State of Knowledge Report

Climate Change Impacts and Adaptation in Washington State:

Technical Summaries for Decision Makers

Prepared by the

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EXECUTIVE SUMMARY

This State of Knowledge Report, *Climate Change Impacts and Adaptation in Washington State,* summarizes existing knowledge about the likely effects of climate change on Washington State and the Pacific Northwest,[A] with an emphasis on research since 2007.[B] This report provides technical summaries detailing observed and projected changes for Washington's climate, water resources, forests, species and ecosystems, coasts and ocean, infrastructure, agriculture, and human health in an easy-to-read summary format designed to complement the foundational literature from which it draws. This literature includes recent major international, United States, and Pacific Northwest assessment reports, especially two recent efforts associated with the Third U.S. National Climate Assessment,[C] scientific journal articles, and agency reports. This report also describes climate change adaptation activities underway across the state and data resources available to support local adaptation efforts.

A rapidly growing body of research has strengthened and added local detail to previous knowledge about the causes and consequences of climate change. *(Sections 1 and 2)* Human activities have increased atmospheric levels of greenhouse gases (carbon dioxide, methane, and nitrous oxide) to levels unprecedented in at least the past 800,000 years. The Earth's climate system is warming, global sea level is rising, snow and ice are declining, and ocean chemistry and climate extremes are changing. From the global scale to the scale of the western U.S., many of these changes can be attributed to human causes.

> *Human influence on the climate system is clear…Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. (IPCC 2013)*

Observed changes in regional climate, water resources, and coastal conditions are consistent with expected human-caused trends, despite large natural variations. *(Section 2)* Washington and the Pacific Northwest have experienced long-

[A] Whenever possible, this report focuses on information about observed and projected changes that are specific to Washington State. In cases where Washington-specific results were unavailable, information is provided relative to the Pacific Northwest as a whole. Because many characteristics of Washington's climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region, results for Washington State are expected to generally align with those provided for the Pacific Northwest, with potential for some variation at any specific location.

[B] Research since 2007 is emphasized in order to capture major contributions to global and regional climate science since release of the fourth global climate change assessment report by the Intergovernmental Panel on Climate Change (IPCC) in 2007. Findings from the IPCC's fifth assessment report, released in September 2013, and from the U.S. National Climate Assessment are included where possible. These and other recent scientific assessment reports most salient to understanding the consequences of climate change for Washington State are described in Appendix 1.

term warming, a lengthening of the frost-free season, and more frequent nighttime heat waves. Sea level is rising along most of Washington's coast,[D] coastal ocean acidity has increased, glacial area and spring snowpack have declined, and peak streamflows in many rivers have shifted earlier. These long-term changes are consistent with those observed globally as a result of human-caused climate change. Still, natural climate variability will continue to result in short-term trends opposite those expected from climate change, as evidenced by recent regional cooling and increases in spring snowpack.

Significant changes in the Earth's climate system and the climate of the Pacific Northwest are projected for the 21st century and beyond as a result of greenhouse gas emissions (Box ES-1, Figure ES-1)**.** *(Sections 3 through 5)* All scenarios indicate continued warming. Projected changes prior to mid-century are largely inevitable, driven by the warming that is already "in the pipeline" due to past emissions of greenhouse gases. In contrast, current and future choices about greenhouse gas emissions will have a significant effect on the amount of warming that occurs after about the 2050s. For example, global warming projected for the end of the century ranges from +1.8°F (range: +0.5°F to +3.1°F), if greenhouse gases are aggressively reduced, to +6.7°F (range: +4.7°F to +8.6°F) under a high "business as usual" emissions scenario.[E][1]

Box ES-1. Projected changes in key Pacific Northwest climate variables.

- *Average annual temperature, for 2050s*: +4.3°F (range: +2.0 to +6.7°F) for a low greenhouse gas scenario or +5.8°F (range: +3.1 to +8.5°F) for a high greenhouse gas scenario (both relative to 1950-1999).
- *Extreme precipitation, for 2050s:* number of days with more than one inch of rain increases +13% (±7%) for a high greenhouse gas scenario (relative to 1971-2000).
- *Average April 1 snowpack in Washington State, for 2040s:* -38 to -46% for a low and a medium greenhouse gas scenario (relative to 1916-2006).
- *Sea level in Washington State, for 2100:* +4 to +56 inches for low to high greenhouse gas scenarios (relative to 2000). Local amounts of sea level rise will vary.
- *Ocean acidity, for 2100:* +38 to +41% for a low greenhouse gas scenario and +100 to +109% for a high greenhouse gas scenario (relative to 1986-2005).

See Sections 3 and 6 for more detailed projections and additional time periods.

C The Northwest chapter of the U.S. National Climate Assessment (scheduled for release in spring 2014) and *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities* (2013; edited by M.M. Dalton, P.W. Mote, and A.K. Snover, Washington, D.C.: Island Press, 271 pp.), a more detailed report developed to support the key findings presented in the Northwest chapter.

D Although *regional* sea level is rising in concert with global sea level rise, *local* sea level change also reflects variations in vertical land motion resulting from plate tectonics and other processes. As a result, sea level is currently falling in some Washington locations.

E These changes are for the period 2081-2100 relative to 1986-2005. The lower amount of warming is for the RCP 2.6 scenario, which requires that global emissions be reduced to about a 50% of 1990 levels by 2050 and for total

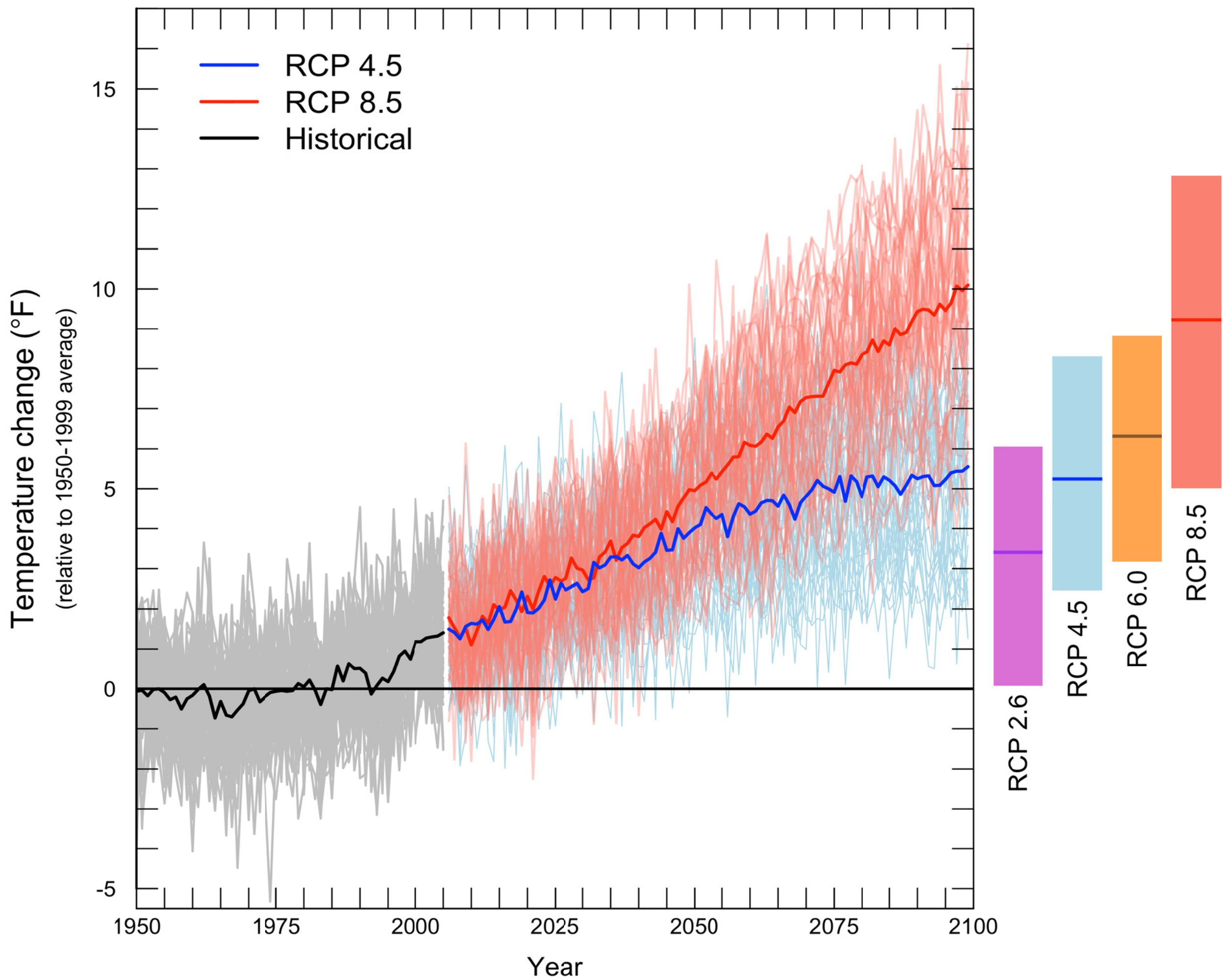

Figure ES-1. All scenarios project warming for the 21st century. The graph shows average yearly temperatures for the Pacific Northwest relative to the average for 1950-1999 (gray horizontal line). The black line shows the average simulated temperature for 1950–2011, while the grey lines show individual model results for the same time period. Thin colored lines show individual model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5 – see Section 3 for details), and thick colored lines show the average among models projections for each scenario. Bars to the right of the plot show the mean, minimum, and maximum change projected for each of the four emissions scenarios for 2081-2100, ranging from a very low (RCP 2.6) to a high (RCP 8.5) scenario. Note that the bars are lower than the endpoints from the graph, because they represent the average for the final two decades of the century, rather than the final value at 2100. *Figure source: Climate Impacts Group, based on climate projections used in the IPCC 2013 report.*[1]

net emissions to become near or below zero in the final decades of the 21st century. The higher amount of warming is for the RCP 8.5 scenario, which assumes continued increases in greenhouse gas emissions through the end of the 21st century. See Section 3 for more on greenhouse gas scenarios.

Projected regional warming and sea level rise are expected to bring new conditions to Washington State. By mid-century, Washington is likely to regularly experience average annual temperatures that exceed the warmest conditions observed in the 20th century. Washington is also expected to experience more heat waves and more severe heavy rainfall events, despite relatively small changes in annual and seasonal precipitation amounts.

These and other local changes are expected to result in a wide range of impacts for Washington's communities, economy, and natural systems. *(Sections 6-12)* These include projected changes in water resources, forests, species and ecosystems, oceans and coasts, infrastructure, agriculture, and human health.

Hydrology and Water Resources (Section 6). Washington's water resources will be affected by projected declines in snowpack, increasing stream temperatures, decreasing summer minimum streamflows, and widespread changes in streamflow timing and flood risk. These changes increase the potential for more frequent summer water shortages in some basins (e.g., the Yakima basin) and for some water uses (e.g., irrigated agriculture or instream flow management), particularly in fully allocated watersheds with little management flexibility. Changes in water management to alleviate impacts on one sector, such as hydropower production, irrigation or municipal supply, or instream flows for fish, could exacerbate impacts on other sectors.[2]

Forests (Section 7). Washington's forests are likely to experience significant changes in the establishment, growth, and distribution of tree species as a result of increasing temperatures, declining snowpack, and changes in soil moisture. A rise in forest mortality is also expected due to increasing wildfire, insect outbreaks, and diseases.[3] The projected changes could affect both the spatial distribution and overall productivity of many ecologically and economically important Pacific Northwest tree species, including Douglas-fir, ponderosa pine, lodgepole pine, and whitebark pine.

Species and Ecosystems (Section 8). Areas of suitable climate for many plants and animals are projected to shift considerably by the end of the 21st century. Many species may be unable to move fast enough to keep up, resulting in local species losses[4] and changes in the composition of plant and animal communities. Challenges are expected for many federally-listed endangered and threatened species dependent on coldwater habitat, including salmon, trout, and steelhead. Projected impacts on other habitat types in Washington State, including wetlands, sagebrush-steppe, prairies, alpine tundra and subalpine habitats, would affect species dependent on those habitats.

Coasts and Oceans (Section 9). Sea level is projected to rise in most areas[F] of the state, increasing the likelihood for permanent inundation of low-lying areas, higher tidal and storm surge reach, flooding, erosion, and changes and loss of habitat. Sea level rise, rising coastal ocean temperatures, and ocean acidification will also affect the geographical range, abundance, and diversity of Pacific Coast marine species. These include key components of the marine food web (phytoplankton and zooplankton) as well as juvenile Chinook salmon and commercially important species such as Pacific mackerel, Pacific hake, oysters, mussels, English sole, and yellowtail rockfish. [5]

Climate change can make today's extreme events more common. For example, two feet of sea level rise in Olympia could turn today's 100-year flood into an annual event.

Built Infrastructure (Section 10). Climate change is expected to affect the longevity and performance of built infrastructure in Washington State. Most climate change impacts are likely to increase the potential for damage and service disruptions, although some risks (such as snow-related highway maintenance and closures) may decrease. Higher operating costs and reduced asset life are also expected. Sea level rise and increased river flooding are important causes of impacts on infrastructure located near the coast or current floodplains.

Agriculture (Section 11). Washington crops and livestock will be affected by climate change via increasing temperatures and water stress, declining availability of irrigation water, rising atmospheric carbon dioxide, and changing pressures from pests, weeds, and pathogens. Some impacts on agriculture may be beneficial while others may lead to losses – the consequences will be different for different cropping systems and locations. While impacts on some locations and subsectors may be significant, most agricultural systems are highly adaptable. As a result, the overall vulnerability of Washington's agricultural sector to climate change is expected to be low. However, given the combination of increasing water demands and decreasing supply in summer, water stress will continue to be a key vulnerability going forward.

Human Health (Section 12). Climate change is expected to affect both the physical and mental health of Washington's residents by altering the frequency, duration, or intensity of climate-related hazards to which individuals and communities are exposed. Health impacts include higher rates of heat-related illnesses (e.g., heat exhaustion and stroke); respiratory illnesses (e.g., allergies, asthma); vector-, water-, and food-borne diseases; and mental health stress (e.g., depression, anxiety). These impacts can lead to increased absences from schools and work, emergency room visits, hospitalizations, and deaths.

[F] Recent research projects +4 to +56 inches of sea level rise by 2100 for Washington State, compared to 2000, which will be modulated by local vertical land movement. The potential for continued decline in local sea level for the Northwest Olympic Peninsula cannot be ruled out at this time. For more information, see Section 5.

While climate change is expected to have important consequences for most sectors, key areas of risk have been identified. According to analyses completed for the U.S. National Climate Assessment, priority issues of concern for the Pacific Northwest are:

- Changes in the natural timing of water availability, due to the impacts of warming on snow accumulation and melt, reducing water supply for many competing demands and causing far-reaching ecological and socioeconomic consequences;
- Coastal consequences of sea level rise, river flooding, coastal storms, erosion, inundation, and changes in the coastal ocean including increasing ocean acidity;
- Additional forest mortality and long-term transformation of forest landscapes, caused by the combined impacts of increasing wildfire, insect outbreaks, and tree diseases.[6]

These key risk areas, identified because of their likely significant consequences for the regional economy, infrastructure, natural systems, and human health, are also relevant to Washington State.

Box ES-2. A sampling of Washington communities, government agencies, and organizations preparing for the local effects of a changing climate.

- *Washington State:* Departments of Ecology, Transportation, Natural Resources, Fish and Wildlife, Health, Agriculture, Office of the Insurance Commissioner.
- *Local governments:* King County, Seattle, Anacortes, Olympia, Sound Transit, Port of Bellingham, Port of Seattle.
- *Federal agencies:* U.S. Army Corps of Engineers, Bureau of Reclamation, Bonneville Power Administration, U.S. Forest Service, National Park Service.
- *Tribal governments*: Swinomish Indian Tribal Community, Jamestown S'Klallam Tribe.

Many Washington communities, government agencies, and organizations are preparing for the impacts of climate change. Washington State—one of 15 U.S. states with a state adaptation plan [G][7] — has been identified as one of "the best states when it comes to planning for climate change." [H] Innovative partnerships are linking science, management, and planning across jurisdictions, helping a growing number of communities and organizations in the public and private sector to begin adapting to climate change (Box ES-2).

[G] *Preparing for Climate Change: Washington State's Integrated Climate Response Strategy* includes recommended adaptation actions for a range of sectors important to Washington State. These recommendations were developed through a year-long, multi-stakeholder collaboration among agencies, non-government organizations, and academic institutions. More information is available at: www.ecy.wa.gov/climatechange/ipa_responsestrategy.htm.

[H] http://www.nrdc.org/water/readiness/

The growth in adaptation efforts across the state has been stimulated by increasing awareness of the potential implications of climate change, the recognition that climate risks can be reduced by advance action, and the availability of locally-specific climate data, tools, and technical guidance to support adaptation planning. However, most efforts are still in the initial stages of assessing potential climate impacts and developing response plans; few have begun the challenging work of implementing adaptive responses. As more entities act to reduce their climate risks, new knowledge gaps and decision support needs will emerge. Building a climate resilient Washington will require effectively and efficiently meeting those needs.

[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] Payne, J. T. et al., 2004. Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change*, *62*(1-3), 233-256. doi: 10.1023/B:CLIM.0000013694.18154.d6

[3] Littell, J. S. et al., 2013. Forest ecosystems: Vegetation, disturbance, and economics. Chapter 5 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.

[4] Groffman, P. M. et al. (In review). Ecosystems, Biodiversity, and Ecosystem Services. Chapter 8 in the *Third U.S. National Climate Assessment*, scheduled for release in early 2014, January 2013 review draft. Available at: http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-chap8-ecosystems.pdf

[5] 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.

[6] Mote, P.M. et al.. (In review). The Northwest. Chapter 21 in the *Third U.S. National Climate Assessment*, scheduled for release in early 2014, January 2013 review draft. Available at: http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-chap21-northwest.pdf

[7] Center for Climate and Energy Solutions. 2013. State and Local Climate Adaptation Map, as of December 9, 2013. Available at: http://www.c2es.org/us-states-regions/policy-maps/adaptation.

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SECTION 1

How Are Global and National Climate Changing?

Global and national temperatures have increased throughout much of the 20th century. Global sea level is rising, the oceans are warming, and ocean chemistry is changing. Many aspects of the earth's physical and biological systems are changing in ways consistent with human-caused warming. Natural variability continues to result in short-term periods that are warmer or cooler than the long-term average. Recent studies have made use of longer observational records and investigated trends in greater detail. These studies have provided new and stronger evidence that warming trends are largely due to human activities.

1. **The Earth's climate is continuing to warm, sea level is rising, and the oceans are changing.** Since the 1950s, many of the observed changes are unprecedented over decades to millennia.[1]

    - *Increasing global temperatures.* Average global temperature increased +1.5°F between 1880 and 2012 (Figure 1-1; Table 1-1). Globally, heat waves and heavy rainfall events have become more frequent since 1950 and cold snaps are becoming rarer.[A][1]

    - *Northern Hemisphere warming.* Each of the last three decades has been successively warmer than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years.[1]

    - *Rising sea level.* Global sea level has risen about +7 inches since 1901. The rate of global mean sea level rise has accelerated during the last two centuries.[1]

    - *Increasing ocean temperatures.* Ocean surface waters (top 250 ft.) warmed by +0.6 to +0.9°F from 1971 to 2009 (global average). Warming trends are evident at nearly all depths in the ocean.[1]

    - *Ocean acidification.* The acidity of the ocean has increased by about +26% since 1750. The current rate of acidification is nearly ten times faster than any time in the past 50 million years.[B][1][2]

2. **The U.S. is experiencing similar changes in climate.**

    - *Increasing U.S. temperature.* U.S. average temperature increased about +1.5°F since record keeping began in 1895, with different rates of warming in different locations (Figure 1-2).[3]

[A] In this section, trends are only reported if they are statistically significant at the 90% level or more.

[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). Ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines the acidity of a fluid) 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.

Observed Change in Temperature, 1901-2012

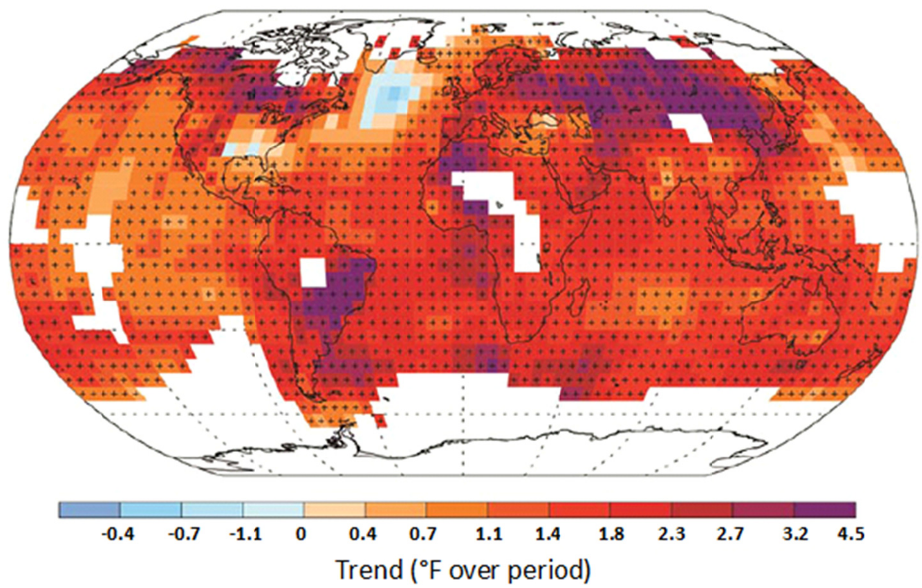

Figure 1-1. Significant warming has been observed in most locations. Observed changes in air temperature at the Earth's surface between 1901 and 2012. Red and purple colors indicate places that warmed while blue colors indicate places that cooled. White areas indicate places where data were insufficient to permit a robust trend estimate. The '+' signs indicate grid boxes where the direction of the trend is statistically significant. *Figure and caption adapted from IPCC 2013 (Figure SPM1.b).*[1]

Observed U.S. Temperature Change from 1901-1960 to 1991-2011

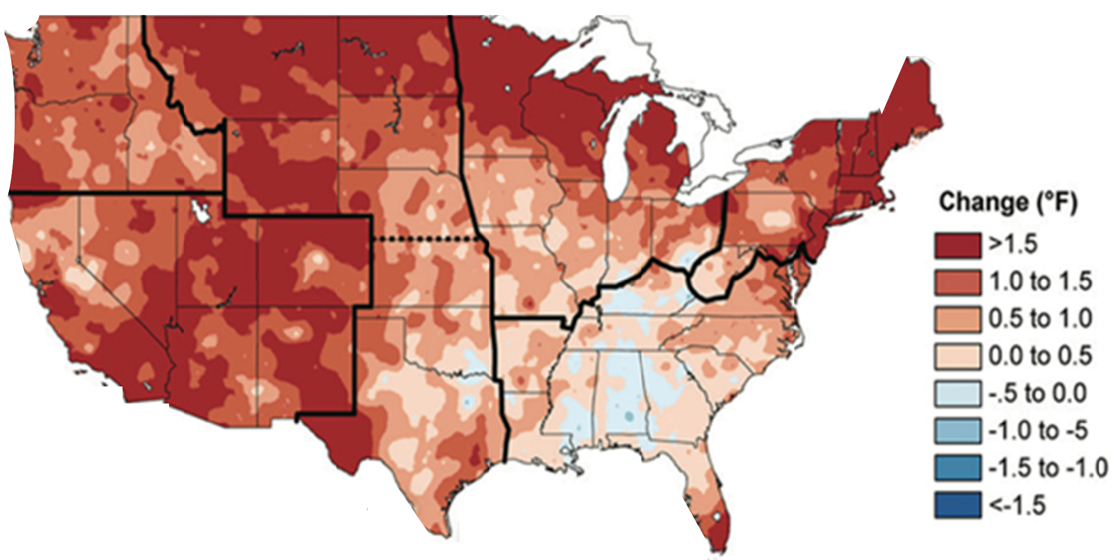

Figure 1-2. Warming has been observed for much of the continental U.S**.** Red colors indicate places that warmed while blue colors indicate places that cooled. In both cases this was calculated as the difference in temperature between the average for 1991-2011 and average temperature for 1901-1960. *Figure and caption adapted from Ch. 2 in Draft 2014 U.S. National Climate Assessment*[3]

- *More heavy rainfall events.* Heavy downpours are increasing in most regions of the U.S., especially over the last three to five decades, although trends for the Pacific Northwest are ambiguous.[3][4]

- *Longer frost-free season.* The length of the frost-free season (and the corresponding growing season) has been increasing nationally since the 1980s. During 1991-2011, the average frost-free season was about 10 days longer than during 1901-1960. The largest increases for this period occurred in the western U.S.[3][4]

3. **Evidence of change is increasingly visible throughout Earth's physical and biological systems.**

- *Widespread declines in glaciers, sea ice, and ice sheets.* Glaciers around the world have become smaller, on average, and Greenland and Antarctica are losing ice overall.[1] Summertime minimum Arctic sea ice extent decreased more than −40% between 1978 and 2012 (relative to the median for 1979-2000), recovering slightly in 2013.[5] Annual average Antarctic sea ice extent increased by +4 to +6% between 1979 and 2012.[6]

- *Declining U.S. ice and snow.* Rising temperatures across the U.S. have reduced lake ice, sea ice, glaciers, and seasonal snow cover over the last few decades.[7] In the Great Lakes, for example, total winter ice coverage decreased substantially between the early 1970s and 2010.[8]

- *Shifting species ranges.* Plant and animal ranges are shifting northward (in the Northern Hemisphere) and to higher elevations (Section 8 of this report).[9][10]

4. **The role of human activities in changing global climate is becoming clearer.**

- *Continued increases in greenhouse gas emissions.* Globally, greenhouse gases emissions are higher and increasing more rapidly since 2000 than during the 1990s.[1]

- *Rising concentrations of greenhouse gases.* The atmospheric concentration of carbon dioxide (CO_2) increased +40% between 1750 and 2011 as a result of human activities, nearly reaching 400 ppm in 2013. Atmospheric concentrations of CO_2, methane, and nitrous oxide have increased to levels unprecedented in at least 800,000 years.[1]

- *Identifying and quantifying human influence.* Human influence is becoming increasingly detectable in the observed warming of the atmosphere and ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes.
    - The IPCC now estimates that "more than half of the observed increase in global average surface [air] temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together."[1]

- The effects of human emissions of greenhouse gases must be included in order for models to correctly simulate the observed 20th century pattern of warming.[1][11]

- Studies conducted at the scale of the western U.S. have attributed some of the observed increases in temperature, decreases in snowpack, and shifts in the timing of peak streamflows to human influence.[12][13][14]

5. Natural climate variability continues to contribute to shorter-term (annual to decades-long) periods that are warmer or cooler than the long-term average.

- *Short-term trends can differ from long-term trends.* There have been periods of accelerated warming and even slight cooling at global and regional scales throughout the course of the 20th century due, in part, to important patterns of natural climate variability such as El Niño, La Niña, and the Pacific Decadal Oscillation.[1]

- *Trends based on shorter periods of time can be misleading.* Due to natural variability, short-term trends can differ substantially from long-term trends.

- *Recent warming "hiatus" is associated with natural variability that favors cool conditions.* The slower rate of global average warming observed for 1998-2012 has coincided with a higher rate of warming at greater depths in the oceans and a dominance of La Niña and the cool phase of the Pacific Decadal Oscillation, two large-scale natural patterns of climate variability that favor cooler surface temperatures in large parts of the world.[1]

- *All climate model scenarios project warming over the course of the 21st century*.[1] The amount of warming observed at any given location and point in time will depend on the combined influences of human-caused global warming and natural climate variations. This means that long-term warming projected for this century will be punctuated by shorter periods of reduced warming, or even cooling, as well as periods of accelerated warming, for both the globe as a whole and for specific places like Washington State.

For more details on observed changes in global and national climate, see Table 1-1.

Table 1-1. Observed trends in national and global climate.

