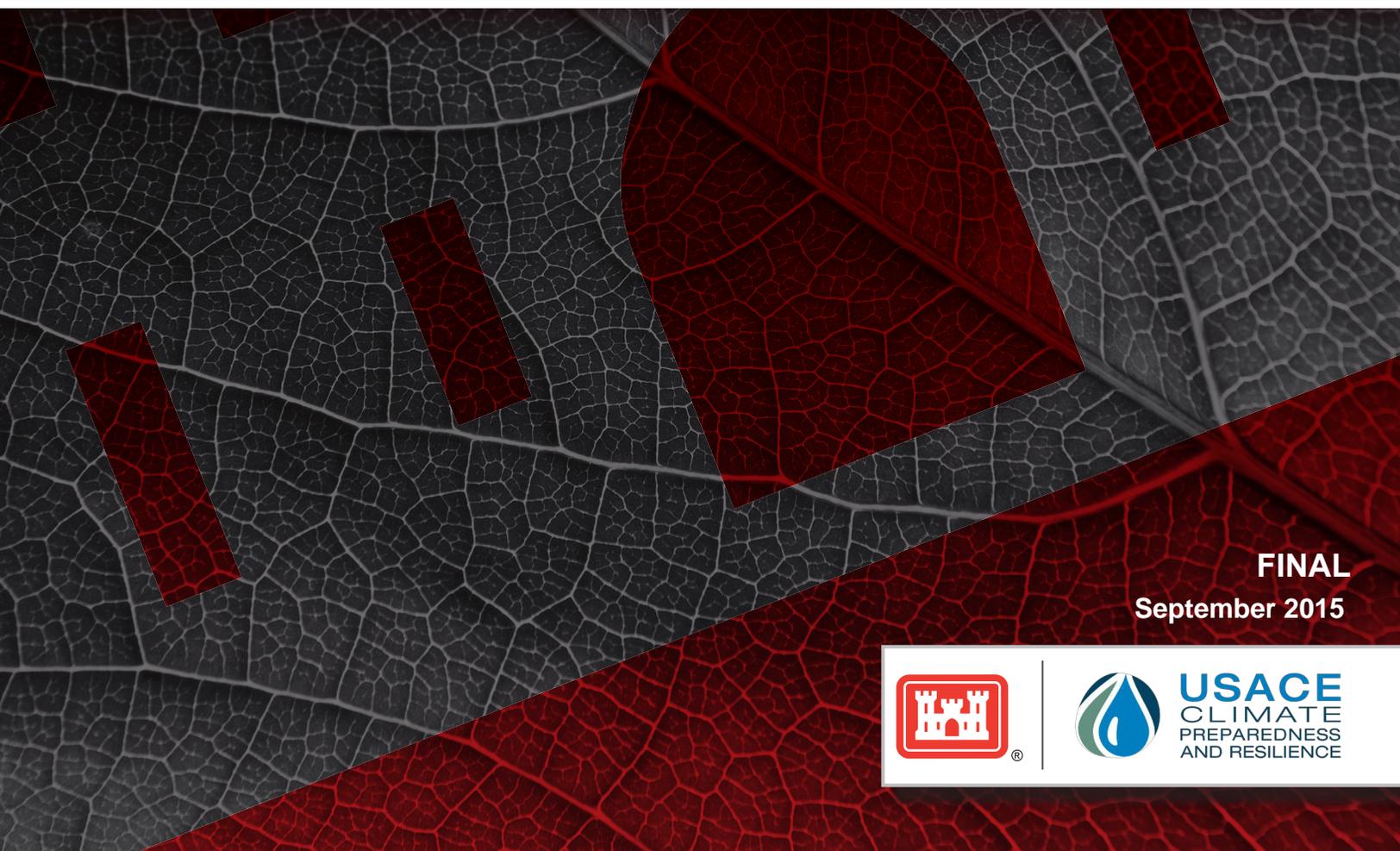


**Recent US Climate Change and Hydrology Literature  
Applicable to US Army Corps of Engineers Missions  
PACIFIC NORTHWEST REGION 17**



