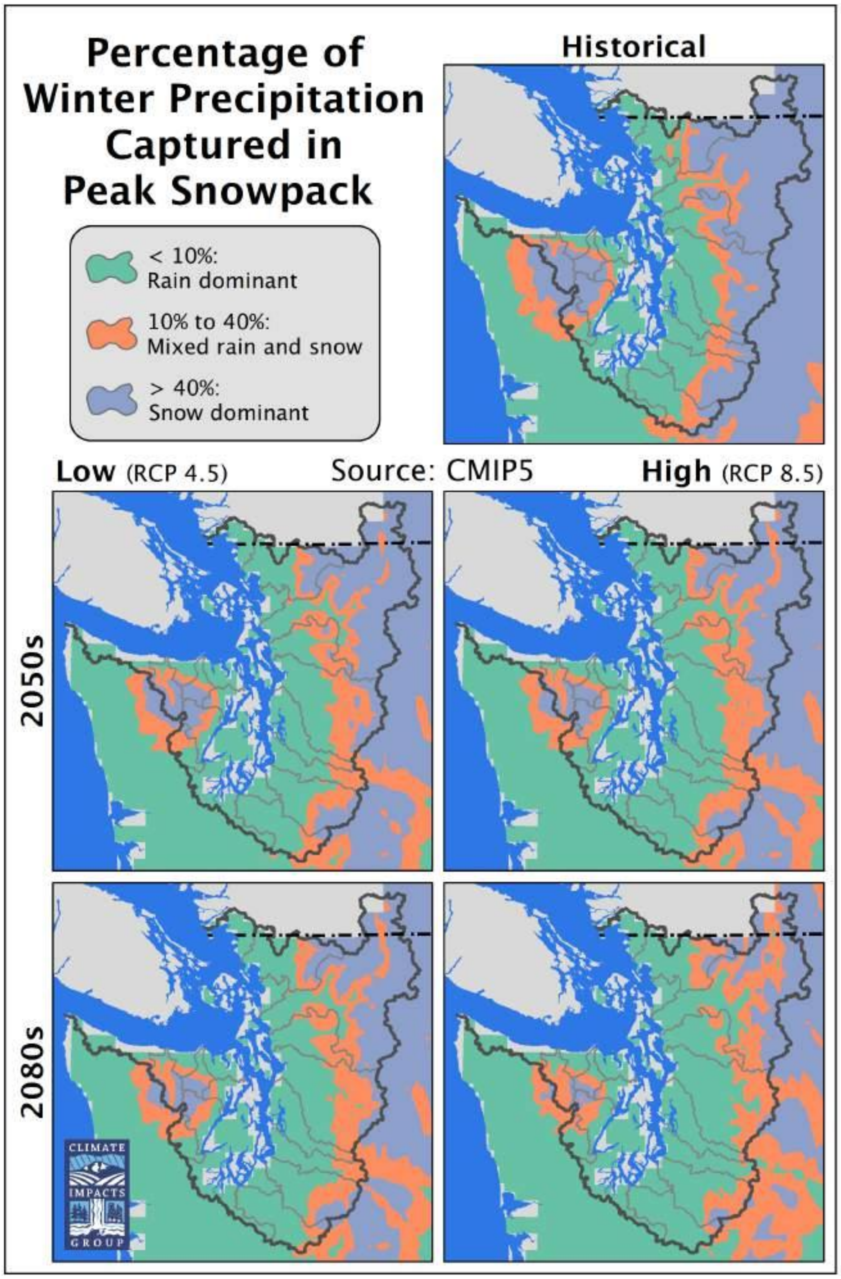

Figure C-12b. Percentage of Winter Precipitation Captured in Peak Snowpack, newer projections. As in Figure C-12a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

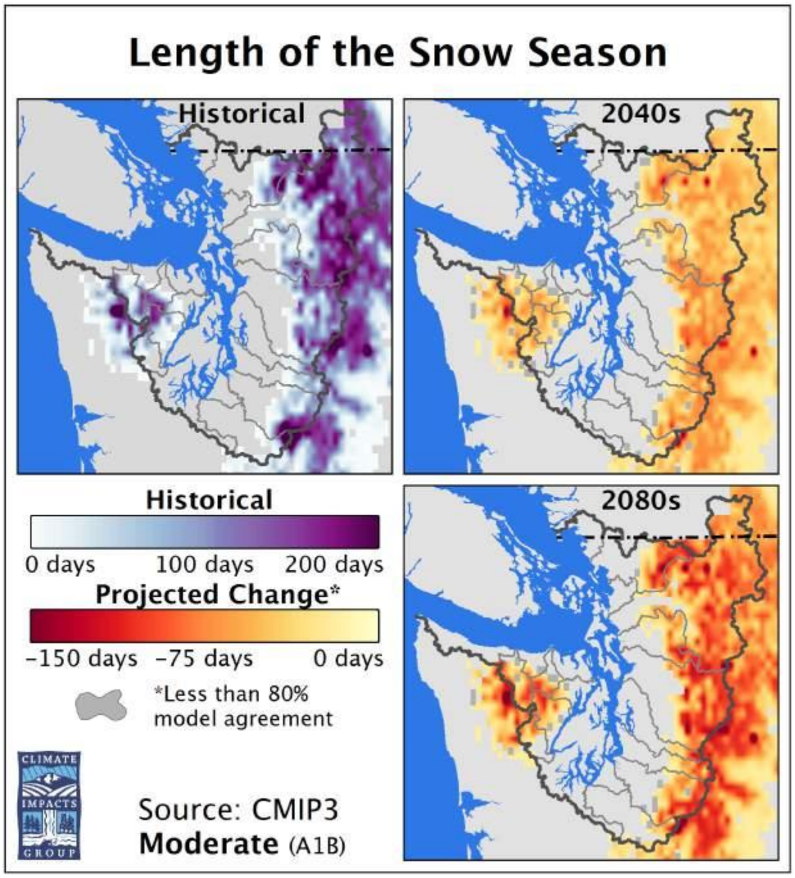

Figure C-13a. Length of the Snow Season, previous projections. Maps show the historical and projected change in the length of the snow season, defined as the number of days between the date of 10% accumulation and 90% melt, relative to annual maximum snow water equivalent (see Figures 11a and 11b). The figure compares historical conditions (1970-1999, in inches) with the projected change (in percent) for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Results are only shown for watersheds with an average historical April 1st SWE of at least 0.4 inch, and for which at least 8 out of the 10 models agree on the direction of change. White to dark blue shading on the historical map indicates areas which received highest levels of April 1st snow water equivalent in Puget Sound. Projected decreases in snow water equivelant are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

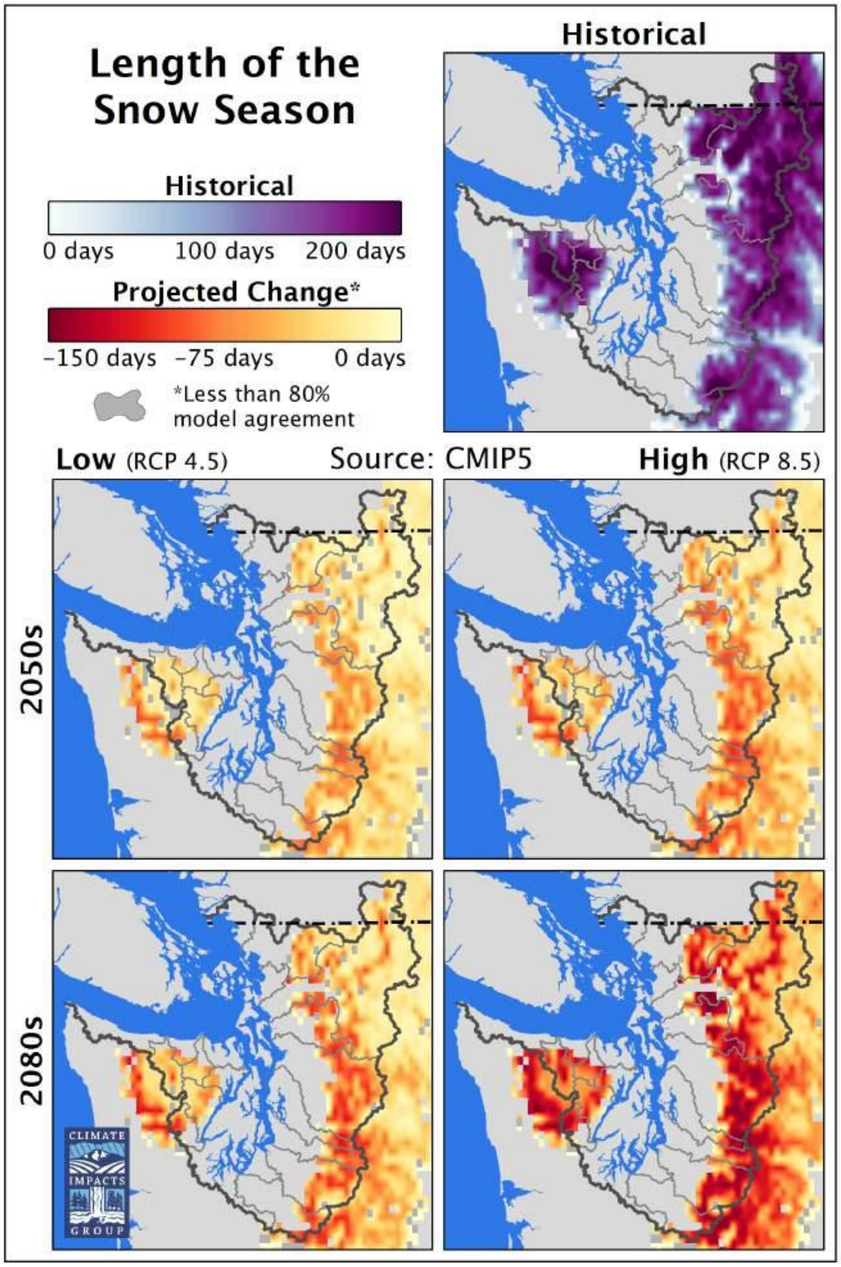

Figure C-13b. Length of the Snow Season, newer projections. As in Figure C-13a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

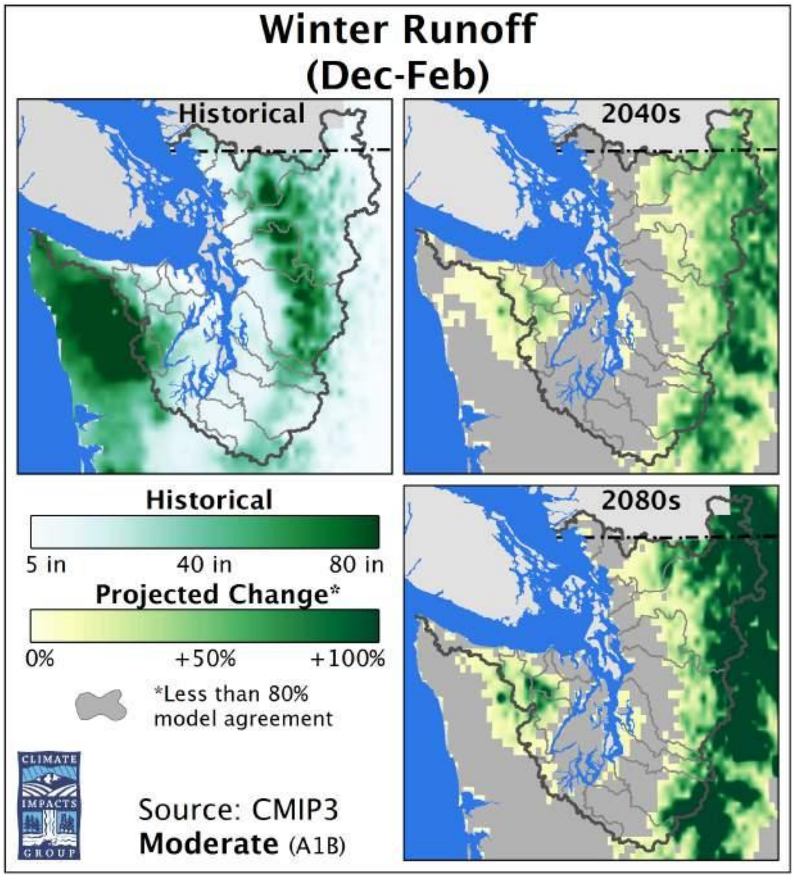

Figure C-14a. Winter runoff, previous projections. Maps show the historical and projected total summer (December-February) runoff. This includes any overland water flows in addition to subsurface runoff in shallow groundwater. The figure compares historical conditions (1970-1999, in inches) with the projected change (in percent) for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Dark green shading on the historical map indicates areas that have received highest levels of total winter precipitation in Puget Sound. Projected changes are depicted by the light to dark green shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Hamlet et al. 2013.[3]*

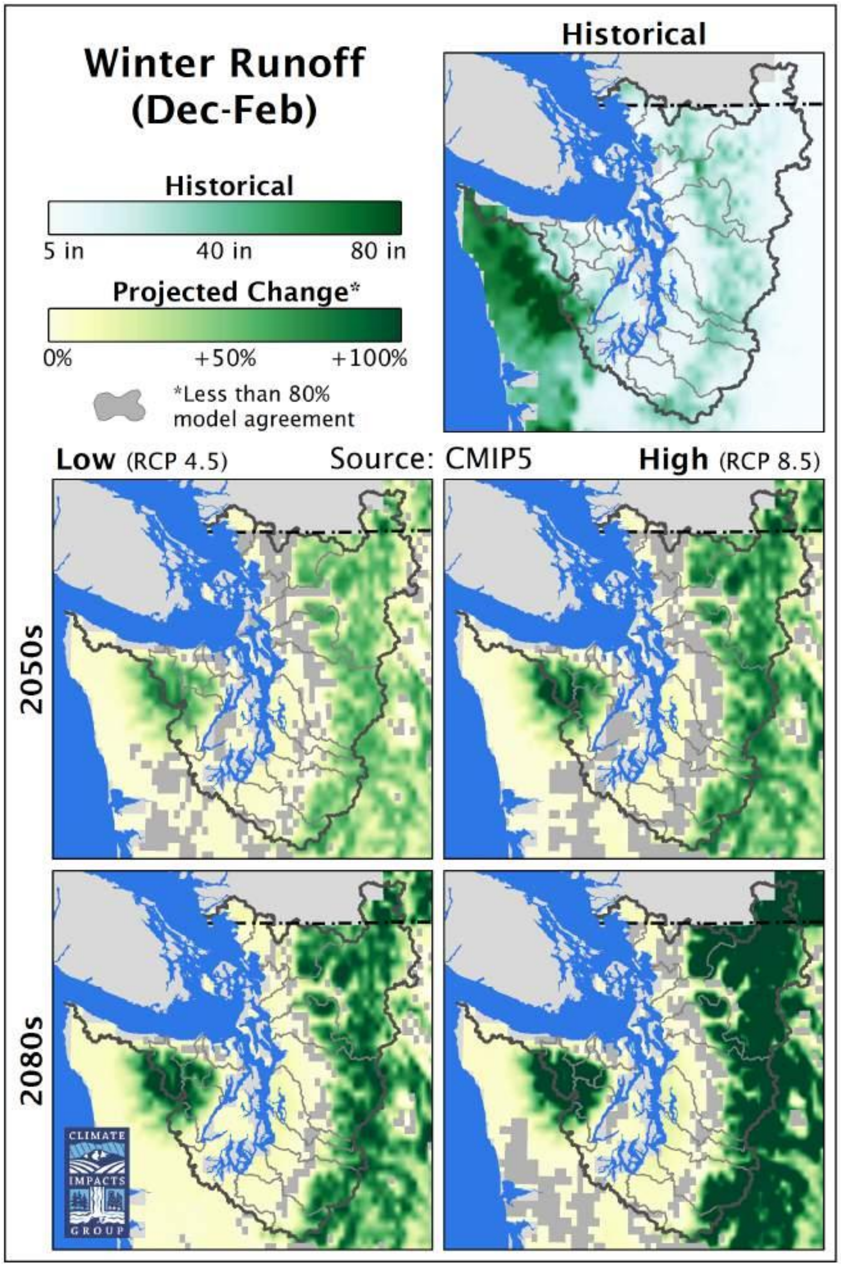

Figure C-14b. Winter runoff, newer projections. As in Figure C-14a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