Variable and Region	*Observed Change*
Global Greenhouse Gas Emissions	Increasing ▪ Emissions increased +3.2% per year between 2000 and 2009. This rate was notably higher than in previous decades; emissions increased at a rate of +1.0% per year during the 1990s.[1] ▪ The atmospheric concentration of carbon dioxide (CO_2) increased +40% between 1750 and 2011 as a result of human activities.[1] ▪ Atmospheric concentrations of CO_2, methane, and nitrous oxide have increased to levels unprecedented in at least 800,000 years.[1]
Temperature	
Average Annual: Global	Warming: +1.5°F (+1.2 to +1.9°F; 1880-2012)[1]
Average Annual: U.S.	Warming: +1.5°F (1895-2011)[3][4] Greatest warming in winter and spring[3]
Extremes	More heat events and fewer cold events globally (1950-2012). No significant trends for the U.S.[C][1][4]
Precipitation	
Annual: Global	No significant trend (1901-2012). Trends vary with location[1]
Annual: U.S.	Slightly wetter (1900-2011) ▪ +5% increase in annual precipitation over the U.S. ▪ Largest increase (+9%) in Midwest ▪ No significant trend for the Pacific Northwest.[3]
Heavy Precipitation: Global	Increasing; more frequent high rainfall events since 1950[1]
Heavy Precipitation: U.S.	Increasing overall (1901-2011), although highly variable by region. ▪ Greatest increase regionally: Midwest and Northeast[3] ▪ Since 1991, all regions have experienced a greater than normal occurrence of extreme events relative to the 1901-2011 average. ▪ Significant trends observed for Southwest (decreasing) and Midwest (increasing), other U.S. regions do not have statistically significant trends.[D][4]

[C] Nationally, the 1930s remain the decade with the highest number of extreme heat events when averaged over the U.S., followed by 2001-2011. In the western U.S., however, the 2000s are the decade with the highest number of extreme heat events.

[D] Extreme events were defined as the number of 2-day extreme precipitation events exceeding a 1 in 5-year recurrence interval for the period of 1901-2011.

Variable and Region	Observed Change
Snow and Ice	
Glaciers, Sea Ice, and Land-based Ice Sheets	Ice coverage is shrinking overall, with some growth in sea ice in the Antarctic ▪ Melting ice from glaciers, Greenland and Antarctica contributed +0.6 to +1.1 inches to sea level rise from 1971 to 2009[1]
Arctic Sea Ice	Decreasing ▪ Average annual extent: decreased −3.5 to −4.1%/decade (1979-2012)[1] ▪ Average summer minimum extent: decreased −9.4 to −13.6%/decade (1979-2012)[1]
Snow Cover: Northern Hemisphere	Decreasing ▪ Total area covered by snow in spring (March-April) decreased by −0.8 to −2.4%/decade (1967-2012)[1]
Oceans	
Ocean Temperature: Global	Warming ▪ +0.16 to +0.23°F warming in the upper ocean (top 250 ft.; 1979-2010)[1] ▪ Over the past 40 years (1971-2010), the oceans have absorbed more than 90% of the excess energy trapped by greenhouse gases emitted due to human activities.[1]
Sea Level: Global	Rising, although amount and rate of rise varies by location and over time. ▪ Rate of rise accelerated between 1993 and 2010, although similarly high rates are likely to have occurred between 1930 and 1950. +0.6 to +0.7 in./decade (1901-2010)[1] +0.7 to +0.9 in./decade (1971-2010)[1]
Ocean Acidification	Increasing acidity. Global ocean acidity has increased by +26% since the beginning of the industrial era (~1750) (this is equivalent to a decline in pH of −0.1) [1][2]

[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] Feely, R.A. et al., 2012. *Scientific Summary of Ocean Acidification in Washington State Marine Waters.* NOAA OAR Special Report.

[3] Walsh, J. et al., 2014. Our Changing Climate. Chapter 2 in the draft 2014 U.S. National Climate Assessment, http://ncadac.globalchange.gov/.

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SECTION 2

How Is Pacific Northwest Climate Changing?

The Pacific Northwest 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 temperatures, a longer frost-free season, decreased glacial area and spring snowpack, earlier peak streamflows in many rivers and rising sea level at most locations. Natural variability can result in short-term trends that are opposite those expected from climate change, as evidenced by recent regional cooling and increases in spring snowpack. Recent studies have investigated trends in greater detail, and clarified the role of variability, in particular regarding changes in extremes, sea level rise, ocean acidification, and snow.

1. Washington and the Pacific Northwest have experienced long-term warming, a lengthening of the frost-free season, and more frequent nighttime heat waves.[1]

- *Increasing temperatures.* The Pacific Northwest warmed about +1.3°F between 1895 and 2011, with statistically-significant warming occurring in all seasons except for spring.[A][1][2] This trend is robust: similar 20th century trends are obtained using different analytical approaches.[3] All but five of the years from 1980 to 2011 were warmer than the 1901-1960 average (Figure 2-1, Table 2-1).[1]

- *Frost-free season.* The frost-free season (and the associated growing season) has lengthened by 35 days (±6 days) from 1895 to 2011.[2]

- *Heat waves.* Nighttime heat events have become more frequent west of the Cascade Mountains in Oregon and Washington (1901-2009).[4] For the Pacific Northwest as a whole there has been no significant trend in daytime heat events or cold events for 1895-2011.

- *Short-term trends.* The Pacific Northwest'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). 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.

- *Challenges in assessing trends.* Estimates of temperature changes over time can be affected by changes in the location and number of measurements made and in the instruments used to make the measurements. The temperature datasets reported here include corrections for these factors,[5] and there is no published evidence that these issues affect long-term regional trends in temperature.[6]

[A] In this section, trends are only reported if they are statistically significant at the 90% level or more.

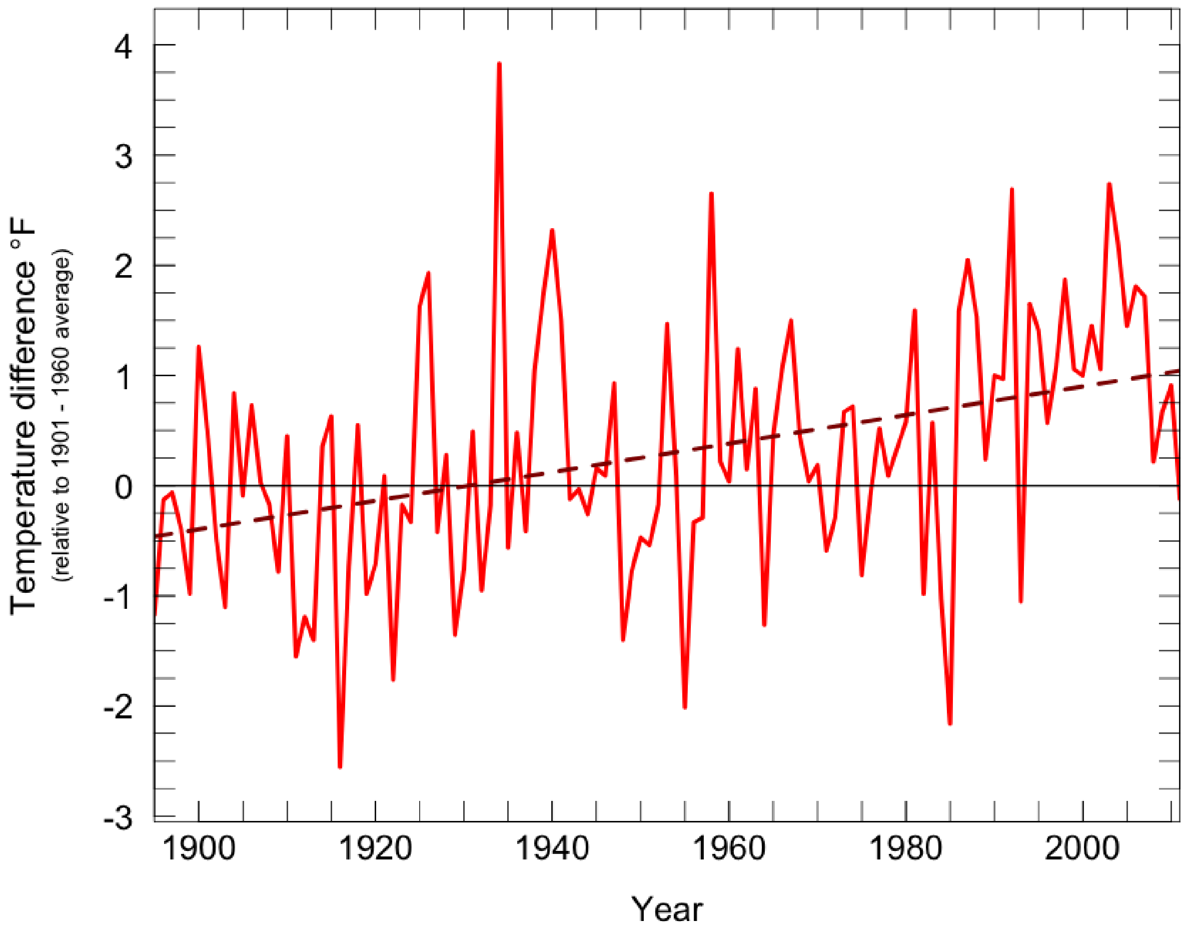

Figure 2-1. Rising temperatures in the Pacific Northwest. Average annual temperature (red line) shown relative to the 1901–1960 average (indicated by the solid horizontal line). The dashed line is the fitted trend, indicating the +0.13°F/decade warming for 1895-2011. *Data source: Kunkel et al. 2013.*[2]

2. **Sea level is rising along some parts of the Washington coastline and falling in others due to the combination of global sea level rise and local vertical land movement.**

- *Local sea level rise.* Although on average sea level is rising in the region, local sea level change is modulated by vertical land motion, in response to tectonics and other processes. Current observations of local sea level changes range from a decline along the northwest Olympic peninsula, a region experiencing uplift, to sea level rise in parts of the Puget Sound and the outer coast where land is subsiding.[7][8]

- *Year-to-year variability.* Local sea level is affected by shorter-term variations in addition to long-term changes in sea level associated with global warming. For example, El Niño conditions can temporarily increase regional sea level up to about a foot during winter months.[9][10]

3. There has been no discernible long-term trend in Pacific Northwest precipitation.

- *Annual precipitation.* There is no statistically-significant trend towards wetter *or* drier conditions in Pacific Northwest precipitation for the period 1895-2011.[2]

- *Year-to-year variability.* Natural variability has a large influence on regional precipitation, causing ongoing fluctuations between wet years and dry years and wet decades and dry decades.

- *Heavy downpours.* Trends in heavy precipitation events are ambiguous for the Pacific Northwest. Most studies find modest increasing trends, but most are not statistically-significant, and results depend on the dates and methods of the analysis.[2][11][12][13]

4. Long-term changes in snow, ice and streamflows reflect the influence of warming.

- *Spring snowpack.* Spring snowpack fluctuates substantially from year-to-year, but declined overall in the Washington Cascades from the mid-20th century to 2006.[14][15] This trend is due primarily to increasing regional temperature and reflects the influence of both climate variability and climate change.[16][17] Natural variability can dominate over shorter time scales, resulting (for example) in an increase in spring snow accumulation in recent decades.[14]

- *Glaciers.* About two-thirds of the glaciated area in the lower 48 states (174 out of 266 sq. miles) is in Washington.[18] Although there are some exceptions, most Washington glaciers are in decline. Declines range from a 7% loss of average glacier area in the North Cascades (1958-1998)[19] to a 49% decline in average area on Mt. Adams (1904-2006).[20]

- *Streamflow timing.* The spring peak in streamflow is occurring earlier in the year for many snowmelt-influenced rivers in the Pacific Northwest (observed over the period 1948-2002) as a result of decreased snow accumulation and earlier spring melt.[21]

5. The coastal ocean is acidifying, but ocean temperatures show no strong trends.

- *Ocean acidification*. The chemistry of the ocean along the Washington coast has changed due to the absorption of excess CO_2 from the atmosphere. Local conditions are also affected by variations and trends in upwelling of deeper Pacific Ocean water that is low in pH and high in nutrients, deliveries of nutrients and organic carbon from land, and absorption of other important acidifying atmospheric gases. Conditions vary by location and from season to season, but appear to have already reached levels that can affect some species.[B][8][22]

[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). Ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines the acidity of a fluid) 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.

- *Coastal ocean temperature.* The long-term trend in coastal ocean temperatures has been small compared to the considerable variations in ocean temperatures that occur from season-to-season, year-to-year, and decade-to-decade. These variations result from both local effects, such as winds and upwelling, to remote effects, such as El Niño. No warming has been detected for the general region of the Pacific Ocean offshore of North America,[23] but warming has been detected for the Strait of Georgia[C] and off the west coast of Vancouver Island.[24]

For more details on observed changes in Pacific Northwest climate, see Table 2-1.

Additional Resources

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

- 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 in the Western U.S.: http://www.wrcc.dri.edu/

[C] The Strait of Georgia is located north of the Puget Sound, between Vancouver Island and British Columbia.

Table 2-1. Observed trends in Pacific Northwest climate.

Variable	Observed Change [A]
Temperature	
Annual	Warming: +0.13°F/decade (1895-2011)[1][2]
Seasonal	Warming in most seasons *Winter* Warming: +0.20°F/decade (1895-2011)[2] *Spring* No significant trend (1895 – 2011)[2] *Summer* Warming: +0.12°F/decade (1895–2011)[2] *Fall* Warming: +0.10°F/decade (1895–2011)[2]
Extremes	Statistically-significant increase in nighttime heat events west of the Cascade Mountains in Oregon and Washington (1901-2009).[4] No significant trends in daytime heat events or cold events (1895-2011).[2]
Freeze-free Season	Lengthening: +3 days/decade (1895–2011)[D][2]
Precipitation	
Annual	No significant trend (1895–2011)[1][2]
Extremes	Ambiguous: Studies find different trends depending on the dates and methods of the analysis[2][11][12][13]
Hydrology	
Snowpack	Long-term declines, recent increases. ▪ Washington Cascades snowpack decreased by about −25% 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)[14][15] ▪ Snowpack in recent decades (1976–2007) has increased but the change is not statistically significant and most likely the result of natural variability.[14]
Glaciers	Declining overall ▪ North Cascades: −7% decline in glacier area (1958-1998)[19] ▪ Mt. Rainier: −14% decline in glacier volume (1970-2007)[25] ▪ Mt. Adams: −49% decline in glacier area (1904-2006)[20] ▪ Olympic Mountains: No published studies on long-term trends.
Annual Streamflow Volume	Declining in some locations Trends in annual streamflow are relatively small in comparison to year-to-year variability. A study of 43 streamflow gauges in the Pacific Northwest found declining trends (1948-2006), ranging from no change to −20% for individual locations.[26]

[D] Number of days between the last freeze of spring and first freeze of fall.

Variable	Observed Change [A]
Timing of Peak Streamflow	Shifting earlier, depending on location ▪ Spring peak streamflow in the Pacific Northwest has shifted earlier in snowmelt-influenced rivers – the shift ranges from no change to about 20 days earlier (1948-2002).[21]
Coastal Ocean	
Ocean Temperature	Varies with location ▪ Over the larger region offshore of North America: no significant warming in ocean surface temperatures (1900-2008)[23] ▪ In the Strait of Georgia and West of Vancouver Island: significant warming observed. Average for top 330 ft: +0.4°F/decade (1970-2005)[24]
Ocean Acidification	Acidifying ▪ Ocean waters on the outer coast of Washington and the Puget Sound have become about +10 to +40% more acidic since 1800 (decline in pH of −0.05 to −0.15).[27]
Sea Level Change	Mostly rising; varies with location ▪ Friday Harbor, WA: +0.4 in./decade (1934-2008) ▪ Neah Bay, WA: −0.7 in./decade (1934-2008) ▪ Seattle, WA: +0.8 in./decade (1900-2008) ▪ Astoria, OR: −0.1 in./decade (1925-2008)[28]

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SECTION 3

Making Sense of the New Climate Change Scenarios

The speed with which the climate will change and the total amount of change projected depend on the amount of greenhouse gas emissions and the response of the climate to those emissions. To make projections, climate scientists use greenhouse gas scenarios – "what if" scenarios of plausible future emissions – to drive global climate model simulations of the earth's climate. Both the greenhouse gas scenarios and global climate models are periodically updated as the science of climate change advances. The most recent projections for 21st century climate change (IPCC 2013)[1] align with and confirm earlier projections (e.g., IPCC 2007).[2]

1. **How much and how fast climate changes occur depends on both the amount of greenhouse gas emissions and how the climate changes in response to those emissions.** As a result, projecting future climate requires making assumptions about future greenhouse gas emissions and then modeling the climate's response to those emissions. Irreducible uncertainty in both climate and future greenhouse gas emissions means that projections of future climate will always involve a range of scenarios.

    - *Since it is impossible to predict exactly how much greenhouse gases will be emitted,* scientists use greenhouse gas scenarios to consider the implications of a range of different future conditions.

    - *We can't know which scenario is more likely.* Since we are unable to predict the future, we can't say with certainty which 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 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.

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

[A] The newest 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[4]).

Table 3-1. Previous greenhouse gas scenarios have close analogues in the new scenarios.

New scenarios	*Scenario characteristics*	*Comparison to old scenarios*	*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	"Medium"
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[B]	"High"

- *The old scenarios have close analogues in the new scenarios*. For example, the A1B scenario – used as the high-end scenario 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 cases, 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.

- *The new 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.

- *All scenarios result in similar warming until about mid-century.* Prior to mid-century, projected changes in 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 3-1).[1]

[B] The A2 greenhouse gas scenario is between the RCP 6.0 and 8.5 scenarios.

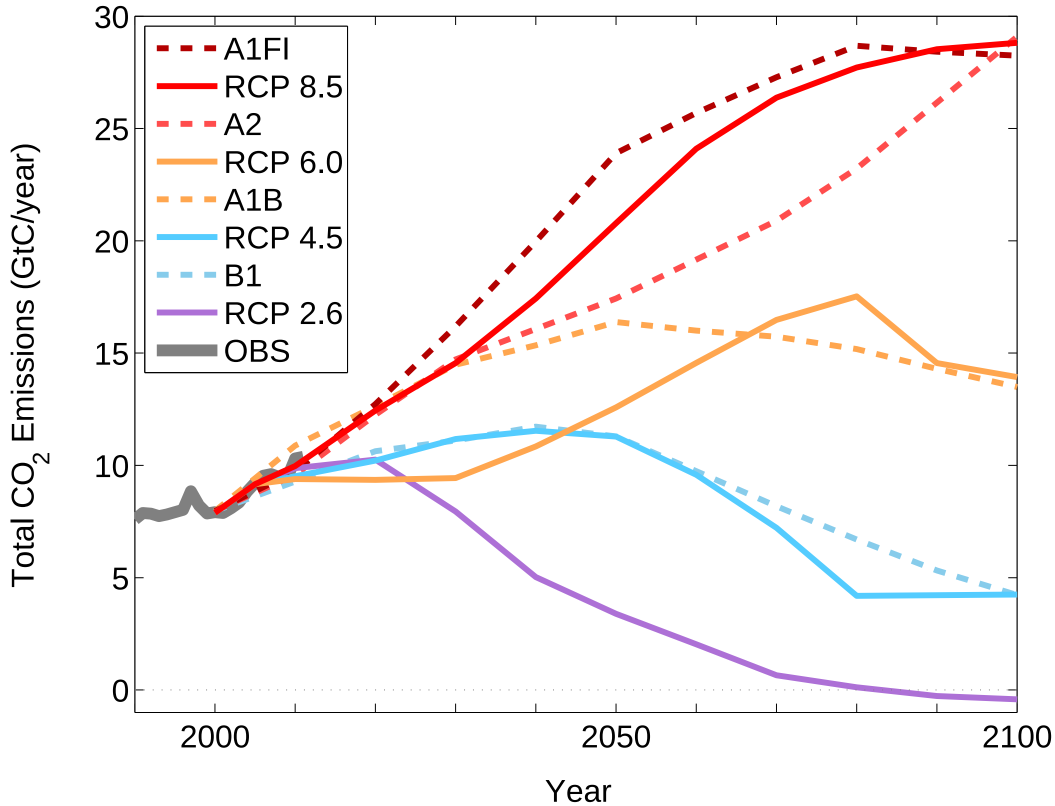

Figure 3-1. Future greenhouse gas scenarios range from aggressive reductions to large increases in greenhouse gas emissions. The figure shows annual total CO_2 emissions in Gigatons of Carbon (GtC). Though not the only greenhouse gas, CO_2 emissions are the dominant driver of global warming. The old greenhouse gas scenarios (dashed lines) have close analogs in the new scenarios (solid lines) – similar scenarios are plotted using similar colors. Actual emissions for 1990-2010 are shown in grey. Year-to-year emissions of greenhouse gases, shown in this graph, accumulate in the atmosphere, causing CO_2 concentrations to rise, as shown in Figure 3-2. Scenarios with higher emissions cause atmospheric concentrations to rise rapidly, while lower scenarios cause concentrations to rise more slowly or decline. *Figure source: Climate Impacts Group, based on data used in IPCC 2007 and IPCC 2013 (http://tntcat.iiasa.ac.at:8787/RcpDb[3] and http://sedac.ciesin.columbia.edu/ddc/sres/[4]).*

3. **New climate change projections (IPCC 2013) also use new versions of climate models that simulate changes in the Earth's climate.** More models are included in the new projections, and they are improved relative to older models.[5][6]

- *New climate models project similar climate changes for the same amount of greenhouse gas emissions.* Differences between warming projections for the 2007 and 2013 IPCC reports are mostly due to differences in greenhouse gas scenarios.[5][7]

- *The range among climate model projections may not encompass the full range of potential future climate changes.* The range among climate model simulations provides an estimate of the uncertainty in projections, but it is important to note that future changes in climate could be outside of the range projected by existing climate models.

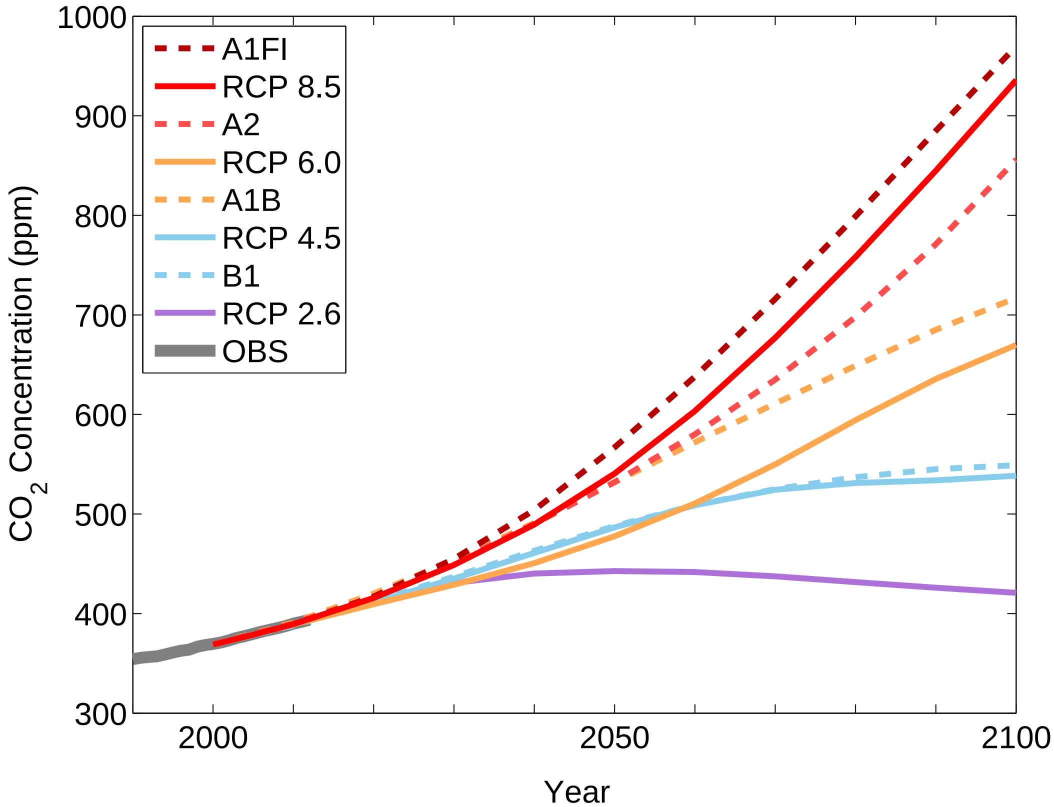

Figure 3-2. All scenarios assume continued growth in atmospheric levels of greenhouse gases for the next few decades. The figure shows total CO_2 concentration, in parts per million (ppm), for each greenhouse gas scenario. Though not the only greenhouse gas, CO_2 emissions are the dominant driver of global warming. The old greenhouse gas scenarios (dashed lines) have close analogs in the new scenarios (solid lines) – similar scenarios are plotted using similar colors. Actual concentrations for 1990-2010 are shown in grey. *Figure source: Climate Impacts Group, based on data used in IPCC 2007 and IPCC 2013 (http://tntcat.iiasa.ac.at:8787/RcpDb[3] and http://sedac.ciesin.columbia.edu/ddc/sres/[4]).*

4. Implications for Pacific Northwest climate projections and climate impacts assessments.[C]

- *Projected Pacific Northwest climate change is similar for new (IPCC 2013) and old (IPCC 2007) scenarios of medium and low greenhouse gas emissions.* The Washington Climate Change Impacts Assessment (WACCIA)[8] and many regional climate impact studies largely used the A1B and B1 greenhouse gas scenarios. These are comparable to RCP 6.0 and RCP 4.5, respectively, at the end of the century, in terms of both greenhouse gas concentrations (Table 3-1) and resultant changes in Pacific Northwest climate (Section 5, Figure 5-2).

[C] See Section 5 (Figure 5-2) for a comparison of projected Pacific Northwest temperature change under the old and new scenarios.

- *Newer scenarios for very low and high greenhouse gas emissions result in a wider range in projected late-century warming for the Pacific Northwest. Previous regional assessments have typically considered a narrower range of greenhouse gas scenarios.*
  - The new 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.
  - The highest scenarios commonly used in many previous climate impacts assessments (A1B, A2) are much lower than the high-end scenario in the new projections (RCP 8.5).
- *The importance of differences between the old and new 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 (Section 5, Figure 5-2). Other differences between the scenarios have not yet been explored.

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SECTION 4

How Are Global and National Climate Projected to Change?

Greenhouse gas emissions are projected to increase global and national average temperatures, precipitation, sea level, and ocean acidity. More extreme heat and heavy rainfall events are also likely. The amount of change that actually occurs will depend on the amount of future greenhouse gas emissions and will vary by location. The most recent projections for 21st century climate change (IPCC 2013) [1] align with and confirm earlier projections (e.g., IPCC 2007), [2] although new estimates indicate faster rates of sea level rise during this century and in the centuries to come.

1. **Significant warming is projected for the 21st century as a result of greenhouse gases emitted from human activities.[1]** The amount of warming that occurs from about mid-century onward depends on the amount of greenhouse gases emitted in the coming decades. Natural variability is expected to remain an important feature of global and regional climate, at times amplifying and at other times counteracting the long-term trends caused by rising greenhouse gas emissions.

   - *Continued rise in global temperatures.* Warming is projected to continue throughout the 21st century. Higher emissions of greenhouse gases will result in greater warming (Figure 4-1; Table 4-1). Projected warming for 2081-2100 (relative to 1986-2005) ranges from +1.8°F (range: +0.5°F to +3.1°F) for a scenario that assumes aggressive reductions in greenhouse gas emissions to +6.7°F (range: +4.7°F to +8.6°F) for a high "business as usual" emissions scenario.[A][B] Heat waves are projected to continue to become more prevalent and cold snaps less frequent.[1]

   - *Ocean warming.* The oceans will continue to warm, and heat will penetrate from the surface to the deep ocean. Projected warming in the top 330 feet of the ocean is +1.1°F to +3.6°F for 2081-2100 relative to 1986-2005.[1]

   - *Past emissions have committed the climate to ongoing changes, regardless of future emissions.* Current and past greenhouse gas emissions have already caused warming that will continue into the 21st century and persist for several centuries or longer.[3] To keep global temperature increases between +0.5 and +3.1°F (by 2081-2100 relative to 1986-2005), net greenhouse gas emissions would have to be reduced by about 50% by 2050 (relative to 1990 emissions), and to near or below zero in the final decades of the 21st century.[4]

[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; "medium" 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 3 for more details.

[B] The RCP 2.6 (very low) and RCP 8.5 (high) scenarios.