**FINAL**  
September 2015



**USACE**  
CLIMATE  
PREPAREDNESS  
AND RESILIENCE

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**CLIMATE CHANGE AND HYDROLOGY LITERATURE SYNTHESIS FOR THE US  
ARMY CORPS OF ENGINEERS MISSIONS IN THE UNITED STATES**

**PACIFIC NORTHWEST REGION 17**

September 21, 2015

CDM Smith  
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Edited by:

Kathleen D. White PhD, PE, Institute for Water Resources - US Army Corps of Engineers  
Jeffrey R. Arnold, PhD, Institute for Water Resources - US Army Corps of Engineers

Prepared by:

Chris Kurtz, PE, CDM Smith  
Tim Cox, PhD, PE, CDM Smith  
Frannie Bui, PE, CDM Smith  
Lauren Klonsky, PE, CDM Smith  
Lauren Miller, CDM Smith  
Jamie Lefkowitz, PE, CDM Smith  
Alexandra Bowen, PE, CDM Smith  
Rebecca Jablon, AICP, LEED AP, CDM Smith  
Quentin Smith, CDM Smith  
Tim Feather, PhD, CDM Smith  
Mark Dunning, PhD, CDM Smith  
David Spector, CDM Smith

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## Water Resources Region 17: Pacific Northwest Region

### 1. Introduction

U.S. Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty-one (21) regional climate syntheses prepared by the USACE under the leadership of the *Response to Climate Change Program* at the scale of the 2-digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty-one Water Resources Regions included in this series of reports is shown in **Figure 1.1** along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and regional vulnerability assessment tools.

This report focuses on Water Resources Region 17, the Pacific Northwest Region, the boundaries for which are shown in **Figure 1.2**. The Pacific Northwest Region boundary is coincident with the USACE district territories of Portland, Seattle, and Walla Walla.



**Figure 1.1.** 2-digit Water Resources Regional Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.



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### 1.1. A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science-based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local-to-regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post-processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit HUC (Water Resources Region), and that confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Regional scale both to introduce relevant climate change literature and to support the vulnerability assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 17, both the 2-digit and 4-digit HUC boundaries are shown in **Figure 1.2**.

## 2. Observed Climate Trends

Observed climate trends within the Pacific Northwest Region are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014), this section is not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth's climate systems are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings. When additional detail is needed, the reader is referred to the specific references cited, including the third National Climate Assessment (NCA), which includes not only regional assessments, but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer-reviewed literature on the subject of observed climate. To the extent possible, studies specific to the Pacific Northwest Region or its subregions were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow

In addition to primary variables, peer-reviewed literature addressing climate change within the geographic region of the Water Resources Region or inclusive of the Water Resources Region (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), evapotranspiration (ET), and soil moisture.

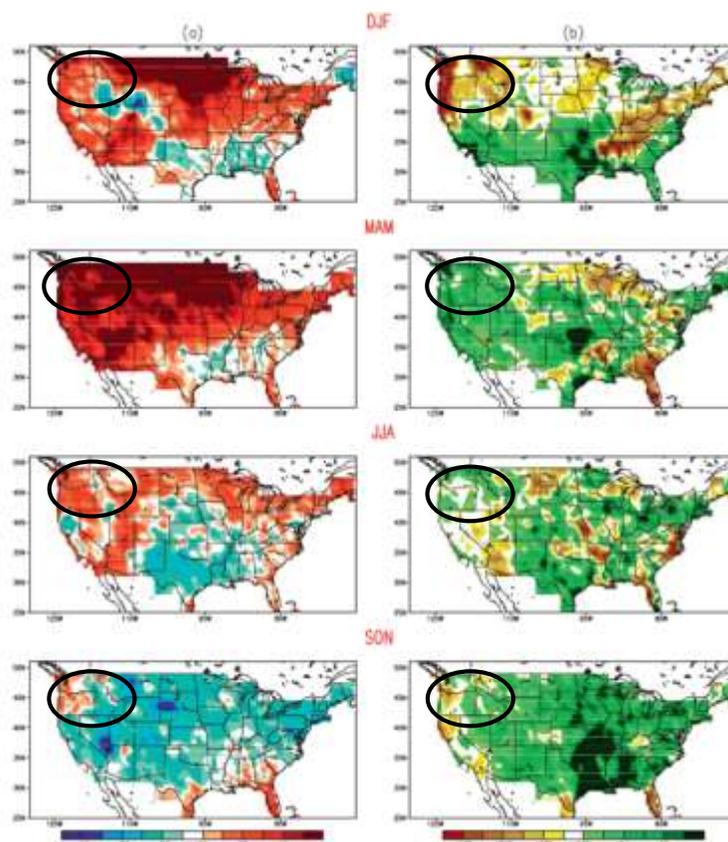
The results presented below indicate increasing trends in temperature for the Pacific Northwest Region. However, clear consensus does not exist for precipitation trends. Studies of regional streamflow reviewed here present evidence of decreasing trends in flow, or a related hydrologic parameter such as snow water equivalent (SWE), over the past 50 to 60 years across most of the region.