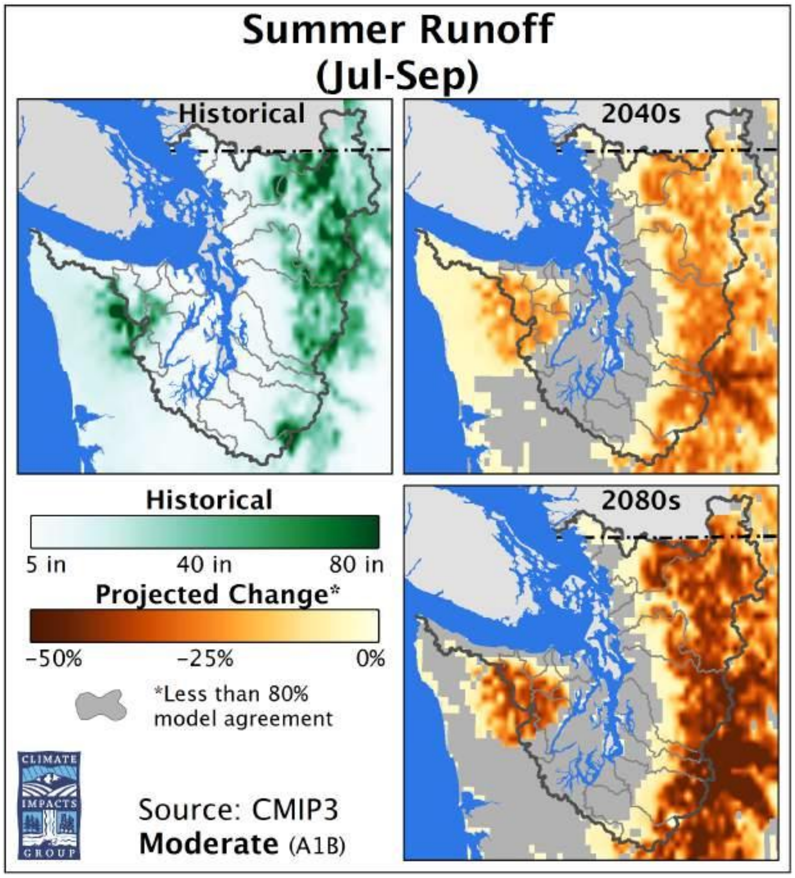

Figure C-15a. Summer runoff, previous projections. Maps show the historical and projected total summer (July-September) runoff. This includes any overland water flows in addition to subsurface runoff in shallow groundwater. The figure compares historical conditions (1970-1999, in inches) with the projected change (in percent) for ten global models, based on a 0.0625-degree (about 3 by 4.5 miles) resolution set of gridded projections. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Dark green shading on the historical map indicates areas that have received highest streamflow in Puget Sound. Projected changes are depicted by the yellow to red shading. *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007*[4] *report. Data source: Hamlet et al. 2013.*[3]

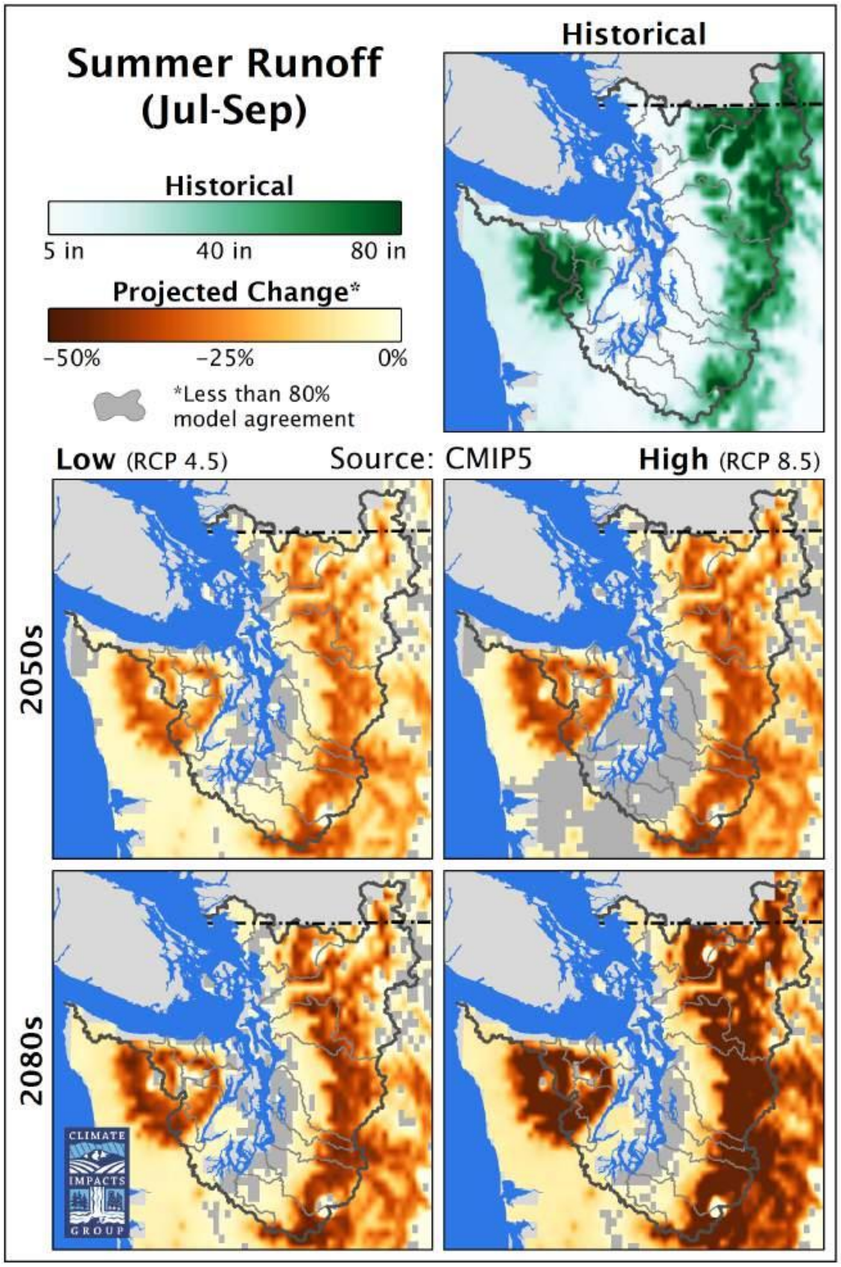

Figure C-15b. Summer runoff, newer projections. As in Figure C-15a, except showing results from the current generation of climate model projections. Instead of the 2040s, mid-century projections are shown for the 2050s (2040-2069), and projections are included for two greenhouse gas scenarios: one low (RCP 4.5) and one high (RCP 8.5). *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP5 projections used in the IPCC 2013[2] report. Data source: Mote et al. 2015.[1]*

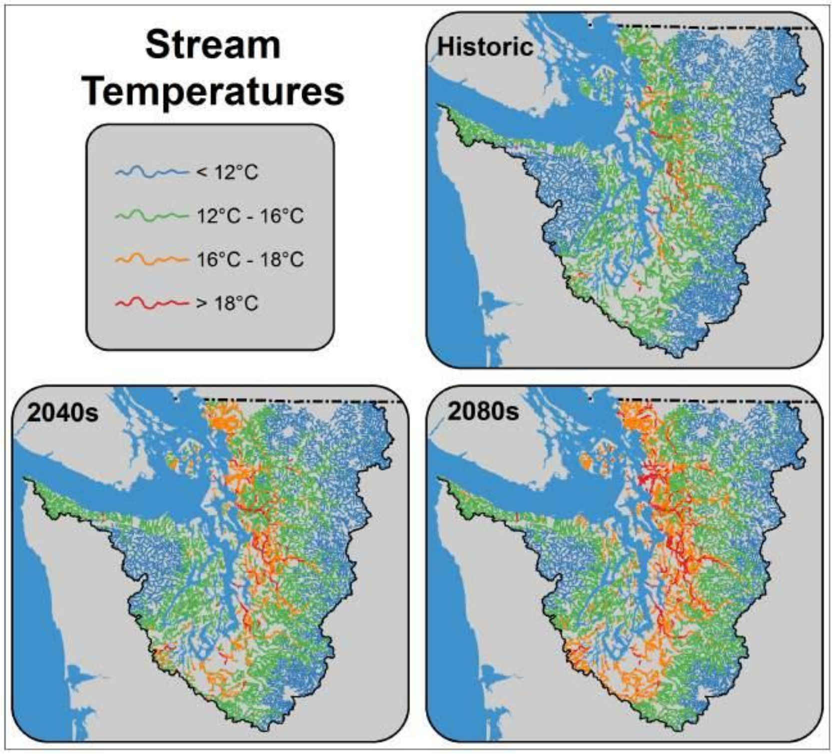

Figure C-16. Average August Stream Temperature. Maps show the historical and projected stream temperatures (in °C), for each 1-km (~0.6 mile) stream segment in the Puget Sound basin. The figure compares results for historical conditions (1970-1999) to projected future conditions for an average of ten global models. Two time periods are considered: the 2040s (2030-2059) and the 2080s (2070-2099), based on a moderate greenhouse gas scenario (A1B). Color-coding is based on temperature thresholds that are commonly used to assess habitat suitability for salmon.[7] *Figure created by Jonathan Picchi-Wilson, Western Washington University, based on the CMIP3 projections used in the IPCC 2007[4] report. Data source: Isaak et al. 2011.*[8]

APPENDIX D

Graphs of Streamflow Change for Major Puget Sound Watersheds

This appendix contains graphs of the historical and projected changes in streamflow for the 12 major Puget Sound watersheds analyzed in this report (see Section 3). Results are shown for changes in monthly average streamflow as well as peak and low flow statistics. As in Appendices B and C, results are included for the following two datasets:

- ***Integrated Scenarios for the Future Northwest Environment.*** The current set of projections, developed by Mote et al. in 2015,[1] which stem from the newer 2013 IPCC report,[2] and

- ***The Pacific Northwest Hydroclimate Scenarios Project.*** A previous set of projections, developed by Hamlet et al. in 2010,[3] which are based on the climate projections used in the IPCC's 2007 report.[4]

The global climate model projections that form the basis of these two datasets stem from the current and previous generations of the Coupled Model Intercomparison Project ("CMIP", see Section 1). The previous projections originate from the CMIP3 archive, while the current projections come from the newer CMIP5 archive.[5,6] Each CMIP experiment is associated with a different set of greenhouse gas scenarios.[A] For simplicity, each figure is labeled with the CMIP experiment on which it is based ("CMIP3" or "CMIP5"), as well as the name(s) of the greenhouse gas scenarios that are the basis of the projections shown in each figure (e.g. "Moderate (A1B)", or "Low (RCP 4.5)").

Projections are included for the following climate and hydrologic variables:

Figures D-1a, b:	Nooksack
Figures D-2a, b:	Samish
Figures D-3a, b:	Skagit
Figures D-4a, b:	Stillaguamish
Figures D-5a, b:	Snohomish
Figures D-6a, b:	Cedar
Figures D-7a, b:	Green
Figures D-8a, b:	Nisqually
Figures D-9a, b:	Puyallup
Figures D-10a, b:	Skokomish
Figures D-11a, b:	Dungeness
Figures D-12a, b:	Elwha

[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 more details.

Each of the following pages includes three plots:

1. The larger plots on the left side of each page show monthly average streamflow for the water year, comparing historical (black) to the range among future projections (colored shading). Results for mid-century are shown in the top plot (2040s for CMIP3, 2050s for CMIP5), and for the end of the century (2080s) on the bottom. Thick colored lines show the average among 10 climate models, and different colors are used to either distinguish among time periods (CMIP3) or between high and low greenhouse gas scenarios (CMIP5).

2. The top-right plots show the projected changes in the annual maximum of daily flows. Results for mid-century are on the left (2040s for CMIP3, 2050s for CMIP5), while the end of century (2080s) projections are on the right. Results are shown for the 10-, 50-, and 100-year return interval flows, with each dot representing one of the 10 model projections for each greenhouse gas scenario. Bars indicate the interquartile range (25^{th} to 75^{th} percentiles) of the projections. Note that for the CMIP5-based projections, there is a range among historical simulations, reflecting the fact that each model has a separate historical simulation.

3. The bottom-right plots show the projected changes in the annual minimum in 7-day streamflow. The format is identical to that used for the peak flows plots, except that results are shown for the 2- and 10-year return intervals.

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1 Mote, P. W., Rupp, D. E., Abatzoglou, J. T., Hegewisch, K. C., Nijssen, B., Lettenmaier, D. P., Stumbaugh, M., Lee, S.-Y., & Bachelet, D., 2015. Integrated Scenarios for the Future Northwest Environment. Version if relevant. USGS ScienceBase. Data set accessed 2015-03-02 at https://www.sciencebase.gov/catalog/item/5006eb9de4b0abf7ce733f5c

2 (IPCC) Intergovernmental Panel on Climate Change. 2013. *Working Group 1, Summary for Policymakers.* Available at: http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

3 Hamlet, A.F. et al., 2013. An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. *Atmosphere-Ocean* 51(4): 392-415. doi: 10.1080/07055900.2013.819555

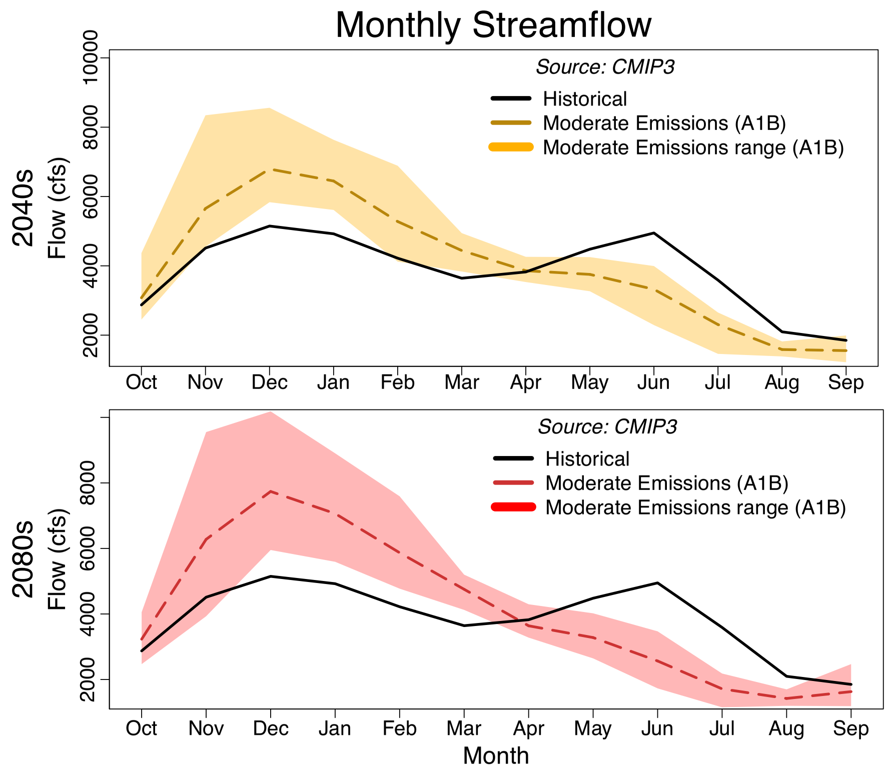
4 (IPCC) Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

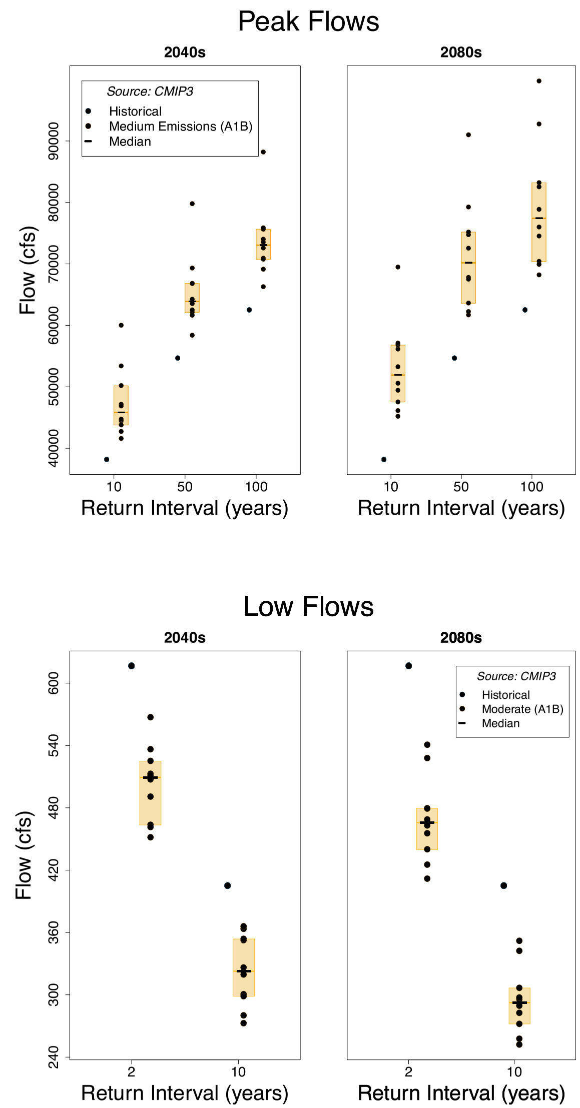
5 Taylor, K. E. et al., 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485-498, doi:10.1175/BAMS-D-11-00094.1