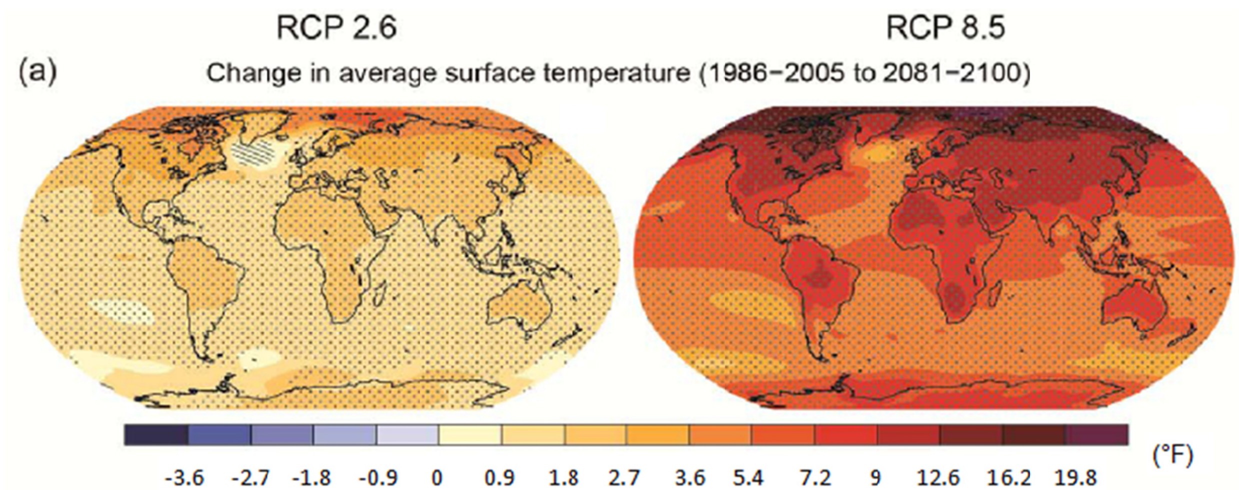

Figure 4-1. All scenarios project warming for the 21st century**.** Projected changes in annual average air temperature at the Earth's surface for 2081-2100 (relative to 1986-2005) for a very low (RCP2.6) and high (RCP8.5) greenhouse gas scenario, from an average of global climate models. Stippling indicates regions where at least 90% of models agree on the direction of change. *Figure and caption adapted from IPCC 2013, Figure SPM.8.[1]*

2. Global warming will be accompanied by changes in precipitation, continued decreases in glaciers and ice sheets, continued sea level rise, and increasing ocean acidity.

- *Modest increases in global average precipitation.* Changes in precipitation will vary by location and are less certain than those in temperature. Overall, global average precipitation is projected to increase modestly, by +0.6 to +1.6% per °F for most greenhouse gas scenarios.[C][4] In general, historically dry regions and seasons are expected to get drier and historically wet regions and seasons are expected to get wetter. Heavy rainfall events are projected to become more intense over most mid-latitude land areas, including much of the continental U.S.

- *Declining ice, snow, and glaciers.* Arctic sea ice, Northern Hemisphere spring snow cover, and the vast majority of glaciers will continue to shrink with warming. Many models project that the Arctic could be nearly ice free in September by mid-century, if greenhouse gas emissions continue to rise significantly.[1]

- *Continued rise in sea level.* Global mean sea level is projected to rise by +11 to +38 inches by the end of the 21st century (2100, relative to 1986-2005), according to the IPCC,[D][1] and +20 to +55 inches (relative to the year 2000), according to a National

[C] Specifically, for the RCP 4.5, 6.0, and 8.5 greenhouse gas scenarios

[D] Sea level rise projections vary depending on the greenhouse gas emissions scenarios used. The average and associated ranges reported in Church et al. 2013 are +17 in. (range: 11-24 in.) for the very low (RCP 2.6) greenhouse gas scenario to +29 in. (range: 21-38 in.) for the high (RCP 8.5) greenhouse gas scenario.

Research Council report.[E][5] In all scenarios, 21st century global sea level is projected to rise faster than it has in recent decades (1971-2010).[4] Sea level rise will continue to rise for several centuries after 2100 as the ocean and ice sheets continue to respond to changes in global temperatures.[3][4]

- *Ocean acidification.* The acidity of the ocean is projected to increase by +38 to +109%[F][1] by 2100 relative to 1986-2005 (or increase roughly +150 to +200% relative to pre-industrial levels)[6] as global oceans continue to absorb carbon dioxide from the atmosphere.

3. **The most recent projections for 21st century climate change (IPCC 2013)[1] align with and confirm earlier projections (e.g., IPCC 2007),[2] although new estimates indicate faster rates of sea level rise during this century and in the centuries to come.**

- *Close agreement in many areas.* Projected changes in temperature, precipitation, snow cover, and ocean acidification closely match the projections from 2007. Differences in warming projections are largely a result of differences between among greenhouse gas scenarios.

- *Exploring the consequences of aggressive greenhouse gas reductions.* The 2013 IPCC report includes a greenhouse gas scenario that requires aggressive reductions in global carbon dioxide emissions, and therefore indicates a lower amount of warming than for the low end of the scenarios used in the 2007 report, which assumed no greenhouse gas reduction efforts.

- *Higher sea level rise projections.* The updated sea level rise projections are about +40% higher, in large part because the new report includes projected changes in ice sheet flow, which were omitted in the 2007 IPCC report.

- *New findings about Greenland.* The Greenland ice sheet may be more easily destabilized by warming than previously thought. Studies indicate that the threshold for initiating a near-complete loss of Greenland ice is a global warming of +2°F to +7°F relative to pre-industrial, well within the projected warming for 2100. This would result in a sea level rise of more than 20 feet over the next one thousand years or more.[4]

- *Antarctic ice sheet stability.* The stability of large Antarctic marine ice sheets in a warmer climate is uncertain; their breakup could also lead to several additional feet of sea level rise, though probably not in this century.

[E] The IPCC projections are lower than those from the National Research Council (NRC 2012),[5] especially at the high end of the range. The two studies employed different analytical approaches and different assumptions about future greenhouse gas emissions.

[F] 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). Ocean pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines the acidity of a fluid) 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.

4. The United States is also projected to experience warming, modest changes in precipitation, and continued sea level rise.

- *Warming.* Continued warming of +3°F to +11°F by the end of this century (2070-2099), relative to recent decades (1971-1999; Figure 4-2).[G][7][8]

- *Variable changes in precipitation.* Precipitation changes will vary by location and season. Winter and spring precipitation are expected to increase in the northern U.S. while summer precipitation is projected to decrease throughout the U.S.[7]

- *More extreme events.* Heavy rains and heat waves will continue to become more frequent.[7] Climate models currently project increases in the frequency and intensity of the strongest Atlantic hurricanes, although there is large uncertainty about these conclusions given the numerous factors that influence the formation of hurricanes.[7]

- *Continued rise in sea level.* Averaged over the U.S., sea level is projected to rise in response to global sea level rise.[7] Locally, sea level rise will vary from place to place due to differences in the rate of vertical land movement, ocean currents, and other factors.

- *Impacts on human and natural systems.* Projected changes in U.S. climate are expected to: increase damage to infrastructure as a result of higher storm surge, increased flooding, and extreme heat events; increase the likelihood of water shortages and competition for water among agricultural, municipal, and environmental uses; and reduce the capacity of ecosystems to moderate the consequences of disturbances such as droughts, floods, and severe storms, among other impacts. Impacts on U.S. agriculture are expected to become more problematic after mid-century as temperature increases and precipitation extremes are further intensified.[9]

For more details on projected global and national changes in climate, see Table 4-1.

[G] U.S. temperature projections from the 2007 IPCC report[2] differ somewhat from the projections presented in IPCC 2013[1] because of the different greenhouse gas scenarios (see Section 3 of this report) and historical base periods used (1971-99 vs. 1986-2005).

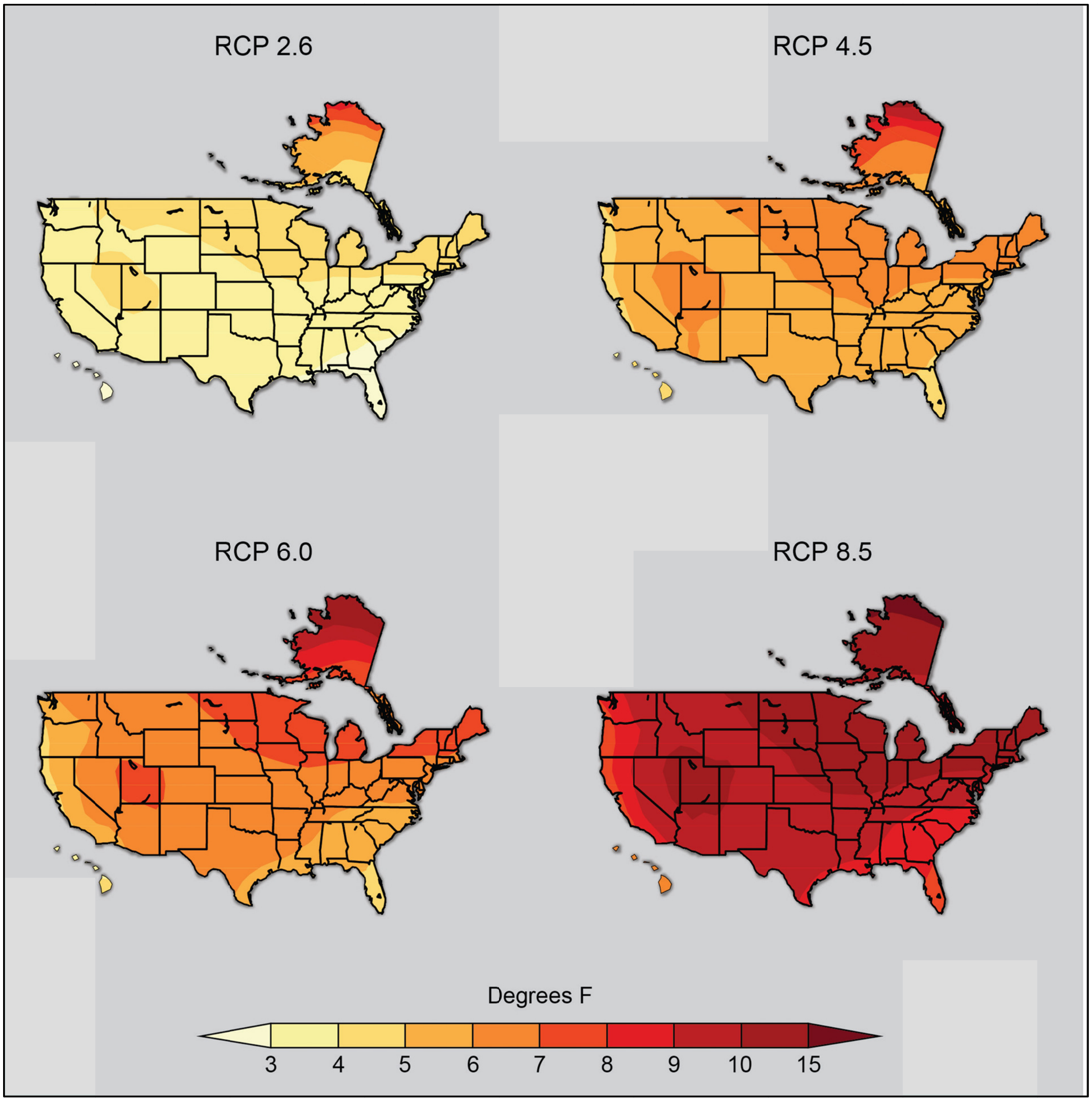

Figure 4-2. All scenarios project warming for the U.S.; the amount of warming depends on the amount of greenhouse gases emitted in the coming decades. Projected changes in annual average air temperature for the U.S. at the Earth's surface for the later part of this century (2071-2099) relative to 1971-2000 for the four greenhouse gas scenarios used to project global changes in IPCC 2013. RCP 2.6 (top left) is a very low greenhouse gas scenario that assumes rapid reductions in emissions – about a 50% cut from 1990 levels by 2050. RCP 8.5 (bottom right) is a high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century. Also shown are temperature changes (°F) for a low scenario (RCP 4.5, top right) and a medium scenario (RCP 6.0, bottom left). For more details on greenhouse gas scenarios, see Section 3 of this report. *Figure and caption adapted from Walsh et al., (in press).*[7]

Table 4-1. Projected changes in global and national climate.

Variable and Region	***Projected Long-term Change***
Temperature	
Global	Warming ▪ Warming projected for *all* greenhouse gas scenarios; amount of warming depends on the amount of greenhouse gases emitted. ▪ Projected change for 2081-2100 relative to 1986-2005: Very low emissions (RCP 2.6): +1.8°F (range: 0.5°F to 3.1°F) High emissions (RCP 8.5): +6.7°F (range: 4.7°F to 8.6°F)[1] ▪ Spatial pattern of warming varies. More warming is projected over land than over oceans, and the Arctic is projected to warm more rapidly than the global average.
U.S.	Warming ▪ Warming is projected for all scenarios for the end of the century (2070-2099, relative to 1971-1999): Low emissions (B1): +3 to +6°F High emissions (A2): +5 to +11°F[8] ▪ Spatial pattern of warming varies. In the continental U.S., the inland West and upper Midwest are projected to warm more rapidly than the coasts.[7]
Extremes	Increasing extreme heat events and decreasing extreme cold events globally and nationally. ▪ Projected change for the U.S. for the 2050s (2041-2070, relative to 1980-2000), under a high emissions scenario (A2): o Increase in number days above 95°F. Greatest increases occur in the southern U.S. and the Midwest.[4] o Decrease in number of days below 10°F. Greatest decreases occur in the interior West, upper Midwest, and Northeast.[4]
Precipitation	
Global	Decreases in annual precipitation at mid-latitudes and in the subtropics, increases at high-latitudes and parts of the tropics.
U.S.	Changes vary by season, location, and time period. ▪ Projected changes for mid-century (2041-2070; relative to 1971-2000) under a high emissions scenario (A2):[4] o Increasing winter precipitation in most of the U.S., including much of the Northwest. o Increasing spring/fall precipitation in most of the U.S., except the Southwest, where decreases are projected. o Decreasing summer precipitation in the Northwest and Southwest, and parts of the Midwest and East.

Variable and Region	***Projected Long-term Change***
Heavy Precipitation	Increasing, but varies by location. ▪ Globally, more frequent and more intense extreme precipitation events expected by the end of this century over most of the mid-latitude land areas and wet tropical regions. ▪ Within the U.S., heavy rainfall events projected to become more frequent. Greatest increases expected in Alaska, the Northeast, and the Northwest.[4]
Snow and Ice	
Glaciers	Continued losses, on average, globally and nationally. Global average projections for 2081-2100, relative to 1986-2005: Very low emissions (RCP 2.6): −15 to −55% decline High emissions (RCP 8.5): −35 to −85% decline[1]
Arctic Sea Ice	Decreasing ▪ Projected decline in total area covered by Arctic sea ice for 2081-2100 relative to 1986-2005 (range from RCP 2.6 to RCP 8.5): February: −8 to −34% September: −43 to −94%[1]
Northern Hemisphere Snow Cover	Decreasing ▪ Projected change in spring (March-April) snow extent for 2081-2100 (relative to 1986-2005) from a very low (RCP 2.6) to a high (RCP 8.5) greenhouse gas scenario: −7 to −25%[1]
Oceans	
Ocean Temperature	Warming ▪ Projected warming greatest near the surface and generally decreasing with depth. Projected change for 2081-2100 relative to 1986-2005: Top 330 ft (RCP 2.6 to RCP 8.5): +1.1 to +3.6°F Top 3,300 ft (RCP 2.6 to RCP 8.5): +0.5 to +1.1°F[1]
Global Sea Level	Rising globally and nationally, on average, although rate and direction of change will vary by location. ▪ Projections of global average sea level:[D] *IPCC (2081-2100 relative to 1986-2005):* Very low emissions (RCP 2.6): +17 in. (range: +11 to +24 in.) High emissions (RCP 8.5): +29 in. (range: +21 to +38 in.) [1] *National Research Council (2100 relative to 2000):* Range from low (B1) to high (A1FI) emissions scenario: +20 to +56 in.[5] ▪ No projected range specific to the U.S. as a whole (projections are for specific regions within the U.S.)

Variable and Region	***Projected Long-term Change***
Ocean Acidification	Global ocean acidity is projected to increase by 2100 for all scenarios (relative to 1986-2005).[1] Low emissions (RCP 4.5): +38 to +41% *(decrease in pH: 0.14-0.15)* High emissions (RCP 8.5): +100 to +109% *(decrease in pH: 0.30-0.32)*

[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] (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.

[3] Solomon, S. et al., 2009. Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences*, 106(6), 1704-1709.

[4] (IPCC) Intergovernmental Panel on Climate Change. 2013. *Climate Change 2013: The Physical Science Basis: Technical Summary*, available at: http://www.ipcc.ch/report/ar5/wg1/#.UluMuxCz4zo

[5] (NRC) National Research Council. 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press, 2012.

[6] Feely, R.A. et al., 2009. Ocean acidification: Present conditions and future changes in a high-CO2 world. *Oceanography* 22(4):36–47, http://dx.doi.org/10.5670/oceanog.2009.95.

[7] Walsh, J., D. Wuebbles, et al. (in press). Our Changing Climate. Chapter 2 in the draft 2014 U.S. National Climate Assessment, http://ncadac.globalchange.gov/.

[8] Kunkel et al. 2013. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 9. *Climate of the Contiguous United States,* NOAA Technical Report NESDIS 142-9, NOAA National Environmental Satellite, Data, and Information Service, Washington, D.C.

[9] (NCADAC) National Climate Assessment and Development Advisory Committee. 2014. U.S. National Climate Assessment, http://ncadac.globalchange.gov/.

SECTION 5

How is Pacific Northwest Climate Projected to Change?

Continued increases in average annual and seasonal Pacific Northwest temperatures are projected as a result of global warming, as well as increases in extreme heat. Projected changes in annual precipitation are small, although heavy rainfall events are projected to become more severe. Regionally, sea level will continue to rise in concert with global sea level. Locally, sea level is projected to rise in most locations, with the amount of rise varying by location and over time. Natural variability will continue to influence shorter-term (up to several decades) climate trends. New climate change projections are very similar to previous projections when similar greenhouse gas emissions are assumed.

1. **The Pacific Northwest is projected to warm rapidly during the 21st century, relative to 20th century average climate, as a result of greenhouse gases emitted from human activities.**[A] The actual amount of warming that occurs in the Pacific Northwest after about 2050 depends on the amount of greenhouse gases emitted globally in coming decades.[1]

   - *Continued rise in annual average temperature.* Warming is projected to continue throughout the 21st century (Figure 5-1). For the 2050s[B] relative to 1950-1999, temperature is projected to rise +5.8°F (range: +3.1 to +8.5°F) for a high greenhouse gas scenario (RCP8.5).[C][D] Much higher warming is possible after mid-century (Figure 5-1, Table 5-1).[1] Lower emissions of greenhouse gases will result in less warming.

   - *Warming is projected for all seasons.* The warming projected for summer is slightly larger than for other seasons.[1][2]

   - *More extreme heat.* There is strong agreement among climate models that extreme heat events will become more frequent while extreme cold events will become less frequent.[1]

   - *Ongoing variability.* 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 Pacific Northwest include the El Niño/Southern Oscillation (i.e., El Niño and La Niña) and the Pacific Decadal Oscillation.

   - *The size of projected change is large compared to observed variability.* The Pacific Northwest is likely to regularly experience average annual temperatures by mid-century that exceed what was observed in the 20th century.[E][1]

[A] Many characteristics of Washington's climate and climate vulnerabilities are similar to those of the broader Pacific Northwest region. Results for Washington State are therefore expected to generally align with those provided for the Pacific Northwest, with potential for some variation at any specific location.

[B] Specifically, "2050s" refers to the 30-year average spanning from 2041 to 2070. Note that this section focuses on changes for the 2050s, because this is the only time period for which there are published results for the Pacific Northwest from the 2013 IPCC[2] projections.

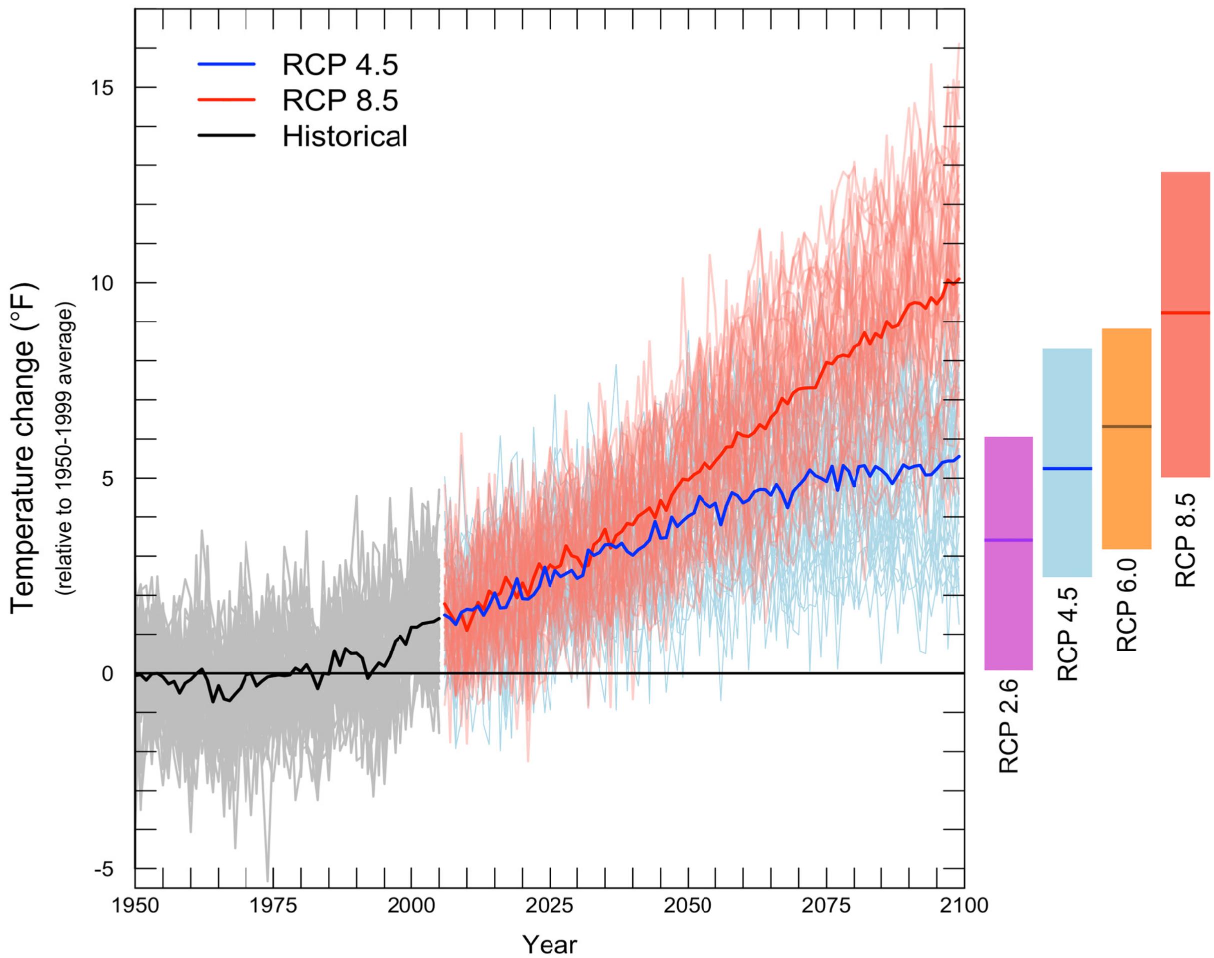

Figure 5-1. All scenarios project warming for the 21st century. The graph shows average yearly temperatures for the Pacific Northwest relative to the average for 1950-1999 (gray horizontal line). The black line shows the average simulated temperature for 1950–2011, while the grey lines show individual model results for the same time period. Thin colored lines show individual model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5 – see Section 3 for details), and thick colored lines show the average among models projections for each scenario. Bars to the right of the plot show the mean, minimum, and maximum change projected for each of the four emissions scenarios for 2081-2100, ranging from a very low (RCP 2.6) to a high (RCP 8.5) scenario. Note that the bars are lower than the endpoints from the graph, because they represent the average for the final two decades of the century, rather than the final value at 2100. *Figure source: Climate Impacts Group, based on climate projections used in the IPCC 2013 report.[2]*

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; "medium" 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 3 for details.

D Scenarios used in this report 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,[2] see Section 3). 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

2. **Changes in annual and seasonal precipitation will continue to be primarily driven by year-to-year variations rather than long-term trends, but heavy rainfall events are projected to become more severe.**

   - *Small changes in annual precipitation.* Projected changes in total annual precipitation are small (relative to variability)[F] and show increases or decreases depending on models, which project a change of −4% to +14% for the 2050s[D] (relative to 1950-1999).[1]

   - *Seasonal changes in precipitation are mixed.* Most models project drier summers, with an average model projection of −6% to −8% for the 2050s for a low and a high greenhouse gas scenario, respectively (2041-2070, relative to 1950-1999).[D][G][2] Some individual model projections show as much as a −30% decrease in summer precipitation. A majority of models project increases in winter, spring, and fall precipitation for this same time period, ranging from +2 to +7%, on average.[1]

   - *Increasing precipitation extremes.* Heavy rainfall events are projected to become more severe by mid-century. Specifically, the number of days with more than 1 inch of rain is projected to increase by +13% (±7%) for the 2050s (relative to 1971-2000) for a high greenhouse gas scenario.[H][3]

   - *Size of projected change is smaller than observed variability.* Projected changes in annual and seasonal precipitation are generally small – throughout the 21st century – compared to the range of precipitation caused by natural variability. In addition, projected changes are not consistent for all scenarios: some models project increases while others project decreases.[1]

3. **Washington's coast will be affected by sea level rise, warmer ocean temperatures, and changing ocean chemistry.**

   - *Coastal areas in Washington will experience sea level rise, although some areas may continue to experience decreases due to trends in vertical land movement.* According to a recent report by the National Research Council, sea level is projected to rise an additional +4 to +56 inches in Washington by 2100 (relative to 2000).[4] Locally, however, sea level will increase by different amounts in different places. Previous research projects a decline

because there are no published projections for the Pacific Northwest based on this scenario. In order to illustrate the full range of projections, Figures 5-1 and 5-2 nonetheless show results from the very low (RCP 2.6) greenhouse gas scenario, among other scenarios ranging up to the highest (RCP 8.5) scenario.

E Specifically, all scenarios project that, by mid-century (2041-2070), annual temperatures will be warmer than the warmest year historically (1950-1999).

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

G The RCP 4.5 (low) and RCP 8.5 (high) greenhouse gas scenarios (see Section 3 for more details).

H Projection based on regional climate model simulations, from the North American Regional Climate Change Program (NARCCAP) multi-model ensemble (http://www.narccap.ucar.edu). These simulations are based on results from 6 different regional models driven by 4 different global model projections, all based on the A2 greenhouse gas scenario, which is slightly lower than the RCP 8.5 scenario used in IPCC 2013. Values denote the average and the standard deviation among model projections. Results are averaged over a large area and may not be applicable to a given locale in Washington State.

in sea level for the northwest Olympic Peninsula through 2100, for scenarios that assume very low rates of global sea level rise and high rates of vertical uplift.[5][6] These projections differ from the NRC projections due to different study approaches. Although most global projections would result in sea level rise for the northwest Olympic Peninsula, it is not yet possible to conclusively rule out a decline in sea level for that region.

- *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 periodic cycles in climate patterns such as El Niño and the Pacific Decadal Oscillation.[4] This variability will continue in the future.

- *Coastal ocean temperatures are projected to increase.* Ocean surface temperatures offshore of Washington are projected to rise by about +2°F by the 2040s (2030-2059, relative to 1970-1999) for a medium greenhouse gas scenario.[I][7] Projected changes in winter sea surface temperatures in the North Pacific are expected to be as large as the range of natural variability by 2030-2050 (relative to 1950-1999) under a medium greenhouse gas scenario.[J][8] However, coastal ocean temperatures are strongly affected by coastal upwelling of colder water from ocean depths, and by large scale climate variability such as El Niño – current research is unclear as to how these might be altered by climate change.

