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

Observed and Projected Climate Changes

INTRODUCTION

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

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

OBSERVED CHANGES IN CLIMATE: PUGET SOUND REGION

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

TEMPERATURE

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

- *The frost-free season has lengthened.* The frost-free season (and the associated growing season) in the Puget Sound region lengthened by +30 days (range: +18 to +41 days) from 1920 to 2014 [3, 4].

- *Nighttime air temperatures are rising faster than daytime air temperatures.* In the Puget Sound lowlands, daily minimum air temperatures (which generally occur at night) have increased by +1.8°F between 1895 and 2014, while daily maximum air temperatures (which generally occur in afternoon) warmed by +0.8°F over the same time period [1, 3].

- *Warm nights have become more frequent, but daytime heat waves have not changed.* Nighttime heat events have become more frequent west of the Cascade Mountains in

Observed trends in climate variability

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

Climate variability in the Pacific Northwest is largely governed by two large-scale oceanic and atmospheric oscillations: the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). ENSO cycles last up to a year, typically peaking between December and April; warm phases are referred to as "El Niño" and cool phases as "La Niña" [107]**. The PDO is also characterized by warm and cool phases, but unlike ENSO the cool/warm phases of PDO typically persist for 10 to 30 years** [108]**.**

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

How and whether ENSO and PDO will change in the future as a result of climate change remain open questions. Some studies suggest that climate change may cause a prolonged persistence of El Niño conditions in the equatorial Pacific, although the reasons remain uncertain [109, 110]**. Despite this uncertainty, we expect ENSO and PDO to continue influencing Pacific Northwest climate in the coming decades, sometimes reinforcing or counteracting the effects of climate change.**

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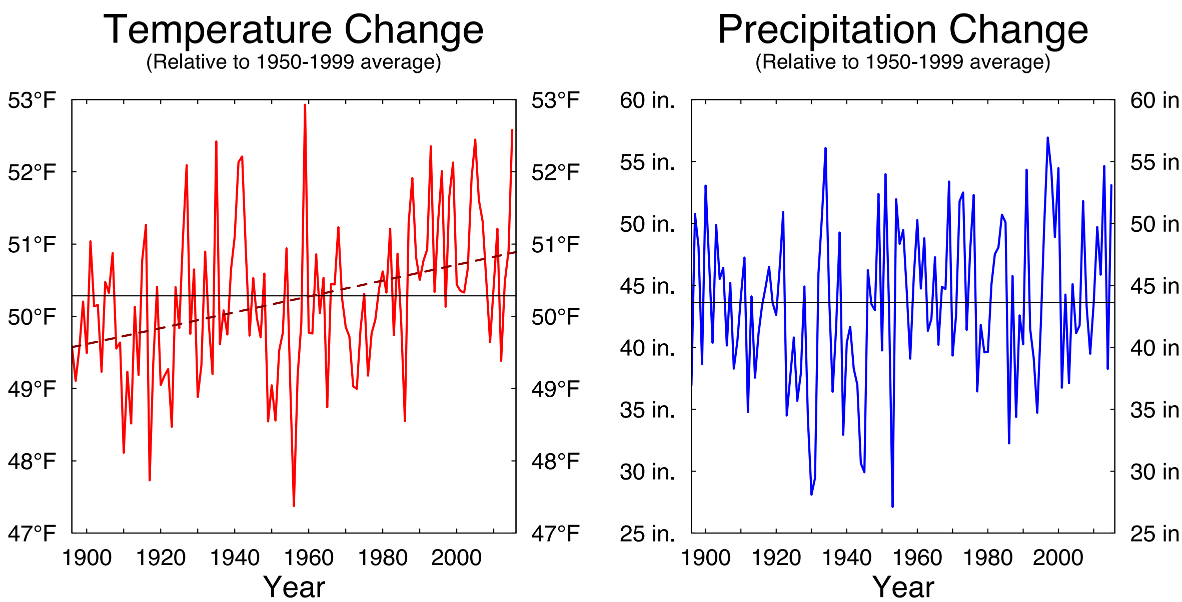
1 The range shows the 95% confidence limits for the trend estimate.

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

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

Oregon and Washington (1901–2009) [5].[4,5] No statistically significant trend has been found for daytime heat events.

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



PRECIPITATION, STORMS, AND WINDS

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

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

- *Modest increases in heavy rainfall have been documented in Western Washington.* Most studies find increases in both the frequency and intensity of heavy precipitation in Western Washington

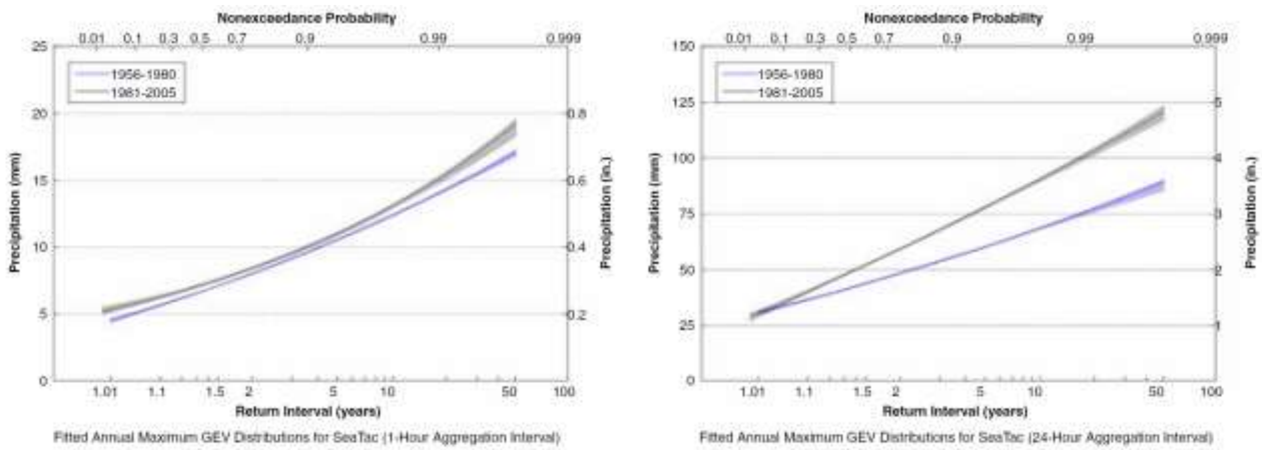
4 Heat events are defined as 3 or more consecutive days above the 99th percentile for the minimum [8.3°F (4.6°C)] temperature anomalies between 1901 and 2009.

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

- [6, 7, 8]. For example, Rosenberg et al. 2010 found a statistically significant +23% increase in the annual-maximum 2-day event for the Puget Sound region (1981–2005 relative to 1956–1980) (see Figure 2) [8]. Not all trends are statistically significant, however. Results depend on the dates and methods of the analysis [8, 9, 10, 11].

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

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



Temperature and Precipitation—Port Gamble S'Klallam Tribe

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

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

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

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

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

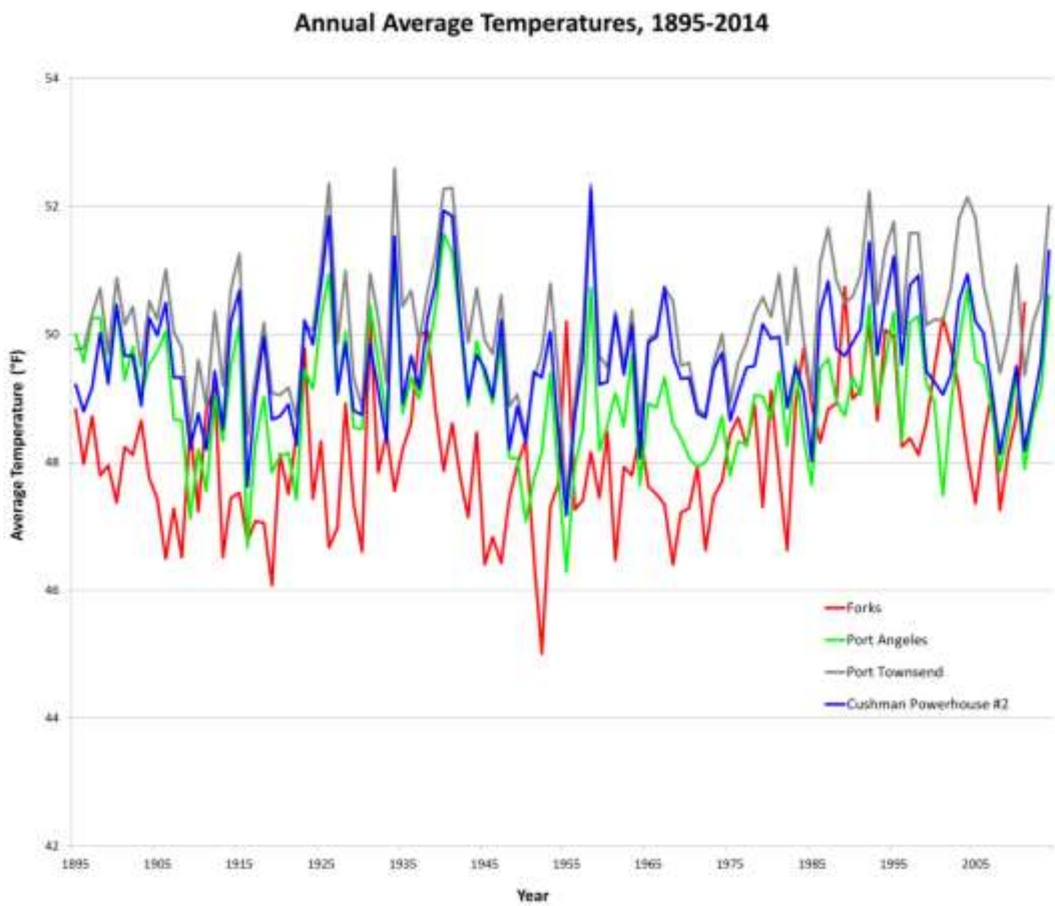
PORT ANGELES	Change in Temperature (˚F)			Change in Precipitation (inches)				
	Annual Mean	Annual Max	Annual Min	Annual Average	Winter *(Dec-Feb)*	Spring *(Mar-May)*	Summer *(June-Aug)*	Fall *(Sept-Nov)*
Trend, 1895–2014	−0.24 (±0.99)	+0.36 (±1.01)	−0.71 (±1.1)	−10.23 (±7.62)	−5.83 (±4.18)	−0.83 (±1.77)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

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

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

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

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



SNOWPACK, GLACIERS, AND STREAMFLOW

Warming temperatures and changes in precipitation over the last century have contributed to declining spring snowpack, receding glaciers, and earlier peak streamflows in Washington's watersheds. These trends reflect the influence of both natural variability and long-term regional warming [12, 13]. Over shorter time scales, however, natural variability can dominate, resulting in short-term trends that may differ from long-term trends.