6 Knutti, R. et al., 2013. Climate model genealogy: Generation CMIP5 and how we got there. *Geophys. Res. Lett*, *40*, 1194-1199, doi:10.1002/grl.50256

Nooksack River Watershed

CMIP3 projections

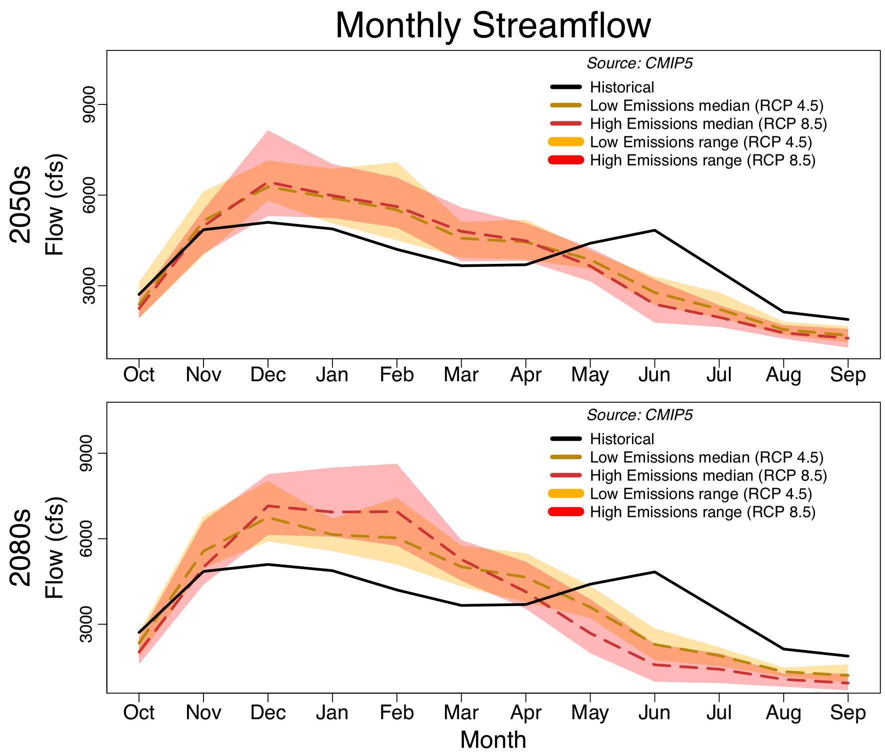


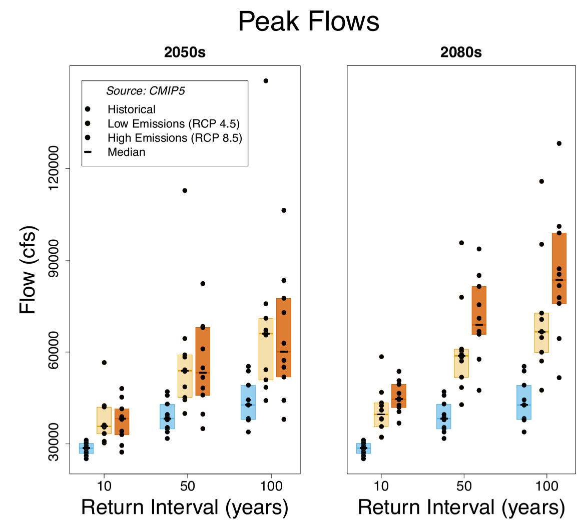


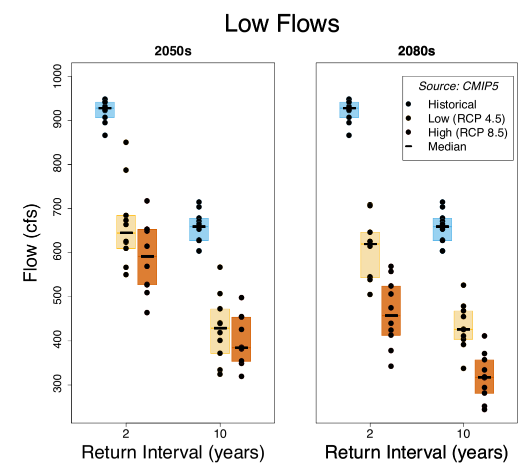
Figures D-1a. As described on Page D-2, for the Nooksack River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Nooksack River Watershed

CMIP5 projections



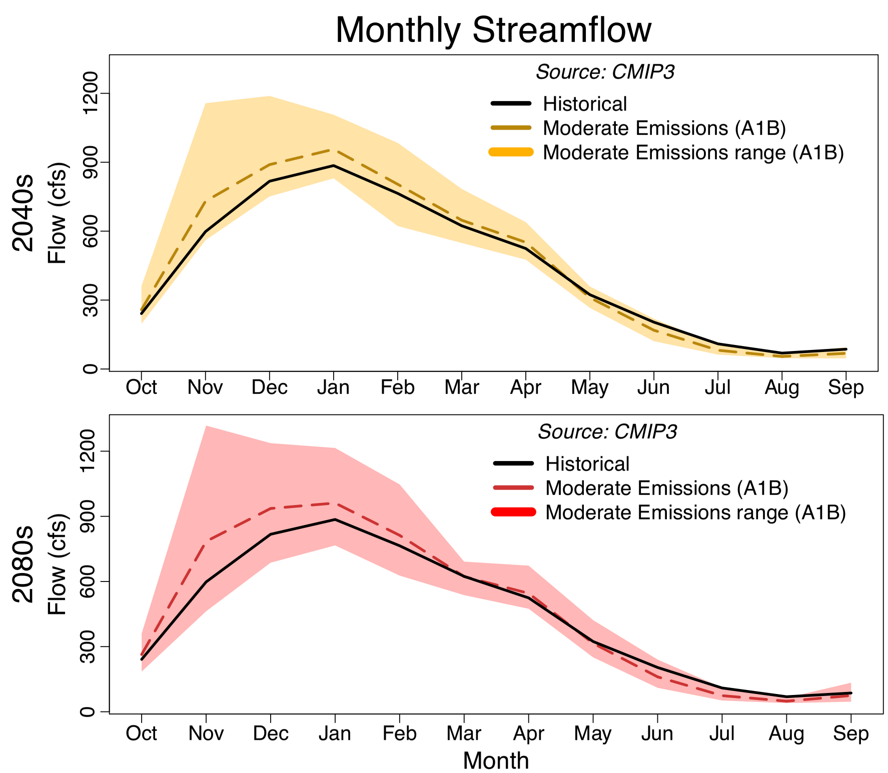


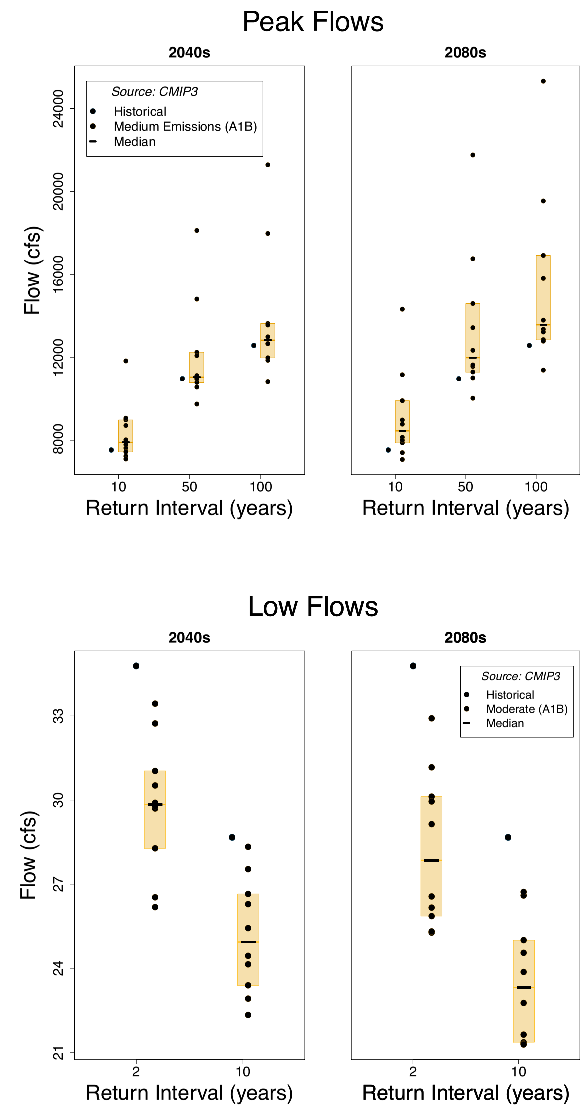


Figures D-1b. As described on Page D-2, for the Nooksack River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Samish River Watershed

CMIP3 projections

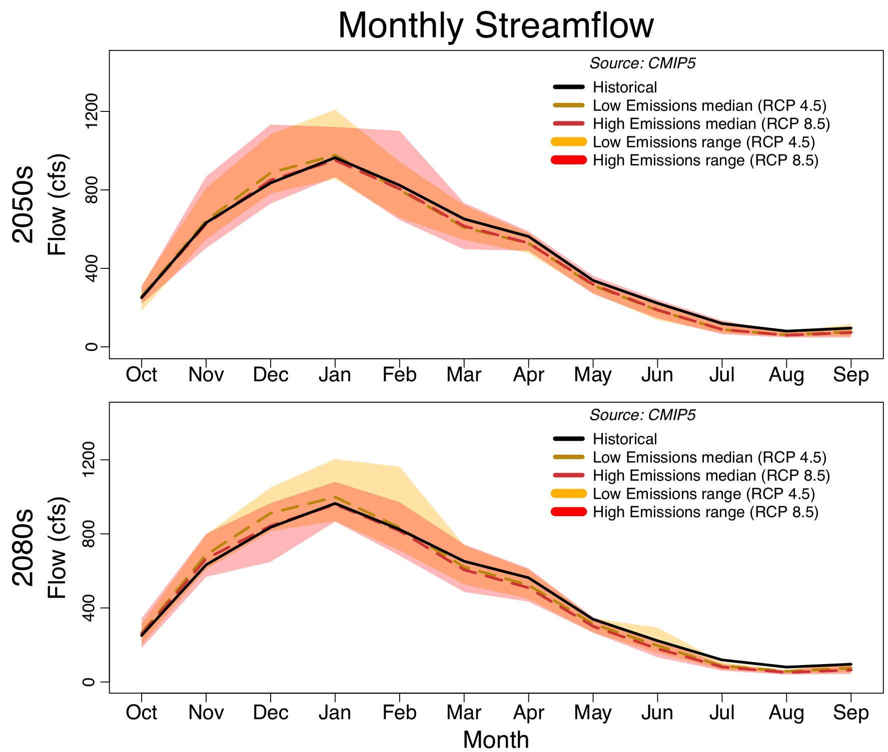


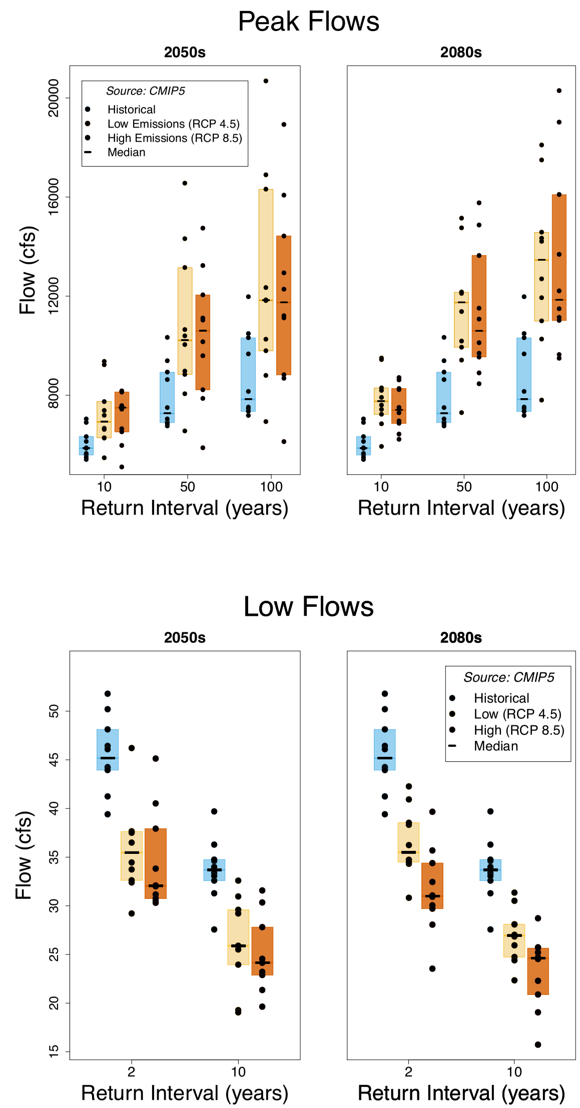


Figures D-2a. As described on Page D-2, for the Samish River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Samish River Watershed

CMIP5 projections

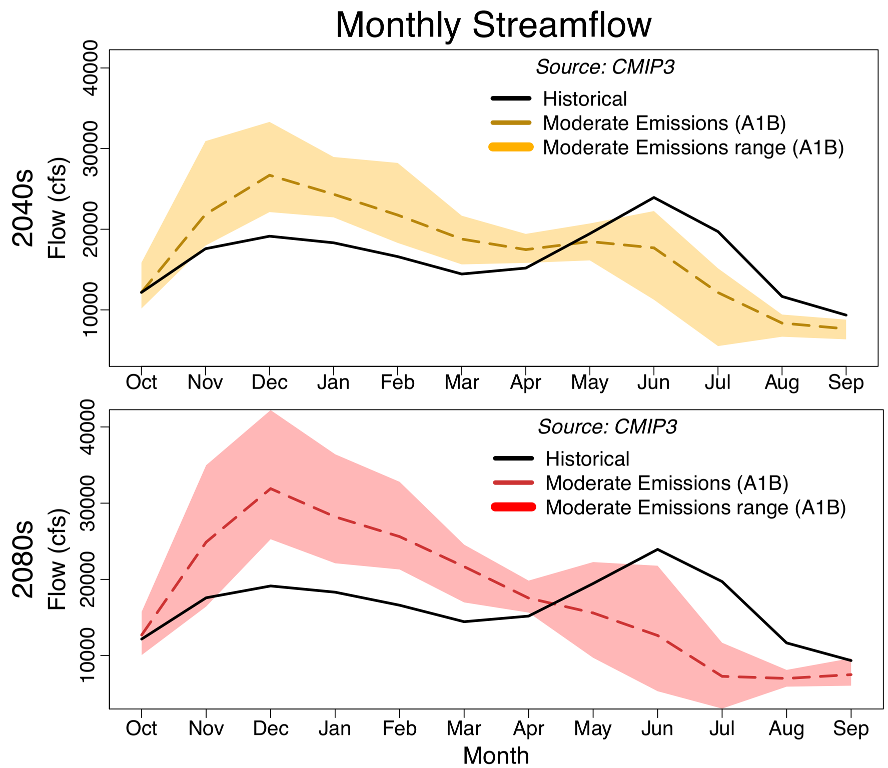


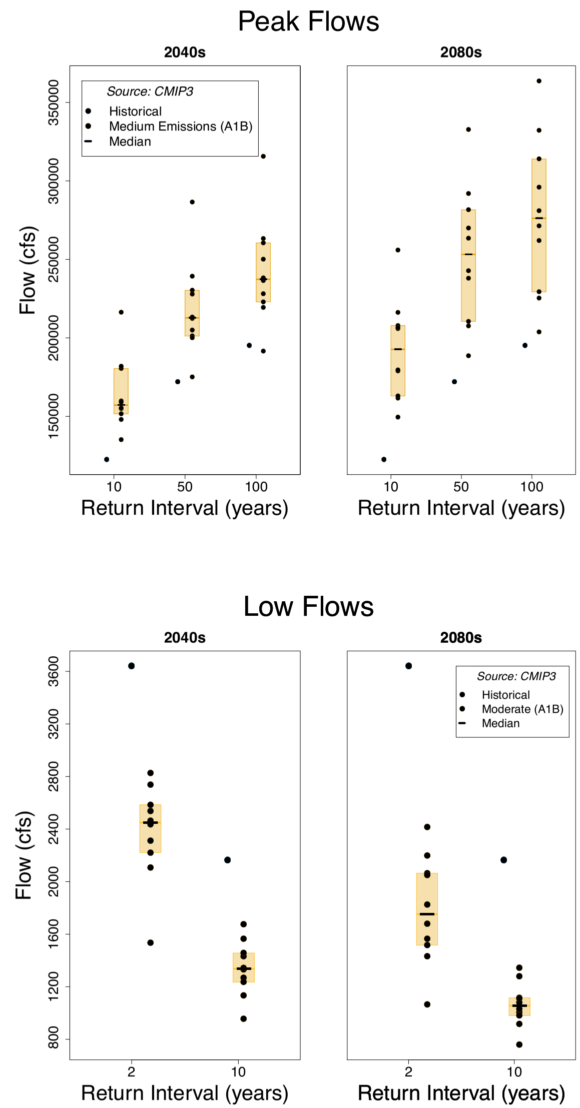


Figures D-2b. As described on Page D-2, for the Samish River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Skagit River Watershed