- *Acidification of Washington's marine waters is projected to continue.* The acidity of Washington's coastal waters is projected to increase due to increases in global ocean acidity (+38 to +109%[K] by 2100 relative to 1986-2005,[2] or roughly +150 to +200% relative to pre-industrial levels)[9]. Local conditions are also affected by seasonal upwelling of deeper Pacific Ocean water that is low in pH and high in nutrients, transport of nutrients and organic carbon from land, and oceanic absorption of other acidifying atmospheric gases.

4. **The new climate projections[1] are very similar to the climate projections from 2007[7] when similar rates of greenhouse gas emissions are assumed.**

- *Projected Pacific Northwest climate change is similar for new (IPCC 2013)[2] and old (IPCC 2007)[10] scenarios of medium and low greenhouse gas emissions.*[C] The Washington Climate Change Impacts Assessment (WACCIA)[11] and many regional climate impact studies largely used the A1B and B1 greenhouse gas scenarios. These are comparable to RCP 6.0 and RCP 4.5, respectively, at the end of the century, in terms of both greenhouse gas concentrations (see Section 3) and resultant changes in NW climate (Figure 5-2).

[I] The A1B greenhouse gas scenario. See Section 3 for more details about scenarios.

[J] Based on analyses of 10 global climate models and the A1B greenhouse gas scenario.

[K] 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.

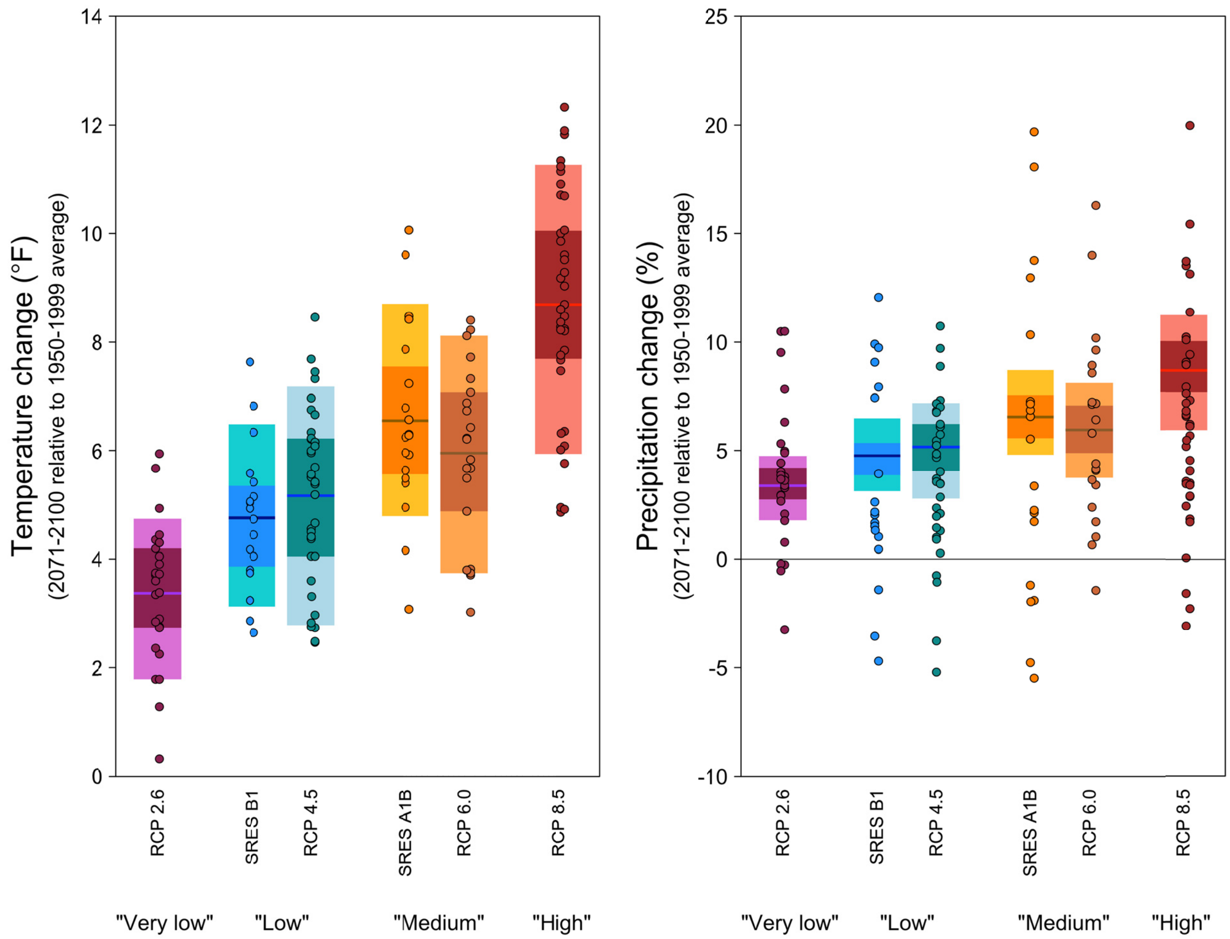

Figure 5-2. Differences among climate change projections for the Pacific Northwest are primarily due to differences among greenhouse gas scenarios. Projected changes in average annual temperature (left) and precipitation (right) for the Pacific Northwest for the 2080s (2071-2100, relative to 1950-1999). Projections are shown for all four new scenarios: RCP 2.6 ("very low"), 4.5 ("low"), 6.0 ("medium"), and 8.5 ("high"), along with the older projections based on the B1 ("low") and A1B ("medium") scenarios used in many Pacific Northwest impacts assessments. Individual climate model projections for each scenario are shown using colored dots. Boxes show the average projected change (in °F for temperature and percent change for precipitation), along with the 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentile values among all climate model projections. The black horizontal line on the precipitation graph denotes zero change. *Figure source: Climate Impacts Group, based on climate projections used in the IPCC 2013 report.[2] and figures 2.5b and 2.6 of Mote et al., 2013.[1]*

- *Newer scenarios for very low and high greenhouse gas emissions result in a wider range among late-century warming projections for the Pacific Northwest.* Previous regional assessments have typically considered a narrower range of greenhouse gas scenarios.
    - The new 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. The older projections do not include a comparable scenario.
    - The highest scenarios commonly used in previous climate impacts assessments (A1B, A2) are much lower than the high-end scenario in the new projections (RCP 8.5).
- *The importance of differences between the old and new 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 precipitation 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 (Figure 5-2). Other differences between the scenarios have not yet been explored.

For more details on projected changes in Pacific Northwest climate, see Table 5-1 at the end of this section. See next page for additional resources for evaluating regional climate change projections.

Additional Resources for Evaluating Regional Climate Change Projections

The following resources provide location-specific information about climate change impacts 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 and hydrologic scenarios.** The Climate Impacts Group provides downscaled daily historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US. These are based on projections in IPCC 2007.[10] http://warm.atmos.washington.edu/2860,[11] http://cses.washington.edu/cig/.

- **Climate scenarios for the Western U.S.** This dataset provides future projections of daily temperature, precipitation, humidity, insolation and wind at a spatial resolution of about 2.5 miles, using new statistical downscaling methods and the new climate projections included in IPCC 2013.[2][11] http://nimbus.cos.uidaho.edu/MACA/

- **Fine scale climate scenarios for the lower 48 states.** Produced by NASA, this dataset provides future projections of monthly temperature and precipitation at a spatial resolution of about half a mile, using updated statistical downscaling methods and the new climate projections included in IPCC 2013.[2][13] https://portal.nccs.nasa.gov/portal_home/published/NEX.html

- **Regional climate model projections for the Pacific Northwest.** Dynamically downscaled data are being developed at the Climate Impacts Group based on projections from both IPCC 2007[10] and 2013.[2] The data are produced using regional climate model simulations over the state of Washington and surrounding region, at a spatial resolution of about 9 miles. Among other advantages, these data are more accurate for projecting changes in extremes.[14][15]

- **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. [10] http://narccap.ucar.edu/

Table 5-1. Projected changes in the climate of Washington and the Pacific Northwest.

Variable	*Projected Long-term Change*
Temperature	
Annual	Warming ▪ Warming projected for *all* greenhouse gas scenarios; amount of warming depends on the amount of greenhouse gases emitted. ▪ Projected change in Pacific Northwest[A] average annual temperature for the 2050s (2041-2070),[B] relative to the average for 1950-1999: Low emissions (RCP 4.5): +4.3°F (range: 2.0 to 6.7°F) High emissions (RCP 8.5): +5.8°F (range 3.1 to 8.5°F)[D][1]
Seasonal	Warming in all seasons for 2041-2070, relative to 1950-1999: *Winter* Low emissions (RCP 4.5): +4.5°F (range: 1.6 to 7.2°F) High emissions (RCP 8.5): +5.8°F (range 2.3 to 9.2°F) *Spring* Low emissions (RCP 4.5): +4.3°F (range: 0.9 to 7.4°F) High emissions (RCP 8.5): +5.4°F (range 1.8 to 8.3°F) *Summer* Low emissions (RCP 4.5): +4.7°F (range: 2.3 to 7.4°F) High emissions (RCP 8.5): +6.5°F (range 3.4 to 9.4°F) *Fall* Low emissions (RCP 4.5): +4.0°F (range: 1.4 to 5.8°F) High emissions (RCP 8.5): +5.6°F (range 2.9 to 8.3°F)[1]
Geography of Change	Overall, warming is expected to be fairly uniform across Washington State. However, there is slightly greater warming projected for the interior – east of the Cascade range.[1]
Extremes	More frequent extreme heat events and less frequent extreme cold events ▪ Projected changes in Pacific Northwest annual temperature extremes for 2041-2070, relative to 1971-2000, for a high greenhouse gas scenario:[L][3] Length of freeze-free period: +35 days (± 6 days) Number of days above 90°F: +8 days (± 7 days) Number of nights below 10°F: −8 days (± 5 days) Heating degree days: −15% (± 2%)[M] Cooling degree days: +105% (± 98%) Growing degree days (base 50°F): +51% (± 14%)

[L] Projection based on regional climate model simulations under a high greenhouse gas scenario (A2).[H]

[M] 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.

Variable	Projected Long-term Change
Precipitation	
Annual	Small changes ▪ Annual changes for all models are small relative to year-to-year variability. ▪ For all greenhouse gas scenarios, some models project wetter conditions while others project drier conditions. ▪ Projected change in annual Pacific Northwest precipitation for the 2050s (2041-2070,[B] relative to 1950-1999): Low emissions (RCP 4.5): −4.3 to +10.1% High emissions (RCP 8.5): −4.7 to +13.5%[D][1]
Seasonal	Projected changes vary seasonally. ▪ A majority of models project increases in winter, spring, and fall precipitation for the Pacific Northwest for mid-century, as well as decreasing summer precipitation. ▪ For all scenarios and seasons, some models project wetter conditions while others project drier conditions. ▪ Projected summer drying is more consistent among models. Some models project more than a 30% decrease in summer precipitation for the 2050s (2041-2070, relative to 1950-1999), although the average projected change for summer is notably smaller: −6 to −8% for a low (RCP 4.5) and high (RCP 8.5) greenhouse gas scenario, respectively.[1]
Geography of Change	Changes in precipitation are expected to be different from place to place.
Heavy Precipitation	Increasing ▪ Heavy rainfall events are expected to occur more frequently. ▪ Projected changes in Pacific Northwest precipitation extremes for 2041-2070, (relative to 1971-2000) for a high greenhouse gas scenario:[H][3] Number of days with rain > 1 inch: +13% (±7%) Number of days with rain > 3 inches: +22% (±22%)
Oceans	
Ocean Temperature	Warming ▪ Ocean surface temperatures off the coast of Washington[N] are projected to warm by +2.2°F by the 2040s (2030-2059, relative to 1970-1999).[4] ▪ Projections of coastal ocean temperatures are unclear due to limited understanding of changes in coastal upwelling and the large influence of natural variability.
Sea Level Change	Rising in general, although considerable variations from location to location due to different rates of subsidence or uplift of land areas. ▪ Regionally, sea level is projected to rise substantially under all

[N] Projected change in sea surface temperature for model grid points near the coast between 46° and 49°N.

Variable	*Projected Long-term Change*
	greenhouse gas scenarios. Locally, however, sea level can rise or fall relative to land due to vertical uplift of land surfaces, primarily as a consequence of the high tectonic activity of the Pacific Northwest. ▪ Projected sea level rise (for 2100 relative to 2000): Seattle, WA: +4 to +56 inches Newport, OR: +5 to +56 inches[O][4]
Ocean Acidification	Increasing acidity ▪ Regionally, coastal ocean acidity is projected to increase in tandem with global ocean acidification (see Section 4).[2]

[1] 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.

[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] Kunkel, K. E. et al., 2013: *Part 6. Climate of the Northwest U.S.*, NOAA Technical Report NESDIS 142-6.

[4] National Research Council. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press, 2012.

[5] Mote, P.W. et al. 2008. *Sea Level Rise in the Coastal Waters of Washington State*. Report prepared by the Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, and the Washington Department of Ecology, Lacey, WA.

[6] 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.

[7] Mote, P. W., and E.P. Salathé. 2010. Future climate in the Pacific Northwest*.* *Climatic Change* 102(1-2): 29-50, doi: 10.1007/s10584-010-9848-z.

[8] Overland, J. E., and M. Wang. 2007. Future climate of the North Pacific Ocean. *Eos*, *Transactions American Geophysical Union*, 88, 178, 182. doi: 10.1029/2007EO160003, 178, 182.

[9] Feely, R. A. et al., 2009. Ocean acidification: Present conditions and future changes in a high-CO_2 world. *Oceanography* 22(4):36–47, doi:10.5670/oceanog.2009.95.

[10] (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.

[11] 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.

[12] Abatzoglou, J. T. and T. J. Brown T.J., 2011. A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology* 32(5), 772-780. doi:10.1002/joc.2313

[13] Thrasher, B. et al., 2013. Downscaled Climate Projections Suitable for Resource Management. *Eos Transactions, American Geophysical Union*, *94*(37), 321-323.

[14] Salathe Jr, E. P. et al., 2010. Regional climate model projections for the State of Washington. *Climatic Change*, *102*(1-2), 51-75.

[15] Salathé Jr, E. P. et al., 2013: *Estimates of 21st century flood risk in the Pacific Northwest based on regional climate model simulations.* Water Resources Research (in review).

O Range includes uncertainty in the estimated rate of melt for glaciers and ice sheets, vertical land motion, and greenhouse gas scenarios, spanning from the B1 (low emissions, similar to RCP 4.5) to the A1FI (high emissions, similar to RCP 8.5) greenhouse gas scenarios.

SECTION 6

How Will Climate Change Affect Water in Washington?

Washington is projected to experience decreases in snowpack, increases in stream temperatures, and widespread changes in streamflow timing, flooding, and summer minimum flows. Annual streamflow volumes are not projected to change substantially. Climate change is projected to result in more frequent summer water shortages in some basins, while others remain unaffected – vulnerability is likely greatest in fully allocated watersheds with little management flexibility. Recent research has largely confirmed previous research, but has contributed increased understanding of the local- and water-use specific implications of climate change. New datasets provide a comprehensive set of projections that can support long-range planning.

1. **As is the case for much of the western U.S., Washington is projected to experience decreasing snowpack, a shifting balance between snow and rain, increasing stream temperatures, and changes in streamflow timing, flooding, and 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 6-1 and 6-2, Table 6-1).[A][1]

Drivers of change: Temperature and precipitation

- *All scenarios project continued warming* during this century, and most scenarios project that this warming will be outside of the range of historical variations by mid-century (Section 3 of this report). As a consequence, there is high confidence in the warming-related changes in water resources.
- *Projected changes in precipitation are mixed.* Changes in precipitation are less clear, and are generally projected to be smaller than natural year-to-year variability. As a result, there is much lower confidence in the precipitation-dependent changes in water resources.

Natural water storage

- *Declining snowpack.* Average spring snowpack in Washington is projected to decline by −56 to −70% by the 2080s (2070-2099, relative to 1916-2006).[B][C][D][2]

[A] 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 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 impacts of climate change. Washington watershed classifications are shown in Figure 6-1.

[B] 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.

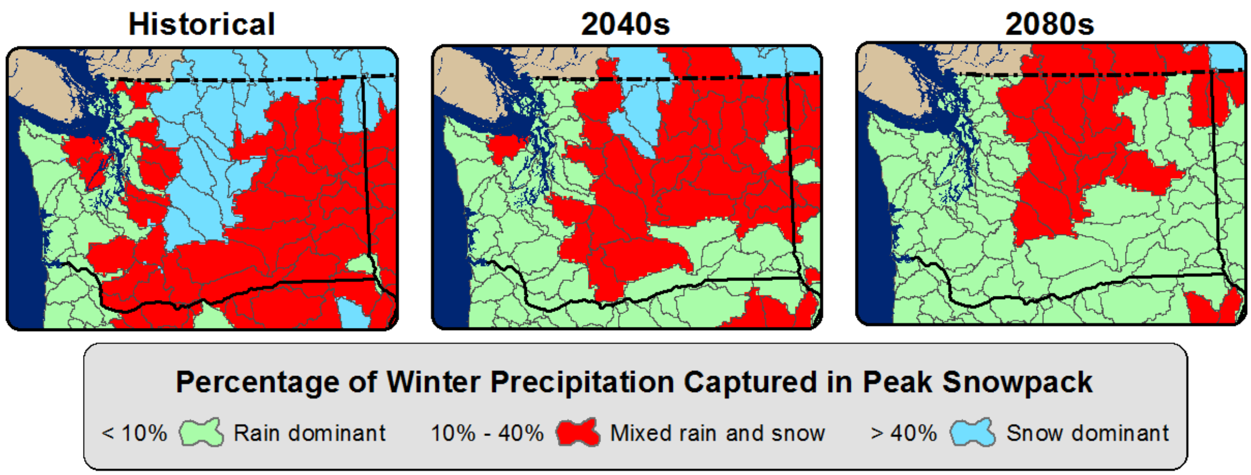

Figure 6-1. Changing hydrology with warming. Maps above indicate current and future watershed classifications, based on the proportion of winter precipitation stored in peak annual snowpack. Graphs below indicate current and future average monthly streamflow for these watershed types. Both compare average historical conditions (1916-2006) and projected future conditions for two time periods, the 2040s (2030-2059) and the 2080s (2070-2099), under a medium 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 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. 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 flows as a result of warming (below, center). *Source: Hamlet et al., 2013.*[3]

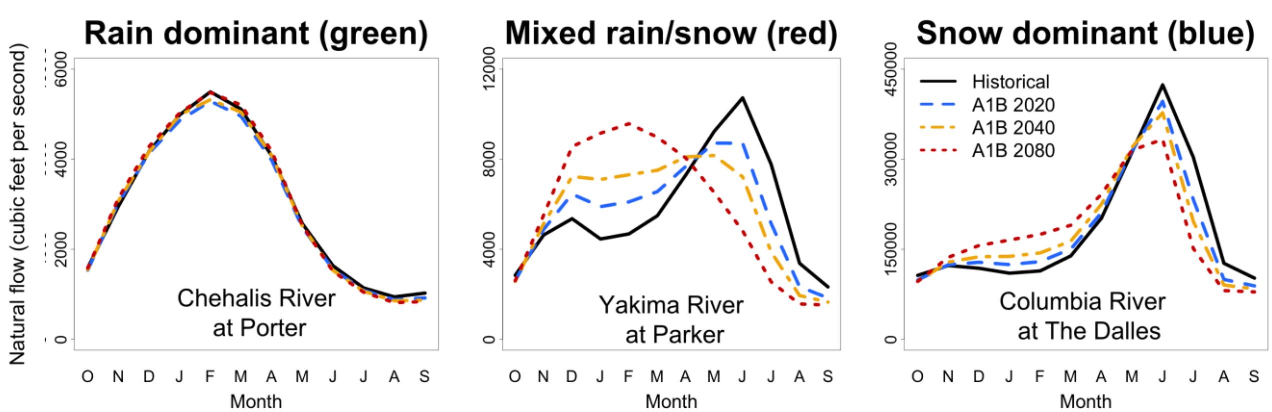

Figure 6-2. Changes in the seasonality of streamflow for three example watersheds in the Pacific Northwest: The Chehalis River, a warm basin (left); the Columbia River, a cold basin with source waters at high elevations (right) and the Yakima River, a middle-elevation basin near the current snowline (middle). *Source: Elsner et al., 2010.*[2]

- *Shrinking glaciers.* There are no published projections of Northwest glacier response to climate change, although most Northwest glaciers are in decline (Section 2) and one study found that only 2 of the 12 North Cascades glaciers with annual measurements are expected to survive the current climate.[4] In the North Cascades, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed.[5]

Watershed type and streamflow conditions

- *Changing watershed type*. The dominant form of precipitation in most Washington watersheds will be rainfall by the end of the 21st century (Figure 6-1). In contrast, many have historically been strongly influenced by snowfall in winter. The one exception is the North Cascades, where snow accumulation is projected to remain important through 2100.

- *Earlier streamflow timing.* 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 6-1). For instance, peak streamflow is projected to occur 4 to 9 weeks earlier by the 2080s (2070-2099, relative to 1917-2006) in four Puget Sound watersheds (Sultan, Cedar, Green, Tolt) and the Yakima basin (Figure 6-2).[D][2]

- *Small increase in annual streamflow.* Annual streamflow is projected to increase by +4.0 to +6.2% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999). These changes are likely to be dwarfed by natural year-to-year variations in streamflow totals through the end of the century.[D][2]

- *Increasing winter streamflow*. Winter streamflow is projected to increase by +25 to +34% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999).[D][2]

- *Declining summer streamflow*. Summer streamflow is projected to decrease by −34 to −44% on average for Washington State by the 2080s (2070-2099, relative to 1970-1999).[D][2]

- *Increasing stream temperatures.* Stream temperatures are projected to increase in response to warming and decreases in summer streamflow. Projections for 124 stream temperature locations across the state find that more sites will experience temperatures that elevate stress for adult salmon.[6] Many will exceed thermal tolerances for the entire summer season by 2080 (2070-2099), despite rarely being in excess of these temperatures in the recent past.[7]

[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; "medium" 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 3 for more details.

[D] Average projected change for ten global climate models, averaged over Washington State. Range spans from a low (B1) to a medium (A1B) greenhouse gas scenario.

Streamflow extremes

- *Flooding*

    - *Projected changes range from modest decreases to large increases in extreme river flows depending on location and watershed type.* The highest river flows are generally expected to increase in rain-dominant and in mixed rain and snow watersheds. Some snow dominant watersheds will see flood increases, while others experience decreases. Projections for specific Washington locations can be found here: http://warm.atmos.washington.edu/2860/products/sites/.

    - *Increases in heavy rainfall events could further increase flood risk.* Heavy rainfall events are projected to become more severe by mid-century (Section 3 of this report). On average in the Northwest, the number of days with more than 1 inch of rain is projected to increase by +13% (±7%) for the 2050s relative to 1971-2000.[8] Preliminary results suggest an increase in the number of heavy rain events occurring in early fall.[9] These changes may result in more severe flooding in rain dominant and mixed rain and snow basins.

    - *Changes in flood management may not be sufficient to mitigate increases in flood risk.* In the upper Skagit basin, for instance, with current flood management practices, the 100-year flood is projected to increase by 24% by the 2080s (2070-2099, relative to 1916-2006)[E]; simulations indicate that changes in water management can only mitigate 7% of this projected increase.[10]

    - *Sea level rise will exacerbate coastal river flooding*. 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. Initial research on this issue suggests that the amount of area flooded in the Skagit would increase by up to 74% by the 2080s when accounting for the combined effects of sea level rise and larger floods.[11]

- *Minimum flows.* Low summer streamflow conditions are projected to become more severe in about 80% of watersheds across Washington State. 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. Changes are more pronounced west of the Cascade mountains because there is "less water to lose" east of the Cascades – historical conditions are already very arid in interior Washington.[F][12]

2. **Year-to-year variability will continue to cause some periods that are abnormally wet, and others that are abnormally dry.** For the foreseeable future, Washington will continue to experience years and decades with conditions that temporarily mask or amplify the projected changes in water resources (Figure 6-3), even as long-term trends continue.

[E] Projected change based on the ECHAM5 global climate model and the A1B greenhouse gas scenario.
[F] Results for a low (B1) and medium (A1B) greenhouse gas scenario for 112 medium-sized watersheds in Washington.

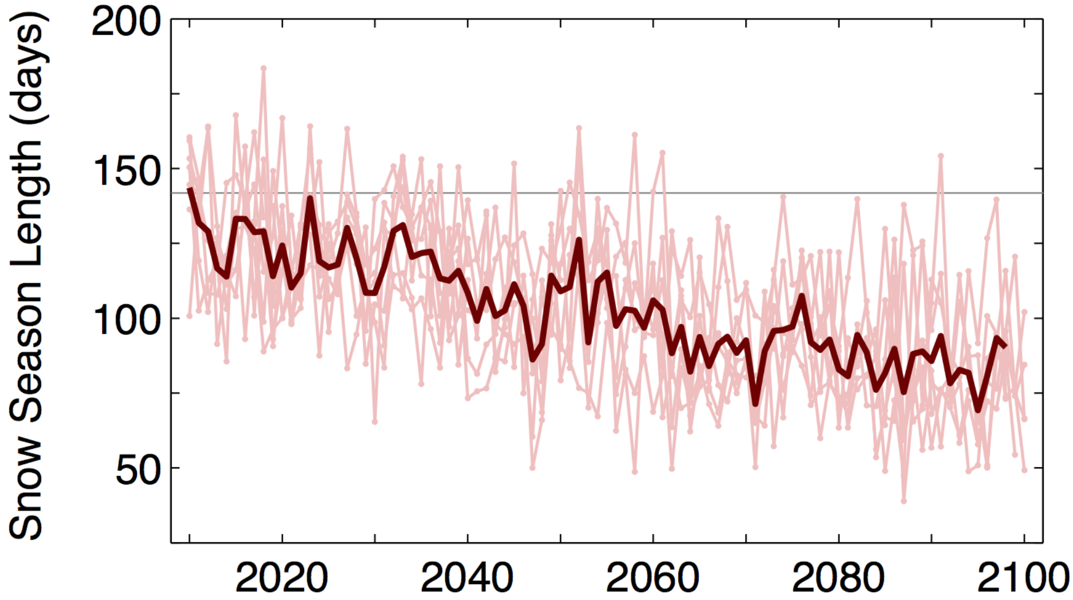

Figure 6-3. Shorter snow season with warming; large year-to-year variability. Projected length of the snow season, in days, for middle elevations (4,000 to 5,000 ft) for the Cascade mountains in Oregon and Washington. The plot shows projected snow season length from seven individual climate models (thin pink lines) and the average among all models (thick red line) for a medium greenhouse gas scenario (A1B). For comparison, the average snow season length for 1950-1999 was 142 days (shown as the gray horizontal line). Although the length of the snow season is clearly expected to decrease significantly over this century, individual years with substantially longer or shorter snow seasons than the general declining trend are also expected to occur. *Data source: Hamlet et al. 2013*[B]

3. **These changes will have far-reaching consequences for people, infrastructure and ecosystems across the state.** Climate change impacts 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 impacts on one sector – i.e., hydropower production, irrigation or municipal supply, or instream flows for fish – could exacerbate impacts on other sectors.[13]

    - *Irrigation water supply.* In the Yakima basin, warming is projected to increase the frequency of water shortage years – i.e., years in which water delivery is curtailed due to insufficient streamflow – from 14% of years historically (1940-2005) to 43-68% of years by the 2080s (2070-2099).[D][14]

    - *Hydropower production.* In response to increases in winter and decreases in summer streamflow, hydropower production in the Columbia River basin is projected to increase by +7 to +10% in winter and decrease by −18 to −21% in summer by the 2080s (2070-2099, relative to 1917-2006).[D][15] Regional power planners have expressed concerns over the existing hydroelectric system's potential inability to provide adequate summer electricity given the combination of climate change, demand growth, and operating constraints.[16][17]

- *Fish and aquatic ecosystems.* Warming streams, declining summer flows, and increasing flood risk are all expected to negatively affect coldwater fish populations such as salmon[18] and trout.[19] Trout populations in the western US are projected to experience a decline of −33 to −77% in suitable habitat area by the 2080s (2070-2099, relative to 1985-2004) under a high greenhouse gas scenario.[G][19] Warming streams are projected to negatively affect salmon health, migration, and survival (see above).