- *Long-term declines in spring snowpack.* Spring snowpack in the Washington Cascades declined by about −25% (or about −4% per decade) from the mid-20th century to 2006 [14, 15, 16]. Spring snowpack also declined at Hurricane Ridge in the northern Olympic Mountains between 1949 (when snow surveying began) through the late 1990s [17]. More recently (1976 to 2007), there was an apparent (though not statistically significant) increase in spring snow accumulation in the Cascades [14].[6]

- *Declining glacier area.* Trends in glacier area and volume can vary substantially from decade to decade but are declining overall.[7] Observed decreases in glacier area range from a −56% (±3%) loss in the North Cascades (1900–2009) [18] to a −34% decline in area in the Olympic Mountains (1980–2009) (Figure 4, left) [19]. Observations also show consistent decreases in glacier volume and the total number of glaciers remaining [19, 20]. Riedel et al. 2015 found that glacier loss in the Olympics was greatest in the drier northeastern part of the peninsula and for south-facing glaciers. For example, Anderson Glacier (Figure 4, right; Table 2) lost 77% of its area between 1980 and 2009, while the nearby north-facing Eel Glacier lost 23% of its area **[19].** The total decline in glacier volume for glaciers in the Olympic Peninsula was 20% **[19].**

- *Changes in streamflow timing.* In addition to observed changes in temperature and precipitation, several Puget Sound region rivers have experienced shifts in seasonal streamflow timing and volume due to long-term changes in temperature, snowpack accumulation, glacial melt, and sedimentation. The spring peak in streamflow is occurring earlier in the year for many snowmelt-influenced rivers in the Puget Sound region (observed over the period 1948–2002) as a result of decreased snow accumulation and earlier spring melt. The shift ranges from no change to about 20 days earlier depending on location (relative to 1948–2002) [21].

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

7 For example, total glacier area in the North Cascades declined rapidly for the first half of the 20th century, followed by a period of little change, then an additional decline since the 1990s [18, 111].

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

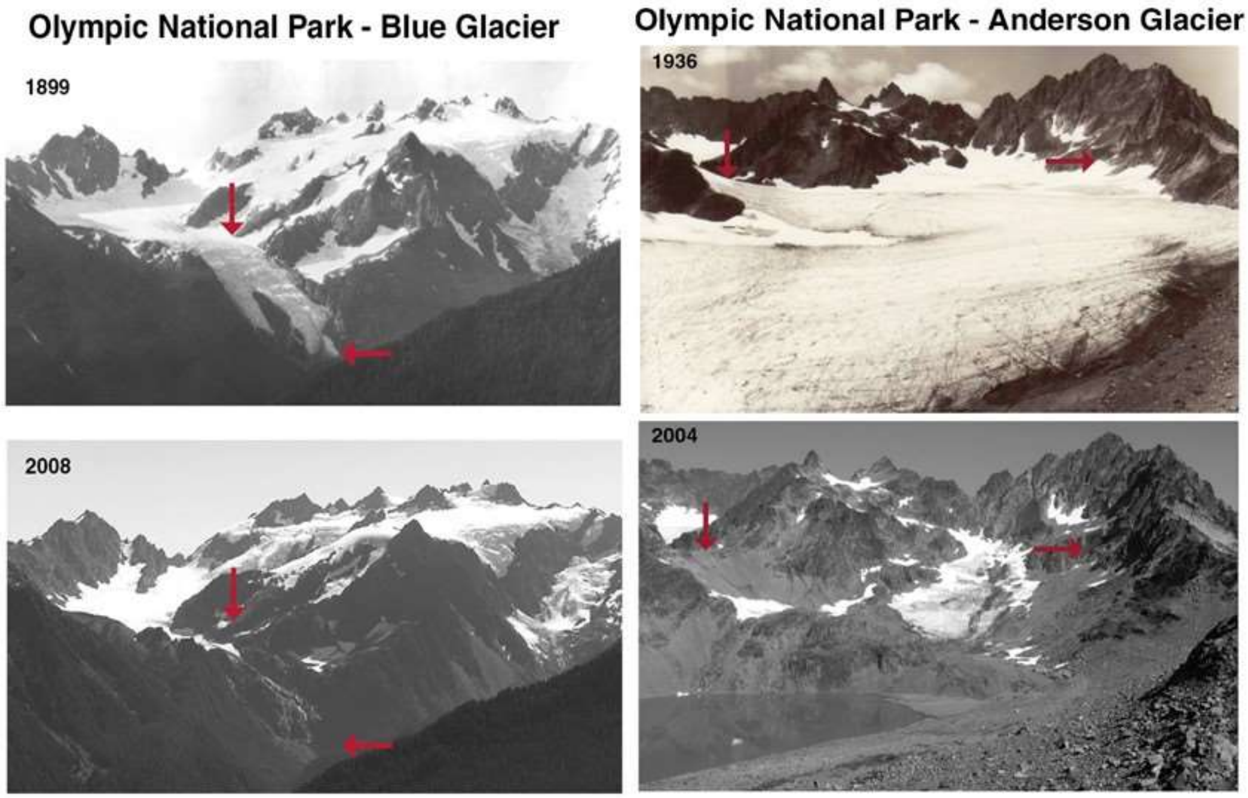


Table 2. Changes in area, in square kilometers, for five Olympic Peninsula glaciers located east of the Elwha Valley. Adapted from Table 1 in Reidel et al. 2015.

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

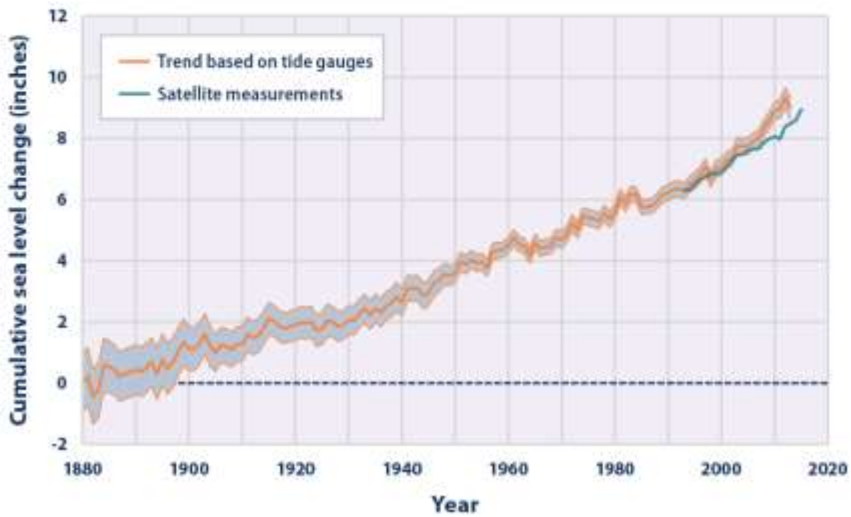
*Based on aerial photographs taken between 1976 and 1982.

SEA LEVEL RISE

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

Globally, sea level has risen approximately 8 inches (averaged across all oceans) since 1880 (Figure 5) [22, 23]. While the total amount of sea level rise is notable, a more significant aspect of this rise is the rate of change. The average annual rate of sea level rise since the mid-1800s is larger than any similar period in the past 2,700 years [24, 25]. It is *very likely* that the rate of global mean sea level rise was +1.7 millimeters per year (range: +1.5 to +1.9 mm/year) between 1901 and 2000 [26].[8] Between 1993—the point when satellite altimetry data became available—and 2010, the rate was *very likely* higher at +3.2 (+2.8 to +3.6) millimeters per year [26, 27]. Similarly high rates occurred between 1920 and 1950 [26].[9,10]

Figure 5. Observed change in global sea level, 1880–2015. The figure shows the change in average absolute sea level change, which refers to the height of the ocean surface regardless of whether nearby land is rising or falling. Since 1880, global sea level has risen over 8 inches. The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used. Figure source: U.S. Environmental Protection Agency, based on data from CSIRO 2015 and NOAA 2016 [28, 29, 30].



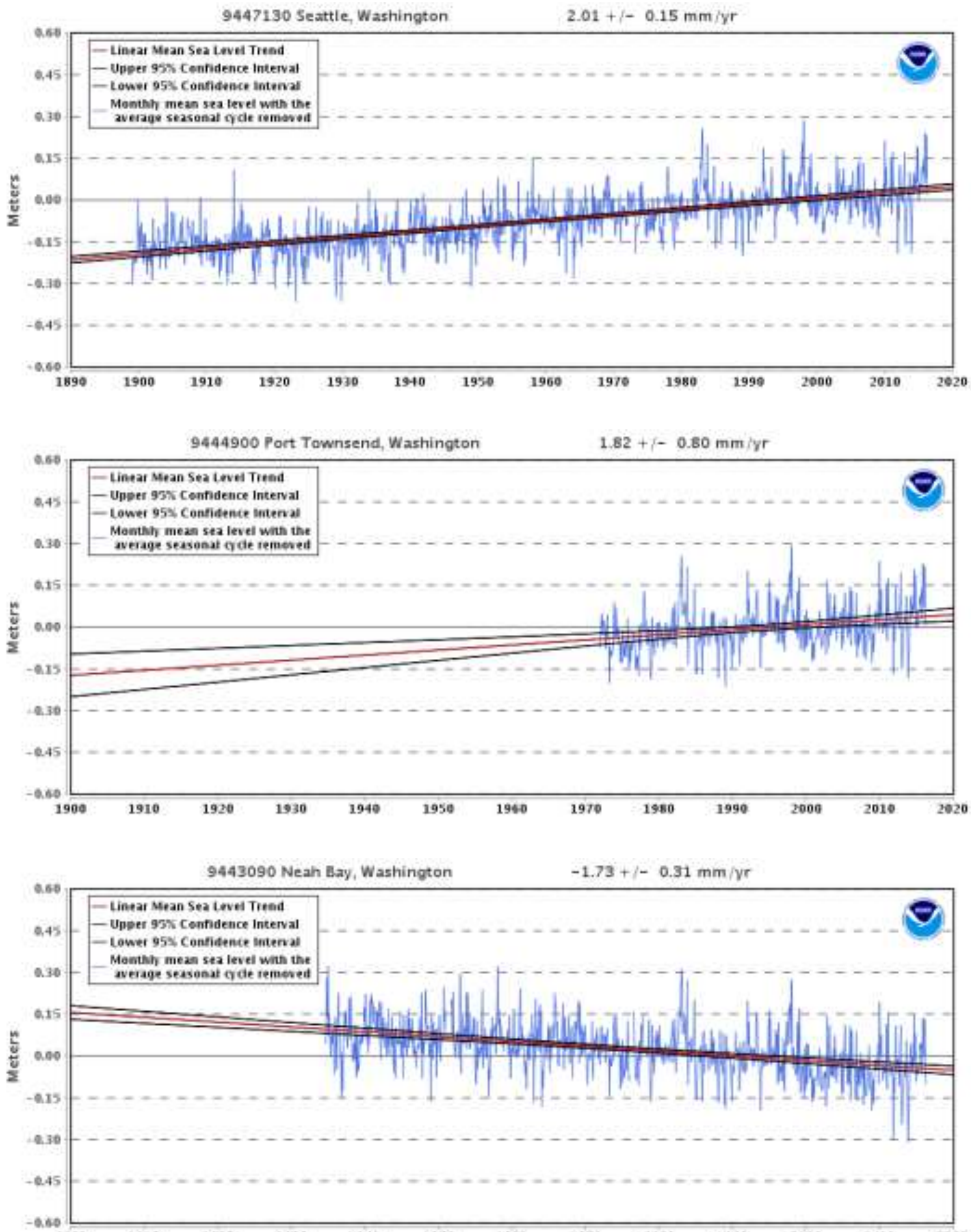
Locally, sea level is rising at most locations in or near the Puget Sound. Sea level at the Seattle tide gauge, the longest running tide gauge in the Puget Sound region, rose +8.6 inches between 1900 and 2008 (+0.8 inches or +20 mm/decade) (Figure 6, top) [31]. The average rate of change in sea level at Port Townsend is comparable to Seattle (+0.7 inch or +17.78 mm/decade), although the total amount of rise for the period of record (+3.2 inches or +81 mm) is lower because of the shorter record length (1972–2015) (Figure 6, middle). In contrast, records show a decline in sea level for the northwest Olympic peninsula, a region experiencing uplift as a result of tectonic processes (Figure 6, bottom). For example, at the Neah Bay tide gauge, relative sea level dropped by −5.5 inches from 1934 to 2015 (−0.7 inch or -17.78 mm/decade) [31].