CMIP3 projections

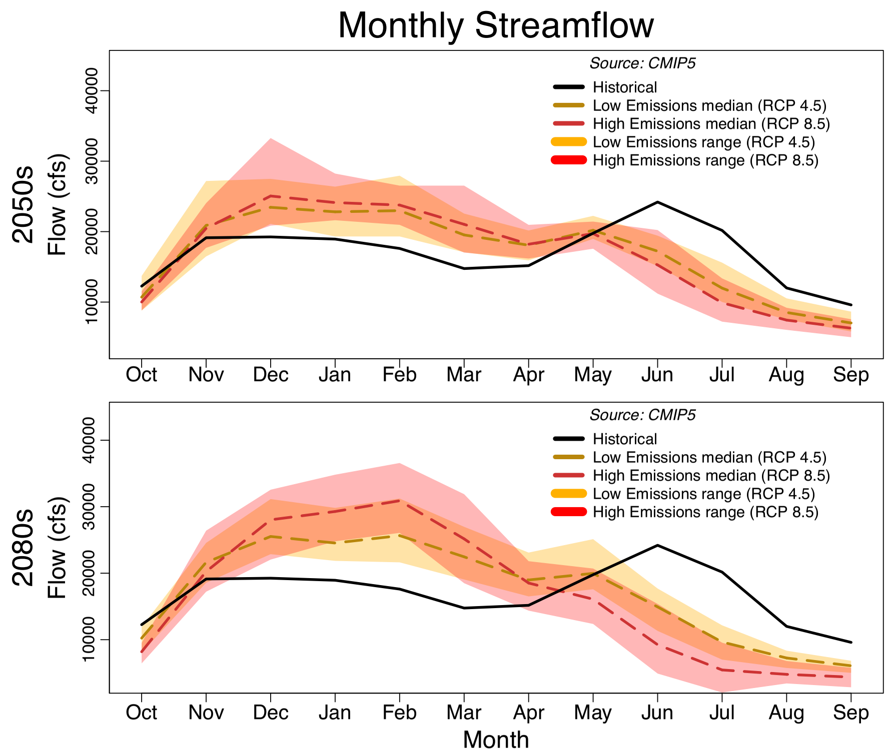


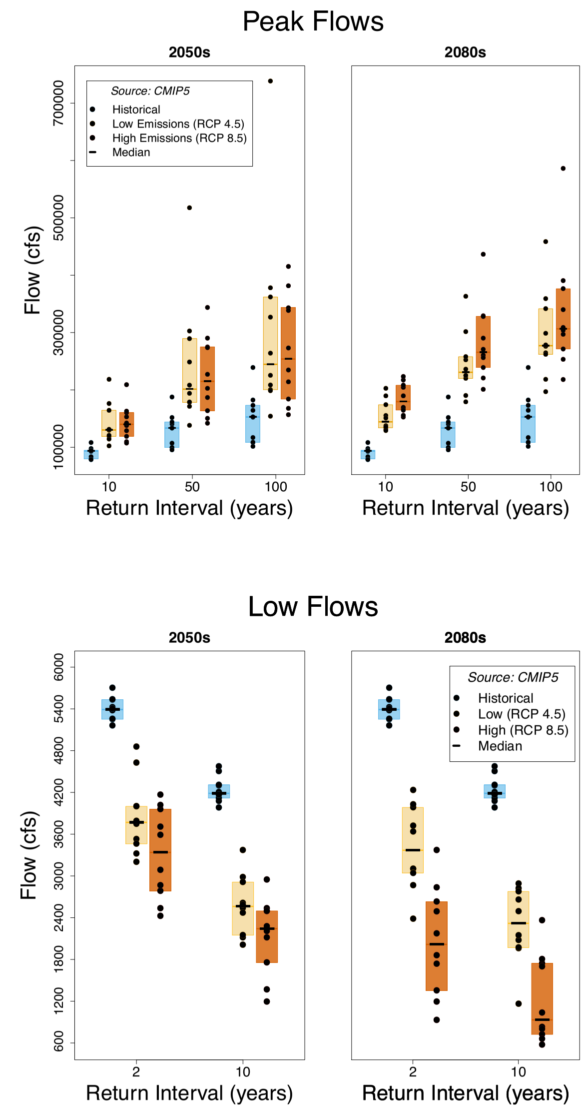


Figures D-3a. As described on Page D-2, for the Skagit River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Skagit River Watershed

CMIP5 projections

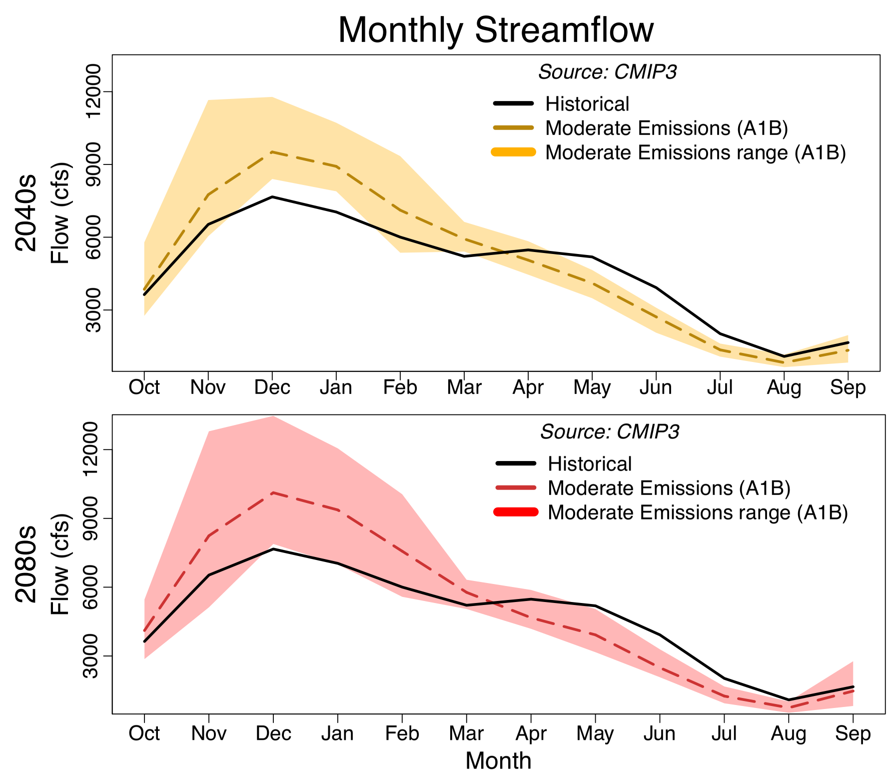


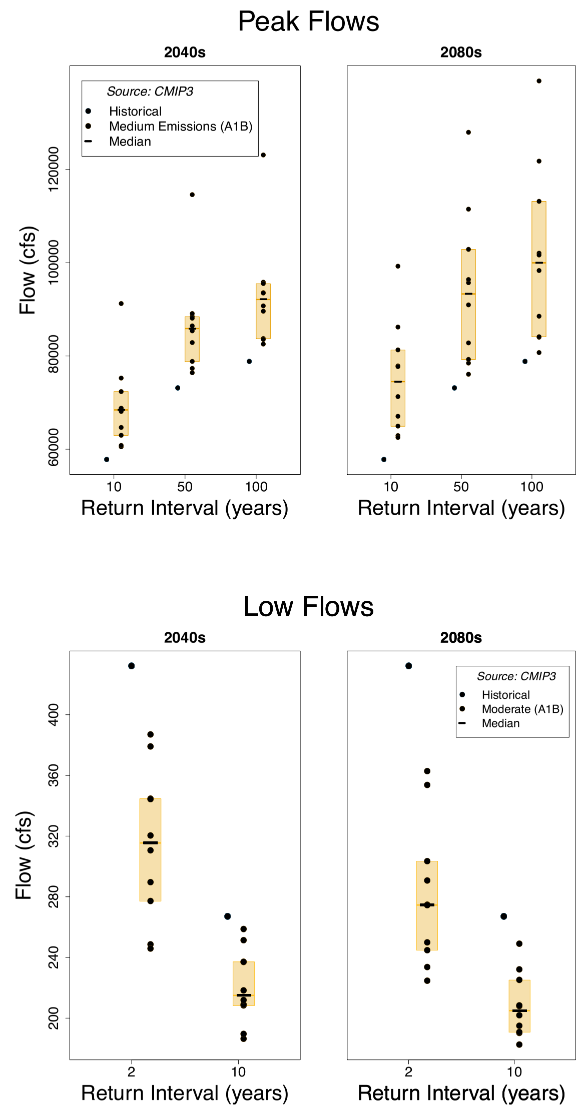


Figures D-3b. As described on Page D-2, for the Skagit River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Stillaguamish River Watershed

CMIP3 projections

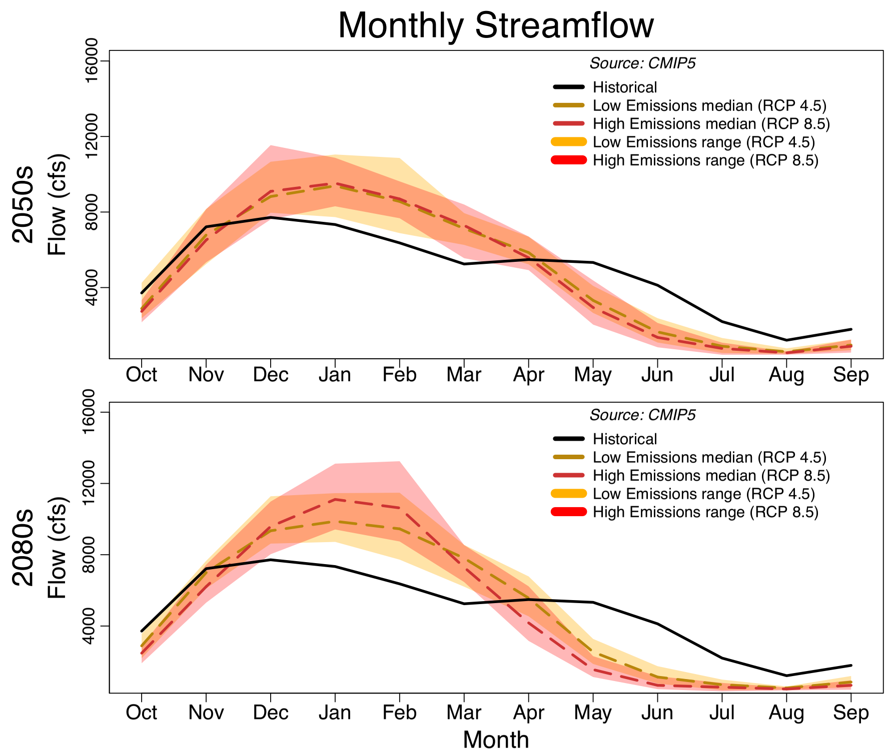


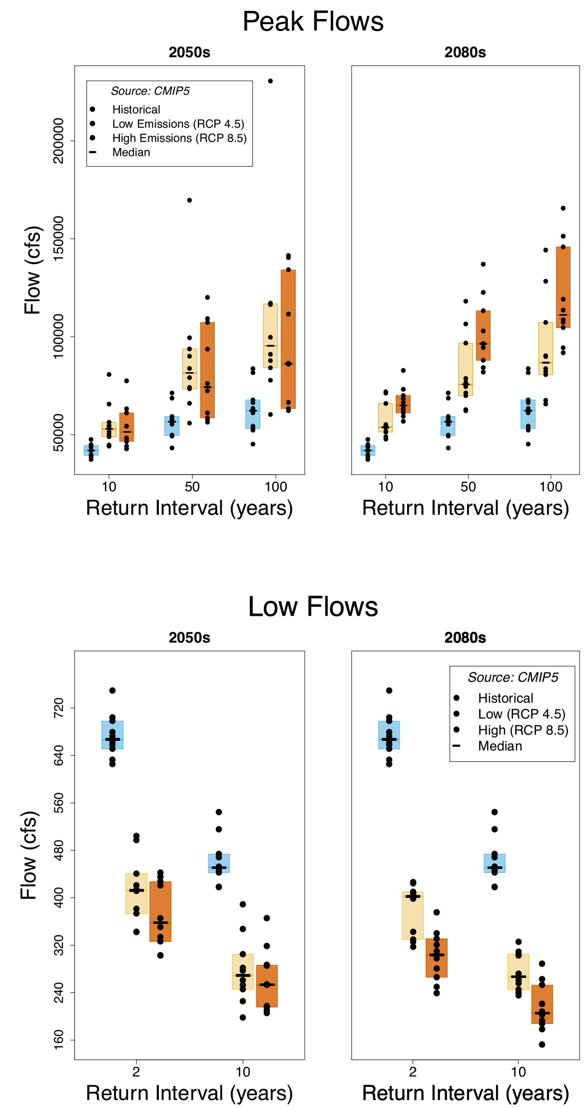


Figures D-4a. As described on Page D-2, for the Stillaguamish River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Stillaguamish River Watershed

CMIP5 projections

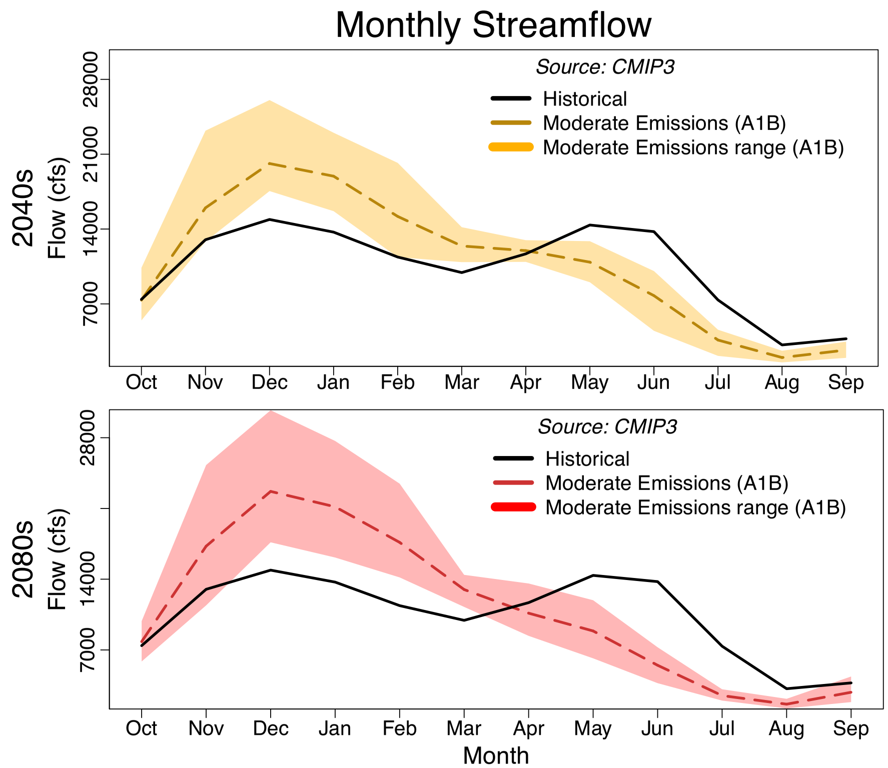


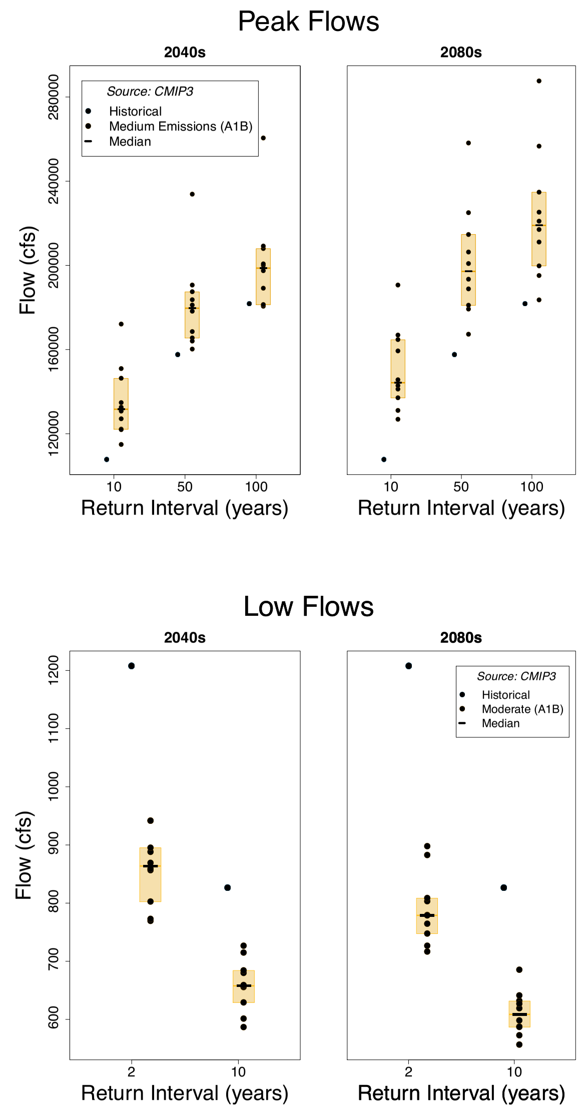


Figures D-4b. As described on Page D-2, for the Stillaguamish River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Snohomish River Watershed