- *Flood protection and stormwater management.* 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 (Section 10).[20]

- *Municipal water supply.* 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 1917-2006) and decrease to 63-96% for Tacoma under low and medium greenhouse gas scenarios.[H][21] Climate change is also projected to increase demand.[22][23] For Seattle, supply is projected to exceed demand in nearly all years, and the City has identified no or low-cost system modifications to mitigate climate change-related supply reductions, keeping supply above demand under all climate change scenarios examined.[I][22]

- *Shortened ski season.* Historically (1971-2000), Washington ski areas have experienced warm winters (average December-February 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 (Section 3) – warm winters would occur 33 to 77% of the time.[J][26]

- *Small increase in irrigation demand projected for eastern Washington*. Forecasted eastern Washington water demand in the 2030s (2020-2049, relative to 1977-2006) indicates a small increase in demand for irrigation (+4% assuming historical cropping patterns, for a mid-range future climate scenario.[K][27]

- *Small increases in municipal demand 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

[G] Change in the length of stream habitat that is suitable to one of the following four trout species: cutthroat (*Oncorhynchus clarkia)*, brook (*Salvelinus fontinalis)*, brown (*Salmo trutta)*, and rainbow (*Oncorhynchus mykiss)*.

[H] 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 medium (A1B) greenhouse gas scenario.

[I] These results are based on a simplified analysis using projections from IPCC 2007.[25] Seattle Public Utilities is currently updating their assessment using 40 new projections from the 2013 IPCC report.[24]

[J] 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.

[K] Projected change is based on a low greenhouse gas scenario (B1) obtained using the HADCM global climate model, which was found to be near the middle of the range among projections for 2030. This projection does not include potential changes in the crop mix in response to climate change, which would likely reduce the impacts on water supply.

(relative to 2000), assuming current population forecasts and no new conservation measures, based on a high greenhouse gas scenario.[L][22]

- *Greatest vulnerability in highly allocated basins with little management flexibility*. 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.[H][28][29][30][31]

4. **Many Washington communities, government agencies, and organizations are preparing for the impacts 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

   - *Preparing King County infrastructure for projected flooding increases:*

     - *Levee improvements and relocation of at-risk structures.* King County formed a new Flood Control District in 2007 to increase capacity for addressing regional flood risks due to climate change and other factors, increasing local funding for flood risk reduction efforts ten-fold.[32]

     - *Widening bridge spans.* King County has replaced 15 short span bridges with wider span structures (including the Tolt Bridge over the Snoqualmie River) and 42 small culverts with large box culverts. These changes will increase resilience to major flooding.[M]

   - *Addressing extreme flood risk to Interstate-5 in Skagit County.* A federally funded pilot project will support development of a series of site-specific adaptation options to improve the resilience of Interstate 5 and state routes in the Skagit basin. These will complement flood hazard reduction strategies proposed by the U.S. Army Corps and Skagit County.

   Drinking water supply

   - *Ensuring supply exceeds demand for Seattle.* Seattle 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 supply reductions and demand increases. The City's analysis indicates that no new source of water supply is needed before 2060 and that, under the warmest scenario considered,

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[L] Projection based on the IPSL global climate model coupled with a high greenhouse gas scenario (A2).
[M] Presentation by Matt Kuharic, Senior Climate Change Specialist, King County Department of Natural Resources and Parks to the Washington State Climate Change Impacts Steering Committee, April 27, 2010.

available supply would exceed forecasted demand if all modifications are implemented. Depending on the relative timing of system modifications and climate change impacts, climate change could increase the frequency of requests to customers to curtail water use.[22]

- *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 (under construction 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.[33][34]

Long-range water planning

- *The Yakima basin long-term water management plan.* Development of the Yakima River Basin Integrated Water Resource Management Plan included an evaluation of the likely efficacy of a suite of water management strategies and storage options under various climate change scenarios. While the Integrated Plan improves basin water supply conditions for all scenarios considered, specific outcomes will be very different under different climate conditions. Under the "moderately adverse" climate change scenario[N] and demand growth, supplies for proratable irrigation districts would be 61% in a severe one-year drought with the Integrated Plan, as opposed to 27% without (compared to 37% during the one-year drought in 2005).[35]

- *Long-range water resources planning in the Columbia Basin.* The U.S. Army Corps of Engineers, the Bureau of Reclamation, and the Bonneville Power Administration collaborated on an assessment of climate change impacts on Columbia River Basin hydrology and water management to support decisions on the Columbia River Treaty and future biological opinions. The three federal agencies are integrating new climate change data derived from this work into their ongoing modeling and planning efforts.[36]

For more details on projected impacts on Water Resources, see Table 6-1.

[N] Corresponds to the low end of the range projected for mid-century (Section 3).

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

- **Climate and hydrologic scenarios.** The Climate Impacts Group provides historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US. http://warm.atmos.washington.edu/2860,[3] http://cses.washington.edu/cig/

- **Water supply and demand forecast.** The *Columbia River Basin long-term water supply and demand forecast*[K] provides historical data and projected changes in water supply and agricultural demand as a result of climate change. Other demand forecasts (municipal, hydropower, and instream flows) do not incorporate climate change. Results are available for each individual Water Resource Inventory Area (WRIA) in eastern Washington and the Columbia River basin as a whole. http://www.ecy.wa.gov/programs/wr/cwp/forecast/forecast.html

Table 6-1. Projected changes in water resources.

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. ▪ Projected change in Washington-average April 1st snowpack[B]; range from a low to a medium greenhouse gas scenario): 2040s (2030-2059, relative to 1916-2006): −38 to −46% 2080s (2070-2099, relative to 1916-2006): −56 to −70%[D][2]
Glaciers	Declines expected, but there are no published projections for Northwest glacier response to climate change. ▪ 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.[4] ▪ In the North Cascades, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed.[5]
Streamflow	
Annual	Mixed, but most models project a small increase in annual streamflow, on average for Washington State. ▪ Total annual streamflow is projected to increase slightly. 2040s (2030-2059, relative to 1917-2006): +2.1 to +2.5% 2080s (2070-2099, relative to 1917-2006): +4.0 to +6.2%[D][2] ▪ Changes are small relative to year-to-year variability in streamflow, and models disagree on the direction of change.
Winter	Mixed, but most models project an increase in winter streamflow, on average for Washington State. ▪ Winter (Oct-Mar) streamflow change: 2040s (2030-2059, relative to 1917-2006): +20 to +16% 2080s (2070-2099, relative to 1917-2006): +25 to +34%[D][2] ▪ Changes are small relative to year-to-year variability in winter streamflow, and models disagree on the direction of change.
Summer	Mixed, but most models project a decrease in summer streamflow, on average for Washington State. ▪ Summer (Apr-Sep) streamflow change: 2040s (2030-2059, relative to 1917-2006): −30 to −23% 2080s (2070-2099, relative to 1917-2006): −44 to −34%[D][2] ▪ Changes are small relative to year-to-year variability in summer streamflow, and models disagree on the direction of change.

Variable	Projected Long-term Change
Streamflow timing	Peak streamflows are projected to occur earlier in many snowmelt-influenced rivers in the Northwest. ▪ Peak streamflow is projected to occur 4 to 9 weeks earlier by the 2080s (2070-2099, relative to 1917-2006) in four Puget Sound watersheds (Sultan, Cedar, Green, Tolt) and the Yakima basin.[D][2]
Stream temperatures	Warming ▪ By the 2080s (2070-2099, relative to 1970-1999)[O], more stream locations are projected to experience weekly summer stream temperatures stressful to adjust salmon (in excess of 67°F):[6] Eastern Washington: 19% more sites Western Washington: 16% more sites ▪ Many stream locations projected to exceed 70°F for the entire summer season by 2080 – resulting in waters that are warm enough to impede migration and increase the risk of fish kills.[7]
Flooding	Increases in most watersheds ▪ Projected changes in streamflow volume associated with the 100 year (1% annual probability) flood event, by basin type, in Washington State for the 2080s (2070-2099, relative to 1916-2006): Rain dominant watersheds: +18% (range: +11 to +26%) Mixed rain-snow watersheds: +32% (range: −33 to +132%) Snow dominant watersheds: −2% (range: −15 to +22%)[F][P][12] ▪ Projected changes in heavy rainfall (Section 3 of this report) are not included in the above projections. Preliminary research indicates an increase in the proportion of heavy rain events occurring in early fall. Both changes will likely increase flood risk in rain dominant and mixed rain and snow watersheds, especially west of the Cascade crest.[9]
Minimum flows	Decreased flow in most watersheds ▪ Projected changes for changes in 7Q10 flows,[Q] by basin type, in Washington State for the 2080s (2070-2099, relative to 1916-2006): Rain dominant watersheds: −14% (−44 to −3%) Mixed rain-snow watersheds: −15% (−60 to +14%) Snow dominant watersheds: −6% (−12 to +4%)[F][P][12]

O Average projected change for 124 stream locations across Washington State. Projections are made using ten global climate models and a medium greenhouse gas scenario (A1B).

P Watersheds were defined as rain dominant if the average winter temperature (Dec-Feb) was greater than 35.6°F (+2°C), mixed rain and snow if the average winter temperature (Dec-Feb) was between 21.2 and 35.6°F (-6 to +2°C), and snow dominant if the average winter temperature (Dec-Feb) was below 21.2°F (-6°C).

Q 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.

<table>
<tr><th>Variable</th><th>Projected Long-term Change</th></tr>
<tr><td>Water Resources</td><td></td></tr>
<tr><td>Irrigation water supply</td><td>Increase in water short years in the Yakima River basin, in which water delivery is curtailed to junior water rights growers.
▪ Likelihood of shortfalls:
Historical (1975-2004): 14%
2020s (2010-2039): 24 to 27%
2040s (2030-2059): 31 to 33%
2080s (2070-2099): 43 to 68%[D][14]</td></tr>
<tr><td>Hydropower production</td><td>Increase in winter, decrease in summer
▪ Average change for the Columbia River basin for the 2080s (2070-2099, relative to 1917-2006):
Winter increase: +8 to +11%
Summer decrease: −17 to −21%[D][15]
▪ Annual average cost of lost hydropower for 2030 (relative to 2010) is projected to be $120 million[R], although estimates range from a slight gain in revenue to much larger losses.[16]</td></tr>
<tr><td>Fish and Aquatic Ecosystems</td><td>Decline in interior western U.S. trout populations for the 2080s (2070-2099, relative to 1985-2004) for a high greenhouse gas scenario:
Suitable habitat extent: −47% (−35 to −77%)[G][19]
Warming stream temperatures are projected to negatively affect salmon health, migration, and survival (see above).</td></tr>
<tr><td>Municipal Water Supply</td><td>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 1917-2006):
Everett: 100%
Tacoma: 63 to 96%[H][21]
▪ For Seattle, supply is projected to exceed demand in nearly all years, and the City has identified no or low-cost system modifications to mitigate climate change-related supply reductions, keeping supply above demand under all climate change scenarios examined.[I][22]</td></tr>
<tr><td>Ski Season</td><td>More warm winters
▪ Probability of a warm winter (average Dec-Feb temperature above freezing) for Washington State ski resorts:</td></tr>
</table>

[R] Estimated using an intermediate climate change scenario for the 2040s (2030-2059), and linearly interpolating the changes in temperature and precipitation to 2030.

	Historic (1971-2000): 0 to 33%, depending on location With +3.6°F[S] warming: 33 to 77%[26]
Changing Water Demand	Small increase projected for the near term for the Columbia River basin ▪ Irrigation demand projected to increase by +4% in eastern Washington by the 2030s (2020-2049; relative to 1977-2006), for a low greenhouse gas scenario.[K][27] 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, based on a high greenhouse gas scenario.[L][22]

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SECTION 7

How Will Climate Change Affect Forests in Washington?

Climate change is expected to transform Washington's forests over the long term by affecting the establishment, growth, and distribution of forest plant species, and by increasing disturbances such as fire, insect outbreaks, and disease.[1] While direct impacts of climate change on tree species (e.g., productivity, distribution) are important, the large projected increases in fire suggest that indirect impacts of climate change through disturbance are likely to be greater and more immediate agents of change for Washington forests. Recent research has provided projected impacts on several Washington forest species and types, as well as on disturbances, particularly fire and insect outbreaks.

1. **The spatial distribution of suitable climate for many ecologically and economically important tree species in Washington may change considerably by the end of the 21st century, and some vegetation types, such as subalpine forests, may become very limited in their ranges.**[A][1]

    - *Area of climatic suitability for Douglas-fir is projected to decline.* Climate is projected to become unfavorable for Douglas-fir over 32% of its current range in Washington by the 2060s, relative to 1961-1990, under a medium greenhouse gas scenario.[B] Areas of climatic suitability for Douglas-fir are projected to decline most noticeably at lower elevations, especially in the Okanagan Highlands and the south Puget Sound/southern Olympics.[C][2]

    - *Area of climatic suitability for pine species are projected to decline*. Only 15% of the area currently suitable for three pine species in Washington (ponderosa pine, lodgepole pine, and whitebark pine) is projected to remain suitable for all three by the 2060s, relative to 1961-1990, under a medium greenhouse gas scenario, while 85% of their current range is projected to become climatically unsuitable for one or more of the three species (Figure 7-1).[C][2]

    - *Area of climatic suitability for subalpine forest is projected to decline*. Suitable climate

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A Much of the material in this document is derived or directly quoted from *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*[1] and Littell et al. 2010.[2] Impacts on specific species and ecosystems described in this document represent examples rather than an exhaustive list of potential regional impacts. In describing potential impacts, we have used the term "projected" where future impacts have been estimated quantitatively (e.g., using models or experiments) and explicitly incorporate climate models and greenhouse gas scenarios (which we report in associated footnotes), and the term "may" where future impacts have been inferred from available biological information and projected climatic changes.

B 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 RCP 2.6; "low" refers to RCP 4.5 or SRES B1; "medium" 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 3 for more details.

C Using results from two global climate models (HadCM3GGa1 and CGCM2) under a scenario that assumes a 1%/year increase in greenhouse gas emissions. This scenario closely resembles the current medium greenhouse gas scenario (RCP 6.0), with the exception that its late 21st century emissions are higher.

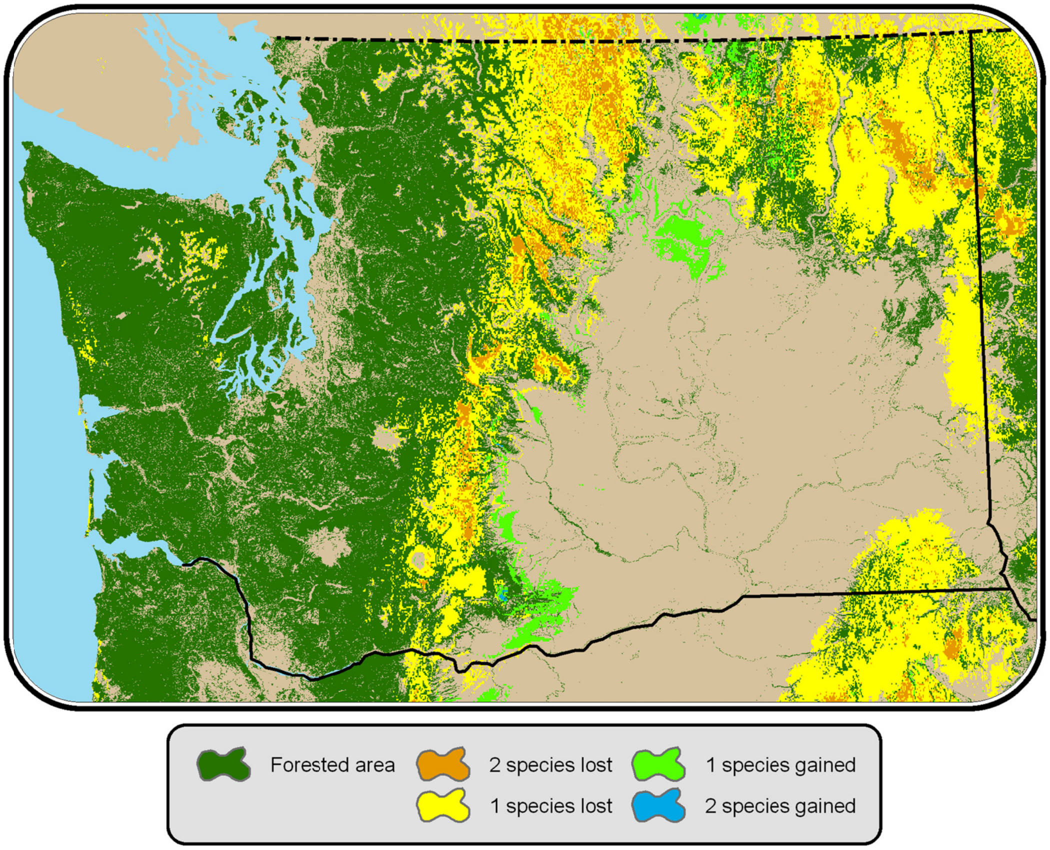

Figure 7-1. Projected changes in climatic suitability for three Washington pine species (ponderosa pine, lodgepole pine, and whitebark pine) by the 2060s relative to 1961-1990, under a medium greenhouse gas scenario.[B][C] Decreases indicate places where climate will be no longer suitable for some species, whereas increases indicate places where climate is currently unsuitable for some species but may be suitable in the 2060s. Reproduced from Littell et al. (2010).[2]

for subalpine forest in Washington is projected to decline substantially in area under a high greenhouse gas scenario.[D][3] Areas of climatic suitability may decline for high-elevation populations of whitebark pine, Brewer spruce, Engelmann spruce, and subalpine fir in the Pacific Northwest.[1]

- *Further research is needed concerning additional species and vegetation types.* Most existing research has focused on economically important species such as Douglas-fir and vulnerable vegetation types such as subalpine forest. Additional projections are needed for a wider range of tree species and forest types.

2. **Changes in forest structure and composition will be driven primarily by disturbance.** Because forests take many years to regenerate, stand-replacing disturbances caused by fire,

[D] Changes from historical (1971–2000) to future (2070–2099) modeled using MC1 vegetation model projections based on three global climate models (CSIRO-Mk3, Hadley CM3, and MIROC 3.2 medres) under a high (A2) greenhouse gas scenario.

insects, and disease will result in more rapid changes to forests than suggested by projections of future species range shifts.[1]

3. **Climate change may affect the productivity of Washington forests.** Given projections of warmer, possibly drier summers in Washington, tree growth may increase where trees are currently energy-limited (e.g., higher elevations) and decrease where trees are currently water-limited (e.g., drier areas).[1]

4. **Washington forests are likely to become increasingly water-limited, with episodes of drought increasing in area and intensity.** This is likely to lower forest productivity in some areas, while also increasing vulnerability to disturbance (e.g., fire, insects, pathogens).

   - *Area of severely water-limited forest is projected to increase.* Under a medium greenhouse gas scenario, the area of Washington forest where tree growth is limited by water availability is projected to increase (relative to 1970-1999) by +32% in the 2020s, with an additional +12% increase in both the 2040s and 2080s. Severely water-limited forests are projected to occur on the east side of the Cascade Range and in the northeastern part of the state.[E][2]

5. **Drier, warmer conditions are likely to increase the annual area burned by forest fires.[F]** This is because projected decreases in summer precipitation and increases in summer temperatures would reduce moisture of existing fuels, facilitating fire, while earlier snowmelt should lead to earlier onset of the fire season.[2]

   - *Annual area burned is projected to increase.* Compared to the median annual area burned in the Northwest during 1916-2006 (0.5 million acres), one set of fire models projects an increase to 0.8 million acres in the 2020s, 1.1 million acres in the 2040s, and 2 million acres in the 2080s, under a medium greenhouse gas scenario.[G][2] Another set of models projects +76% to +310% increases in annual area burned for the Northwest from 1971-2000 to 2070-2099 under a high greenhouse gas scenario.[D][3]

   - *Increases in area burned are projected to vary across the region.* For example, in forested ecosystems (Western and Eastern Cascades, Okanogan Highlands, and Blue Mountains), annual area burned is projected to increase by about a factor of 4 by the 2040s, compared to 1980-2006, under a medium greenhouse gas scenario. In non-forested areas (Columbia Basin and Palouse Prairie), annual area burned is projected to increase on average by about a factor of 2.[G][2]

E Based on hydrologic simulations of annual precipitation and summer potential evapotranspiration, which were averaged over 20 global climate models and a low (B1) and medium (A1B) greenhouse gas scenario. Energy-limited forests were defined as those where annual precipitation exceeds summer evapotranspiration, and water-limited forests were defined as those where summer potential evapotranspiration exceeds annual precipitation.

F Compared to area burned, there is much less quantitative information about the likely consequences of climate change for forest fire frequency, severity, and intensity (Littell et al. 2013).[1]

G Average of area burned calculated separately for climate simulated by two global climate models (CGCM3 and ECHAM5) under a medium (A1B) greenhouse gas scenario.

- *Fires may occur in areas where they have been rare in the past.* While it is difficult to project future fire risk for wetter regions (e.g., Puget Trough, Olympic Mountains) with low historical annual area burned, it is expected that rising summer temperatures, lower soil moisture, and higher evaporation rates could result in more area burned in western Washington forests that have not traditionally been considered fire-prone.[2] One set of projections estimates that annual area burned for Northwest forests west of the Cascade Range crest will be about +150% to +1000% higher in 2070-2099 compared to 1971-2000, under a high greenhouse gas scenario.[D][3]

- *Further research is needed.* In particular, models are needed that account for climate-fire severity relationships and provide projections of future fire severity as a function of climate change.

6. **Insect outbreaks are likely to change in frequency and affected area, as forests become more susceptible due to climatic stressors (e.g., drought), and areas climatically suitable for outbreaks shift**.

- *The area of forest susceptible to mountain pine beetle outbreaks is projected to first increase then decrease.* Under a medium greenhouse gas scenario, area susceptible to mountain pine beetle outbreak is projected to first increase (+27% higher in 2001-2030 compared to 1961-1990) as warming exposes higher elevation forests to the pine beetle, but then decrease (−49 to −58% lower by 2071-2100) as temperatures exceed the beetle's thermal optimum.[H][4]

- *Ranges of other bark beetles may also decrease.* Ranges of some bark beetles (e.g., pine engraver beetle) may decrease due to climatic conditions less favorable for outbreaks.[1]

- *Further research is needed into how other insects may respond to climate change.* Anticipating future impacts will require better understanding the role of climate in other insects' (e.g., spruce and fir beetles or defoliators) life cycles and host vulnerabilities.

7. **Climate change is likely to influence forest disease outbreaks, but because climatic influences are likely to be species- and host-specific, generalizations are difficult to make.[5]**

- *Climate change is projected to increase Northwest forests' susceptibility to several diseases.* With warmer future temperatures, risk of forest damage from yellow-cedar decline and Cytospora canker of alder may be high if annual precipitation decreases, while risk of forest damage from dwarf mistletoes and *Armillaria* root disease may be high whether precipitation increases or decreases.[5] Several studies have suggested that future increases in temperature and precipitation may lead to increased risk of sudden oak

[H] Historical (1961-1990) temperatures were used to predict current climatic suitability for outbreaks. Future (2001–2030, 2071–2100) temperature suitability estimated for one future climate scenario (CRCM) assuming a high (A2) greenhouse gas scenario.

death in the Northwest.[5][6] In addition, swiss needle cast is projected to have increased capacity to affect Douglas-fir in Northwest forests by 2050, under a low greenhouse gas scenario.[I][7]

8. **Climate change may affect the ability of Washington's forests to sequester carbon by increasing disturbances such as fire, which may alter the amount of carbon stored in soils and vegetation.[1]**

   - *Increased annual area burned is projected to lower the amount of carbon stored in Washington forests.* By 2040, increasing burn area in Washington is projected to reduce the amount of carbon stored by forests by 17 to 37%.[J][8]

   - *Changes in carbon stores may vary regionally.* Forests of the western Cascades are projected to be more sensitive to climate-driven increases in fire, and thus projected changes in carbon dynamics, than forests of the eastern Cascades.[J][8]

9. **Due to recent research, scientific understanding of impacts has advanced and the specificity and quality of projections has increased.** Almost all of the impacts described in this document have been quantified since 2010, and include finer spatial and temporal resolution than previous analyses, as well as additional detail on impacts to particular species.

   - *New information for Washington and the Northwest includes the following:*

     - Projected changes in areas of climatic suitability for forest species (e.g., Douglas fir), and forest types (e.g., subalpine forest).
     - Projected changes in annual area burned.
     - Projected changes in ability of forests to store carbon.

   - *Available studies are still limited to a relatively small proportion of Washington forest species and disturbance processes.* Projections for a wider variety of tree species and forest types are needed, as well as more sophisticated models of fire and disease.

10. **Many Washington communities, government agencies, and organizations are preparing for the impacts of climate change on forests.** Most are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

    - *Science-management partnerships have been established to approach adaptation to climate change.*[1] For example, the *North Cascadia Adaptation Partnership* is a Forest

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[I] Projection based on continuing winter temperature increases for the Pacific Northwest of approximately 0.72°F/decade through 2050 (for a total increase of 3.6°F, which is near the average projected warming for mid-century in the Pacific Northwest, assuming a low greenhouse gas scenario).

[J] Based on estimates of historical and future carbon carrying capacity of forest types based on potential productivity, maximum carbon storage, historical fire regimes, and projections of 21st century area burned from Littell et al. 2010.[2]

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 Northcascadia.org.

- *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.[9]

- *Climate adaptation strategies have been or are being developed for specific national forests.* A completed example is: Adapting to Climate Change at Olympic National Forest and Olympic National Park.[10]

Additional Resources for Evaluating Changes in Forests

The following resources provide local information about hydrologic conditions and water availability and demand to support assessment of climate impacts on forested ecosystems, and on forest management and forest uses.

- **Climate and hydrologic scenarios.** The Climate Impacts Group provides historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, plant water demand, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US. http://warm.atmos.washington.edu/2860,[11] http://cses.washington.edu/cig/

- **Data Basin,** 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/

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SECTION 8

How Will Climate Change Affect Plants and Animals in Washington?

Climate change is expected to cause significant changes in plant and animal distributions and communities, and may threaten the some of the region's iconic species.[A] The timing of biological events, such as spring budburst and migration, will shift for many species. Sea level rise is projected to displace coastal habitats and the species that depend on them. Ocean acidification will negatively impact marine species and ecosystems, particularly shellfish. Recent studies have provided projections specific to Pacific Northwest species and ecosystems, and significantly more detail on the impacts of ocean acidification on Washington's marine species.

1. **The spatial distributions of suitable climate for many species of plants and animals are projected to change considerably by the end of the 21st century.** Many species may be unable to move fast enough to keep up with shifting areas of climatic suitability, which may result in local extirpations. Both range shifts and local extirpations are likely to lead to changes in the composition of Washington's biological communities.[1]

    - *Areas of suitable climate for alpine and subalpine species are projected to significantly decline.* Suitable climate for alpine tundra and subalpine vegetation in Washington is projected to decline substantially in area or disappear by the end of the century under a high greenhouse gas scenario.[B][C][2] These reductions may negatively affect associated wildlife species, such as American pika.[3] Areas of contiguous habitat for Pacific Northwest populations of wolverine[D][4] and American marten[E][5] are projected to significantly decrease by the late 21st century under a medium greenhouse gas scenario.

    - *Areas of suitable climate for several Washington tree species are projected to decline.* For example, climate is projected to become unfavorable for Douglas-fir over 32% of its

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[A] Impacts on specific species and ecosystems described in this document represent examples rather than an exhaustive list of potential regional impacts. In describing potential impacts, we have used the term "projected" where future impacts have been estimated quantitatively (e.g., using models or experiments) and explicitly incorporate climate models and greenhouse gas scenarios (which we report in associated footnotes), and the term "may" where future impacts have been inferred from available biological information and projected climatic changes.

[B] Changes from historical (1971–2000) to future (2070–2099) modeled using MC1 vegetation model projections based on CSIRO-Mk3, Hadley CM3, and MIROC 3.2 medres global climate models under the SRES-A2 greenhouse gas scenario.

[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; "medium" 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 3 for more details.

[D] Models of future (2070-2099) wolverine connectivity based on projected late spring snow cover under 10 global climate models and the A1B greenhouse gas scenario.