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

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

[10] A recent (2003–2011) slowing in the annual rate of sea level rise (average of +2.4 mm/year versus +3.5 mm/year) has been attributed to natural variability, in particular a succession of La Niña years since the 1997–1999 El Niño [112]. However, even at that slower rate, the annual rate of sea level rise remained well above the average annual rate observed between 1901 and 2010.

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



OCEAN TEMPERATURE

Surface and subsurface water temperatures in Puget Sound and the northeast Pacific Ocean have warmed over the long term. Water temperature for stations located at Admiralty Inlet, Point Jefferson, and in Hood Canal increased +0.8 to +1.6°F, depending on location, from 1950 to 2009 [32]. A similar range of warming has been observed along the coast and at depth; northeast Pacific coastal sea surface temperature increased about +0.9 to +1.8°F over the past century (1900–2012) [33]. Northeast Pacific subsurface temperatures (~300 to 1,300 feet deep) increased +0.45 to +1.1°F (1956–2006) [33].

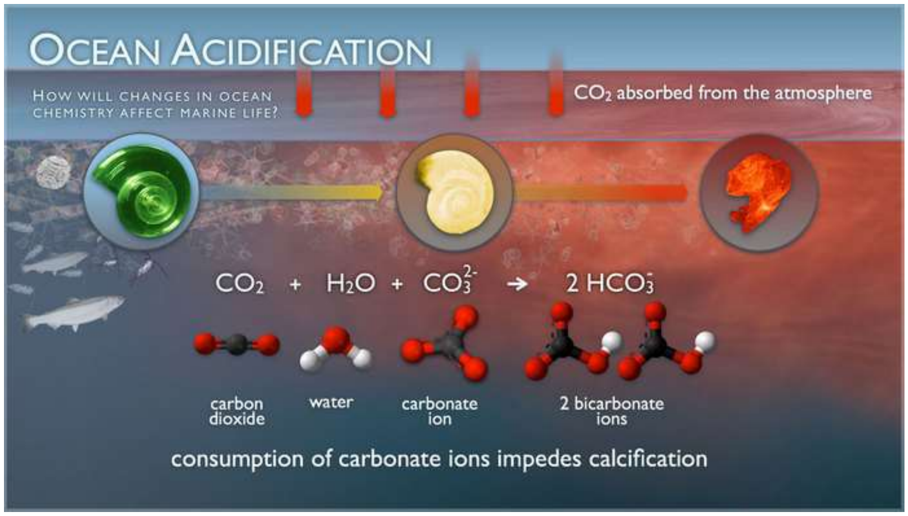
Natural variability can influence sea surface trends over shorter time periods, especially along the U.S. West Coast. For example, while most (71%) of the world's coastlines warmed between 1982 and 2010, sea surface temperatures along the U.S. West Coast decreased up to 2°F (or 0.72°F per decade) during that period [34]. The strong influence of El Niño and the Pacific Decadal Oscillation, as well as intensification of upwelling along the coast, are believed to have contributed to this trend (similar cooling was also observed along the west coast of South America, a region that is also strongly affected by the El Niño/Southern Oscillation and coastal upwelling). More recently, sea surface temperatures in the northeast Pacific were dominated by an unusually warm (2°F to 7°F above normal), expansive (1,000 miles wide and 300 feet deep), and persistent (2014–2015) patch commonly referred to as "the blob" [35]. The pattern of sea surface temperatures that have characterized "the blob" has largely diminished, however, as of July 2016.

OCEAN ACIDIFICATION

Ocean acidification, like climate change, is generated by increasing levels of carbon dioxide in the atmosphere. Ocean acidification is not, however, caused by the warming and alteration of climate systems and patterns [36].

Oceans naturally absorb carbon dioxide from the atmosphere (Figure 7). As more carbon dioxide is introduced to the atmosphere (i.e., greenhouse gas emissions), the oceans absorb the carbon dioxide (Figure 8). Worldwide, the oceans have absorbed about 30% of the carbon dioxide associated with human activities since the start of the industrial age (about 1750) [25]. The added carbon dioxide has changed the ocean's chemistry by increasing its acidity and reducing the availability of carbonate ions [37]. More specifically, the pH of the northeast Pacific Ocean surface waters decreased by −0.1, corresponding to a +26% increase in the hydrogen ion concentration, since the pre-industrial era (~1750) and by −0.027 from 1991 to 2006 [25]. The increase in the hydrogen ion concentration reduces the amount of calcium carbonate—a critical mineral used by many marine organisms to form hard body parts such as shells and skeletons—in marine water, affecting the ability of those organisms to build and maintain body parts dependent on calcium carbonate.

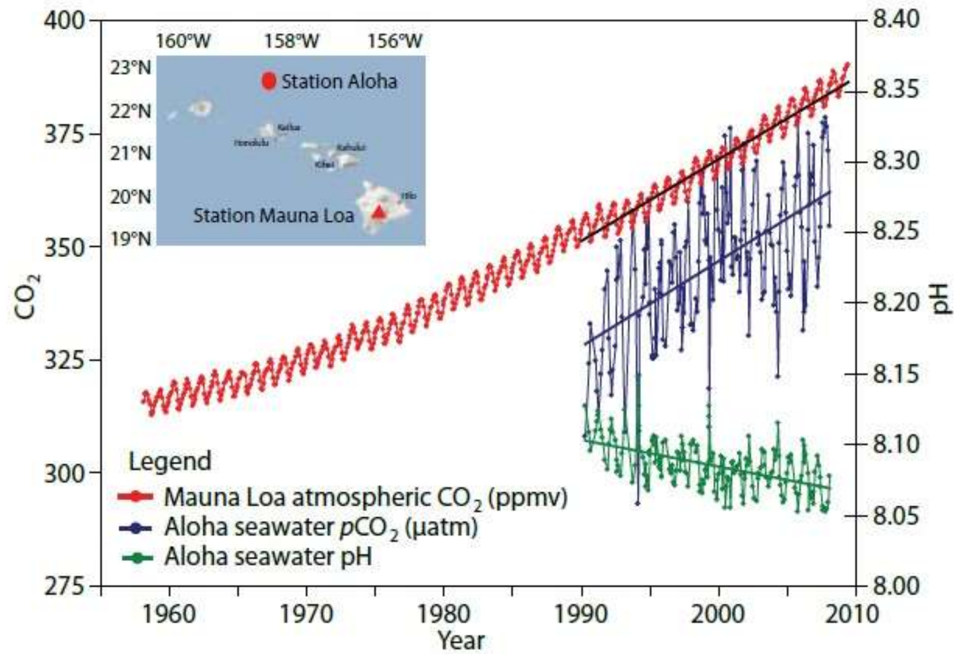
Figure 7. Ocean acidification occurs when carbon dioxide, which is being released at increasingly higher levels as a result of human activities, is absorbed by the ocean. When mixed with seawater, carbon dioxide chemically changes into carbonic acid. Carbonic acid lowers the ocean's pH level, nudging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



Washington's marine waters are particularly susceptible to ocean acidification because of the influence of regional upwelling, which transports offshore, carbon-rich water to the continental shelf [38]. In urbanized estuaries and restricted inlets of Puget Sound (such as Hood Canal), runoff containing nutrients and organic carbon from land sources also influences pH levels. Added nutrients and organic carbon stimulate algal growth, ultimately increasing acidity as the algae and other associated organic matter decompose [37, 39].

The lack of high-quality, long-term, carbon time-series measurements in Puget Sound makes it hard to directly determine the effects of locally emitted carbon dioxide on pH changes in the region [39]. Feely et al. 2010 estimated that ocean acidification has already caused a decrease in pH of 0.05 to 0.15 units in Puget Sound. That study also estimated that ocean acidification accounted for 24 to 49% of the decrease in pH in the deep waters of Hood Canal, relative to estimated pre-industrial values.

Figure 8. Time series of atmospheric CO_2 at Mauna Loa (in parts per million volume, ppmv; red), surface ocean pCO_2 (µatm; blue) and surface ocean pH (green) at Ocean Station ALOHA in the subtropical north Pacific Ocean. Note that the increase in oceanic CO_2 over the past 17 years is consistent with the atmospheric increase within the statistical limits of the measurements. Figure and caption source: Doney et al. 2009 [40]. As of the time of this writing (March 2017), CO_2 at Mauna Loa is now over 400 ppm (www.co2.earth/daily-co2).



PROJECTING CHANGES IN CLIMATE USING GREENHOUSE GAS SCENARIOS

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

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

Table 3. Greenhouse gas scenarios used in global and regional climate studies. The scenarios most commonly used in Pacific Northwest climate change studies are noted with an asterisk (*). Greenhouse gas scenarios are typically updated every 5 to 10 years for use in Intergovernmental Panel on Climate Change (IPCC) global assessment reports. Table modified from Snover et al. 2013, Table 3-1 [41].

Representative Concentration Pathway (RCP) scenarios (IPCC 2013) [25].	Scenario characteristics	Amount of carbon dioxide in the atmosphere, 2100 [42]	Comparable SRES scenarios (IPCC 2001, 2007; replaced by RCPs starting in ~2012)	Qualitative description
RCP 4.5*	A low scenario in which greenhouse gas emissions stabilize by mid-century and fall sharply thereafter	538 parts per million (ppm)	Very close to B1 by 2100, but higher emissions at mid-century	Low
RCP 6.0	A medium scenario in which greenhouse gas emissions increase gradually until stabilizing in the final decades of the 21st century	670 ppm	Similar to A1B by 2100, but closer to B1 at mid-century	Medium
RCP 8.5*	A high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century	936 ppm	Nearly identical to A1FI	High

PERSPECTIVE ON RECENT AND PROJECTED GREENHOUSE GAS TRENDS

As shown in Table 3, the concentration of greenhouse gases in the atmosphere is projected to increase dramatically in the 21st century absent substantial reductions in greenhouse gas emissions. Prior to the start of the Industrial Revolution, the concentration of carbon dioxide in the atmosphere was 280 parts per million (ppm). By the end of 2014, the annual average concentration of carbon dioxide in the atmosphere as measured at Hawaii's Mauna Loa Observatory was 398.61 ppm, and three individual months in 2014 (April, May, and June) exceeded 400 ppm for the first time since observations at Mauna Loa began in 1958.[11] The annual average for 2015 was 400.83 ppm. The high greenhouse gas emissions scenario (RCP 8.5), often referred to as a "business as usual" scenario, has an atmospheric concentration of carbon dioxide of 936 ppm in 2100 and levels out at 1,962 ppm by the year 2250 [42]. Annual greenhouse gas emissions will vary from year to year but are generally tracking with RCP 8.5.

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

PROJECTED CHANGES IN THE TERRESTRIAL ENVIRONMENT

TEMPERATURE

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

By mid-century, the Puget Sound region is likely to regularly experience average annual air temperatures that exceed what was observed in the 20th century [43].

As shown in Figure 9 and Table 4, the range of warming produced by the different greenhouse gas scenarios prior to 2050 is relatively small compared to the range of warming that occurs later in the century. This difference reflects the fact that warming prior to the 2050s is largely driven by past (i.e., 20th century) and early 21st century greenhouse gas emissions. After about 2050, differences in the underlying assumptions of future conditions that inform the greenhouse gas scenarios (e.g., later 21st century global population levels, reliance on fossil fuels) start to have a larger role in determining the range and rate of projected warming and the impacts that result from that warming [2, 43].