CMIP3 projections

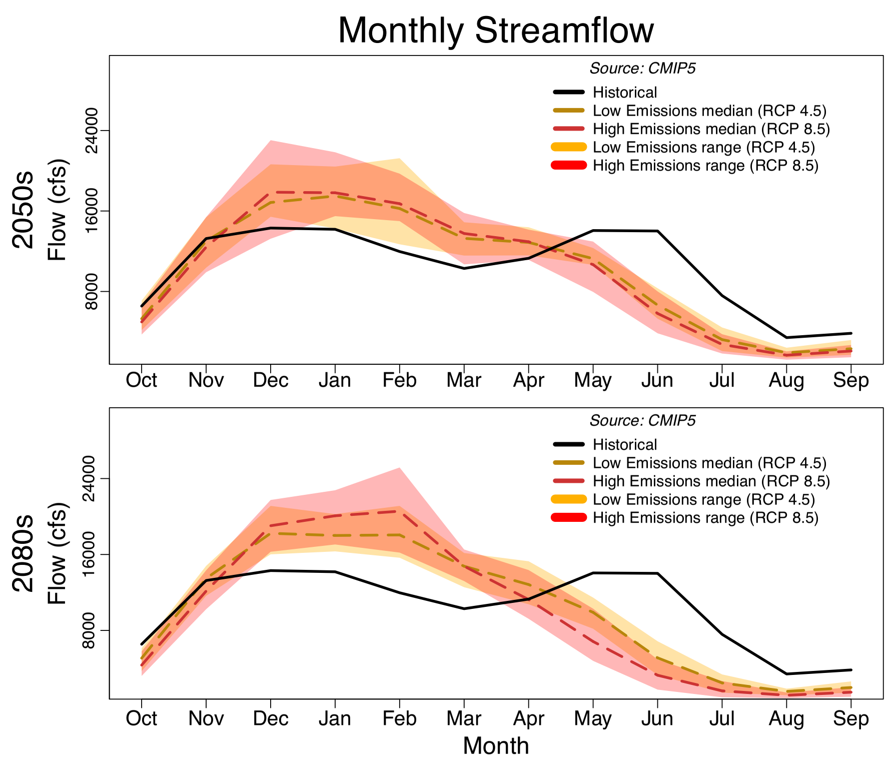


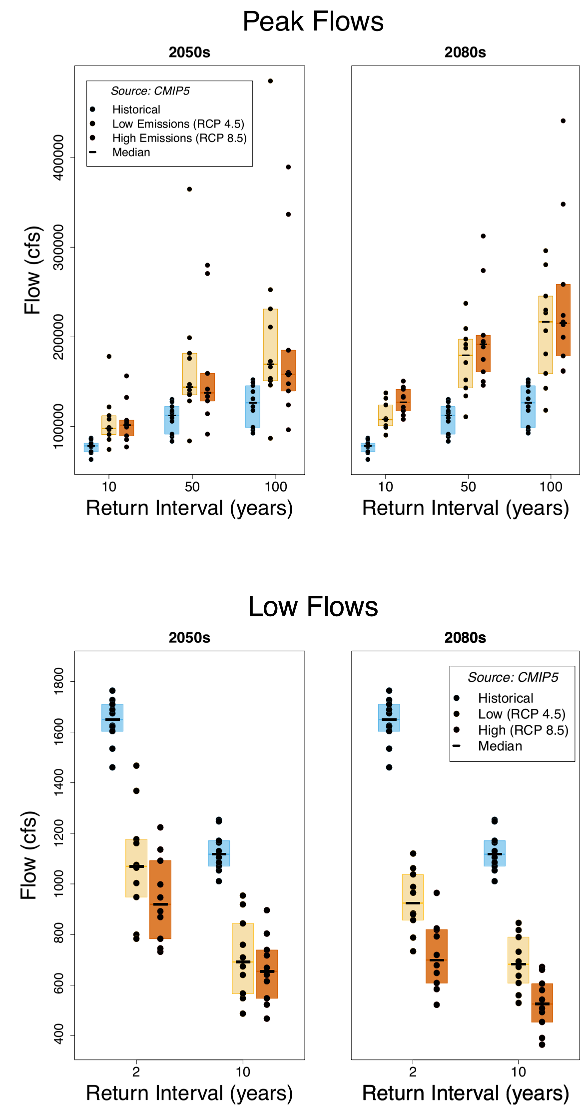


Figures D-5a. As described on Page D-2, for the Snohomish River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Snohomish River Watershed

CMIP5 projections





Figures D-5b. As described on Page D-2, for the Snohomish River watershed, based on the CMIP5-based hydrologic projections.[1,2]

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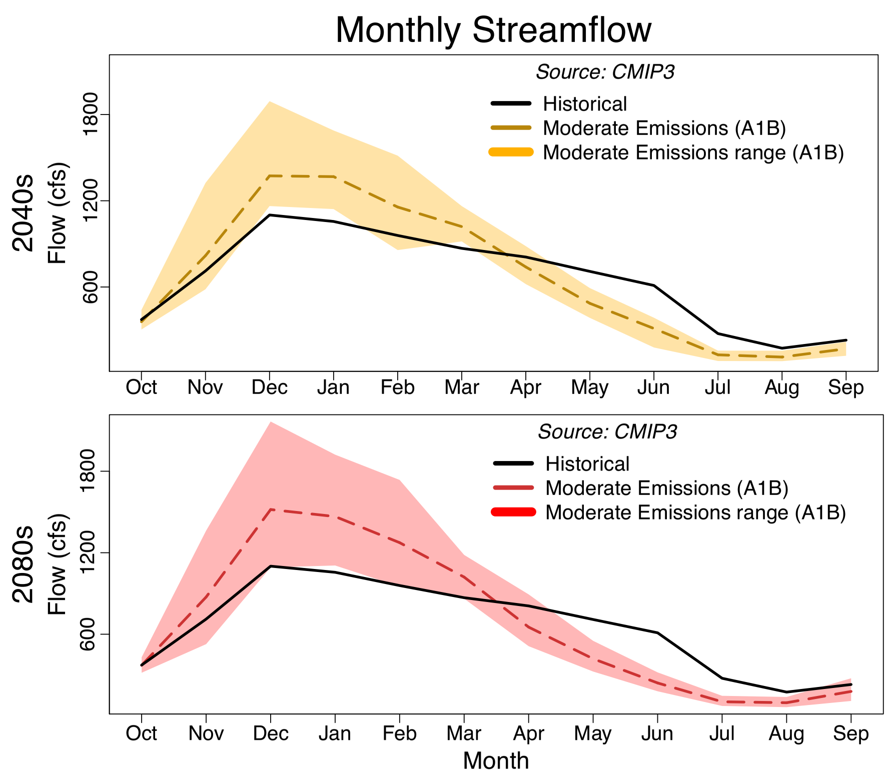
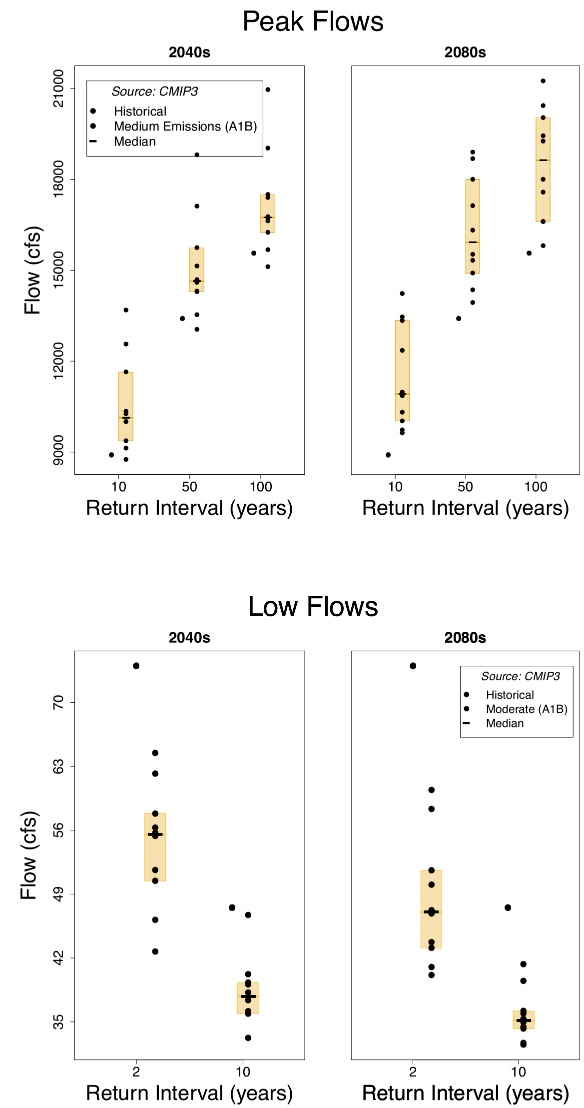
Cedar River Watershed

CMIP3 projections

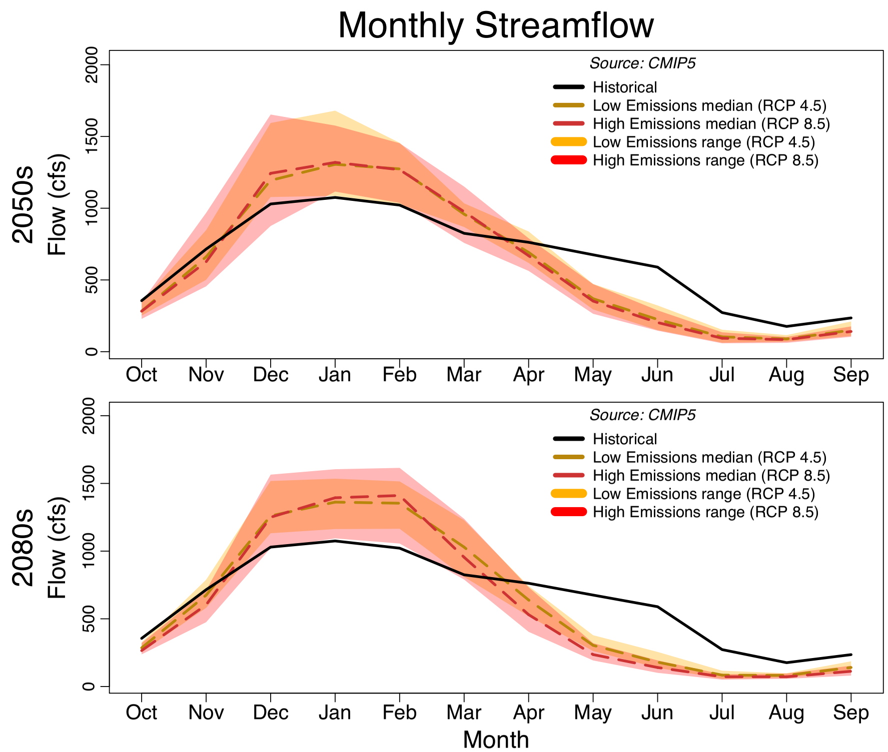


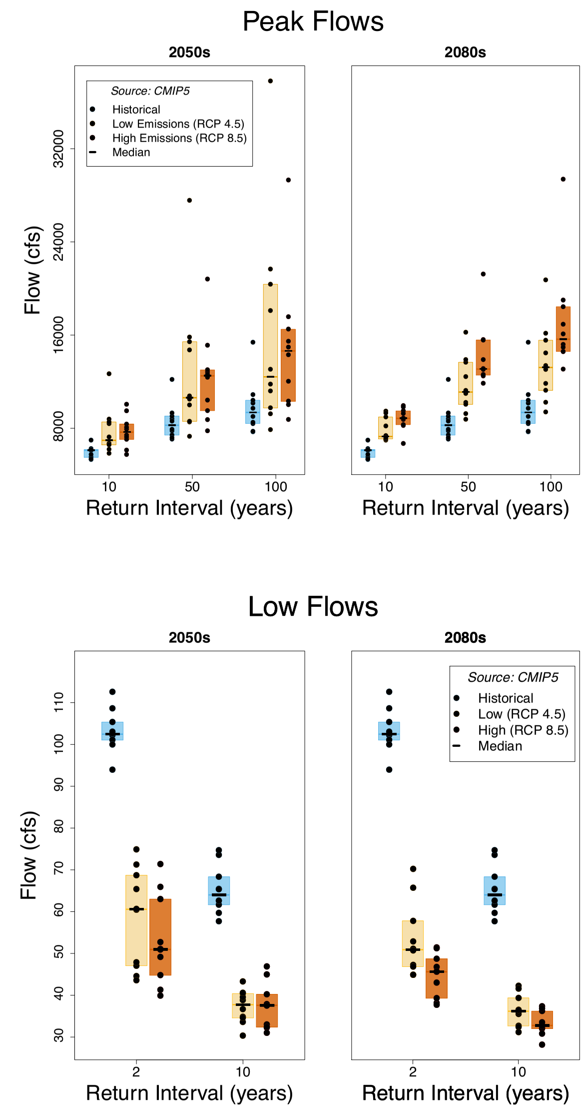


Figures D-6a. As described on Page D-2, for the Cedar River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Cedar River Watershed

CMIP5 projections

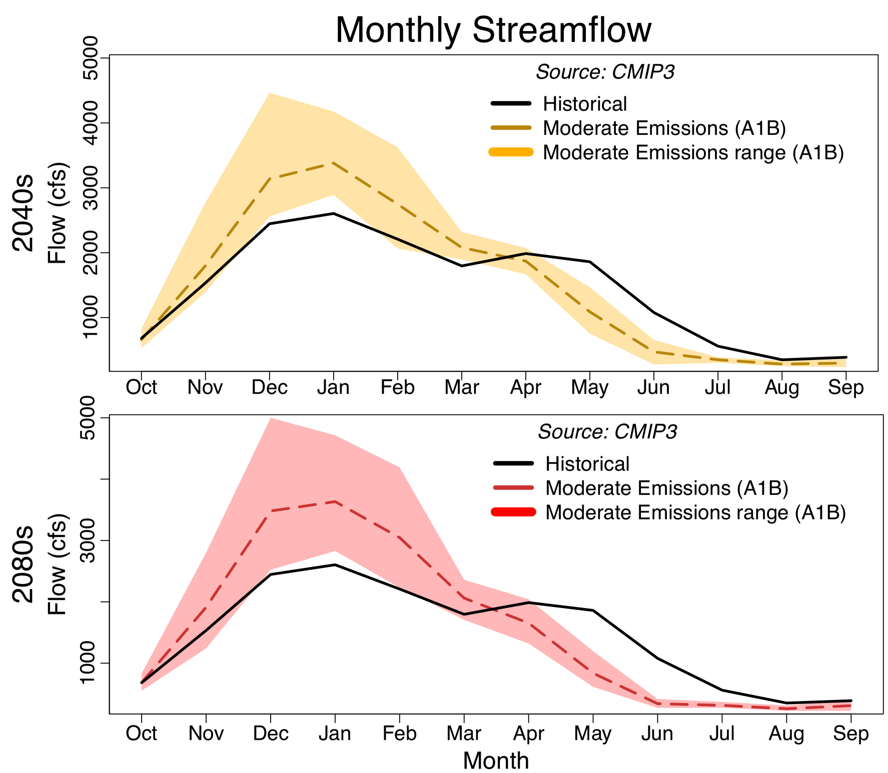


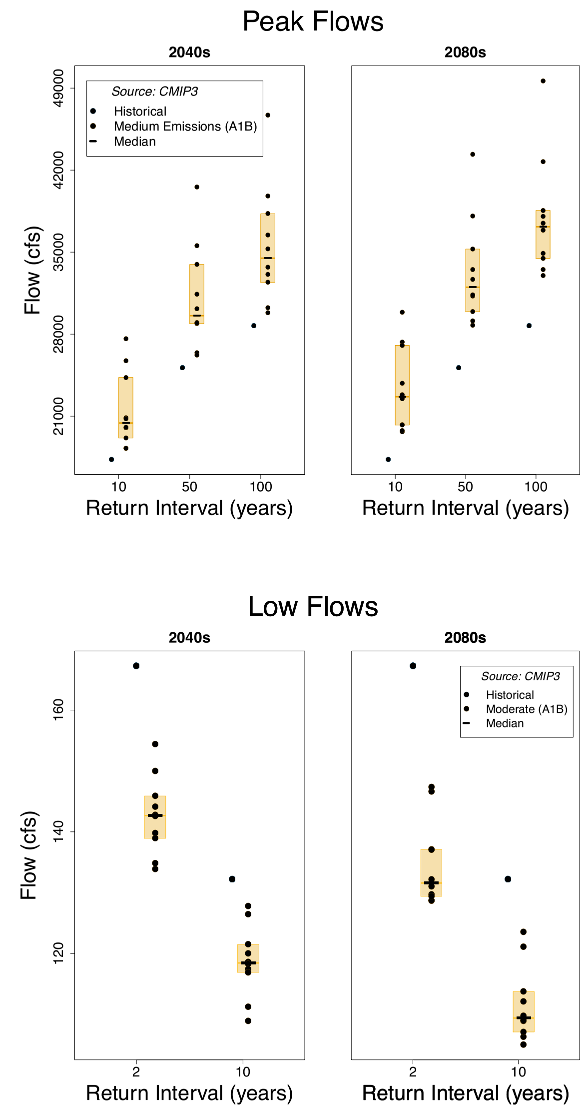


Figures D-6b. As described on Page D-2, for the Cedar River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Green River Watershed