[E] Models of future marten connectivity based on upward shifts of current temperatures by approximately 325, 650, 985, 1310, and 1640 ft from the current optimum elevation of 4920 ft, which correspond to a low to medium increase in temperature by 2081-2100, relative to 1950-1999.

current range in Washington by the 2060s relative to 1961-1990, under a medium greenhouse gas scenario.[F][6] Only 15% of the area currently suitable for three pine species in Washington (ponderosa pine, lodgepole pine, and whitebark pine) is projected to remain suitable for all three by the 2060s relative to 1961-1990, under a medium greenhouse gas scenario, while 85% of their current range is projected to become climatically unsuitable for one or more of the three species. [F][6]

- *Area of suitable climate for sagebrush-steppe vegetation is projected to decline.* Sagebrush-steppe ecosystems in eastern Washington are projected to decline in extent by the 2080s (2070-2099), relative to 1970-1999, under a high greenhouse gas scenario.[B][2] This has negative implications for associated wildlife, such as greater sage grouse and pygmy rabbit.

- *Climate change may lead to reductions in the extent of wetlands and ponds.* Reduced snowpack and altered runoff timing may contribute to the drying of many ponds and wetland habitats across the Pacific Northwest.[7]

- *Climate change may result in the expansion of prairies.* Projected increases in summer drought may result in an expansion of Pacific Northwest prairies. Projected increases in winter precipitation may lead to the expansion of wetland prairies on poorly drained soils in areas such as the South Puget Sound.[8] However, high levels of human land use in future areas of climatic suitability may limit opportunities for expansion.

2. **Timing of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, will continue to shift, leading to significant impacts on species and habitats.[1]** For example, some migratory birds now arrive too late for the peak of food resources at breeding grounds because temperatures at wintering grounds are changing more slowly than at spring breeding grounds.[9] There are currently few studies on such impacts specific to the Pacific Northwest.

3. **Climate change will affect biodiversity through major ecosystem disturbances, including fire, drought, and flooding.[1]** For example, climate change may increase the risk of severe, stand-replacing fires, which may negatively impact species associated with old-growth forest, such as marbled murrelets and northern spotted owls. Species that thrive in conditions after severe fires, such as the northern flicker and hairy woodpecker, may benefit under an altered fire regime.[1]

4. **Climate change may promote the spread of invasive species.[1]** This will include both native invasive species (e.g., western juniper) moving beyond their historical ranges, and non-native species (e.g., cheat grass) increasing due to improved conditions. Moreover, responses of invasive species to climate change will vary, so that some may benefit while others will not.[1]

[F] Using results from the HadCM3GGa1 and CGCM2 global climate models (GCMs) under a scenario that assumes a 1%/year increase in greenhouse gas emissions. This scenario closely resembles the RCP 6.0 scenario, with the exception that late 21st century emissions are higher.

- *Some invasive species are projected to benefit from climate change.* For example, changes in salinity due to sea level rise may facilitate invasion by non-native species better adapted to salinity variations, such as the invasive New Zealand mud snail, which has been found in the Columbia River estuary.[G][10]

- *Some invasive species may not benefit from climate change.* For example, suitable habitat for cheatgrass is projected to increase in some areas of the Pacific Northwest and decrease in others by 2100, relative to 1971-2000, under a medium greenhouse gas scenario; its future distribution will be strongly influenced by future changes in precipitation.[H] [11]

5. **Changes in the timing and quantity of streamflows, together with increasing stream temperatures, are projected to cause significant changes in freshwater aquatic species and ecosystems.[7]**

- *Suitable stream temperatures for aquatic species may shift upstream.* Suitable stream temperatures for many aquatic species across the Pacific Northwest could shift a few to nearly one hundred miles upstream, with smaller changes seen along steep streams, and larger changes along relatively flat streams.[I][12]

- *Rising stream temperatures and altered streamflows will likely reduce the reproductive success of many Washington salmon populations, though impacts will vary by location.* Relative to 20th century conditions, under a low-warming scenario, juvenile salmon growth rates by mid-21st century are projected to be lower in the Columbia Basin, but unchanged or greater in coastal and mountain streams. [J][13] By the 2080s (2070-2099, relative to 1970-1999), for a medium emissions scenario, the duration of summertime stream temperatures that cause thermal stress and migration barriers to salmon is projected to at least double for many areas in eastern Washington and along the lower Columbia River.[K][14] Earlier spring runoff may alter migration timing and survival rates for salmon smolts in snowmelt-dominated streams.[14]

- *Steelhead vulnerability to climate change varies across the region.* Steelhead vulnerability to streamflow change at mid-century (2030-2059) relative to 1970-1999 under a medium greenhouse gas scenario is projected to be high in northeastern Washington and Cascade Mountain rivers (both east and west side), and lowest in coastal rivers. Vulnerability to stream temperature change is projected to be high in eastern and

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G Based on experiment demonstrating increased salinity tolerance of New Zealand mud snails from the Columbia River estuary compared to those found in a freshwater lake.

H Based on bioclimatic envelope models under the SRES A1B greenhouse gas scenario and 10 general circulation models for 2100.

I Assuming a warming of 3.6°F, which is near the average projected warming for mid-century in the Pacific Northwest, under a low greenhouse gas scenario.

J Fish growth from winter to summer was projected with temperature-dependent models of egg development and juvenile growth using empirical temperature data from 115 sites.

K Based on the average of 10 climate models run under the A1B emissions scenario.

southwest Washington, but low in most Cascade Mountain rivers.[L][15][16]

6. **Rising sea levels are projected to displace many coastal habitats and the species that depend on them**. Most of the region's important coastal habitats have already been damaged or destroyed by extensive dredging, coastal modifications, pollution, and other development. Natural barriers and coastal modifications such as dikes and seawalls may significantly impede the ability of habitats to migrate inland to accommodate sea-level rise.[17]

   - *Sea level rise is projected to cause reductions in the extents of many coastal habitats*. By 2100, under a medium greenhouse gas scenario, sea level rise in Washington and Oregon is projected to result in the loss of as much as 44% of tidal flat, 13% of inland freshwater marsh, 25% of tidal fresh marsh, 61% of tidal swamp, and 65% of estuarine beaches.[M][17]

   - *Sea level rise is projected to change the composition of many existing coastal habitats*. By 2100 in Washington and Oregon, under a medium greenhouse gas scenario, 52% of brackish marsh is projected to be converted to tidal flats, transitional marsh and saltmarsh; 11% of inland swamp is projected to be inundated with salt water; and 2% of undeveloped land is projected to be inundated or eroded to form other habitat types.[M][17]

7. **Ocean acidification is expected to threaten coastal and marine species and ecosystems.**

   - *Ocean acidification is likely to reduce shellfish populations.* By the end of the century, ocean acidification is projected to result in a 40% reduction, globally, in the rate at which mollusks (e.g., mussels and oysters) form shells, as well as a 17% decline in growth, and a 34% decline in survival.[N][18]

   - *Ocean acidification may negatively impact some fish species.* By 2028, ocean acidification impacts on shellfish and plankton are projected to result in a 10–80% decline in the abundance of commercially important groundfish on the US west coast, including English sole, arrowtooth flounder, and yellowtail rockfish, owing to the loss of shelled prey items from their diet. [O][19]

L Based on Elsner et al.'s (2010)[16] historical and future hydrologic projections, which stem from an average of 20 global climate models and the A1B greenhouse gas scenario.

M Based on a 27.3-inch global sea-level rise by 2100 relative to 1980-1999 (projected under a medium greenhouse gas scenario) and the Sea Level Affecting Marshes Model (SLAMM) applied to 11 coastal sites in Puget Sound and along the Pacific Coast in southwestern Washington and northwestern Oregon. Projected changes in habitat are relative to total habitat amounts in 2007.

N Based on statistical synthesis of results from 228 experimental assessments of responses of marine organisms to acidification, with end-of-century projections based on 0.5 unit reduction in global average ocean surface pH relative to current pH. This is higher than the change projected for 2100 by the IPCC (0.30 to 0.32 unit reduction under the high RCP 8.5 scenario, for 2081-2100 relative to 1986-2005) and also higher than the projections of Feely et al. 2009 (0.4 to 0.48 unit reduction, under a high (A2) greenhouse gas scenario, for 2095 relative to pre-industrial (1875) levels).

O Relative to 2009 (with baseline conditions established 1995-2005), and based on a 20-year model run of the Atlantis ecosystem model, using four scenarios treating acidification as a range of additional mortality rates on shelled plankton and benthos groups.

- *Ocean acidification may benefit some species*. For example, seagrasses may experience increased growth rates with elevated ocean carbon dioxide levels.[20]

8. **Increasing sea surface temperatures may alter the ranges, types, and abundances of Pacific Northwest marine species.** However, projections specific to waters off of Washington and the Pacific Northwest are currently limited relative to terrestrial and freshwater studies.[21]

9. **As a result of recent research, scientific understanding of the biological impacts of anthropogenic climate change in Washington State has advanced and the specificity of projections has increased.**

   - *Ocean acidification has become a primary area of study and concern.* Ocean acidification has only recently been widely recognized as a concern, and there has been a tremendous increase in studies documenting projected impacts.

   - *Changes in suitable climate have been projected for several species and habitat types.* However, many of these are for economically important species such as Douglas-fir and salmon, and projected climate impacts on most Washington species and ecosystems remain understudied.

10. **Various Washington communities, government agencies, and organizations are preparing for the impacts of climate change on plants and animals.[22]** Examples include:

   - *The Pacific Northwest Vulnerability Assessment* is a collaboration among researchers, managers, and planners from Pacific Northwest universities, agencies, and non-government organizations. It will soon be releasing products indicating the potential effects of future climate change on regional species and habitats. More information is available at: Climatevulnerability.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*.[P] WHCWG products offer tools for implementing this recommendation. More information is available at: waconnected.org.

   - The new *Washington Ocean Acidification Center* at the University of Washington (funded by the State Legislature in summer 2013) will coordinate scientific research, monitoring and data-sharing related to ocean acidification, and work with partners in state and federal agencies, tribes, industries, and academic institutions to link ocean-acidification science with decision-making.

[P] Available at: http://www.ecy.wa.gov/climatechange/ipa_responsestrategy.htm

- 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.

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SECTION 9

How Will Climate Change Affect the Coast and Ocean in Washington?

A major driver of climate change impacts on Washington's coasts is sea level rise, which is expected to affect most locations in Washington State. Key impacts include inundation of low-lying areas, increased storm surge reach, flooding, erosion, and changes and loss of habitat types. These impacts are likely to affect a wide range of communities, species, and infrastructure. Since 2007, studies have provided more regional specificity about how coastal ocean conditions may change in the Pacific Northwest, particularly with respect to sea level rise and ocean acidification.

1. **Changes in Pacific Northwest coastal waters are strongly influenced by changes in global sea level and ocean conditions.**[1] 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.[A][2] This will cause Washington's marine waters to rise, although how much change occurs at a specific location depends on a variety of local factors, as described below. Additionally, coastal sea surface temperatures and the acidity of Washington's marine waters are projected to increase.[B][3][4]

2. **Sea level is projected to continue rising in Washington through the 21st century, increasing by +4 to +56 inches by 2100, relative to 2000.**[5]

   - *Multiple factors affect local sea level.* The amount of sea level change at a given location and time will depend both on how much global sea level rises and on local factors such as seasonal wind patterns, vertical land movement associated with plate tectonics, and sediment compaction. These local factors may result in higher or lower amounts of local sea level rise (or even declining sea level) relative to global projections depending on the rate and direction of change in these local factors.

   - *Sea level rise is expected to continue in most of Washington's coastal areas (Table 9-1).* Most areas in Washington are expected to experience sea level rise through 2100. This includes the Puget Sound region and the central and southern outer coast.[6]

   - *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 caused by plate tectonics continues to exceed the rate of global sea level rise.[6] Although most *current* global projections would result in sea level rise for the northwest Olympic Peninsula, it is not yet possible to conclusively rule out a decline in sea level for that region.

[A] Sea level rise projections vary with greenhouse gas scenarios. The average and associated ranges reported in IPCC 2013[2] 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 3 for more details on greenhouse gas scenarios and Sections 4 and 5 for more on global and Pacific Northwest sea level rise projections.

[B] See Section 5 for more on projected changes in regional sea surface temperatures and ocean acidity.

Table 9-1. Sea level rise projections for Washington State and sub-regions. Projections are in inches, for 2030, 2050, and 2100 (relative to 2000), from two regionally-specific studies: Mote et al 2008[6] and NRC 2012[5]. Values shown are the central (for NRC 2012), or medium (for Mote et al. 2008) projections, with the projected range shown in parentheses. *Table and caption adapted from Reeder et al. 2013.[1]*

Domain	2030	2050	2100
Washington State (NRC 2012)[C],[D]	+3 inches *(-2 to +9 in.)*	+7 inches *(-1 to +19 in.)*	+24 inches *(+4 to +56 in.)*
Puget Sound (Mote et al. 2008)[E]	---	+ 6 inches *(+3 to +22 in.)*	+13 inches *(+6 to +50 in.)*
NW Olympic Peninsula (Mote et al. 2008)	---	0 inches *(-5 to +14 in.)*	+2 inches *(-9 to +35 in.)*
Central & Southern WA Coast (Mote et al. 2008)	---	+5 inches *(+1 to +18 in.)*	+11 inches *(+2 to +43 in.)*

- *Sea level rise is not expected to occur in a consistent, linear fashion*. Episodes of faster and slower rise, as well as periods of no rise, are likely due in part to natural variability, especially as you move to regional (e.g., the Pacific Northwest) and smaller scales.[7]

3. **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 low-lying areas.* Where and how much inundation occurs will depend on the rate of sea level rise and shoreline characteristics. Communities and organizations that have mapped sea level rise inundation zones include the City of Olympia,[8] City of Seattle, King County,[9] the National Wildlife Federation (mapped for Puget Sound, southwestern Washington, and northwestern Oregon), [10] the Swinomish Indian Tribal Community,[11] and the Jamestown S'Klallam Tribe.[12]

[C] Calculated for the latitude of Seattle, Washington (NRC 2012).[5] The mean value reported in NRC 2012 is based on the A1B greenhouse gas emissions scenario. The range values are projections for a low (B1) to a high (A1FI) greenhouse gas emissions scenario. See Section 3 for more details on greenhouse gas scenarios.

[D] Regional comparisons between Mote et al. 2008[6] and NRC 2012 differ due to the different approaches taken by the studies to estimate global sea level rise and local influences on the relative rate of rise. Also, Mote et al. 2008 does not provide projections for 2030 and NRC 2012 did not provide projections for sub-regions of Washington State.

[E] The sub-regional sea level rise projections for Washington State in Mote et al. 2008 integrate projected changes in global sea level rise, potential changes in wind direction (which can push waves onshore or off shore for prolonged periods of time depending on wind direction), and different rates of vertical land motion. 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 3 for more details on greenhouse gas scenarios.

- *Sea level rise will exacerbate coastal river flooding*. 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. Projected increases in both the size and frequency of high river flows due to climate change will compound this risk.[13]

- *Sea level rise increases the frequency of today's extreme tidal/storm surge events.* Higher sea level amplifies the inland reach and impact of high tides and storm surge, increasing the likelihood of today's extreme coastal events. For example, +6 inches of sea level rise[F] in Olympia shifts the probability of occurrence for the 100-year flood event from a 1% annual chance to 5.5% annual chance (1-in-18 year) event.[8] With +24 inches of sea level rise,[G] the 100-year flood event would become an annual event (Table 9-2).

- *Sea level rise can increase coastal erosion.* Higher sea level and storm surge reach exposes more areas to erosion, which can affect the stability of coastal infrastructure. For example, analysis of beach erosion rates in Oregon for the period 1967-2002 found that significant beach erosion occurred in areas where relative sea level (north-central Oregon) increased. In contrast, beaches were relatively stable in areas experiencing sea level decline (e.g., along the southern Oregon coast, where the rate of uplift is greater than observed sea level rise).[14]

Table 9-2. Impact 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. *Figure and caption adapted from Simpson 2012.[8]*

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%

F A +6 inch increase in regional sea level is currently near the average value (+6.5 inches) projected in NRC 2012 for Seattle for 2050, and within the range of values projected for Seattle as early as 2030 (range of -1.5 in. to +8.8 in.). See Table 9-1 for more detail.

G A +24 inch increase in sea level is currently the average value (+24.3 inches) projected in NRC 2012 for Seattle for 2100 (range: +4 in. to +56 in.). See Table 9-1 for more detail.

4. **Sea level rise and changes in coastal ocean conditions[H] impact human, plant, and animal communities in important ways.**

- *Economic and cultural impacts on human communities are expected.* Efforts to better understand and adapt to coastal impacts are occurring in a variety of organizations and coastal communities.

    - *Projected impacts.* Impacts on human communities include the potential for increased damage to coastal infrastructure from storm surge or flooding [8][9][15] permanent inundation of important commercial and industrial areas, [8][11][16] loss of culturally important sites,[11] and impacts on commercial fishing and shellfish harvesting.[1]

    - *Adapting to sea level rise.* Adaptive decisions based on sea level rise projections have already been made by the City of Olympia,[17] City of Seattle,[I] King County,[18] Port of Bellingham,[19] and the Swinomish Indian Tribal Community.[20] Analyses of sea level rise impacts have also been completed by the Port of Seattle,[21] the Jamestown S'Klallam Tribe,[12] and Sound Transit.[J] For more on some of these efforts, see this Section 10 on infrastructure and the built environment.

- *Sea level rise and changes in the marine environment will affect the geographical range, abundance, and diversity of Pacific Coast marine species and habitats.*[K][22]

    - *Coastal 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.[10]

    - *Coastal species.* Species potentially affected by sea level rise and changes in ocean conditions include key components of the marine foodweb (phytoplankton and zooplankton) as well as juvenile Chinook salmon and commercially important species such as Pacific mackerel (*Scomber japonicus*), Pacific hake (*Merluccius productus*), oysters, mussels (*Mytilus edulis*), English sole (*Pleuronectes vetulus*), and yellowtail rockfish (*Sebastes flavidus*).[4][23] A species' ability to adapt to climate change will vary based on physiology and life cycle traits. How quickly climate changes, how large the change is, and the impact of other non-climate stressors such as fishing or pollution will also influence adaptive capacity.

H This includes changes sea surface temperature, salinity, pH, ocean circulation patterns and other factors that can affect species.

I See http://sdotblog.seattle.gov/2013/01/23/sea-level-and-the-seawall/ for more details on how the Seattle Department of Transportation evaluated sea level rise projections for the new Seattle sea wall.

J As announced by the U.S. Federal Transit Administration, http://www.fta.dot.gov/sitemap_14228.html. Final project report scheduled for release by FTA in winter 2014.

K For more on impacts to Pacific Northwest species and ecosystems, including projected percentage losses of specific coastal habitat types, see Section 8 on species and ecosystems.

Additional Resources for Evaluating Coastal Impacts. The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **NOAA Tides and Currents** (http://tidesandcurrents.noaa.gov/): for information on observed trends in sea level
- **NOAA Coastal Services Center** (https://csc.noaa.gov/): provides technical information and support for managing coastal hazards. 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.
- **Georgetown Climate Center Adaptation Clearinghouse: Rising Seas and Flooding** (http://www.georgetownclimate.org/adaptation/rising-seas-and-flooding): provides links to a variety of case studies and regulatory analyses related to sea level rise.

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Section 10

How Will Climate Change Affect Infrastructure in Washington?

Climate change is expected to increase the potential for infrastructure damage and service disruptions, and may also lead to higher operating costs and reduced asset life. Some minor benefits may also be realized, including the potential for fewer snow-related road closures. The specific nature of impacts on infrastructure will vary depending on infrastructure location, age, design tolerances, and other factors. Studies completed since 2007 have increased our understanding of how climate change may affect transportation and coastal infrastructure in Washington State. However, more detailed studies are needed to assess potential costs and to understand the implications for asset management.

1. **Most climate change impacts are likely to increase the potential for damage and service disruptions to infrastructure in Washington State, although some risks may decrease.** Studies to date on infrastructure impacts in Washington State and the Northwest have primarily focused on transportation infrastructure and coastal infrastructure (particularly as it relates to sea level rise). In general:

   - *Most climate change impacts evaluated are expected to increase risks to infrastructure.* Impacts that can increase risks to infrastructure include projections for more frequent or more severe flooding, extreme heat, extreme precipitation, storm surge, salt water intrusion, mudslides, erosion, wildfire, and inundation of low-lying areas.[1][2][3] Projected changes in extreme events are more likely to damage infrastructure than are changes in average conditions. [1][2][3]

   - *Some climate change impacts may slightly decrease risks or otherwise create minor benefits.* Projections for lower winter snowpack and warmer winter temperatures may decrease the frequency of snow-related closures on mountain highways.[1][2] However, extreme snowfall events will still occur, requiring continued maintenance of emergency response capacity.[2] Warmer spring and fall temperatures may extend the construction season, possibly improving cost efficiencies.

   - *Understanding the specific nature of climate change impacts on infrastructure often requires detailed, locally-specific studies.* Similar types of infrastructure can have very different responses to climate change, depending on its specific location, age, and how it is designed, maintained, and operated.[1][3] 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 State-owned coastal transportation infrastructure do not begin to emerge until much higher amounts (>+2 feet) of sea level rise occur.

2. Analysis by the Washington State Department of Transportation (WSDOT) finds that the majority of State-owned and operated transportation infrastructure is resilient to a range of projected climate change impacts, including sea level rise under +2 feet.[3]

However, all regions of the State include transportation infrastructure identified by WSDOT as being moderately or highly vulnerable to climate change (Figure 10-1).

- *Climate change exacerbates many issues already affecting WSDOT infrastructure*. This includes unstable slopes, flooding, and coastal erosion. 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.[A][3]

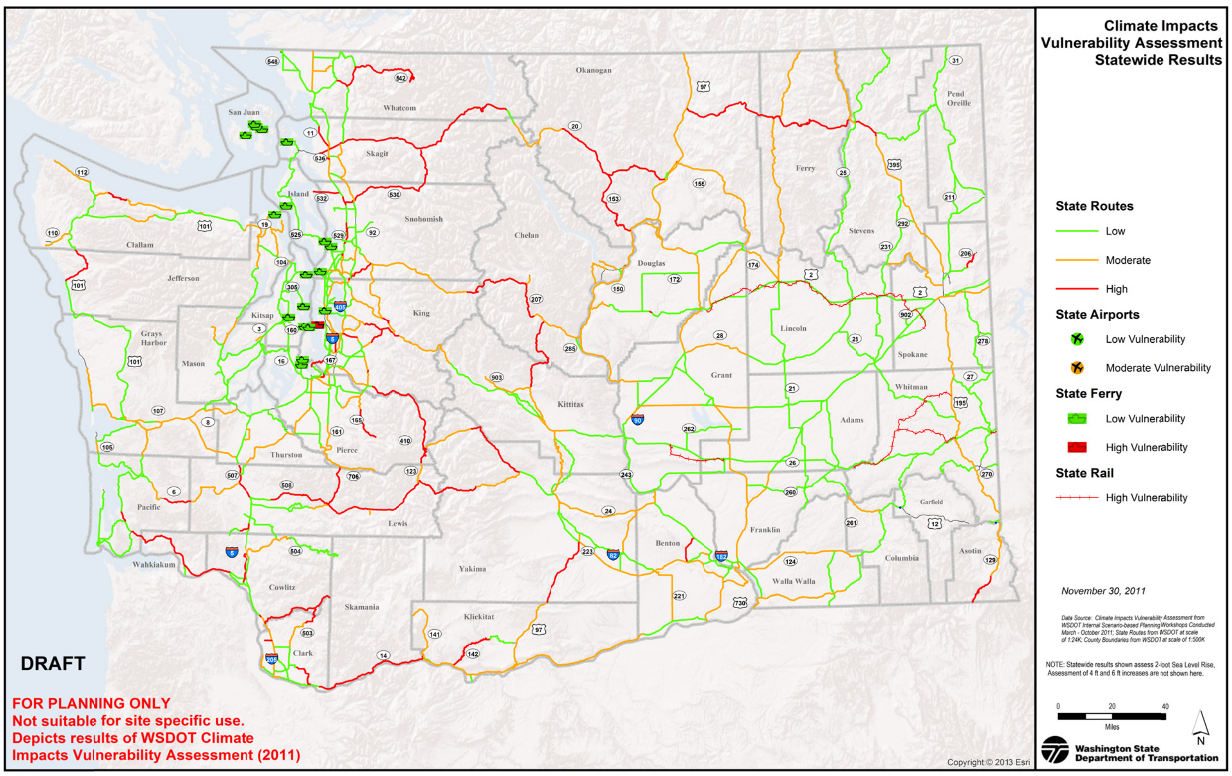

Figure 10-1. Summary of WSDOT's climate impacts vulnerability assessment for State-owned infrastructure. Results are for a range of temperature and precipitation changes and +2 feet of sea level rise. Red denotes roads or facilities that may be vulnerable to catastrophic failure along some portion of the road or at the facility. Yellow denotes roads or facilities that could experience temporary operational failures at one or more locations. Green indicates roads that could experience little or negligible impact. *Figure source: WSDOT 2011[3]*

[A] 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 to fish and fish habitat.

- *Climate change impacts on state highway, ferry, aviation, and rail operations may result in more frequent travel delays, closures, and re-routes.* For example, projected increases in wildfires and the potential for more dust storms tied to drought may cause more frequent temporary closures of airports and roads due to decreased visibility.

- *Vulnerability to climate change is higher in certain locations.* State-owned infrastructure is most likely to be impacted by climate change when located:

    - in the mountains,
    - above or below steep slopes,
    - in low-lying areas subject to flooding,
    - along rivers that are aggrading[B] due to glacier melt, and
    - in low-lying coastal areas subject to inundation from sea level rise.[3]

- *Many ongoing infrastructure improvements benefit climate resilience.* Many infrastructure improvements made for other reasons, such as seismic retrofits, fish passage improvements, culvert replacement, and drilled shaft bridges, also make infrastructure more resistant to climate change impacts.[3]

- *Newer infrastructure is generally more resilient to climate impacts, although the resilience of individual pieces of infrastructure can be affected by vulnerabilities in other parts of the system.* For example, most of WSDOT's newer bridges were found to be resistant to climate change impacts, including some that were resilient to up to +4 feet of sea level rise.[3] Road approaches to bridges are often more vulnerable than the bridges themselves, however.[3] As infrastructure ages, it becomes more vulnerable to extreme weather events and other climate related stressors affecting the structure.[1]

3. **Sea level rise increases the potential for damage to stormwater and wastewater systems, ports, and other public and private coastal infrastructure**.[C] Studies to date have focused on infrastructure in the Puget Sound region. Similar impacts are likely on the outer coast, however.

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

        - *King County.* 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 storms sizes.[D][4] The County has also identified 20

[B] Aggrading refers to the raising of a stream or river bed due to sediment deposition. Glacial recession can cause aggradation below a glacier by exposing unstable sediments to erosion by rain or other factors.

[C] See Section 5 and Section 9 for more details on projected sea level rise.