Figure 9. All scenarios project warming in the Puget Sound region for the 21st century; projected changes in annual precipitation are small compared to year-to-year variability. The graphs show average yearly air temperature and precipitation for the Puget Sound region, relative to the average for 1950–1999 (horizontal gray line, corresponding to an annual average temperature of 44°F and an annual total precipitation of 78 inches). The black line shows the average simulated air temperature or precipitation for 1950–2005, based on the individual model results indicated by the thin gray lines. The thick colored lines show the average among model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5; see Section 1), while the thin colored lines show individual model projections for each scenario. Figure source: Climate Impacts Group, using downscaled climate projections developed by Abatzoglou and Brown (2011) [25, 43].

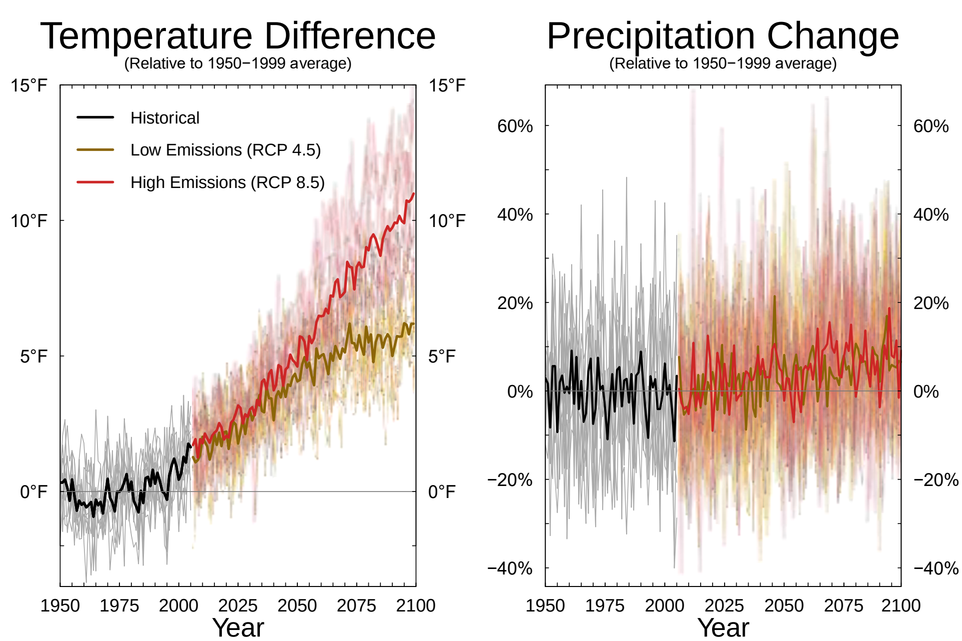


Table 4. Projected changes in average annual and seasonal temperature and extreme heat and cold events for the Puget Sound region for the 2050s and 2080s [44].

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

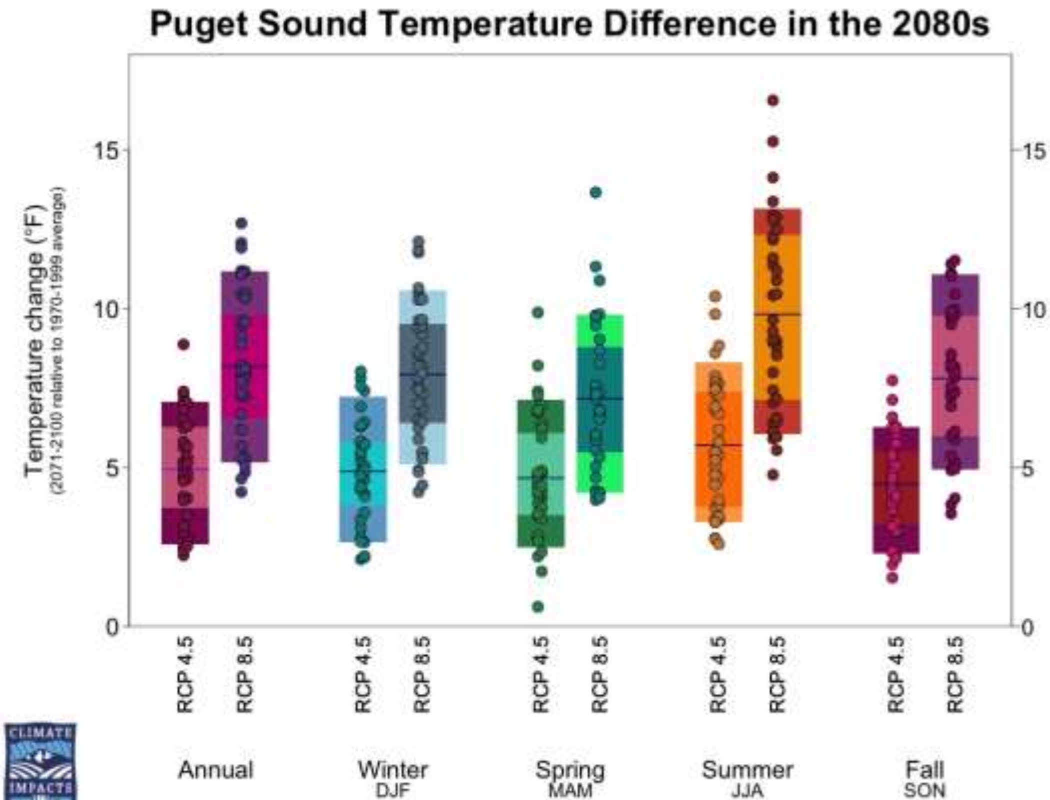
* Winter = Dec–Feb, Spring = Mar–May, Summer = June–Aug, Fall = Sept–Nov

** Under the low greenhouse gas scenario (RCP 4.5), global greenhouse gas emissions stabilize by mid-century and fall sharply thereafter. Under the high greenhouse gas scenario (RCP 8.5), emissions continue to increase through 2100 and beyond. RCP 8.5 is considered a "business as usual" scenario; global emissions are currently following this trajectory (footnote adapted from Raymond 2016) [45].

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

13 Projected change in bottom 1% of daily minimum temperature for climate scenarios described in Footnote 12.

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



PRECIPITATION

Annual and Seasonal Precipitation

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

Climate scenarios currently show modest increases in average annual precipitation (about +7%, on average for the 2080s, relative to 1970–1999), although these changes are small relative to historical variability (Figure 9, right panel).[14] Changes in annual precipitation also vary widely in size and direction depending on models; most models show increasing annual precipitation while some models show a decrease (Table 5).

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

Projected changes in fall, winter, and spring precipitation for the Puget Sound region are mixed (Table 5; Figure 11). While some models project decreases in cool-season precipitation, the majority of models project increasing fall, winter, and spring precipitation. In contrast, all scenarios project up to a −27% decline, on average, in summer precipitation (June-August) for the Puget Sound region by the 2080s, relative to 1970–1999.[15] It is important to note that because only 10% of annual precipitation falls during summer, the projected decline in summer precipitation would not lead to large changes in the amount of summer rainfall. Nevertheless, even small reductions are important given the importance of summer rain in lessening municipal and agricultural water demand on already limited summer water supplies.

Table 5. Projected changes in average annual and seasonal precipitation for the Puget Sound region for the 2050s and 2080s [44].

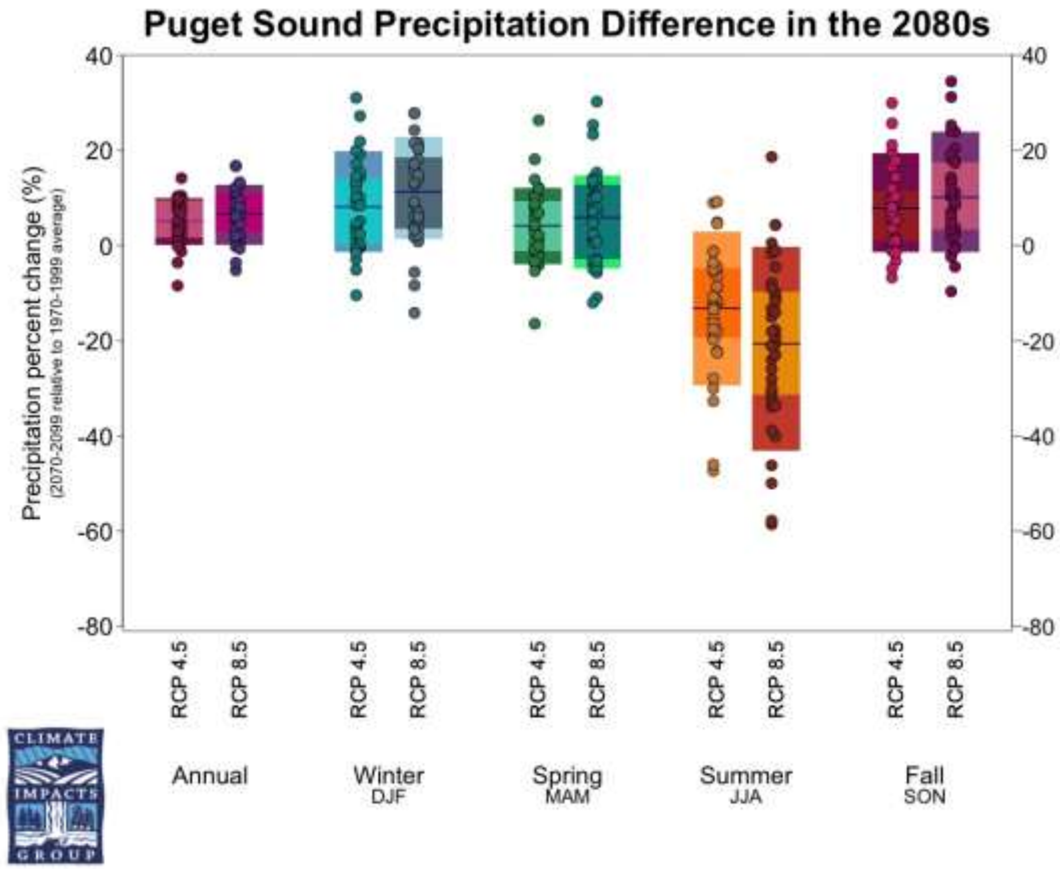
		2050s (2040–2069, relative to 1970–1999)		2080s (2070–2099, relative to 1970–1999)	
Change in…*	Greenhouse gas scenario**	Mean	Range	Mean	Range
Average annual precipitation	Low (RCP 4.5)	+4.2%	+0.6 to +12%	+6.4%	−0.2 to +10%
	High (RCP 8.5)	+5.0%	−1.9 to +13%	+6.9%	+1.0 to +9.4%
Average winter precipitation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