CMIP3 projections



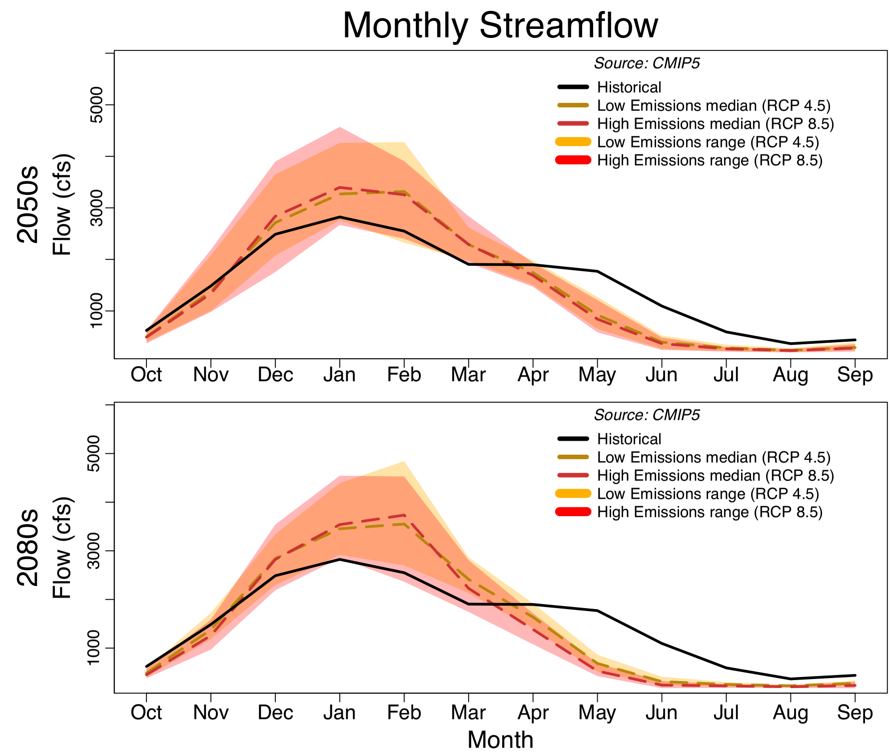


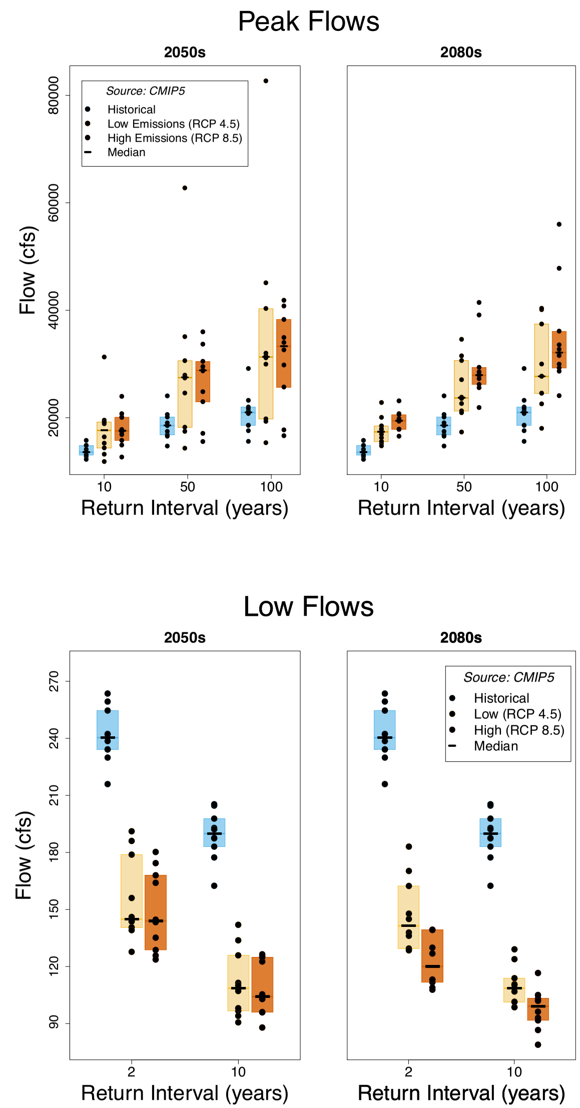
Figures D-7a. As described on Page D-2, for the Green River watershed, based on the CMIP3-based hydrologic projections.[3,4]

AR029056

Green River Watershed

CMIP5 projections

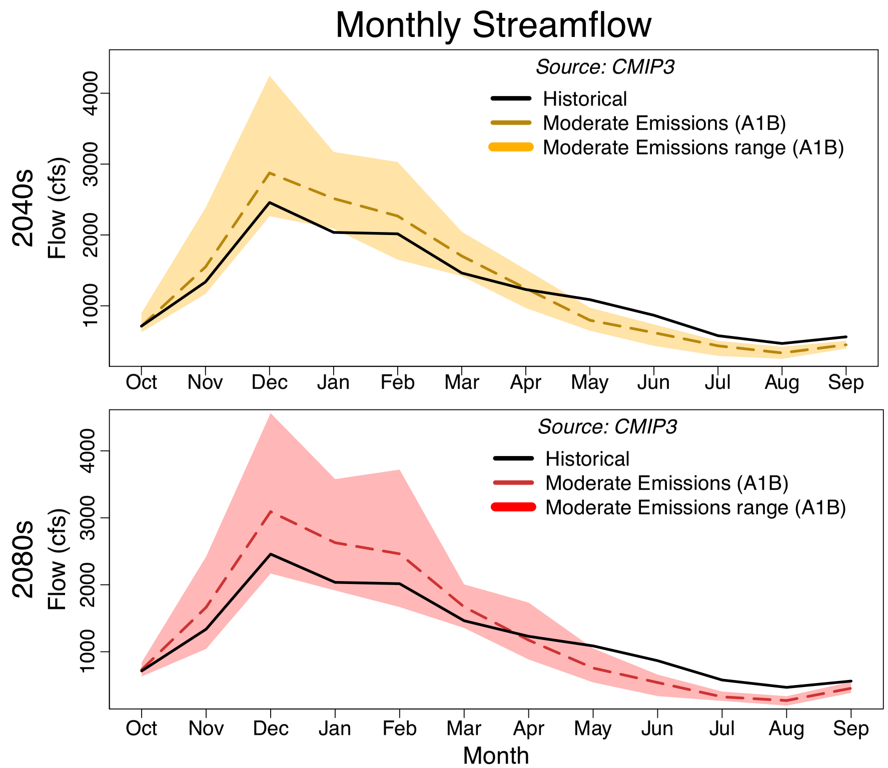


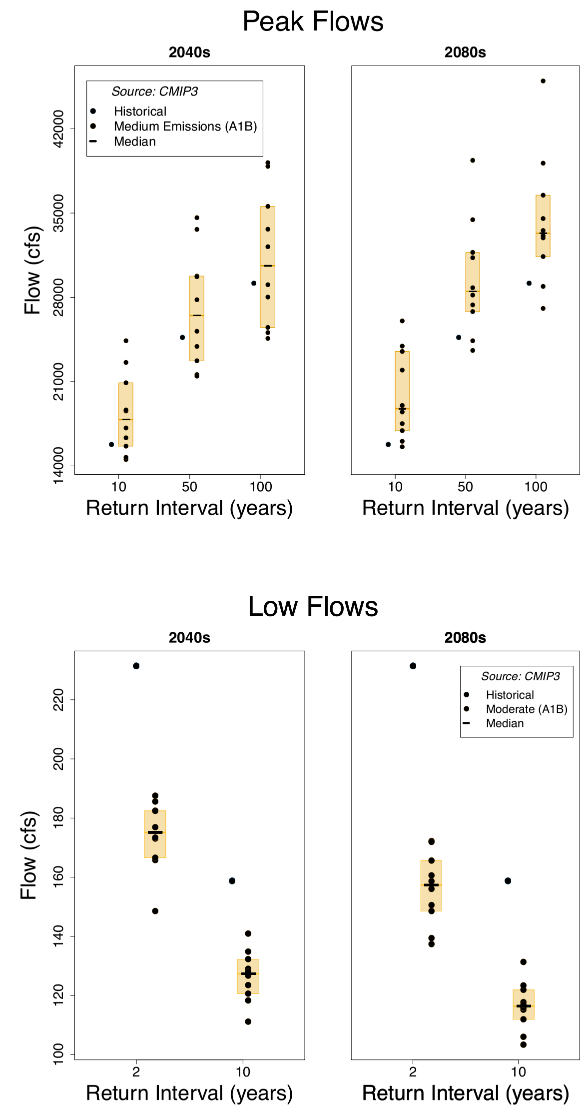


Figures D-7b. As described on Page D-2, for the Green River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Nisqually River Watershed

CMIP3 projections

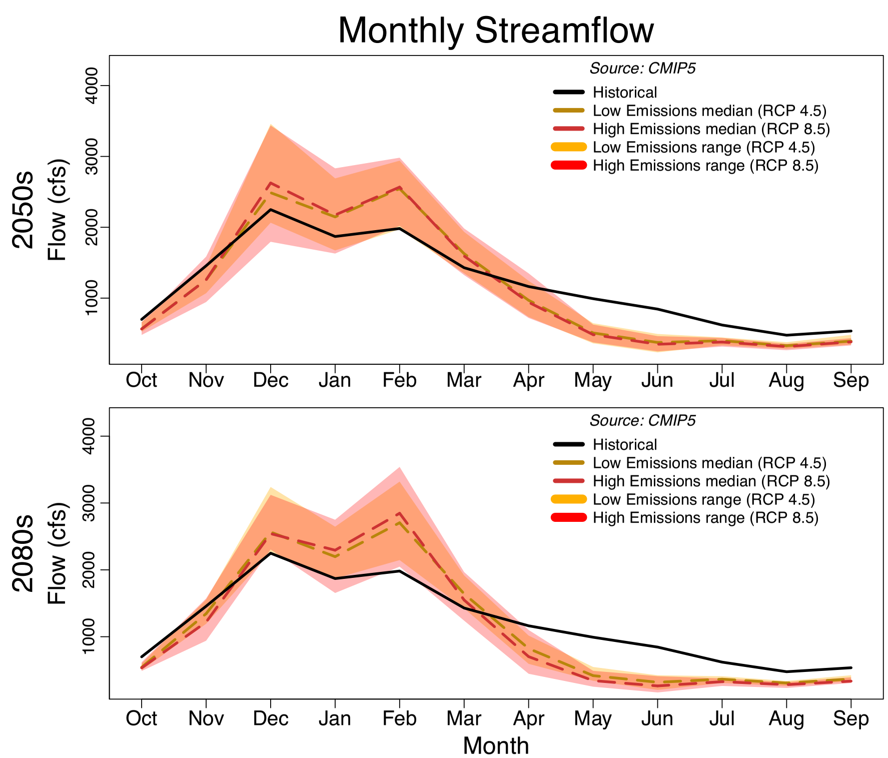


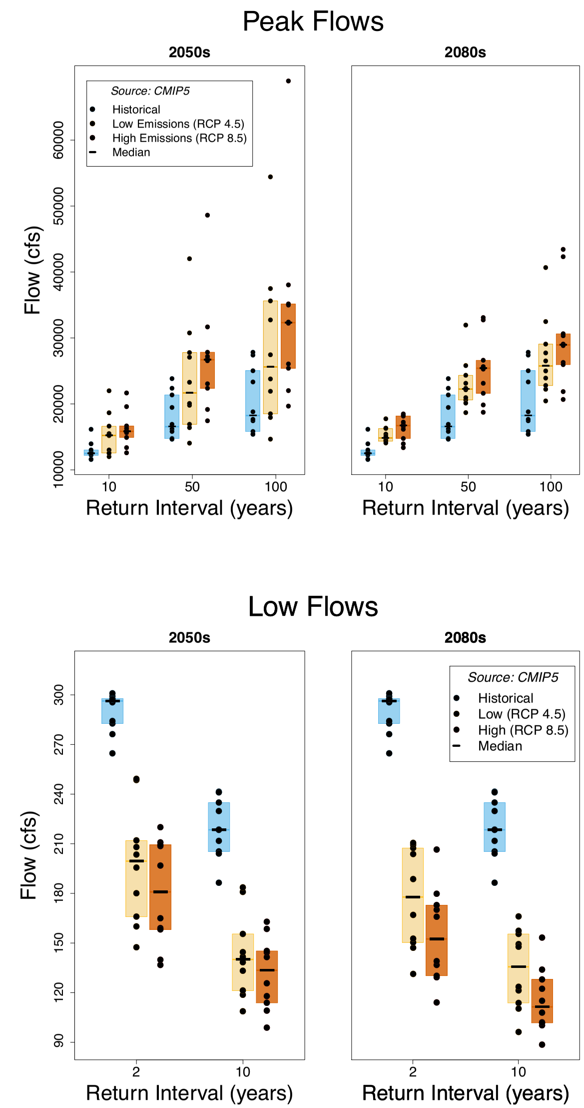


Figures D-8a. As described on Page D-2, for the Nisqually River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Nisqually River Watershed