[D] 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% probability (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 (today's 1% annual probability storm surge).

facilities that are at risk of saltwater inflow into the conveyance system due to sea level rise, high tides, and storm surge by 2050.[5][6] This additional inflow can increase the volume of wastewater that has to be conveyed and treated, shortening equipment lifespan and increasing treatment costs.[7] King County estimates the current cost of treating saltwater already entering the system[E] during high tides to be $0.5 to $1.0 million annually.[F]

- *City of Olympia.* Modest amounts of sea level rise (as little as +3 inches) increase 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.[8]

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

  - *Swinomish Indian Tribal Community.* Approximately 15% (over 1,100 acres) of Swinomish Indian Tribal Community Reservation lands are potentially at risk of inundation from sea level rise, including the tribe's primary economic development zone at the north end of Fidalgo Island and more than $100 million in residential and non-residential/commercial structures.[9]

  - *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 10-2).[8][10]

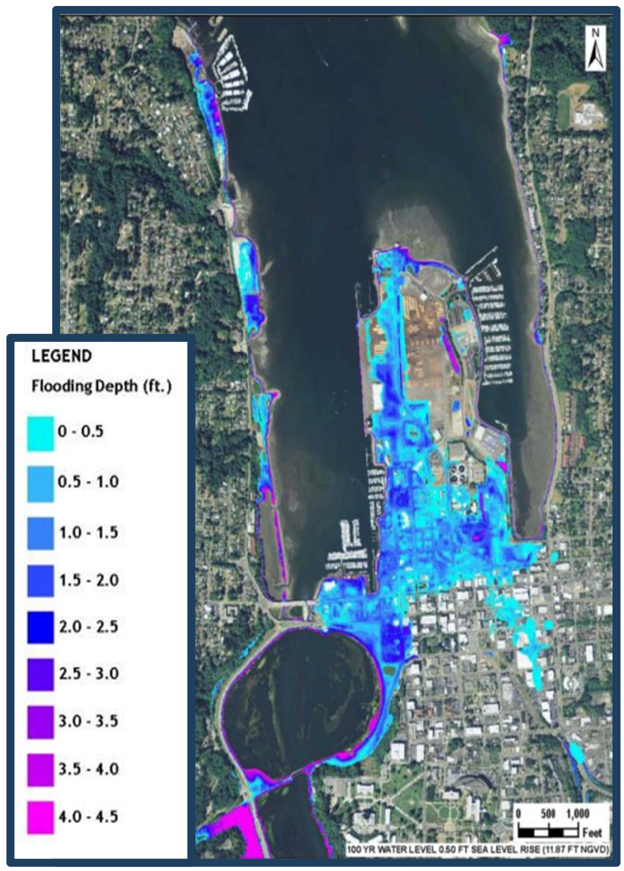

Figure 10-2. Projected flooding in the City of Olympia during a 100-year flood event with +6 inches of sea level rise. The projected depth of flood waters ranges from less than 6 inches to 4.5 feet, as indicated by the map colors. *Figure source: Simpson 2012*

E 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.[7]

F 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.[7]

    - 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.[8]
    - 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.[8]

- *Port operations and infrastructure, including access to port facilities, are likely to be affected by sea level rise and increased coastal flooding.*[11][12] Climate-related impacts in other parts of the world[G] may also affect Washington's marine trades, although little is known about the specific nature and potential size of those impacts on port business.[1][11]

    - *Direct sea level rise impacts identified by the Port of Seattle:*[11]

        - Increasing rates of corrosion in docks and other infrastructure (e.g., piles, pile caps, and beams) exposed to saltwater more frequently as a result of sea level rise and increased tidal and storm surge reach.
        - Increased difficulty draining stormwater from port facilities due to increasing extreme precipitation and sea level rise.
        - Increased storm surge damage to port facilities.

    - *Impacts 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 adapts its own infrastructure.[12]

4. **Projected increases in river flooding increase the risk of damage and service interruptions for infrastructure located in or near current floodplains.** In coastal drainages, sea level rise can exacerbate existing flood risks.[H]

    - *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.[13] Sea level rise is also expected to reduce the effectiveness of tide gates for draining low lying cropland in the Skagit Valley.[13]

    - *The ability of dams to mitigate increasing flood risk may be limited.* Initial research for the Skagit basin suggests that reducing community vulnerability to increasing flood risk

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G 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.

H 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 can produce larger flood impacts in the lower portion of a river basin in the future relative to today's flood events.

and sea level rise will be more effective if those efforts focus primarily on improving management of the floodplain rather than on increasing flood storage in headwater dams (e.g., Upper Baker Dam).[I][13] 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 +15% to +76% relative to historical (1916-2006) climate for a medium greenhouse gas scenario.[J] A change of this upper magnitude shifts the probability of today's 1-in-500 year (0.2% annual probability) flood event on the Green River to a 1-in-100 year (1% annual probability) flood event.[14] Potential inundation mapping of the current 500-year flood event by the U.S. Army Corps of Engineers projects flood depths of 0-15 feet in the Kent-Auburn area.[K] This could affect residential and commercial properties, local roads, access to SR 167, and rail services in the area.

- *More sediment and flood debris in coastal rivers could affect port and ferry facilities.* Increased river flooding and reduced snow and ice cover in mountain watersheds is projected to increase the amount of sediment and flood debris carried by coastal rivers.[13] As a result, more frequent dredging near port facilities and ferry terminals is likely to be needed.[3][11] Damage to port facilities and ferry terminals is also possible due to the potential for more flood debris.[3]

5. **Many Washington communities, government agencies, and organizations are preparing for the impacts 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:

   - *Increasing the resilience of State-owned transportation infrastructure:*

     - *Considering climate change and extreme weather events in project-level environmental review.* WSDOT is integrating the results of its vulnerability assessment into the environmental review of proposed projects. For example, the

I Preliminary results based on use of 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 the Echam5 global climate model run with the A1B greenhouse gas emissions scenario. For more on climate scenarios, see Section 3 of this report.

J Range based on data from the University of Washington Climate Impacts Group's Columbia Basin Climate Change Scenarios Project website (http://warm.atmos.washington.edu/2860/) for the A1B greenhouse gas emissions scenario. Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These scenarios are described in this report as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "medium" 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 3 for more details.

K 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. Existing levees are assumed to be intact but the map does not reflect ongoing levee fortification efforts, which could reduce flood risk. Map available at: http://www.nws.usace.army.mil/Missions/CivilWorks/LocksandDams/HowardHansonDam/GreenRiverFloodRiskMaps.aspx

Mukilteo Multimodal Terminal environmental impact statement evaluated impacts of sea level rise and increased rainfall.

- *Long-term planning for corridor improvements.* Recent studies for US 2, SR 516 and SR 520 include vulnerability ratings developed by WSDOT in 2011. These plans discuss the level of 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.* A federally funded pilot project will support development of a series of site-specific adaptation options to improve the resilience of Interstate 5 and state routes in the Skagit basin (Figure 10-3). These will complement flood hazard reduction strategies proposed by the U.S. Army Corps and Skagit County.

- *Increasing the resilience of King County infrastructure to increased flooding and sea level rise:*

    - *Levee improvements and flood-risk reduction activities.* King County formed a new Flood Control District in 2007 to increase capacity for addressing regional flood risks due to climate change and other factors. The creation of the new District resulted in a

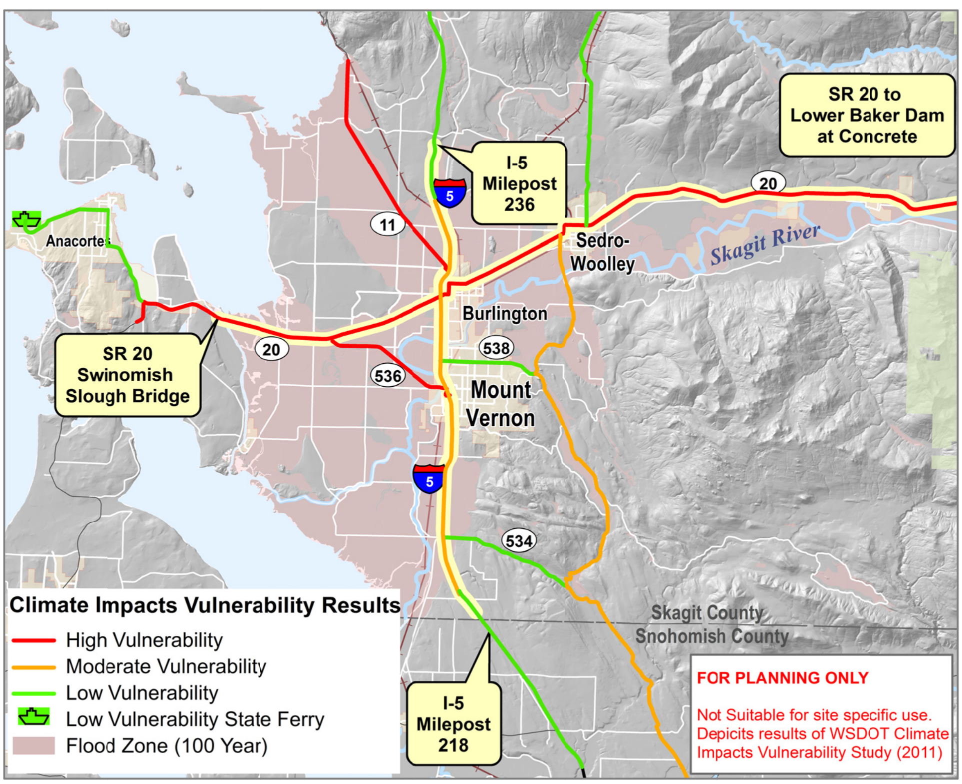

Figure 10-3. Study area for WSDOT's Preparing Interstate and State Routes in the Skagit River Basin pilot project, funded by the Federal Highway Administration. *Figure source: WSDOT.*

ten-fold increase in local funding[L] for flood risk reduction efforts. Accomplishments in 2012 included mapping flood hazards on the Sammamish River and the coastal shoreline, completing five levee repair projects and six projects that raised structures in flood zones, and purchasing sixty acres of floodplain on the Tolt, Snoqualmie, Cedar, and White rivers. Public ownership of this land and removal of structures will reduce flood risks and preclude development in these flood prone areas.[6]

  - *Widening bridge spans.* King County has replaced 15 short span bridges with wider span structures (including the Tolt Bridge over the Snoqualmie River) and 42 small culverts with large box culverts. These changes will increase resilience 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.[6]

- *Redesigning the Anacortes Water Treatment Plant to reduce 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 (under construction in 2013). The altered design 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.[10]

- *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 (shown previously in Figure 10-2), incorporated sea level rise considerations into the City's Comprehensive Plan and Shoreline Management Plan, and develops annual work plans to address key information needs.[15]

- *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.[16]

- *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 three feet above the new still water level[M] with 50 inches of sea level rise. 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.[N]

- *Increasing capacity to manage extreme precipitation events in Seattle.* Seattle Public Utilities' RainWatch system[O] provides operators and decisions makers with 1-hour precipitation forecasts and 1- to 48-hour rain accumulation totals that can be used to

[L] 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/).

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

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

[O] See http://www.atmos.washington.edu/SPU/

manage extreme precipitation risks at the neighborhood- or basin-scale in real-time. RainWatch represents a "no regrets" climate change adaptation strategy by improving operations response to extreme events today and in the future.

- *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.[9]

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[1] MacArthur, J. et al. 2012. *Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska.* Region X Northwest Transportation Consortium, OTREC-RR-12-01, WA-RD #772.1.

[2] Hamlet, A.F. 2011. Impacts of climate variability and climate change on transportation systems and infrastructure in the Pacific Northwest. White Paper prepared for the Western Federal Lands-Highway Division by the Climate Impacts Group, University of Washington, Seattle.

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SECTION 11

How Will Climate Change Affect Agriculture in Washington?

Washington crops and livestock will be affected by climate change via warming temperatures, rising atmospheric carbon dioxide, increasing water stress, declining availability of irrigation water, and changing pressures from pests, weeds, and pathogens. Different crops and locations will experience different impacts. Because of the high adaptability in most agricultural systems, overall vulnerability is low. However, given the combination of increasing water demands and decreasing supply in summer, water stress will continue to be a key vulnerability going forward. Since 2007, new studies have quantified impacts on specific crops and locations, and evaluated the combined effects of warming and CO2. New research has also begun to integrate impacts and economic modeling as a means of assessing market influences and the potential for adaptation.

1. **Washington State agriculture is projected to be affected by warming temperatures, rising carbon dioxide (CO_2) concentrations, and changes in water availability.**[1] Some changes may be beneficial while others may lead to losses – the consequences will be different for different crops and locations (Figure 11-1). Ultimately, impacts will reflect a combination of all of the factors listed below, the specific changes in climate that will occur, and the extent and effectiveness of adaptive actions that are taken in anticipation of the effects of climate change.

   - *Warming.* The longer growing seasons and fewer winter freezes projected for the region (Section 5) will benefit many crops and allow greater flexibility in crop selection, but in some cases may result in increased incidence and severity of pests, weeds, and diseases. Warming may decrease crop yields by accelerating the rate of development, and can have negative effects on wine grapes and some species of tree fruit due to insufficient winter chilling. Warmer summer temperatures will also result in increased heat stress and greater drought stress, affecting many Northwest crops and livestock.

   - *Increasing CO_2 concentrations.* 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.

   - *Changing precipitation.* Although year-to-year variations will continue to dominate annual and seasonal changes in precipitation (Section 3 of this report), the general tendency towards wetter winters will increase water available in spring but may also impede spring planting due to wetter soils. Projected decreases in summer precipitation would result in increased water stress in both rain-fed and irrigated agriculture.

   - *Irrigation water supply.* Water supply is a chief concern for Northwest agriculture, where the growing season coincides with the dry season. Projected reductions in summer

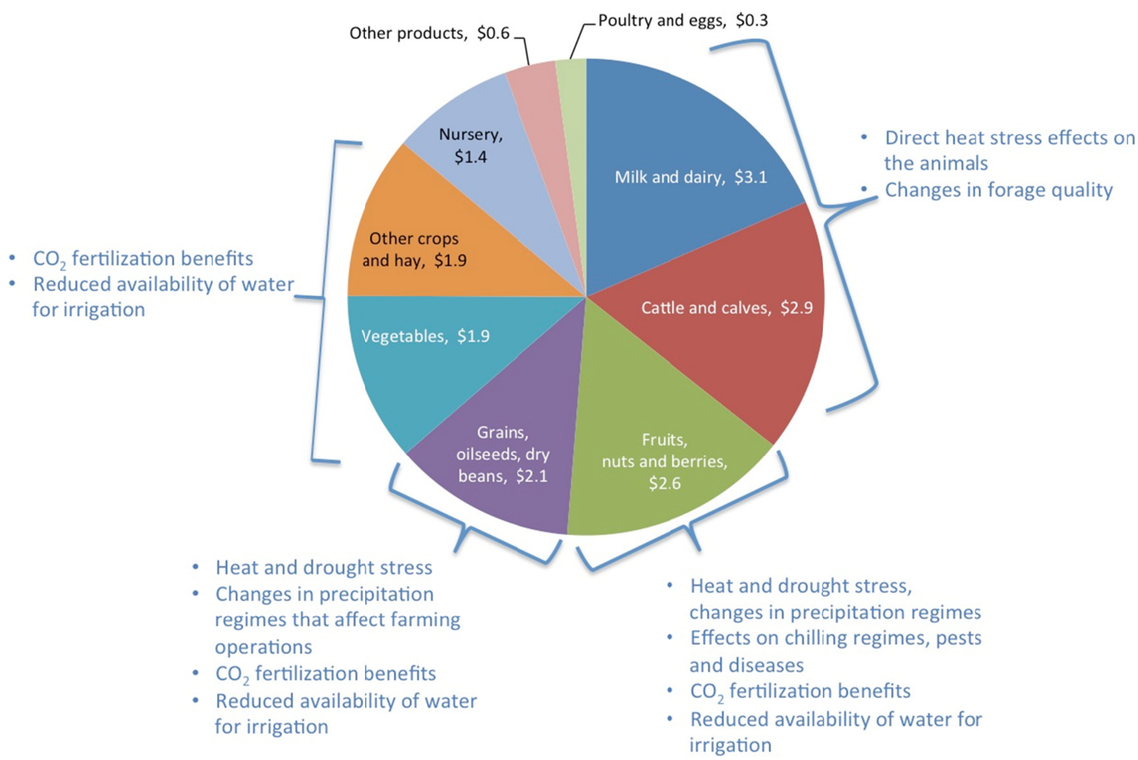

Figure 11-1. Climate change impacts on Pacific Northwest agriculture. Pacific Northwest agricultural commodities, with potential climate change impacts listed for each sector. Market values are shown in $ (billion), with a total value of $16.8 billion. *Figure source: Eigenbrode et al., 2013.*[1]

streamflow, combined with increasing evaporative demand (Section 6 of this report) will pose continued challenges to agricultural operations. In the Yakima basin, for example, water shortage years – years with curtailed water delivery to junior water rights holders – are projected to increase from 14% of years historically (1979-1999) to 43 to 68% of years by the 2080s (2070-2099) for a low and a medium greenhouse gas scenario, respectively.[A][B][2]

- *Climate extremes and fire.* Projected increases in the frequency of heat waves and heavy rainfall events (Section 5 of this report), and the area burned by wildfire (Section 7) can

[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; "medium" 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 3 for more details.

[B] Average projected change for ten global climate models. Range is from two greenhouse gas scenarios: B1 (low) and A1B (medium).

all have deleterious effects on crops and livestock and potentially increase risks of damage from pests, invasives, and disease.

- *Additional research is needed to quantify the above impacts on different crops and locations.* To date, most studies have focused on one specific crop in a handful of locations, and only consider a subset of all relevant climate impacts on production. Impacts can differ substantially for different crops and locations, and little is known about the combined effects of all of the changes listed above.

2. **Annual crops in Washington State are projected to experience a mix of increases and decreases in production, primarily in response to warmer temperatures and CO_2 fertilization.** Projections are based on changes in temperature, precipitation, and evaporative demand, but do not consider other factors such as changes in water availability and pests.[C]

   - *Winter wheat yields are projected to increase.* Projected change is +23 to +35% in four eastern Washington locations by the 2080s (2070-2099, relative to 1975-2005), under a medium greenhouse gas scenario.[D][3]

   - *Spring wheat yields are projected to either remain the same or decrease.* Projected change ranges from no change to −11% in the same four eastern Washington locations by the 2080s (2070-2099, relative to 1975-2005) for a medium greenhouse gas scenario.[D][3]

   - *Potato yields are projected to decrease slightly*. Projected declines in potato yields are small: −3% for Othello, WA by the 2080s (relative to 1975-2005) under a medium greenhouse gas scenario.[E][3] Warmer temperatures can result in lower quality potatoes.[4]

3. **Perennial crops in Washington State are projected to experience a mix of increases and decreases in response to a longer growing season, reduced winter chilling, and CO_2 fertilization.**

   - *Apple yields are projected to increase*. Under a medium greenhouse gas scenario, apples in Sunnyside Washington (near Yakima) are projected to increase in yield by +16% for the 2080s (2070-2099, relative to 1975-2005).[3] However, these results assume no change in water availability – since apples are a relatively water-intensive crop, production could be negatively affected by projected decreases in water availability (Section 6).

   - *Wine grapes require winter "chilling"; new vineyards take years to establish.* Wine grapes, especially the cool climate varieties that are typically produced in Washington –

[C] Impacts on specific crops and locations described in this document represent examples rather than an exhaustive list of potential regional impacts.

[D] Changes in crop yield were simulated for 4 eastern Washington locations: Pullman, St. John, Lind, and Odessa, using the average projection from four global climate models (PCM1, CCSM3, ECHAM5, and CGCM3) and a medium greenhouse gas scenario (A1B; see Section 3). The range in projections is a result of differences in growing season and precipitation at these four locations.

[E] Based on the average projection from four global climate models (PCM1, CCSM3, ECHAM5, and CGCM3) and a medium greenhouse gas scenario (A1B; see Section 3).

e.g., Pinot Gris, Pinot Noir – require winter "chilling" conditions in order to produce fruit of sufficient quality. Annual frost-free days are projected to decrease by −35 days on average by the 2050s (2041-2070, relative to 1970-1999) under a high greenhouse gas scenario.[F][5] There are significant costs associated with shifting to warmer grape varieties: grapes are a multi-decade investment for farmers, taking 4 to 6 years to mature and remaining productive for several decades.

4. **Pests are affected by warming, which can increase growth and reproductive success, and alter their vulnerability to predators.** Projections are limited to a small selection of species and locations, and do not include the combined effects of changing crops, predators, and other factors.

   - *Codling moth (Cydia pomonella) populations are expected to increase, affecting apples.* The codling moth, which is the main pest attacking apples in Washington, is projected to reproduce more rapidly with warming. For Sunnyside, Washington (near Yakima), warming under a medium greenhouse gas scenario is projected to cause adult moths to hatch about 2 weeks earlier and increase the fraction of the third generation hatch by +81% by the 2080s (2070-2099, relative to 1975-2005) for a medium greenhouse gas scenario.[E][3]

   - *Populations of the cereal leaf beetle (Oulema melanopus) are expected to increase*. Temperatures in the Northwest are projected to become more favorable for the invasive cereal leaf beetle. Preliminary work also indicates that the parasitoid wasp (*Tetrastichus julis*), which attacks cereal leaf beetles, may become less effective as a population control as a consequence of warmer springs.[6]

   - *Parasitic wasp (Cotesia marginiventris) populations are projected to decrease*. Reproduction by this wasp, which attacks caterpillars, including those species affecting Northwest crops, is projected to decline substantially in response to warming, potentially allowing caterpillar populations to increase.[7]

5. **Livestock are affected by climate via impacts on food sources as well as the direct effects of heat stress.** Research has generally focused on the isolated effect of warming or CO_2 fertilization in specific locations, and does not include factors such as changing water availability, fire risk, and invasive species.

   - *Rangeland grasses are expected to have increased growth but decreased digestibility.* Experiments have shown increased forage growth in grazing lands in response to both elevated CO_2 concentrations[8] and warming[9]. However, these studies also found a decrease in digestibility of grasses grown under these conditions and a changing balance of grass species, as some benefit more from the changes than others. Invasive species may also benefit from warming and rising CO_2 concentrations[10]. Warming is likely to decrease soil water availability, especially in late summer, resulting in decreased forage growth and an increased risk of fire.[11][12]

[F] Projection based on regional climate model simulations under a high greenhouse gas scenario (A2; see Section 5 of this report).[5]

- *Increases in forage and pasture crop production, decreases in digestibility.* Experiments indicate that CO_2 fertilization will result in reduced nutritional value in these crops, for instance finding up to a −14% reduction in digestibility for livestock in response to a doubling of CO_2.[13] In spite of decreases in nutritional value, alfalfa production is projected to increase by +27 to +45% in response to a doubling of CO_2 and a warming of 4.5°F.[G][14] Projected decreases in irrigation water supply (Section 6 of this report) may limit forage production.

- *Impacts on livestock are minor.* Livestock eat less in response to heat stress, are less efficient at converting feed into protein (either dairy or meat), and have reduced reproductive rates. Dairy cows in Washington are projected to produce slightly less milk in response to heat stress – about −1% less by the 2080s (2070-2099, relative to 1970-1999) for a medium greenhouse gas scenario.[15] Preliminary results project that beef cattle will mature more slowly, taking +2.2 to +2.5% longer to achieve finishing weights in response to a doubling of CO_2, which is projected to occur by about mid-century under a high greenhouse gas scenario.[16]

6. 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 Pacific Northwest is very diverse.* The diverse climates of the Pacific Northwest host a wide range of agricultural production. This will likely facilitate adaptation, as some crops fare better than others.

- *Selective breeding and improved management practices could outpace climate impacts.* 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 change impacts.[15]

- *Western Washington agriculture is likely less vulnerable than the interior.* 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. Areas in the interior, especially semi-arid regions with limited access to irrigation water, have much less capacity for adaptation.

- *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,

[G] 4.5°F is near the middle of the range projected for mid-century (2041-2070), relative to 1950-1999, under a low greenhouse gas scenario (RCP 4.5).

environmental regulations, and certain tax policies – may reduce the incentive for adaptation.

7. **Since 2007, new studies have quantified impacts on specific crops and locations, evaluated the combined effects of warming and CO_2, and begun to integrate climate impacts with economic modeling of market influences and adaptation.**

- *New advancements include the following:*
    - Improved understanding of climate impacts on specific crops and locations, and studies of impacts on new species not previously assessed.
    - More information on the combined effects of warming, CO_2 fertilization, predator-prey interactions, and other factors impacting the response of crops to climate change.
    - New efforts to integrate climate impacts modeling with economic models that consider market influences and potential for adaptation.
- *Available studies are still limited to a subset of Washington crops and locations.* Research is needed to quantify impacts on additional crop, weed, and pest species; assess the synergistic effects of multiple stressors on yields; and identify vulnerabilities in the food system and barriers to adaptation.[17]

Specific Information and Resources to Support Adaptation to Changes in Agriculture
The following resources are suggested for additional information beyond the summaries provided in this document.

- **Integrated modeling of climate change, agriculture, and economics.** The *Regional Approaches to Climate Change for Pacific Northwest Agriculture* integrates climate modeling with research and modeling of economics, crop systems, and agriculture. Driven by stakeholder needs, this research will evaluate the combined effects of climate change and adaptation on Pacific Northwest agriculture. www.reacchpna.org
- **Water supply and demand forecast.** The *Columbia River Basin long-term water supply and demand forecast*[18] provides historical data and projected changes in water supply and agricultural demand as a result of climate change. Other demand forecasts (municipal, hydropower, and instream flows) do not incorporate climate change. Results are available for each individual Water Resource Inventory Area (WRIA) in eastern Washington and the Columbia River basin as a whole. http://www.ecy.wa.gov/programs/wr/cwp/forecast/forecast.html
- **Climate and hydrologic scenarios.** The Climate Impacts Group provides downscaled daily historical data and future projections of temperature, precipitation, snowpack, streamflow, flooding, minimum flows, and other important hydrologic variables for all watersheds and 112 specific streamflow locations in Washington State, as well as for locations throughout the Columbia River basin and the western US. These are based on projections in IPCC 2007.[19] http://warm.atmos.washington.edu/2860,[19] http://cses.washington.edu/cig/
- **Modeling the interactions between climate, water, carbon, and nitrogen.** The *Regional Earth System Modeling Project (BioEarth)* links global climate model projections with a regional model that simulates complex interactions between the land, water, and atmosphere, including vegetation changes, water and nutrient cycling, and agriculture. www.cereo.wsu.edu/bioearth/
- **Modeling the interactions between water resources, water quality, climate change, and human decisions.** The *Watershed Integrated Systems Dynamics Modeling (WISDM)* project is focused on agricultural and urban environments. A primary goal is to engage stakeholders in the development of scientifically sound and economically feasible water policy. www.cereo.wsu.edu/wisdm/

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2 Vano, J. A. et al., 2010. Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA. *Climatic Change*, *102*(1-2), 287-317.

3 Stöckle, C. O. et al., 2010. Assessment of climate change impact on Eastern Washington agriculture. *Climatic change*, *102*(1-2), 77-102.

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[19] (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.

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SECTION 12

How Will Climate Change Affect Human Health in Washington?

Studies of climate change impacts on human health in the Pacific Northwest are limited. Research to date finds that climate change is likely to increase rates of heat related illnesses (including heat exhaustion and stroke); respiratory illness (e.g., allergies, asthma); vector-, water-, and food-borne diseases; and mental health stress. These impacts can lead to increased absences from schools and work, emergency room visits, hospitalizations, and deaths. Efforts to adapt Washington's public health systems are in the early stages due in part to the limited information available to agencies.

1. **Climate change is expected to affect both the physical and mental health of Washington's residents by altering the frequency, duration, or intensity of climate-related hazards to which individuals and communities are exposed.**[A][1] In some cases (e.g., disease vectors), climate change may also lead to the introduction of new risks.

    - *Health impacts are under-studied.* A small but growing number of local studies provide more regionally-specific information about the types and scale of human health impacts likely to be experienced in the Pacific Northwest as a result of climate change. However, the area remains under-studied and no studies on the individual and societal costs of climate change impacts on human health have been done to date in the Pacific Northwest region.

    - *Health impacts stem from a wide range of projected climate change impacts.* Human health in Washington State is likely to be affected by projected increases in extreme heat events, flooding, sea level rise, drought, and forest fires; increased allergen production and summer air pollution; and changes in the types, distribution, and transmission of infectious diseases (e.g., West Nile Virus) and fungal diseases (Table 12-1).

    - *Health impacts are diverse.* Anticipated health impacts include higher rates of heat related illnesses (including heat exhaustion and stroke); respiratory illness (e.g., allergies, asthma); vector-, water-, and food-borne diseases; and mental health impacts.[1][2]These impacts can lead to increased absences from schools and work, emergency room visits, hospitalizations, and deaths.

    - *Some populations are more vulnerable to health impacts.* Vulnerable populations include those over age 65, children, poor and socially isolated individuals, the mentally ill, outdoor laborers, and those with cardiac or other underlying health problems (e.g., asthma or reduced immunity due to chemotherapy, illness, or disease).[1][2]

[A] Unless otherwise noted, material in this document is derived or directly quoted from Bethel et al. 2013,[1] prepared as part of the U.S. National Climate Assessment.