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

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

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

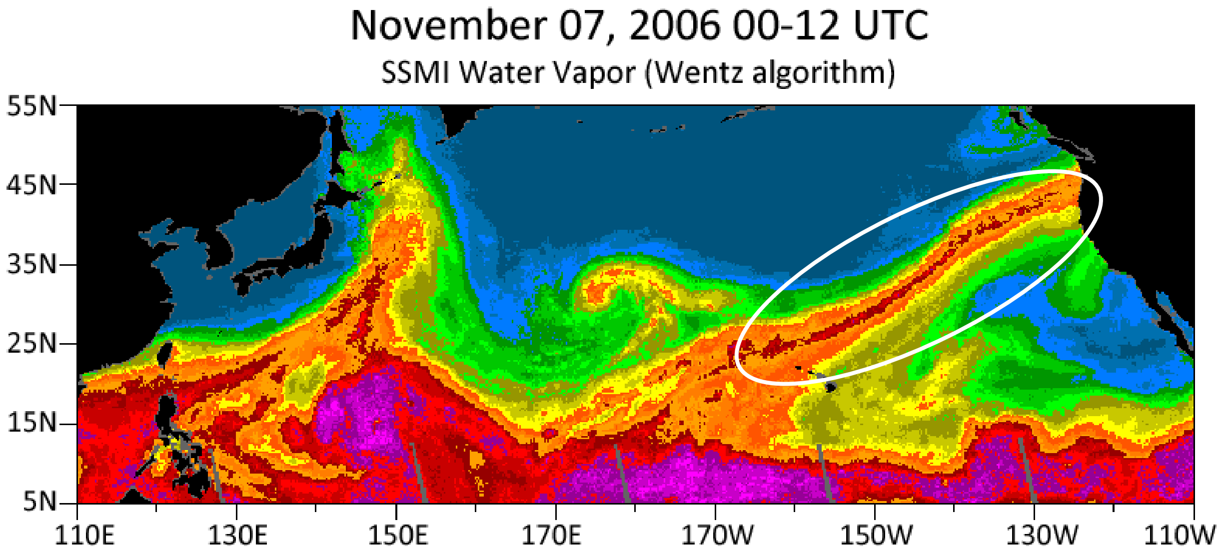
Figure 11. Projected change in annual and seasonal Puget Sound precipitation, in percent, for the 2080s (2070–2099), relative to 1970–1999. Projections are based on statistical downscaling of 10 global climate models and two greenhouse gas scenarios: a low (RCP 4.5) and a high (RCP 8.5) scenario. Individual climate model projections for each scenario are shown using colored dots. Boxes show the average projected change along with the 10th, 25th, 75th, and 90th percentile values among all climate model projections. The horizontal line denotes zero change. Figure source: Climate Impacts Group, based on Figures 2.5b and 2.6 in Dalton et al., 2013 [46].



Extreme Precipitation

Extreme precipitation events, frequently caused by atmospheric rivers, are expected to increase in both frequency and intensity. Atmospheric rivers are narrow ribbons of water vapor transport extending from the tropics to the west coast of North America during the winter months (Figure 12). An atmospheric river event that forms in the tropics near Hawaii is often referred to as a "Pineapple Express" [47].

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



An in-depth examination of precipitation projected by climate models shows that atmospheric river events will increase in frequency and intensity during winter along the U.S. West Coast [15]. For the 2080s (2070–2099, relative to 1970–1999), the heaviest 24-hour rain events in western Oregon and Washington are projected to intensify, on average, by +22%, for a high (RCP 8.5) greenhouse gas scenario. In addition, atmospheric river events are projected to occur 7 days per year by the 2080s in comparison to 2 days per year historically, under a high (RCP 8.5) greenhouse gas scenario [48].[16]

Similar increases in frequency and intensity are reported by Hagos et al. 2016 for the west coast of North America. Hagos et al. found that the number of days meeting the definition of an atmospheric river ("landfalling atmospheric river days") increased 35% (+8%) in the period 2080–2099, relative to 1980–1999, for a high (RCP 8.5) emissions scenario [49].[17] The intensity of atmospheric river events, defined as events with daily precipitation values higher than the 97.8 percentile, increased 28% (+7%) for the same period [49].

The location and intensity of the Puget Sound convergence zone is an important component of extreme precipitation events in the central Puget Sound region. The impact of climate change on the convergence zone is unknown, however [50, 51].

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

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

WIND

Preliminary analysis of projected changes in winds finds that wind patterns and the strength of low pressure systems in the Puget Sound region are not projected to change as a result of climate change.[18] Although some studies suggest that warming will result in a "wavier" (i.e., more variable) storm track, this is considered highly speculative [52, 53, 54].

The behavior of the jet stream is governed by many factors; understanding how these combine to drive changes in its behavior is still an active area of research [55, 56]. In addition, it is unclear how such changes might affect the Puget Sound region [57].

SNOWPACK, GLACIERS, AND STREAMFLOW

Snowpack and Glaciers

Projected changes in temperature and precipitation result in less snow accumulation and a shorter snow season as more precipitation falls as rain instead of snow and as snow melts earlier in spring (Figure 13, Figure 14). Average spring snowpack in the Puget Sound region is projected to decline by −42% to −55% by the 2080s (2070–2099, relative to 1970–1999), on average, for a low (B1) and moderate (A1B) greenhouse gas scenario [58].[19,20,21]

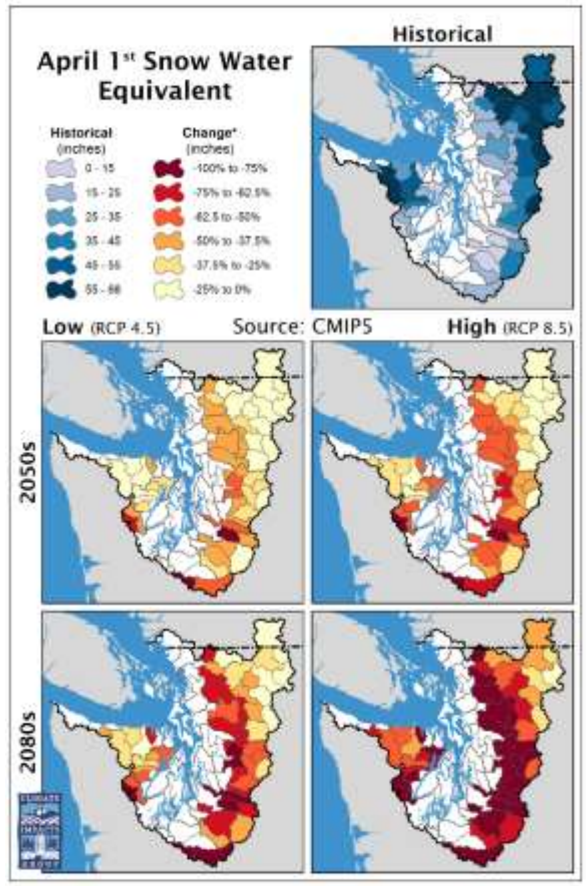


Figure 13 (at right) Projected changes in April 1st Snow Water Equivalent (SWE) for the HUC-10 scale. Maps show the historical and projected April 1st SWE, a measure of the total amount of water contained in the snowpack. The figure compares watershed averages for historical conditions (1970–1999, in inches) and the projected change (in percent) for 10 global models. Two time periods are considered: the 2050s (2040–2069) and the 2080s (2070–2099), based on a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario. Results are only shown for watersheds with an average historical April 1st SWE of at least 0.4 inch. White to dark blue shading on the historical map indicates areas which received highest levels of April 1st SWE in Puget Sound. Projected decreases in SWE are depicted by the yellow to red shading. Figure created by Robert Norheim, Climate Impacts Group, based on CMIP5 projections used in the IPCC 2013 report [25]. Data source: Mote et al. 2015 [43].

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

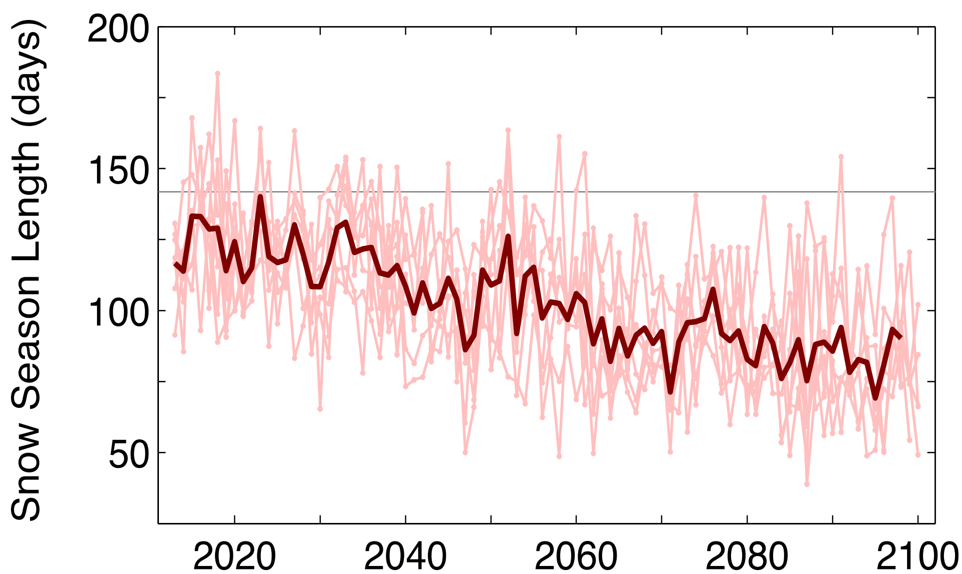
[19] Specifically, changes in April 1st Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1st is the approximate current timing of peak annual snowpack in the mountains of the Pacific Northwest. Changes are only calculated for locations that regularly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

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

[21] Two principal datasets are often used to evaluate hydrologic projections for Puget Sound and the greater Pacific Northwest: (1) the latest set of projections, developed by Mote et al. in 2015 [43], which stem from the newer 2013 IPCC report [25], and (2) the previous set of projections, developed by Hamlet et al. in 2013 [58] based on the climate projections used in the IPCC's 2007 report [97]. Although newer, the more recent projections appear to have temperatures that are too cold in mountainous areas. For this reason, most of the results presented in this section stem from the 2010 dataset.

Continued declines in glacial area are also expected. To date, only two studies have evaluated the projected effects of climate change on Puget Sound glaciers, and both studies suggest that continued glacial recession in the region is likely. One study found that only two (Easton Glacier and Rainbow Glacier) of the 12 North Cascades glaciers with annual measurements are expected to persist under current climate conditions, regardless of projected warming [59]. An additional study modeled glacier response in three Puget Sound tributaries (Thunder Creek, Cascade River, and Nisqually River). All scenarios showed that the glaciers persisted through 2100, but glacier area decreased substantially, especially after the 2050s [60].[22]

Figure 14. Shorter snow season with warming; large year-to-year variability. Projected length of the snow season, in days, for middle elevations (4,000 to 5,000 feet) for the Cascade Mountains in Oregon and Washington. The plot shows projected snow season length from seven individual climate models (thick pink lines) and the average among all models (thick red line) for a medium greenhouse gas scenario (A1B). For comparison, the average snow season length for 1950-1999 was 142 days (shown as the gray horizontal line). Although the length of the snow season is clearly expected to decrease significantly over this century, individual years with substantially longer or shorter snow seasons than the general declining trend are also expected to occur. [19] Data source: Hamlet et al. 2013 [58].



Streamflow Timing and Volume

Climate change impacts on the hydrology of Puget Sound watersheds will vary by watershed depending on the balance of wintertime rain and snow accumulation within a watershed, among other factors. Changes for two watersheds that bracket the north and south ends of the Port Gamble S'Klallam Tribe's primary traditional use area—the Dungeness and the Skokomish watersheds—and the Puget Sound region are summarized here.[23] Note that the hydrologic changes reported in this section do not take into account the effects of dams, which can mitigate the impacts of climate change by reducing peak flows or holding water for release during low-flow periods.