CMIP5 projections

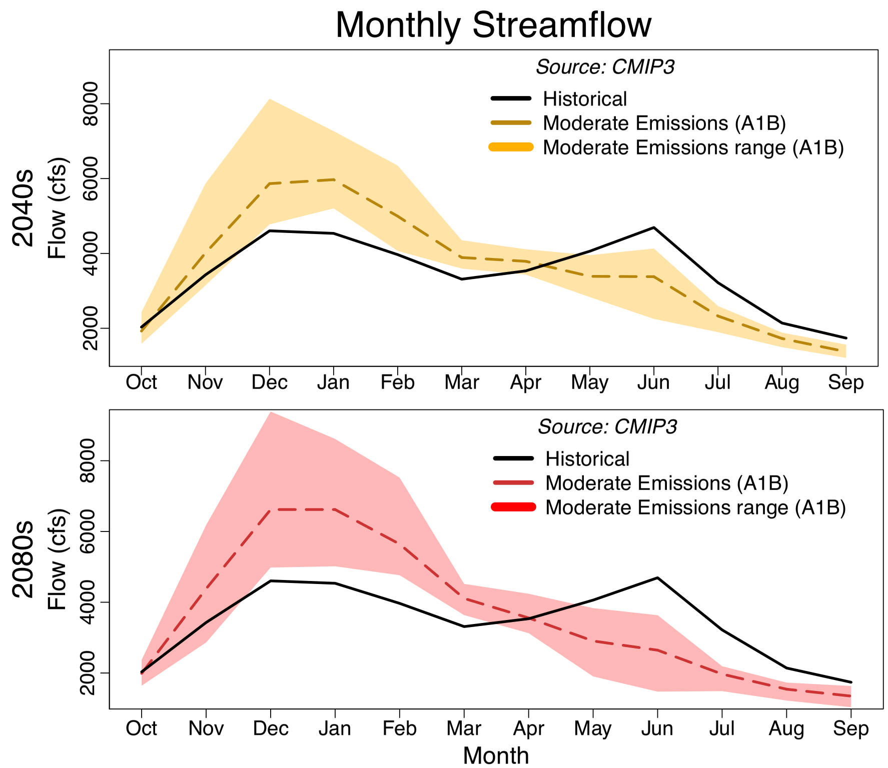


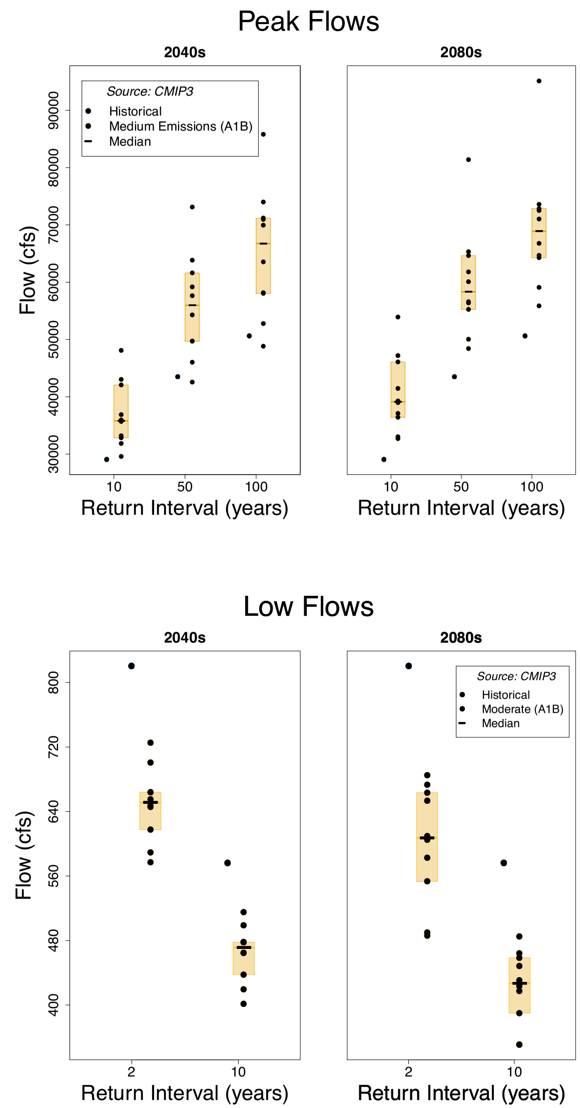


Figures D-8b. As described on Page D-2, for the Nisqually River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Puyallup River Watershed

CMIP3 projections

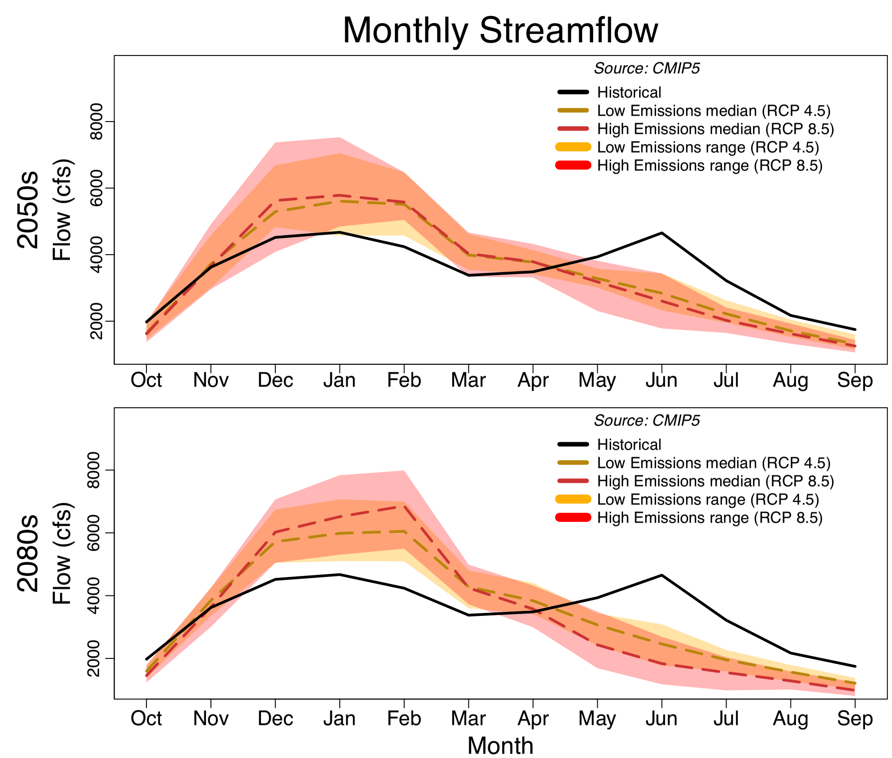


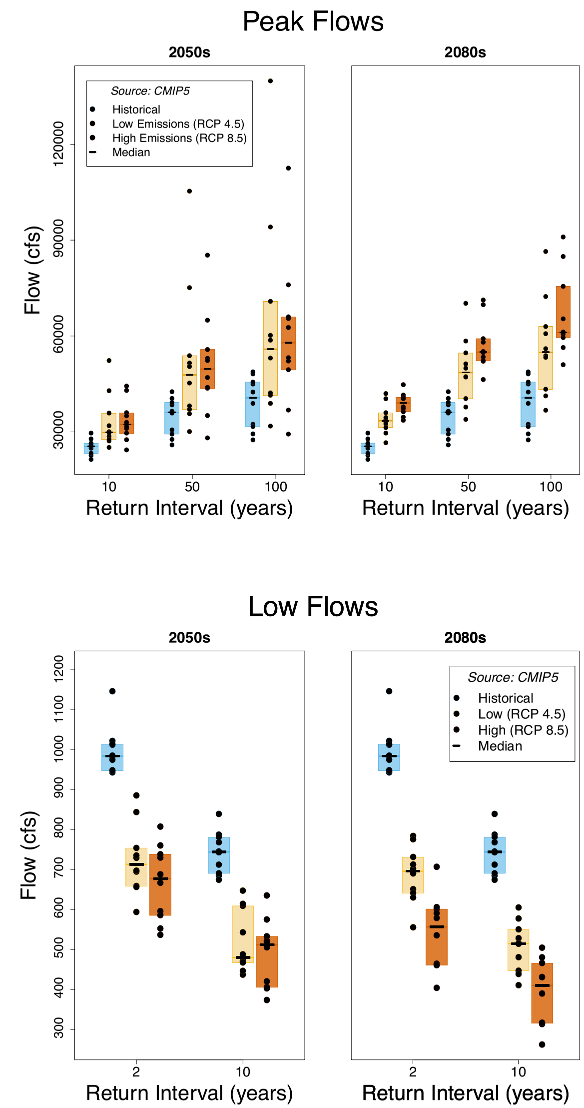


Figures D-9a. As described on Page D-2, for the Puyallup River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Puyallup River Watershed

CMIP5 projections

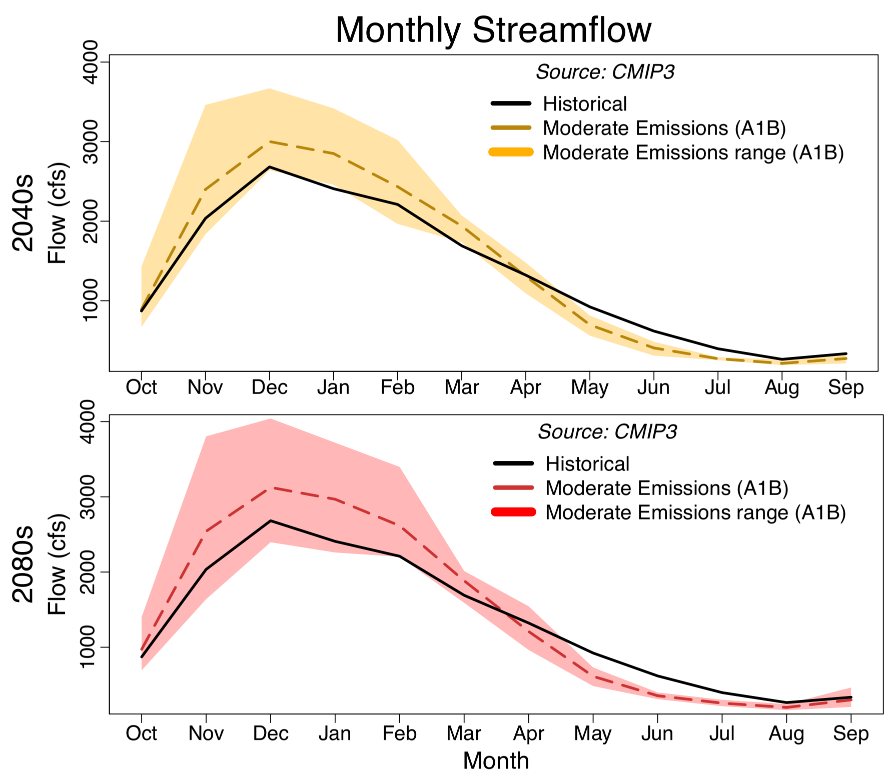


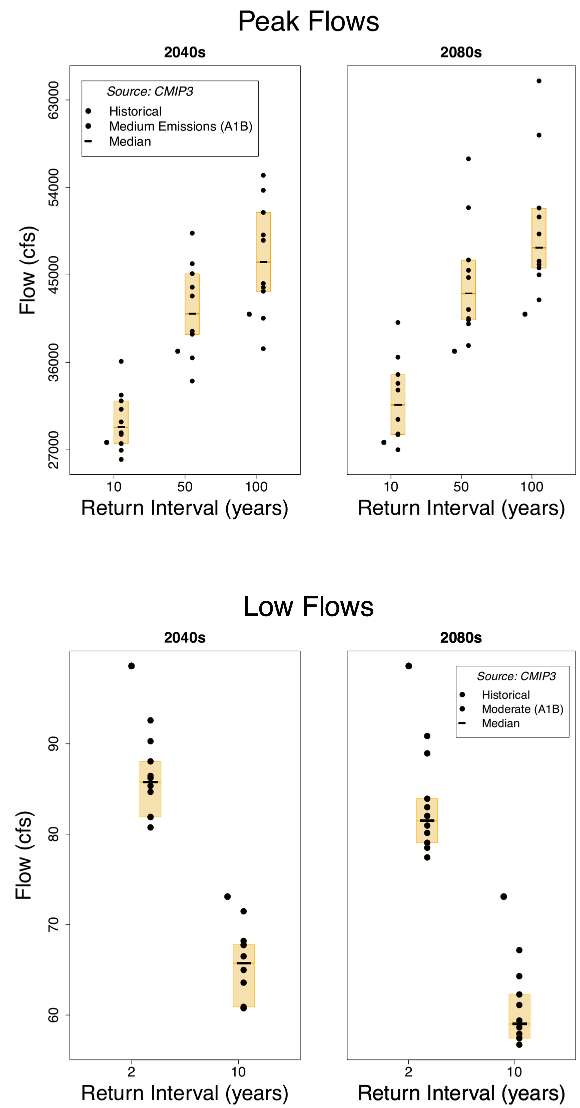


Figures D-9b. As described on Page D-2, for the Puyallup River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Skokomish River Watershed

CMIP3 projections

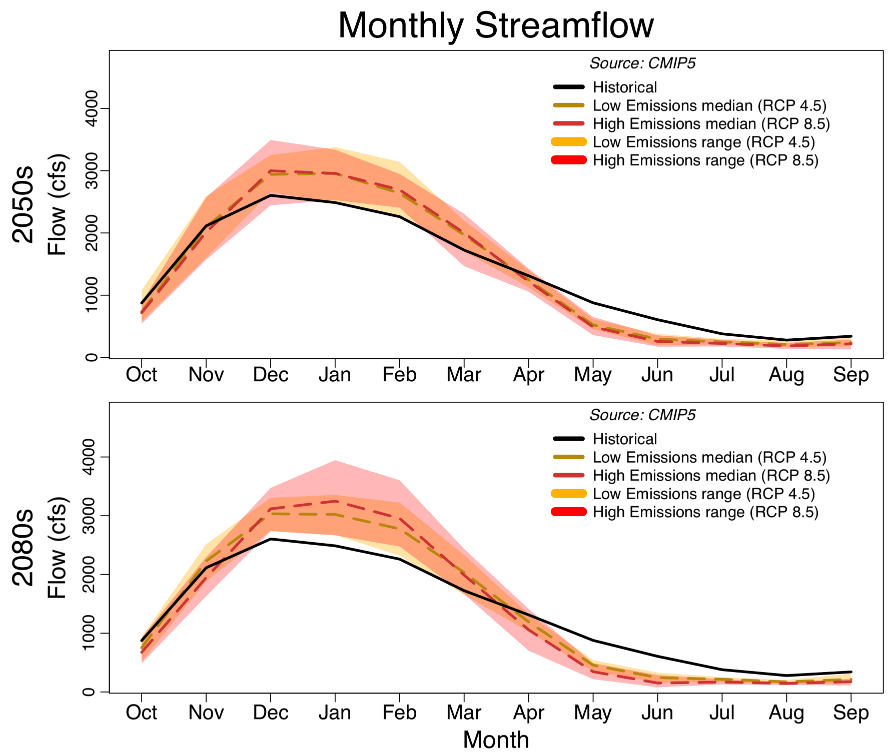


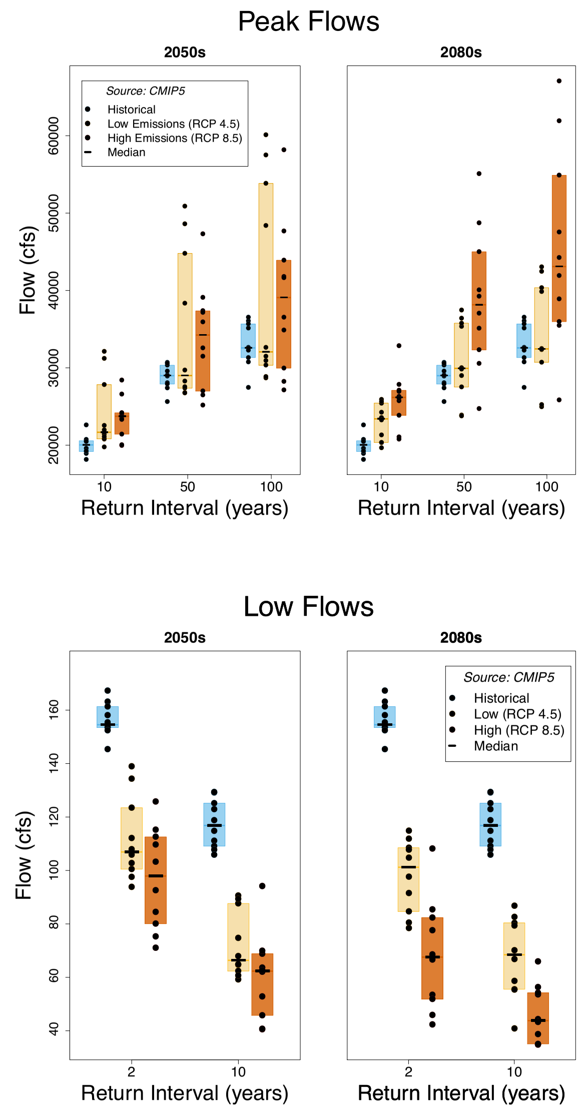


Figures D-10a. As described on Page D-2, for the Skokomish River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Skokomish River Watershed