2. 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 Dept. of Health.* The Washington State Department of Health is:

    - developing strategies to support enhanced emergency preparedness and response, specifically focused on heat waves;
    - looking at ways to enhance how the agency can track air quality and disease to detect and address public health threats; and
    - partnering with communities to build environments that manage growth, decrease urban sprawl, support efficient transportation modes, and offer protection from flooding and landslides.[3]

    The Department of Health has also developed the Washington Tracking Network (WTN), which is part of a national effort to develop better and more integrated ways of sharing environmental public health data that can be used to track and analyze climate-related health impacts over time.[B]

- *King County.* Health-related adaptation activities at King County include the following:

    - *Climate change health indicators.* King County is tracking human health and economic impact indicators to help monitor how climate change may be affecting key issues in the County.[C]

    - *Heat impacts assessment.* King County is partnering with the University of Washington to identify and plan for the impact of climate change on human health, including synthesizing data on the effects of changing temperature on illness and death in King County.[4]

[B] See https://fortress.wa.gov/doh/wtn/WTNPortal//Help/AboutTracking.aspx for more information.
[C] More information available at: http://www.kingcounty.gov/environment/climate/climate-change-resources/impacts-of-climate-change/health-economic-impacts.aspx

Table 12-1. Summary of projected Pacific Northwest climate change impacts and related projected human health impacts, based on Bethel et al. 2013[1] and other sources. More details, where available, on the projected climate change impacts listed here are included in other sections of this report. Few studies have been conducted to date on climate change impacts to human health in the Pacific Norwest. The health impacts listed here represent examples rather than an exhaustive list of potential impacts.

Projected Climate Change Impact *General Trend*	 *Specific Changes Projected*	**Related Human Health Impacts**
More extreme heat events [D]	• The number and duration of days above 90°F increases throughout the state.[5] • Increases in number of days in Washington above 95°F annually range from less than 3 days to up to 10 days by 2050s, compared to 1980-2000, depending on the greenhouse gas scenario and location.[E][5]	Increased potential for:[1] • worsening of existing problems with respiratory illness, cardiovascular disease, and kidney failure; • more heat exhaustion, heart attacks, strokes, and drownings; and • more heat related deaths, although the projected numbers vary widely. Related information: • One study for the greater Seattle area projected an additional 157 annual heat-related deaths by 2045 under a moderate (A1B) greenhouse gas emissions scenario.[F][2] Another study projected only an additional 14 annual heat-related deaths in Seattle for approximately the same time period under a very high (A1FI) emissions scenario.[G][6]

D The temperature thresholds used to define an extreme heat event will vary by location. The thresholds used for Seattle and Spokane in Jackson et al. 2010 were 92.5°F and 100.6°F, respectively. For more on projected changes in extreme events, see this report's section on projected Pacific Northwest climate.

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; "medium" 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 3 for more details.

F Study inclusive of King, Pierce, and Snohomish Counties. Projected change in mortality for those over age 45, relative to a base period of 1980-2006. Projections based on the average of the climate change scenarios derived from two global climate models and two greenhouse gas emissions scenarios: the PCM model run with the B1 emissions scenario and the HADCM1 model run with the A1B emissions scenario. Population levels were held constant at year 2025.

G Projected change in mortality relative to a base period of 1975-95. Projections cited here based on modeling of the A1FI greenhouse gas emissions scenario with the PCM global climate model.

Projected Climate Change Impact *General Trend*	*Specific Changes Projected*	**Related Human Health Impacts**
Increased winter flooding[H]	• More winter flooding is expected west of the Cascades. The largest projected changes are found in mid-elevation mixed rain and snow basins, which are most sensitive to warming winter and spring temperatures.[I][7] • Some higher elevation snow dominant watersheds will see increasing flooding, while others experience decreased flooding.[7]	Increased potential for:[1] • injuries and death, • exposure to hazardous and toxic substances released and spread by flooding, • respiratory illness from mold and microbial growth in flood-impacted structures, • contamination of, or disruption to, public water supplies,[8] • mental health impacts[J] associated with damage to homes, communities, places of employment.
Increased drought[H]	• Lower summer streamflows, warmer summer temperatures, and earlier spring snowmelt contribute to increased risk of drought, particularly in eastern Washington. • Drought impacts can affect food production, the potential for wildfire in forests and rangeland, water supply, and water quality.	Increased potential for:[1] • respiratory illness associated with increased forest fires (see next row), • reduced water supplies, including impacts to groundwater supplies used by private wells, and • mental health effects.

[H] For more on projected impacts on Pacific Northwest hydrology, see Section 6.

[I] Projections for specific Washington locations can be found here: http://warm.atmos.washington.edu/2860/products/sites/

[J] Mental health impacts are common to most climate change impacts. Potential mental health impacts include: emotional and psychological stress associated with weather-related trauma, including loss of homes or places of employment, financial concerns, recovery and rebuilding, family pressure, loss of leisure and recreation, loss of security; physical impacts of stress, including post-traumatic stress disorder, high blood pressure, 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 and despair over the loss, or potential loss, of culturally important resources, traditions, or places.

Projected Climate Change Impact *General Trend*	*Specific Changes Projected*	**Related Human Health Impacts**
Increased forest fires[K]	• Most models project increases in the amount of area burned in Washington by forest fires. The projected change is less than 100% to greater than 500% by mid-century.[9] • Risk of fires is greatest east of the Cascades, but air quality around the state is affected.	Increased potential for:[1] • more asthma, bronchitis, and pneumonia hospital admissions; • missed school and work days; • mental health effects due to potential or actual loss of property and disruptions to communities. Related information: • Smoke from the 2012 wildfires in Chelan and Kittitas Counties contributed to an additional 350 hospitalizations for respiratory conditions and 3,400 student absences from school.[L] • Studies in California found that fine particulate matter concentrations in the air were higher and more toxic during wildfires that occurred in 2003 and 2007.[10]
Increased production of allergens	• The pollination season is projected to lengthen.[11][12] • The amount of allergy-causing proteins in pollen is also projected to increase.[12]	Increased potential for:[1] • more severe and longer-lasting allergy symptoms; • asthma attacks, and • missed school and work days.
Increased air pollution	• Warmer 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.[2]	Increased potential for:[1] • Cardiovascular disease, respiratory disorders (e.g., asthma), and mortality. Related information: • Under a high emissions scenario (A2), the annual number of additional May-September deaths due to ozone is projected to increase from 69 in 1997-2006 to 132 by mid-century in

[K] For more on projected impacts on Pacific Northwest forests and forest fire risk, see this report's section on forests.
[L] Glen Patrick, Manager of the Environmental Epidemiology, Washington State Dept. of Health, personal communication

Projected Climate Change Impact *General Trend*	*Specific Changes Projected*	**Related Human Health Impacts**
		King County, and from 37 (1997-2006) to 74 in Spokane.[2]
Infectious, vector-born, and fungal diseases	• Higher temperatures may increase the incidence of West Nile virus. The impact of climate change on Lyme disease, hantavirus, malaria, and dengue in the PNW is unknown. [1] • Warmer ocean temperatures increase the risk of *Vibrio parahaemolyticus* outbreaks in oysters and shellfish, which can cause illness in humans. [1] • Projected increases in precipitation and flooding increase the potential for *Cryptosporidium* contamination in water supplies. [1]	Increased potential for:[1] • More illness and mortality associated with infectious diseases. The emergence of new diseases and/or expansion of existing diseases is expected to exacerbate these impacts.
Harmful Algal Blooms (HABs)	• Models project the window of opportunity for *A. catenella*, which can cause illness or death via paralytic shellfish poisoning, in Puget Sound to increase by an average of 13 days by the end of the century under a moderate (A1B) greenhouse gas emissions scenario.[13]	Increased potential for:[1] • More illness and mortality associated with infectious diseases.
Sea Level Rise	• Sea level is projected to increase +4 to +56 inches overall in Washington State by 2100, relative to 2000, although some locations may experience sea level fall because of uplift caused by plate tectonics. [M][14] • Associated impacts with the potential to impact human health include inundation of low-lying areas, increased coastal river flooding, increases in the frequency of today's extreme tidal/storm surge events, and changes in coastal habitats that may affect culturally and economically important species.	Increased potential for: [1] • Mental health stress associated with storm surge damage and loss of culturally or economically important areas to inundation, erosion, or storm surge. • Reduced drinking water quality due to saltwater intrusion into coastal aquifers and rivers.

[M] Mean value: +24 inches (± 12 inches) for a moderate (A1B) greenhouse emissions scenario for 2100, relative to 2000. The range values reported in the table are for the lowest (B1) to the highest (A1FI) greenhouse gas emissions scenarios used prior to the release of the CMIP5 RCP scenarios. For more on sea level rise and coastal impacts, see this report's sections on projected Pacific Northwest climate and projected impacts on oceans and coasts.

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[2] Jackson, J.E. et al. 2010. Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution. *Climatic Change* 102(1-2): 159-186, doi: 10.1007/s10584-010-9852-3.

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APPENDIX

Bibliography: Key References on Climate Change

The basis for our understanding of observed and projected climate change is scientific findings published in the peer-reviewed literature. Scientists periodically convene to assess and synthesize the peer-reviewed science. These assessments serve to integrate scientific information from various sources, to emphasize the key findings, to draw broader conclusions about the state of the science and to identify significant gaps in our understanding of the climate change science and impacts. The following lists the primary syntheses useful for understanding climate change impacts. Since the peer-reviewed journal articles are the primary source for these documents, we have also included annotations for several noteworthy papers.

Synthesis Reports: Global

1. **IPCC, 2013: Intergovernmental Panel on Climate Change (IPCC), *IPCC Fifth Assessment Report, Working Group I Report***

   The IPCC is the leading international, scientific organization providing assessments on climate change and its projected impacts on resources and societies worldwide. Teams composed of thousands of scientists from around the world collaborate to develop periodic assessments of the current state of knowledge in climate change and its potential environmental and socioeconomic impacts. The Working Group I report ("The Physical Science Basis") consists of a synthesis of the science on global climate change. The fifth assessment report (AR5) was released in September of 2013.

Link to report	http://www.ipcc.ch/report/ar5/wg1/#.UqI6miTHRow
Publishing body	IPCC (Cambridge Press)
Literature included	Contributions are supported by references to peer-reviewed and internationally available literature. Sources other than scientific journals include reports from governments, industry, research institutions, international organizations and conference proceedings. Each IPCC Working Group sets cut-off dates by which time the literature must be accepted for publication by scientific journals (~2-3 months prior to final draft completion), thereby assuring that the literature included is up-to-date.
Review process	IPCC review process includes wide participation, with hundreds of Expert Reviewers and governments invited at different stages to critique the accuracy and completeness of the scientific assessment. The review process consists of 3 stages: 1. Authors prepare a first order draft of the report based on scientific, technical and socioeconomic literature and other relevant publications. Experts from a wide

	range of views, expertise and geographical representation review the first order draft. 2. Authors prepare a second order draft based on the review comments of the first order draft. The Summary for Policymakers (SPM) is drafted at this time. Both drafts are subject to simultaneous review by experts and governments. 3. Author teams prepare the final drafts of the full report and the SPM accounting for the reviewers' comments. The final drafts are submitted to governments to for a last round of comments on the SPM. The process concludes with a plenary session where the governments meet to approve the SPM line-by-line and to accept the final report. For additional details, see "IPCC Factsheet: How does the IPCC review process work?: http://www.ipcc.ch/news_and_events/docs/factsheets/FS_review_process.pdf
Geographical domain	Global, regional (continental)
Subject matter	Climate science.
Citation	Not yet available. (Official publication date in January of 2014.

2. **IPCC, 2012:** ***Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation***

The purpose of this synthesis report is to integrate expertise in climate science, disaster risk management, and adaptation to inform decisions on reducing and managing the risks of extreme events and disasters associated with climate change.

Link to report	http://ipcc-wg2.gov/SREX/
Publishing body	IPCC (Cambridge Press)
Literature included	Contributions are supported by references to peer-reviewed and internationally available literature. Unpublished material needs citation and a copy must be provided.
Review process	Authors and review editors for special report are nominated by governments and selected by the WGI and WGII bureaus. The report and summary for policymakers (SPM) undergo an expert review and an additional expert and government review. http://ipcc-wg2.gov/SREX/ipcc-process/
Geographical domain	Global, national, regional

Subject matter	Climate science, climate impacts, adaptation and vulnerability, mitigation (very broad for state-level adaptation efforts).
Citation	Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (Eds.). (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

3. **IPCC, 2007: *IPCC Fourth Assessment Report, Working Group I Report***

The IPCC is the leading international, scientific organization providing assessments on climate change and its projected impacts on resources and societies worldwide. The Working Group I report ("The Physical Science Basis") consists of a synthesis of the science on change in the global climate system. The fourth assessment report (AR4) was released in 2007.

Link to report	http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html
Publishing body	IPCC (Cambridge Press)
Literature included	Contributions are supported by references to peer-reviewed and internationally available literature. Unpublished material needs citation and a copy must be provided.
Review process	IPCC authors are directed to "seek the participation of reviewers encompassing the range of scientific, technical and socio-economic views, expertise, and geographical representation". The review process consists of 2 stages: 1. Review by experts from a range of scientific, technical and socio-economic views, expertise and geographical backgrounds, and 2. Review by governments and experts chosen to include "as wide a group of experts as possible". For additional details, see "IPCC principles, Appendix A: http://www.ipcc.ch/organization/organization_procedures.shtml
Geographical domain	Global, regional (continental)
Subject matter	Synthesis of the current state of climate science.
Citation	Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis,

	K.B. Averyt, M. Tignor and H.L. Miller (eds.). (2007). *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Synthesis Reports: United States

4. Kunkel, K.E. et al. 2013*: Regional Climate Trends and Scenarios for the U.S. National Assessment. Part 9. Climate of the Contiguous U.S.*

This report is one in a series of nine, eight of which cover a region of the U.S. and this one covering the contiguous U.S. This report provides a synthesis of the most recent climate science for the CONUS, based on previously published papers, datasets and model output. The reports include two components: historical climate based on core climate data and future climate conditions projected by two greenhouse gas emissions scenarios. Collectively, these reports provide the technical input for the Third National Climate Assessment.

Link to report	http://scenarios.globalchange.gov/regions
Publishing body	NOAA
Literature included	Previously published literature and datasets on historical and plausible future climate scenarios specific to the Northwest region
Review process	National Climate Assessment working group including university-based and Federal research scientists
Geographical domain	Contiguous United States
Subject matter	Documents, graphics, references to data sets, and other resources depicting a range of plausible future conditions to inform decisions and assessments of risk, vulnerability and opportunities for adaptation on a regional scale.
Citation	Kunkel, K.E, L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, K.T. Redmond, and J.G. Dobson, 2013: Part 9. Climate of the Contiguous U.S., NOAA Technical Report NESDIS 142-9, 85 pp.

5. USGCRP 2014: US Global Change Research Program (USGCRP), *Third National Climate Assessment (NCA)*

The NCA evaluates and summarizes current climate science from the US Global Change Research Program and other sources. The report is intended to inform national priorities for future climate science research and adaptation to climate impacts. The assessment is undergoing final federal agency review (as of December 2013) and is scheduled for release in spring 2014.

Link to report	Public comment draft available at: http://ncadac.globalchange.gov/
Publishing body	National Climate Assessment Development Advisory Committee
Literature included	Synthesis reports (e.g., IPCC), peer-reviewed literature, technical inputs
Review process	Input from stakeholders that was compiled into a separate Technical Input Report (TIR) for each chapter. The entire 3rd NCA draft was released for an expert review and public comment period from January to April 2013.
Geographical domain	National and regional
Subject matter	Climate science, climate impacts, vulnerability
Citation	TBD

6. NRC 2011: National Research Council (NRC), *America's Climate Choices*

America's Climate Choices is a five report series developed by the National Research Council, as requested by Congress. Developed between 2009 and 2011, the report discusses climate change adaptation and mitigation policy as well as the relevant science and technology. The report focusing on the science of climate impacts, *Advancing the Science of Climate Change*, includes impacts by sector such as freshwater resources, agriculture, public health and transportation. The report also covers adaptation options and climate change drivers in each sector.

Link to report	http://nas-sites.org/americasclimatechoices/sample-page/panel-reports/
Publishing body	National Research Council of the National Academy of Sciences
Literature included	Peer-reviewed science and other assessments such as IPCC AR4, USGCRP's *Global Climate Change Impacts in the United States* and previous NRC reports
Review process	A different authoring panel is responsible for each report in

	the series, with outside input received from public presentations and workshops and comments submitted on the website.
Geographical domain	U.S.
Subject matter	Climate science, adaptation and mitigation policy, technology
Citation	National Research Council (2011). *America's Climate Choices*. Washington, DC: The National Academies Press.

Synthesis Reports: U.S. West Coast

7. NRC, 2012: *Sea level rise for the coasts of California, Oregon and Washington: Past, Present and Future*

Several federal and state agencies collaborated to produce this assessment of sea level rise along the West Coast of the U.S. The report, produced by the National Research Council, reviews and synthesizes the current, published research on global and regional sea levels and applies established process-based approaches to project global sea level rise through the 21st century.

Link to report	http://www.nap.edu/catalog.php?record_id=13389
Publishing body	National Academy of Sciences
Literature included	Committee reviews and synthesizes current, published research.
Review process	The NRC appointed a Report Review Committee to select experts from a variety of backgrounds to independently review the report. The review process ensures that the report meets institutional standards of objectivity, evidence and responsiveness to the study charge. Reviewers are listed in the Acknowledgements of the report.
Geographical domain	West Coast of U.S. (California, Oregon and Washington)
Subject matter	Sea level rise, coastal impacts, vulnerability – specific to coastal systems along the U.S. West Coast.
Citation	National Research Council. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press, 2012.

Synthesis Reports: Pacific Northwest

8. **Kunkel, K.E. et al. 2013: *Regional Climate Trends and Scenarios for the U.S. National Assessment. Part 6. Climate of the Northwest U.S.***

This report is one in a series of nine, eight of which cover a region of the U.S. and one cover the contiguous U.S. Each report provides a synthesis of the most recent climate science for the given region, based on previously published papers, datasets and model output. The reports include two region-specific components: historical climate based on core climate data and future climate conditions projected by two greenhouse gas emissions scenarios. These reports provide the technical input for the Third National Climate Assessment.

Link to report	http://scenarios.globalchange.gov/regions/northwest
Publishing body	NOAA
Literature included	Previously published literature and datasets on historical and plausible future climate scenarios specific to the Northwest
Review process	National Climate Assessment working group including university-based and Federal research scientists
Geographical domain	Regional (Northwest U.S.)
Subject matter	Documents, graphics, references to data sets, and other resources depicting a range of plausible future conditions to inform decisions and assessments of risk, vulnerability and opportunities for adaptation on a regional scale.
Citation	Kunkel, K.E, L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, K.T. Redmond, and J.G. Dobson, 2013: Part 6. Climate of the Northwest U.S., NOAA Technical Report NESDIS 142-6, 76 pp.

9. **Dalton et al. 2013: *Climate Change in the Northwest: Implications for our Landscapes, Waters, and Communities***

As companion report for the Northwest chapter of the Third National Climate Assessment, the objective of this synthesis is to assess the state of knowledge about key climate impacts and consequences to multiple natural resource sectors and communities in the Northwest U.S. This report is the culmination of an iterative process involving workshops with regional stakeholders to identify climate risks and consequences in their respective sectors. This report is designed to serve as an updated resource for scientists, decision makers, stakeholders and adaption planning in the PNW.

Link to report	http://islandpress.org/ip/books/book/distributed/C/bo9111930.html

Publishing body	Island Press
Literature included	Previously published literature representing best available science on regional climate change, impacts, vulnerability assessments, mitigation and adaptation.
Review process	27 expert reviewers drawn from federal, state, tribal, private, nonprofit, universities and other regional agencies.
Geographical domain	Regional (Northwest U.S.)
Subject matter	A review of the historic, current and projected climate conditions for the Northwest region. Interactions among important sectors, and cross-sectoral topics: climate change mitigation, adaptation, education and outreach.
Citation	Dalton, M.M., P.W. Mote, and A.K. Snover. (Editors). 2013. Climate Change in the Northwest: Implications for our Landscapes, Waters, and Communities. Washington, D.C.: Island Press. 271 pp.

Synthesis Reports: Washington State

10. CIG, 2009: Climate Impacts Group (CIG), *Washington State Climate Change Impacts Assessment (WACCIA)*

The WACCIA was produced in 2009 by the Climate Impacts Group in collaboration with researchers and Washington State University and the Pacific Northwest National Laboratory, as mandated by Washington State House Bill 1303. The WACCIA reported on new research assessing climate impacts on Washington State's resources. The WACCIA involved developing updated climate change scenarios for Washington State and using these scenarios to assess the impacts of climate change on the following sectors: hydrology, water management and irrigation, energy, agriculture, salmon, forests, coasts, stormwater infrastructure, human health and adaptation.

Link to report	http://cses.washington.edu/cig/res/ia/waccia.shtml
Publishing body	Climate Impacts Group, University of Washington
Literature included	Synthesis reports (e.g., IPCC), peer-reviewed literature
Review process	Anonymous peer review: all chapters were published as a special edition in the journal *Climatic Change*.
Geographical domain	Focused on WA state, but also includes results for the full Columbia River basin.
Subject matter	Climate impacts, by sector.
Citation	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.

11. Feely et al. 2012: *Scientific Summary of Ocean Acidification in WA State Marine Waters*

This scientific summary was a collaborative effort among natural scientists from Washington and Oregon States. The purpose of this NOAA special report is to inform members of the WA Shellfish Initiative Blue Ribbon Panel on ocean acidification and to summarize and synthesize the state of knowledge with regards to the conditions and probable biological and ecological responses to changes in ocean chemistry in the estuaries and coastal waters of WA.

Link to report	https://fortress.wa.gov/ecy/publications/summarypages/1201016.html
Publishing body	NOAA OAR Special Report
Literature included	Synthesis reports (e.g., IPCC), peer-reviewed literature.
Review process	Federal scientists from NOAA, and where relevant subject matter experts at the WA State Department of Ecology
Geographical domain	Focused on WA state, but provides global overview of the mechanisms driving ocean acidification
Subject matter	Ocean acidification and related regional dynamics contributing to changes in ocean chemistry, impacts to regional marine ecosystems and to shellfish industries.
Citation	Feely, R.A., Klinger, T., Newton, J.A., Chadsey, M. [Eds.] 2012. Scientific Summary of Ocean Acidification in Washington State Marine Waters. NOAA OAR Special Report. Seattle, Washington.

Key Peer-reviewed Journal Articles and White Papers

The following list includes noteworthy references to papers that provide the foundation for the syntheses listed above.

Greenhouse gases

This study describes recent trends in global greenhouse gas emissions, including the substantial acceleration in emissions since the year 2000:

- Peters, G.P., G. Marland, C. Quéré, T. Boden, J.G. Canadell, and M.R. Raupach. 2012. Rapid growth in CO2 emissions after the 2008–2009 global financial crisis. *Nature Climate Change* 2, 2–4. 2012, doi:10.1038/nclimate1332

Temperature trends

This study investigates the impact of measurement issues (changes in location of measurements, the instruments used, or in the overall number of observing stations in operation) on estimates of long-term trends in temperature. They find that correcting for these issues generally has a small effect on estimated trends:

- Menne, M. J., Williams, C. N., & Palecki, M. A. (2010). On the reliability of the US surface temperature record. *Journal of Geophysical Research: Atmospheres (1984–2012)*, 115(D11).

Detection and attribution

These four studies evaluate role of human activity in driving recent observed changes in temperature, precipitation, snowpack, and streamflow in the Western U.S.:

- Bonfils, C., and Coauthors. 2008. Detection and attribution of temperature changes in the mountainous western United States. *Journal of Climate*, 21, 6404–6424. doi:10.1175/2008JCLI2397.1

- Barnett, T., D.W. Pierce, H. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nazawa, A, Mirin, D. Cayan, and M. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. *Science Express Reports* 10.1126/science.1152538.

- Pierce, D.W., T. Barnett, H. Hidalgo, T. Das, C. Bonfils, B.D. Santer, G. Bala, M. Dettinger, D. Cayan, A, Mirin, A.W. Wood, and T. Nazawa. 2008. Attribution of declining western U.S. snowpack to human effects. *Journal of Climate* 21(23): 6425–6444, doi:10.1175/2008JCLI2405.1.

- Hidalgo H.G., Das T., Dettinger M.D., Cayan D.R., Pierce D.W., Barnett T.P., Bala G., Mirin A., Wood A.W., Bonfils C., Santer B.D. and T. Nozawa, 2009, Detection and Attribution of Streamflow Timing Change in the Western United States, *J. Climate, 22(13): 3838-3855.*

Streamflow

This is a landmark paper summarizing observed changes in streamflow timing across Western North America for the period 1948-2002. They find that the majority of streamflow sites show a shift to earlier peak flows, with implications for summer water availability.

- Stewart, I., D. R. Cayan and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate*, 18: 1136-1155.

Sea level rise

This report consists of a synthesis of findings concerning the global and local factors contributing to sea level rise along the coasts of Washington state. The report provides summaries of sea level rise projections for 3 areas in WA state: the Puget Sound basin, Central/Southern WA coast, and the NW Olympic peninsula.

- Mote, P., Petersen, A., Reeder, S., Shipman, H., Whitely Binder, L.C. (2008). *Sea level rise in the coastal waters of Washington State.* Report prepared by the Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington and the Washington Department of Ecology, Lacey, Washington.

This study demonstrates the potential impacts to coastal ecosystems as a result of projected sea level rise in the Puget Sound and along the Washington and northern Oregon coasts.

- Glick, P., Clough, J., and Nunley, B. 2007. Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon (Reston, VA: National Wildlife Federation).

Ocean temperatures

This study evaluates observed changes in ocean temperatures in the Strait of Georgia (North of Puget Sound) and West of Vancouver Island, and finds a statistically significant warming trend for the top 1300 ft of ocean depth.

- Masson, D., & Cummins, P. F. (2007). Temperature trends and interannual variability in the Strait of Georgia, British Columbia. *Continental shelf research*, 27(5), 634-649.

Forested and non-forested ecosystems

This study assessed the likely impacts of climate change on wildfire, tree growth, tree species distributions, and mountain pine beetle outbreaks in the Pacific Northwest.

- Littell, J.S., E.E. Oneil, D. McKenzie, J.A. Hicke, J.A. Lutz, R.A. Norheim, and M.M. Elsner. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Climatic Change 102(1-2): 129-158, doi: 10.1007/s10584-010-9858-x.

This paper describes an analysis of projected climate change impacts on diverse ecosystems found in the Pacific Northwest. It provides an indication of the sensitivity of the various vegetation types to increased fire occurrence and the potential response of carbon dynamics.

- Rogers, B. M., R. P. Neilson, R. Drapek, J. M. Lenihan, J. R. Wells, D. Bachelet, and B. E. Law (2011), Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest, Journal of Geophysical Research 116: G03037.

Agriculture

This paper summarizes the current research on rangeland vulnearbilities and also provides a synopsis of anticipated impacts in the Pacific Northwest.

- Polley, H. W. et al., 2013. Climate Change and North American Rangelands: Trends, Projections, and Implications. *Rangeland Ecology and Management*, *66*(5), 493-511.

This paper argues for a more comprehensive look at food system vulnerability (i.e., "food security") — including not just agricultural production but also delivery, processing, and storage food. The paper also includes a review of existing research on impacts and adaptation.

- Miller, M. et al., 2013. Critical research needs for successful food systems adaptation to climate change. *Journal of Agriculture, Food Systems, and Community Development, 3*(4)*,* 161-175. doi: 10.5304/jafscd.2013.034.016

Water Resources

Water management in the context of climate change has been the focus of much research over the past decade. This is a classic study that highlights some of the conflicting objectives that water managers will face in attempting to mitigate the effects of climate change.

- Payne, J. T. et al., 2004. Mitigating the effects of climate change on the water resources of the Columbia River basin. Climatic Change, 62(1-3), 233-256. doi: 10.1023/B:CLIM.0000013694.18154.d6

This paper reviews the development, methods, and results of the Columbia Basin Climate Change Scenarios Project, which includes a comprehensive set of high resolution climate and hydrologic projections for the entire state of Washington, as well as summaries for 112 specific streamflow locations across the state.

- 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

Hydrologic Extremes

Much recent work has been devoted to assessing the impacts of climate change on precipitation and streamflow extremes. The following two papers present different approaches to assessing changes in extremes, both of which include results for Washington State.

- Tohver, I. et al., 2013. Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. Journal of the American Water Resources Association, in press.

- Salathé, E.P. Jr et al., 2013. Estimates of 21st Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations. Submitted

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