Dungeness River Watershed. The Dungeness River watershed is a moderate elevation, mixed rain-and-snow watershed that empties into the Strait of Juan de Fuca on the northwest side of the Olympic Peninsula. Streamflows in the Dungeness are characterized by two periods of relatively high streamflows. The first peak is during fall, coinciding with the return of the fall rains. Streamflows drop during winter when

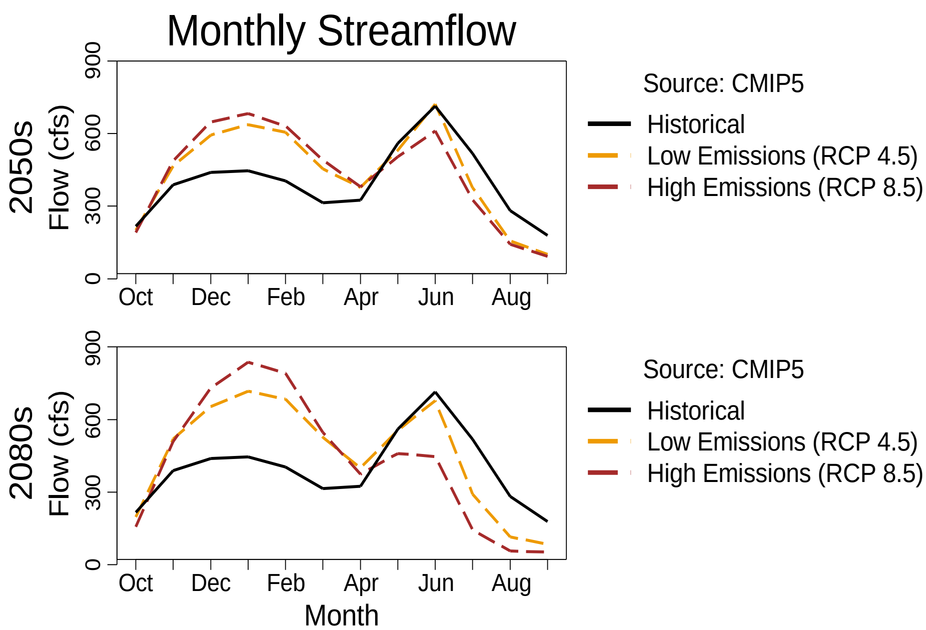
[22] See footnote 20.

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

temperatures are cold enough for snow to accumulate at higher elevations. A second peak in streamflows occurs in early spring as a result of snowmelt (Figure 15).

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

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



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

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

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

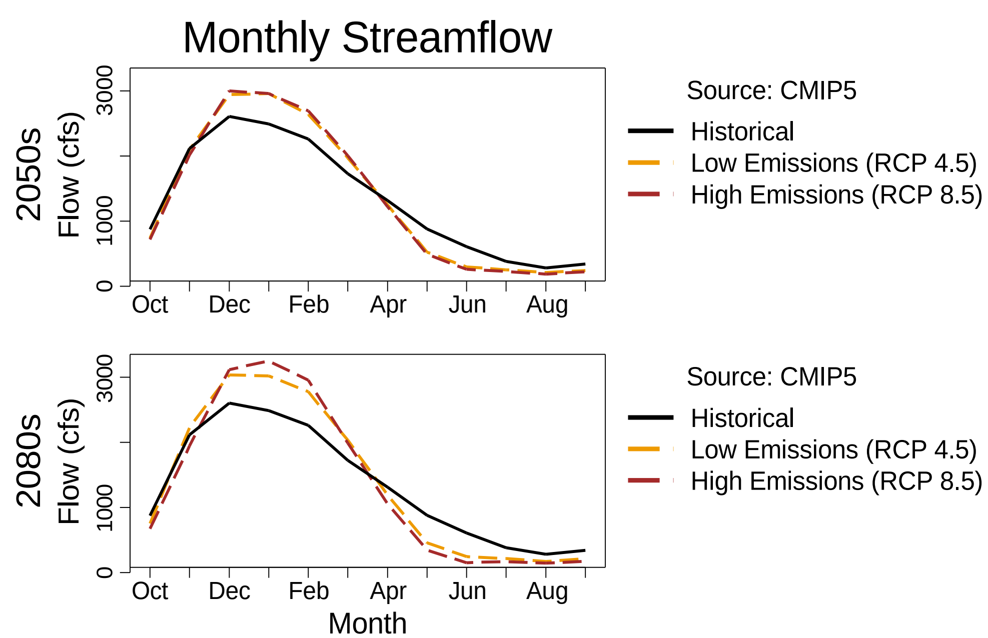
- The center timing for annual streamflow is projected to occur 15 days (−35 to −6 days) earlier by the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B) [58].[24]

- Summer minimum streamflow (7Q10, or the lowest 7-day average flow that occurs on average once every 10 years) is projected to decrease −35% (range: −45 to −27%) for the 2080s (relative to 1970–1999) for a moderate greenhouse gas scenario (A1B) [58].

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

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

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



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

- The average summer (June through August) streamflow in the Dungeness River is projected to decrease −35% (range: −60 to −19%) by the 2040s (2030–2059; relative to the 1970–1999) and

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

−56% (range: −76 to −32%) by the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B).

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

- The center timing for annual streamflow is projected to occur –46 days earlier (range: −56 to −38 days), on average, by the 2080s (2070–2099, relative to 1970–1999) for a moderate emissions scenario (A1B) [58].

- Summer minimum streamflow (7Q10) is projected to decrease −18% (range: −22 to −8%) for the 2080s (2070–2099, relative to 1970–1999) for a moderate greenhouse gas scenario (A1B) [58].[25]

Puget Sound Region. By the 2080s (2070–2099), watersheds in the Puget Sound region are projected to be primarily rain-dominant as a result of warming temperatures (Figure 17). For the 12 major watersheds in the Puget Sound region:[26]

- Total annual streamflow is projected to increase +6% to +7%, on average, by the 2080s (2070–2099, relative to 1970–1999) for a low (B1) and moderate (A1B) greenhouse gas scenario [58].[27]

- Total winter streamflow is projected to increase by +28% to +34% on average by the 2080s (2070–2099, relative to 1970–1999) for a low (B1) and moderate (A1B) greenhouse gas scenario [58].

- Total summer streamflow is projected to decrease by −24% to −31% on average by the 2080s (2070–2099, relative to 1970–1999) for a low (B1) and moderate (A1B) greenhouse gas scenario.

- Minimum summer streamflow is projected to decline between −16% and −51%, on average, by the 2080s (2070–2099, relative to 1970–1999) for a moderate (A1B) greenhouse gas scenario.

As noted previously, the effects of reservoir operations are not included in these projections. The projected changes in summer streamflows also do not account for contributions from (and eventual losses of) glacier melt. The degree to which this matters will vary by watershed. For example, Riedel et al. 2015 estimate that glacial ice, snow, and firn (glacial snow) contributions to summer (May 1–September 30) streamflows in the Hoh River range from 8.9% to 15.4%. Contributions to late summer flows (August and September) in the Hoh are higher (18-30%) [19].[28] Contributions to May 1–September 30 summer flows for the Elwha and Dungeness rivers are estimated to be 2.5 to 4% and 3.0 to 3.8%, respectively [19].

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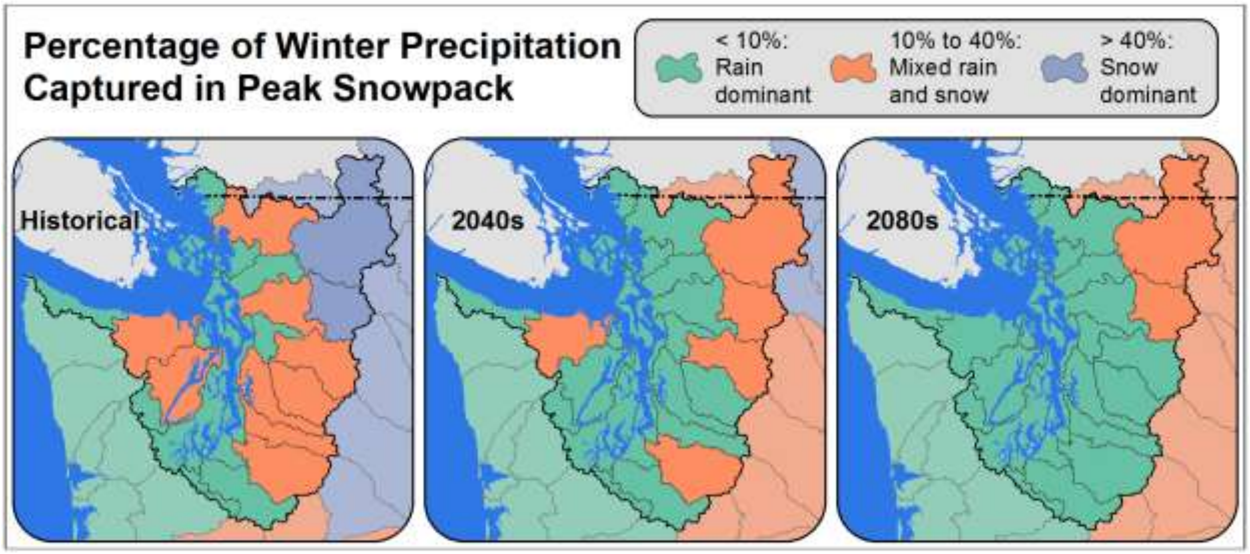
[25] Projected change for 10 global climate models for a moderate (A1B) greenhouse gas scenario.

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

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

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

Figure 17. Current and future watershed classifications, based on the proportion of winter precipitation stored in peak annual snowpack. Map compares average historical conditions (1970–1999) and average projected future conditions for 10 global models, 2 time periods: the 2040s (2030–2059) and the 2080s (2070–2099) and a moderate greenhouse gas scenario (A1B). By the end of the 21st century, Puget Sound will no longer have any snow-dominant watersheds, and only a few remaining that can be classified as mixed rain-and-snow. Data source: Hamlet et al., 2013 [58].



Similar variance is found in other areas. In the North Cascades, for example, 10% to 44% of total summer streamflow is estimated to originate from glaciers, depending on the watershed [61]. In the near term, increasing melt from glaciers may help offset lower summer streamflows. However, over the longer term, glacier contributions will decline and ultimately be eliminated.

Flooding

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

- Peak streamflow volume is projected to increase by +18% to +55%, on average, for 12 Puget Sound watersheds by the 2080s (2070–2099, relative to 1970–1999), based on a moderate (A1B) emissions scenario [58].

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

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

The Elwha, Dungeness, Quilcene, Dosewallips, and Duckabush rivers are also expected to experience more severe winter peak flows and increased flooding, although specific projections are not available at this time [62].

In addition to increasing the peak flows in the region, floods are also expected to become more frequent. For example, by the 2040s, the volume of flows associated with the historical 100-year flood event in the Skagit River become a 32-year event; the historical 30-year flood event becomes a 10-year event [63].[29] Similarly, by the 2040s, the historical 100-year flood event in the Snohomish River becomes a 30-year event, and the historical 10-year event becomes a 5-year event [64].