CMIP5 projections

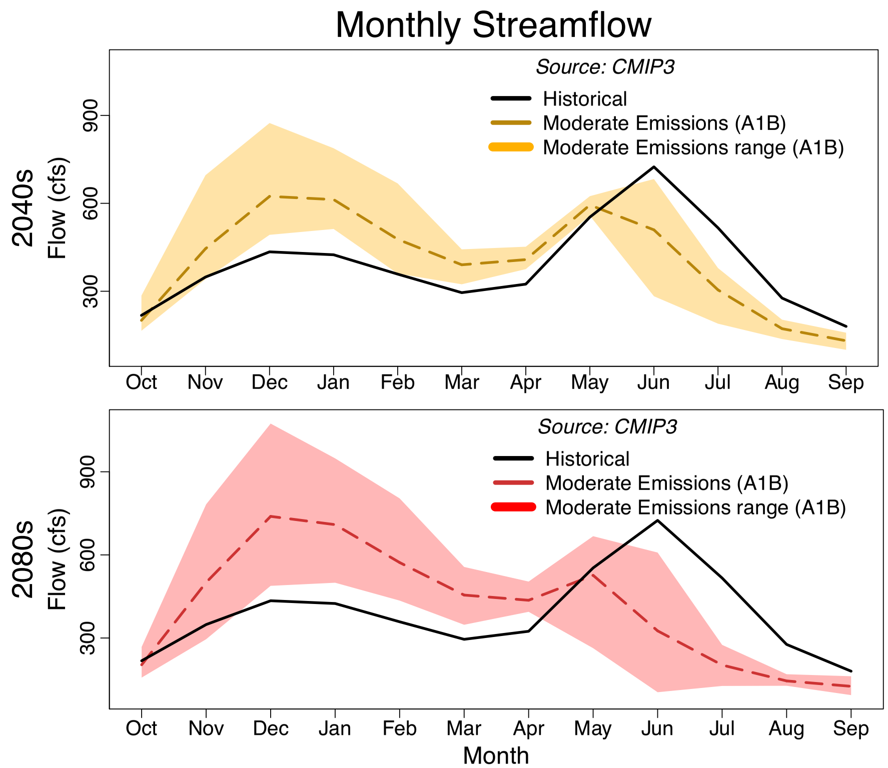


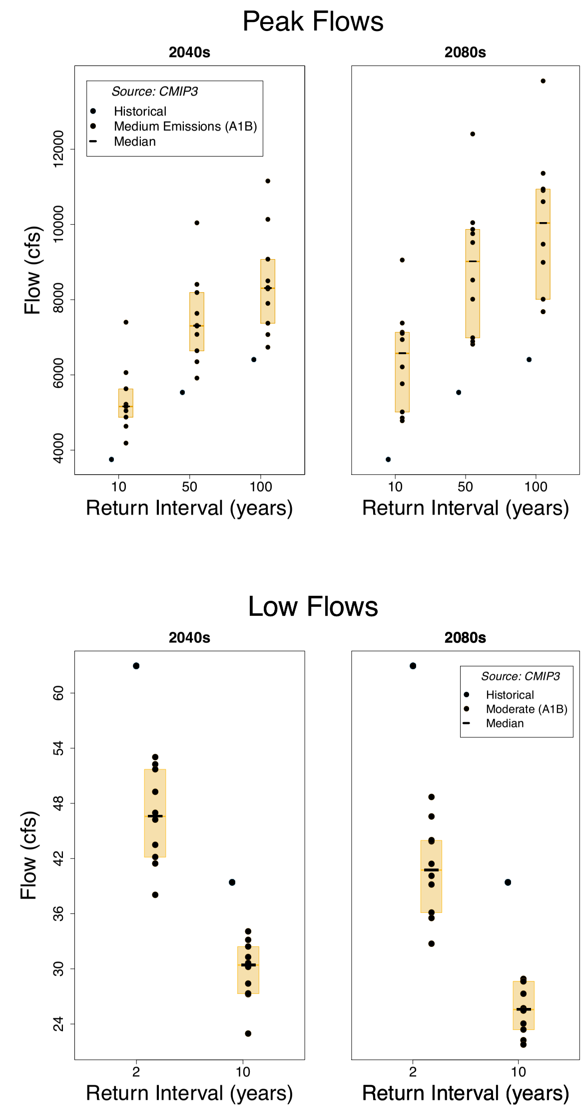


Figures D-10a. As described on Page D-2, for the Skokomish River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Dungeness River Watershed

CMIP3 projections

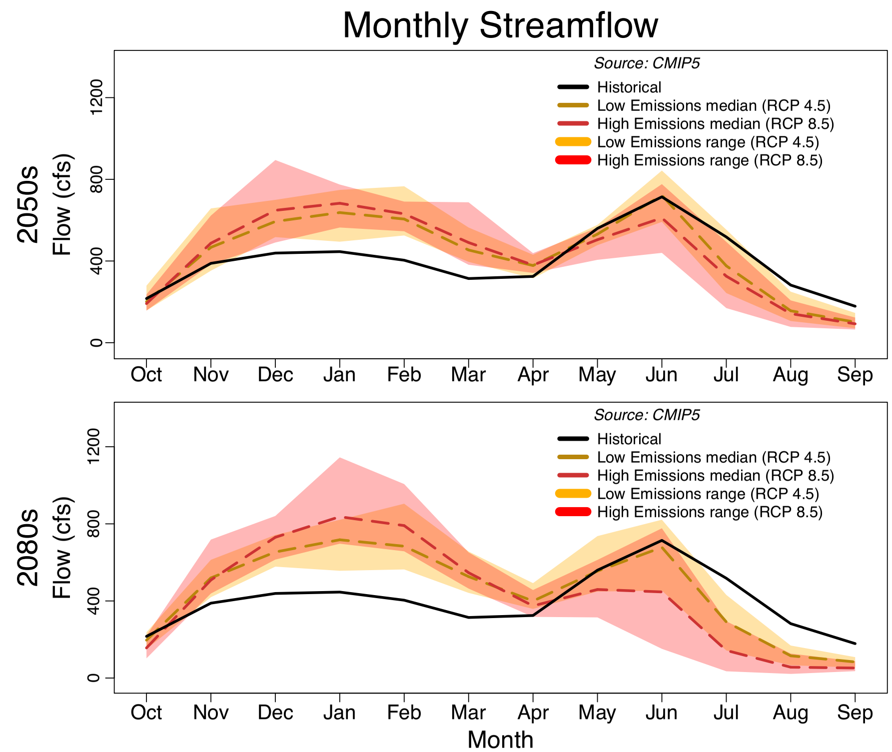


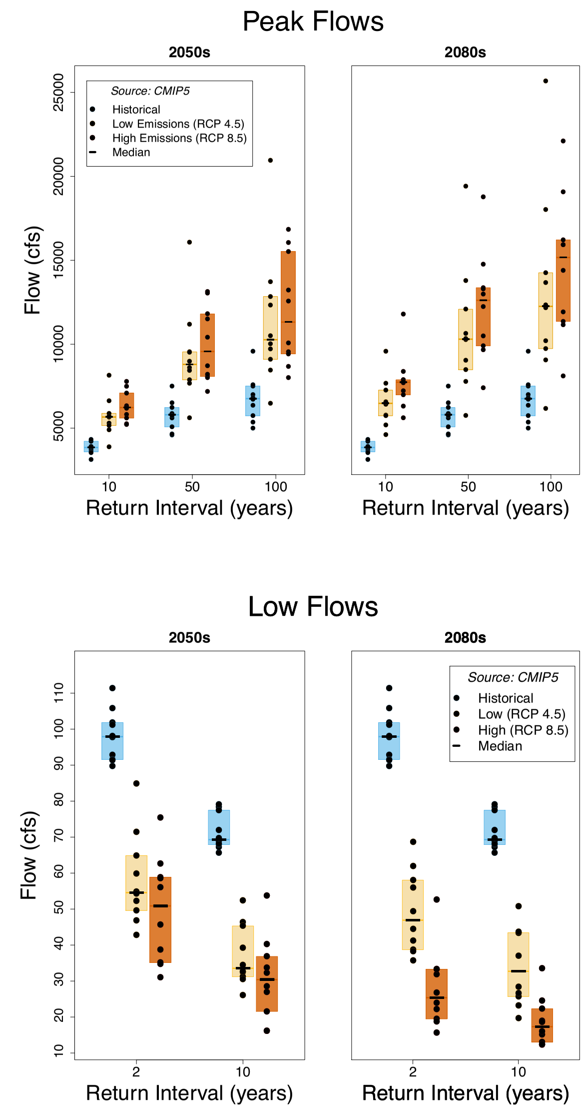


Figures D-11a. As described on Page D-2, for the Dungeness River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Dungeness River Watershed

CMIP5 projections

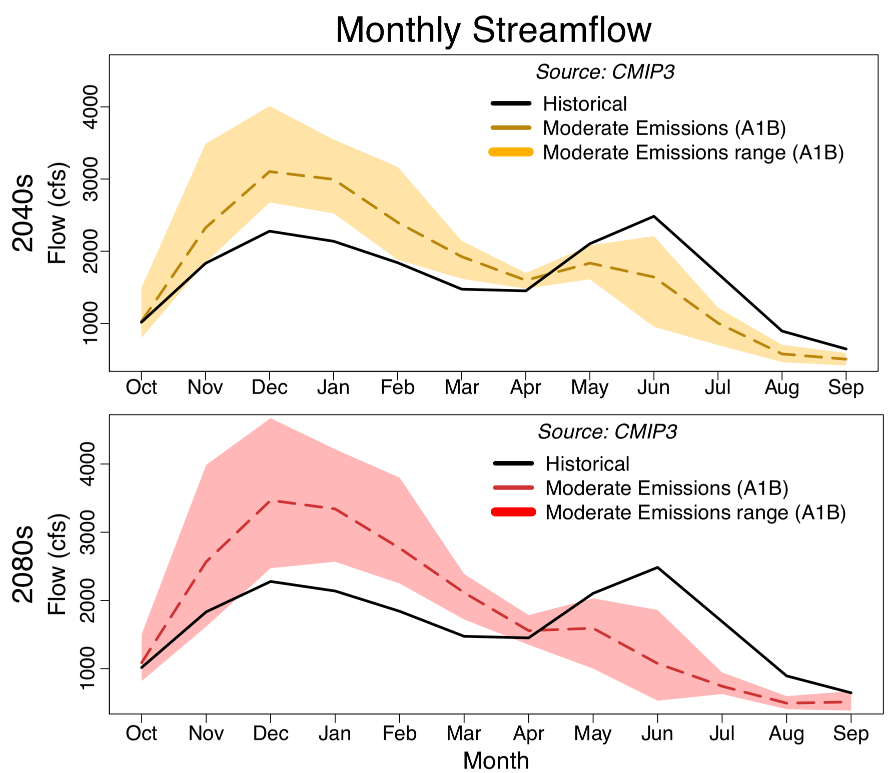


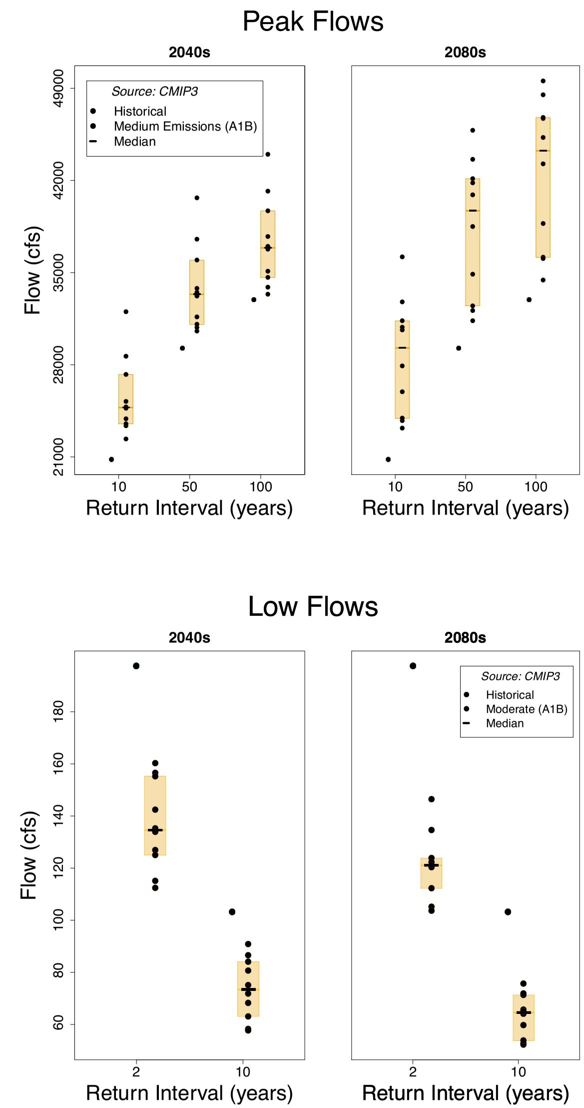


Figures D-11b. As described on Page D-2, for the Dungeness River watershed, based on the CMIP5-based hydrologic projections.[1,2]

Elwha River Watershed

CMIP3 projections

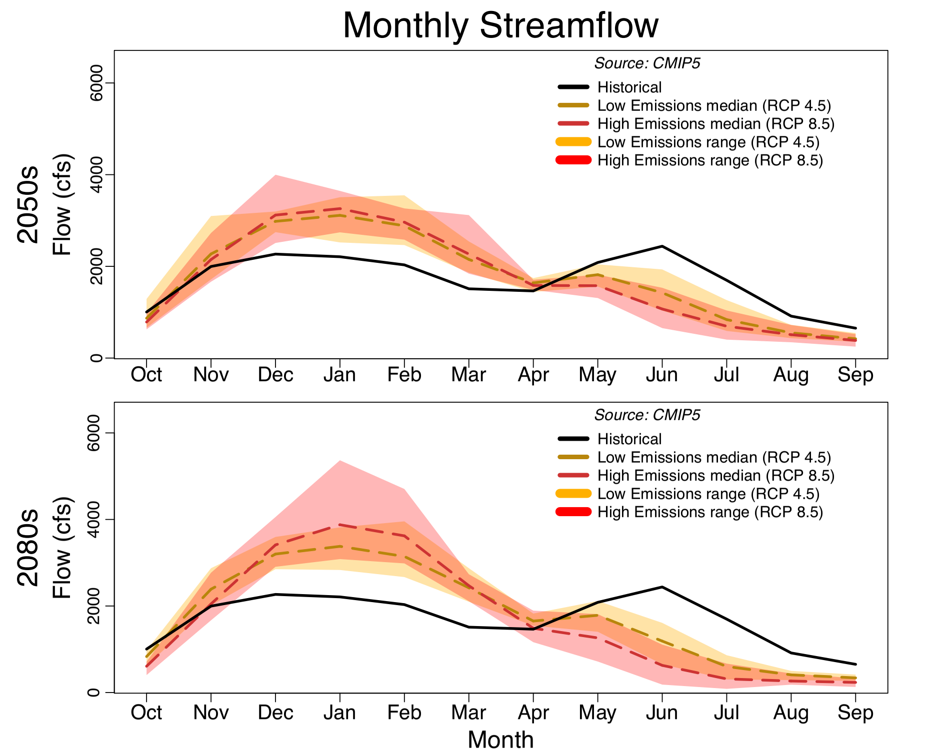


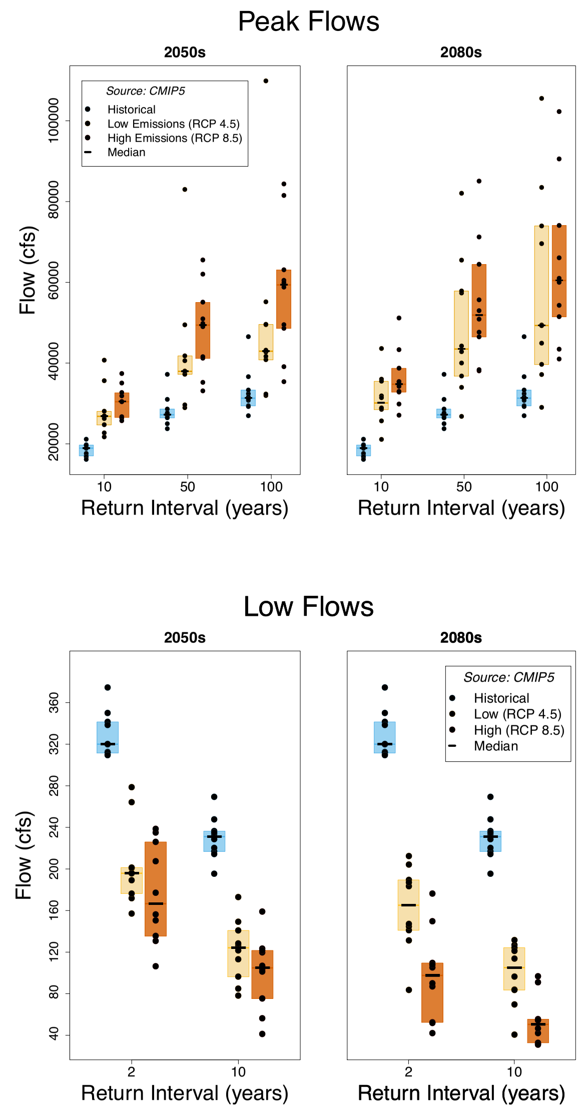


Figures D-12a. As described on Page D-2, for the Elwha River watershed, based on the CMIP3-based hydrologic projections.[3,4]

Elwha River Watershed

CMIP5 projections





Figures D-12b. As described on Page D-2, for the Elwha River watershed, based on the CMIP5-based hydrologic projections.[1,2]

The Climate Impacts Group

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