STREAM TEMPERATURES

Water temperatures are projected to increase. Stream temperatures are doubly affected by climate change: both by warmer air temperatures and declining summer flows. River and stream temperatures generally track air temperatures, but they do not change as rapidly. River and stream temperatures throughout the Puget Sound region are projected to increase as a result of increasing air temperatures and declining summer streamflow. Stream temperatures in the Puget Sound region are projected to increase by +4.0°F to +4.5°F by the 2080s (2070–2099, relative to 1970–1999), in response to both increasing air temperatures and decreasing summer streamflows [65].[30]

Puget Sound rivers are projected to exceed thermal tolerances more frequently for cold-water fish species. Stream temperatures are an important determinant in the quality of Puget Sound aquatic habitat and salmon health. When exposed to warm water temperatures, salmon (>64°F)[31] and char (>54°F)[31] become more susceptible to pathogens, suffer higher mortality, and stop or slow their migration (see the Salmon chapter for more detail on these impacts). The Tribe experienced a "sneak preview" of these impacts during the summer of 2015, when unusually low streamflows and unusually warm spring and summer temperatures pushed river and stream temperatures above maximum Department of Ecology water quality temperature thresholds for long periods of time. By the 2080s (2070–2099, relative to present), 12 out of 37 Puget Sound stream monitoring sites are expected to experience weekly average stream temperatures which exceed thermal tolerances for salmon (64°F) for as much as 7.5 weeks longer. For the Dungeness and Skokomish rivers:

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

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

LANDSLIDES AND SEDIMENT TRANSPORT IN RIVERS AND STREAMS

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

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[29] Results based on running the Echam 5 global climate model with a moderate warming scenario (the A1B emissions scenario).

[30] Based on a composite of 10 global climate model projections for a moderate (A1B) greenhouse gas scenario.

[31] In this report we use regulatory thresholds listed in EPA (2007) [73], which defines 12°C (54°F) and 17.5°C (64°F) as the criteria for protecting adult char and salmon, respectively. Note that some analyses consider the average monthly temperature for August, which will likely result in an underestimate of the implications for maximum August temperatures.

Landslides

The topography and geography of the Port Gamble S'Klallam Tribe's primary traditional use area make the area prone to landslide events. The location and size of landslides depend on several factors, including precipitation duration and intensity, antecedent soil moisture, soil types, slope gradients, runoff patterns, land cover, and land use [66]. Most landslides in the Pacific Northwest occur on the west side of the Cascades during the rainy season (October–May). They are predominantly initiated by intense rain events or by lower intensity, but persistent rainfall over a prolonged period (precipitating high soil moisture content), rapid snow or ice melt, or low evaporative demand that allow soil moisture to persist [51].

While there are currently no published projections for changing landslide hazards in the Puget Sound region, studies in nearby areas [67] and expected shifts in the mechanisms linking climate with landslides suggest an increase in the likelihood of landslides in winter and early spring and a decreased likelihood in summer. One study in the Queets Basin on the west slope of the Olympic Peninsula projected a +7 to +11% increase in areas with high landslide susceptibility[32] by 2045, relative to 1970–1999 [67].[33] Another study focused on Howe Sound, British Columbia, projected a 28% increase in debris flow currents into Howe Sound between 2075 and 2100 [68].[34] The authors note, however, that the projected increase is significantly lower than past changes in landslide activity associated with logging practices and roadbuilding, underscoring the role that changes in land use have on landslide risk [68]. More information on the projected seasonal shifts relevant to the Puget Sound region are noted below.

Increasing landslide risk in winter. Higher winter temperatures, declining snowpack levels, and increasing heavy rain events are expected to increase landslide risk during winter in the Puget Sound region. Warmer winter temperatures can reduce slope stability by affecting the rate and type of weathering that occurs on slopes [69, 70, 71], decreasing the viscosity of groundwater (i.e., more lubricating), and thawing frozen ground, which enables increased infiltration through the soil [72, 73]. Lower snowpack also allows for increased infiltration and exposes more area to erosion during heavy rain events [74]. Finally, heavy rain events reduce slope stability by rapidly raising the water table and by enhancing water drainage through the soil to lower layers [70]. Each of these factors plays a role in increasing winter soil water content west of the Cascades, and with that, the potential for landslides. For example, December 1st soil moisture is projected to increase by up to +35% by the 2040s (2030–2059) relative to 1970–1999 along the slopes of the Cascade Mountains, under a moderate emissions scenario (A1B) [75].

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

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

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

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

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

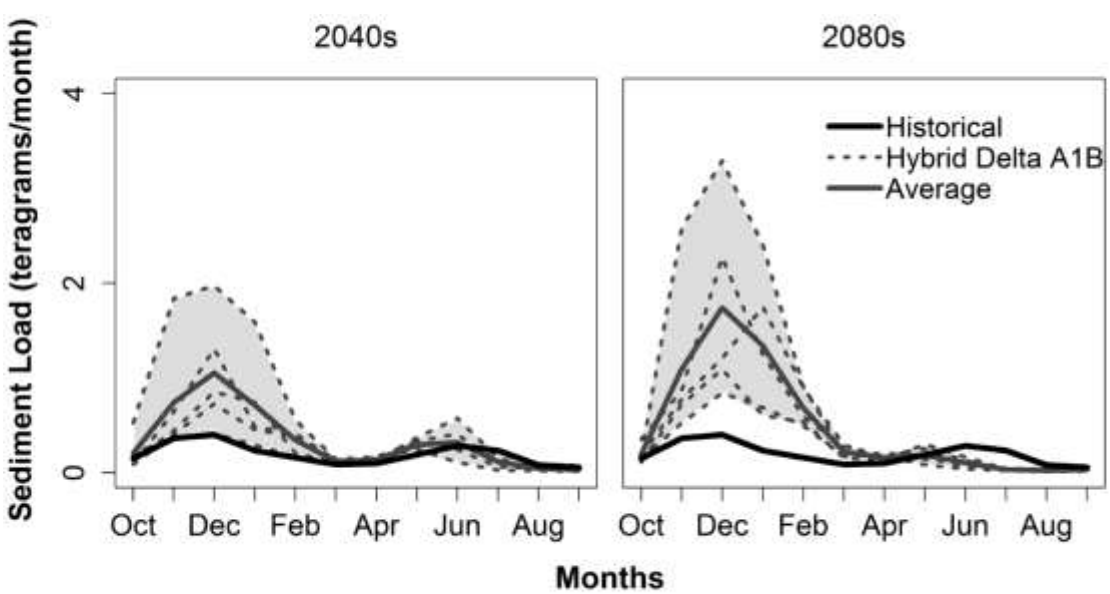
Sediment Transport

Annually, Puget Sound rivers carry 6.5 million tons of sediment into Puget Sound and its surrounding waters. The amount and size of sediment particles in a river or stream is largely driven by discharge volume and river slope. Steep, fast-flowing rivers carry gravel, rocks, and boulders, while smaller rivers transport clay and silt [76]. While sediment particle size is largely dependent on river discharge and slope, overall river sediment load is not. The Skagit, Nooksack, and Puyallup rivers have the largest sediment loads draining into Puget Sound [76].

Projections of climate change-induced changes to sedimentation in Puget Sound are not available for most Puget Sound river systems and remain a complicated dynamic to capture in modeling studies. However, sediment transport in Puget Sound rivers is expected to decrease in summer and increase in winter and spring as declining snowpack and glacial recession expose more unconsolidated soils to rain and as extreme precipitation events become more frequent and severe [77, 78].

A recent assessment for the Skagit River illustrates how sediment transport could be affected within Puget Sound rivers. Lee et al. 2016 found that peak sediment delivery in the Skagit River is projected to increase during winter and decrease during summer [63]. Specifically, by the 2080s, peak sediment delivery is projected to increase by +376% (range: +140% to +730%) between December and February and to decrease by −76% (range: −60% to −90%) between July and September relative to historical conditions using a moderate greenhouse gas scenario (A1B) (Figure 18). Considering a 5 GCM ensemble average, researchers project that the Skagit River's annual average sediment load will reach 4.1 teragrams or 4.1 million metric tons per year (1 teragram = 1 trillion grams) by the 2040s and 5.8 teragrams per year by the 2080s, relative to 2.3 teragrams per year historically [63]. This projected increase in sediment loading in the Skagit River could be both advantageous and hazardous to surrounding ecosystems and human populations. For example, an increased sediment load could facilitate marsh accretion but may simultaneously reduce the river's carrying capacity, increasing the risk of overtopping and flooding [63].

Figure 18. Simulated monthly average sediment loading for the Skagit River near Mount Vernon for the 2040s (left) and 2080s (right). Figure source: Lee et al. 2016 [63].



Riverbed aggradation due to sediment transport has recently been observed in the Puyallup River [79]. Between 1984 and 2009, the average elevation change of the Puyallup River channel rose by as much as 7.5 feet. Conveyance capacity, or the discharge conveyed through a given channel reach for a given stage, is frequently used to assess the susceptibility of specific river reaches to flooding [79]. Certain sections of the Puyallup River have experienced a decrease in conveyance capacity between 1984 and 2009 as a result of riverbed aggradation. Specifically, between 1984 and 2009 the conveyance capacity of the upper Puyallup (between river mile 21.5 and 19.5) decreased by as much as 9,000 cubic feet per second [79]. This decrease in conveyance capacity could potentially lead to increased risk of flooding in these specific reaches. The Puyallup can give us an idea of what might occur in other rivers important to the Port Gamble S'Klallam, where measurements of this type have not yet been made.

FOREST FIRE, INSECT, AND DISEASE RISK

Climate change will affect forests in multiple ways, including changes in growth and productivity, species distribution and forest composition, phenology, and changes in disturbance agents such as wildfire, insect infestations, and disease. While each of these will play a role in determining how forests respond to a changing climate, changes in disturbance agents are expected to have a greater impact on forests relative to other changes [80, 81].

Forest Fire

Climate change is projected to increase the risk of forest fires in Western Washington, although quantifying the change in fire risk is difficult due to the low frequency of large wildfires in western Washington. Fire history west of the Cascades is defined by infrequent, large, stand-replacing fires (where most of the forest is killed) occurring every 200 to 500 years [82, 83, 84]. There were three major burning episodes on the Olympic Peninsula during the Little Ice Age (1300–1750), the last of which occurred between 313 and 346 years ago. This fire (or multiple fires) burned more than 1 million acres on the Olympic Peninsula and between 3 and 10 million acres in western Washington [85].

Climate change impacts on fire risk are frequently described in terms of changes in frequency, severity, intensity, and area burned (see box at right.) [86]. In general, Western Washington is expected to see more frequent and more severe wildfires, resulting in an increase in annual area burned by forest fire over the coming century (Figure 19). Two studies project that the annual area burned west of the Cascades could more than double, on average, by 2070–2099 compared to 1971–2000 [81, 87]. Multiple factors contribute to this expected increase in area burned, including the following:

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

Key Forest Fire Risk Metrics

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

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

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

(Peterson and Littell 2012)

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

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

Additional information can be found in the Forest Resources chapter.

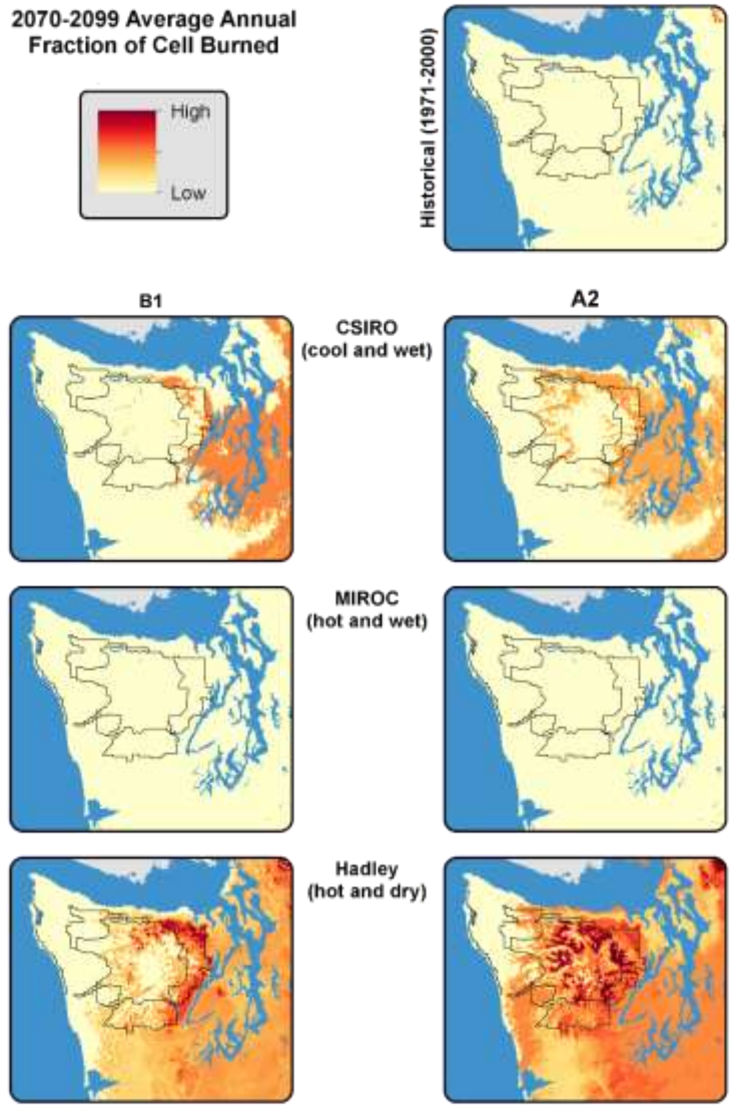


Figure 19 (at right). Projected average annual fraction of cell burned on the Olympic Peninsula for the 2070–2099 time period compared to modeled historical fire activity. This output is derived by averaging the area of a cell that is burned over the period of interest. Numbers are not shown in the legend because they are not intuitive. However, darker colors indicate more fire. Projections are from the MC1 model for three global climate models (GCMs) (rows) and two Intergovernmental Panel on Climate Change carbon dioxide emissions scenarios (columns). The B1 emissions scenario is characterized by relatively low future emissions, and the A2 scenario is characterized by relatively high future emissions. Olympic National Park and Olympic National Forest are outlined in black. CSIRO = Commonwealth Scientific and Industrial Research Organization; MIROC = Model for Interdisciplinary Research on Climate. (Data from R. Neilson and the MAPSS Team, USDA Forest Service and Oregon State University, Corvallis, Oregon.) Figure and caption source: Halofsky et al. 2011 [88].

Insects and Disease

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

In addition to insects, forest disease prevalence is expected to change as a result of climate change. Location, changes in host species, and disease sensitivity to changes in seasonal precipitation, temperature, and moisture stress are some of the key factors influencing how diseases may be affected by climate change. For example, wetter and warmer winter and spring conditions (which are consistent with current climate projections) with may increase the severity and distribution of Swiss needle cast [89]. If conditions are warmer and drier, however, the effect of Swiss needle cast may be reduced [90].

Increasing air temperatures and declining summer water availability are also expected to increase the impact of *Armillaria* root disease and some canker pathogens on conifer and hardwood forest communities in the Puget Sound region [87, 90].

PROJECTED CHANGES IN THE NEARSHORE AND MARINE ENVIRONMENT

SEA LEVEL RISE

Coastal areas in Washington State and the Puget Sound region will experience a variety of impacts associated with sea level rise.[35] Key impacts include inundation of low-lying areas, increased exposure to storm surge, increased coastal flooding and erosion, and shifting or loss of habitat types. The amount of sea level rise at any specific location will reflect projected global rates of rise as well as regional factors that influence local sea levels, including seasonal wind patterns, vertical land movement resulting from plate tectonics, glacial rebound or isostatic rebound, thermal expansion, and sedimentation.

Projected Changes in Global Sea Level Rise

Global sea level is projected to increase by +11 to +38 inches by 2100 (relative to 1986–2005), depending on the amount of 21st century greenhouse gas emissions [25].[36,37] All studies project an increase in global sea level for emissions scenarios, although different approaches result in different estimates of the exact amount of sea level rise projected.

Recent studies suggest that the likely range of global sea level rise reported by the Intergovernmental Panel on Climate Change could underestimate how much sea level rise may occur during (and after) the 21st century. This is primarily because of concerns that the approaches underestimate the contributions from melt on Greenland and Antarctica. For example, Rietbroek et al. 2016 found that the amount of thermal expansion in the ocean, which occurs as a result of warming ocean temperatures and is a major component of global sea level rise, was almost double the amount previously assumed for the period 2002–2014 [91]. The new calculation was based on Gravity Recovery and Climate Experiment (GRACE) satellite data, which became available starting in 2002.

Joughin et al. 2014 concluded that collapse of Thwaites Glacier in Antarctica may already be underway, although at a relatively moderate rate [92]. The key cause is an increased presence of warm water circulating at depth around Antarctica. A full collapse of the ice sheet is expected to be triggered when melt rates exceed 1 millimeter per year (0.4 inches) sea level equivalent. According to most model scenarios,

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

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

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

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

Most recently, DeConto and Pollard 2016 reported that sea level rise contributions from Antarctica could exceed 3 feet by 2100 as a result of the destabilizing effects of warm ocean currents on ice sheets in Antarctica, ultimately resulting in 5 to 6 feet of global sea level rise when accounting for other contributions [93]. While these studies all point to the potential for higher amounts of global sea level rise, a new consensus estimate is not currently available.

Projected Changes in Puget Sound Sea Level Rise

Sea level in the Puget Sound region is projected to continue rising through the 21st century. The relative rise in sea level projected for Seattle is +24 inches, on average (range: +4 to +56 inches) by 2100 (relative to 2000) [31]. Local amounts of sea level rise in other locations could be higher or lower than this range, depending on local rates of vertical land motion (Table 6).

Emerging efforts to provide probabilistic estimates of sea level rise show the potential for higher amounts of sea level, although at a relatively low level of probability. For example, Petersen et al. 2015 found a 1% probability that sea level rise in Port Townsend will reach or exceed +62 inches (5.4 feet) by 2100 [35]. The 50% probability threshold is +28 inches (2.4 feet). Projections are lower for Port Angeles and Neah Bay due to uplift along the north Olympic Coast (Table 7).

Table 6. Regional absolute sea level rise projections for Puget Sound are roughly similar among different studies, but there are important differences. Projections are for "eustatic" sea level, which is independent of changes in land elevation. Results are shown in inches for 2030, 2050, and 2100 (relative to 2000), from three regionally specific studies: Petersen et al. 2015 [35] (based on Kopp et al. 2014, NRC 2012, and Mote et al. 2008 [94, 31, 95]). Values shown are the central (for NRC 2012), medium (for Mote et al. 2008), or median (for Petersen et al. 2015) projections, with the projected range included for each (for Petersen et al. 2015, the range corresponds to the 99% confidence limits). For simplicity only the results for the high (RCP 8.5) scenario from Petersen et al. 2015 are included in the table [35].

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

Table 7. Relative sea level (third column) and annual extreme coastal flood projections (right column, which includes sea level rise) for the coastal communities of the Strait of Juan de Fuca relative to the contemporary Mean Higher High Water (MHHW) tidal datum. The third column of the table provides the probability (in percent) that mean sea level will be at or above a certain elevation (in feet) above contemporary MHHW by 2030, 2050 or 2100. The right column of the table provides the probability in a given year that the largest single coastal flooding event will reach a given elevation (in feet) above the contemporary MHHW. This column reflects how storm surge amounts vary at locations across the peninsula. Table and caption from Petersen et al. 2015 [35].

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

Coastal Flooding, Storm Surge, and Erosion

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

Sea level rise will exacerbate coastal flooding, including flooding in coastal river deltas, including flooding associated with atmospheric low pressure systems. In coastal river deltas, higher sea level can increase the extent, depth, and duration of flooding by delaying flood waters in rivers and streams to draining into Puget Sound. In the Skagit River floodplain, for example, the area flooded during a 100-year event is projected to increase by +74% on average by the 2080s (2070–2099, relative to 1970–1999), when accounting for the combined effects of sea level rise and increasing peak river flows (see Section 3) [96, 97]. In Olympia, +6 inches of sea level rise shifts the probability of occurrence for the 1-in-100-year flood event from a 1% annual chance to 5.5% annual chance (1-in-18-year) event [98].[38] With +24 inches of sea level rise, the 1-in-100-year flood event would become an annual event.[39]

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

Coastal Erosion, Bluff Erosion, and Sediment Transport. Shoreline erosion along the Puget Sound coast is a major sediment source [76]. One study estimated that shoreline erosion contributes 9.1 million tons of sediment per year [99]; it should be noted that the uncertainty surrounding this estimate is considered high [76]. Increased erosion is expected in many coastal areas as sea levels rise, although the effects depend on the geology and exposure of each location. Coastal bluffs are expected to be particularly sensitive to sea level rise. One study projects that coastal bluffs in San Juan County could recede by −75 to −100 feet by 2100 (relative to 2000) as a result of sea level rise [100].[40] This amount corresponds to a doubling, on average, of the current rate of recession [1]. Another study focused on the Dungeness and Elwha drift cells (areas for which distinct sediment sources and sinks can be identified) projected that sea level rise would increase average annual bluff erosion rates by approximately 4 inches per year by 2050. Heavy precipitation, nonpoint source runoff, groundwater saturation, development near bluffs, and the presence (or absence) of shoreline protection can also affect to erosion rates [101, 102].

Sediment inputs from coastal erosion are necessary for the persistence of beaches and coastal areas, which provide food and habitat for estuarine and nearshore plant and animal species in the Puget Sound region. However, while insufficient sediment transport can lead to beach and habitat erosion, excess sediment loads can fragment or bury important habitat types, such as eelgrass beds [76]. It remains uncertain if bluff erosion will mitigate sea level rise in nearshore areas or if sediment will be transported offshore by increased wave exposure due to higher water levels [103].

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

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

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

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

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

OCEAN TEMPERATURE

Sea surface temperatures in the northeast Pacific Ocean are projected to warm by about +2.2°F by the 2040s (2030–2059, relative to 1970–1999), although short-term (up to several decades) variability resulting from coastal upwelling, ENSO, and PDO could affect this projected change [104]. These results are consistent with the +2°F warming projected for the Northwest coastal ocean by mid-century (2040–2049) under a moderate (A1B) warming scenario [105].

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

OCEAN ACIDIFICATION

The pH of Washington's coastal waters is projected to continue to decrease as the atmospheric concentration of carbon dioxide climbs. Based on current carbon dioxide emissions scenarios, ocean acidity is projected to increase by 100 to 150% globally by 2100 (a decline in pH of −0.06 to −0.32), relative to pre-industrial levels [25].[41] According to NOAA's Pacific Marine Environmental Laboratory, the pH level projected for the end of the 21st century is a level "that the oceans haven't experienced for more than 20 million years" [106].

As noted previously, research on Hood Canal finds that ocean acidification currently accounts for 24 to 49% of the decrease in pH in the deep waters of Hood Canal relative to estimated pre-industrial values. This contribution increases to 49 to 82% with a doubling of atmospheric carbon dioxide, relative to pre-industrial levels [39]. Under greenhouse gas current scenarios, atmospheric carbon dioxide could double by about 2050 for a high emissions scenario (RCP 8.5) or after 2100 for a low scenario (RCP 4.5).

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

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