### 2.1. Temperature

A number of studies focusing on observed trends in historical temperatures were reviewed for this report. These include both national scale studies inclusive of results relevant to the Pacific Northwest Region and regional studies focused more specifically and exclusively on the Pacific Northwest Region. Results from both types of studies, relevant to the Pacific Northwest Region, are discussed below.

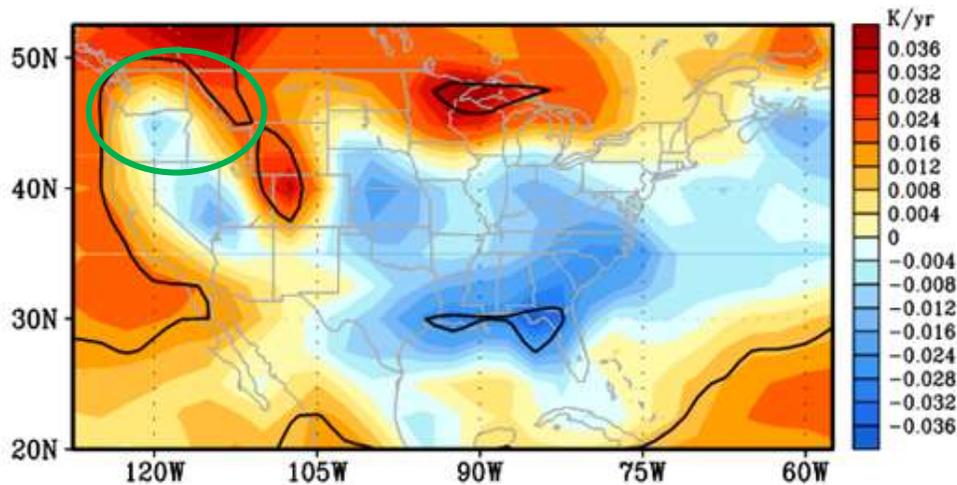
At a national scale, a study by Wang et al. (2009) examined historical climate trends across the continental United States. Gridded (0.5 degrees x 0.5 degrees) mean monthly climate data for the period 1950 – 2000 were used. The focus of this work was on the link between observed seasonality and regionality of trends and sea surface temperature variability. The authors

identified positive trends in recent observed seasonal mean surface air temperature for most of the U.S. (**Figure 2.1**). For the Pacific Northwest Region, seasonal differences were identified in the historic mean air temperatures. A positive warming trend is identified for the Pacific Northwest Region in the spring (March – May). A historic cooling trend is observed in the fall (September – November) in the eastern portion of the region while the western portion was found to have a slight warming trend during the same months. Similar spatial variability in historic temperature trends throughout the Pacific Northwest Region is shown for the winter (December – February) and summer (June – August) as well with coastal areas (western) showing increasing temperature trends and eastern areas showing decreasing temperature trends. The authors do not provide information on statistical significance of the presented observed trends.



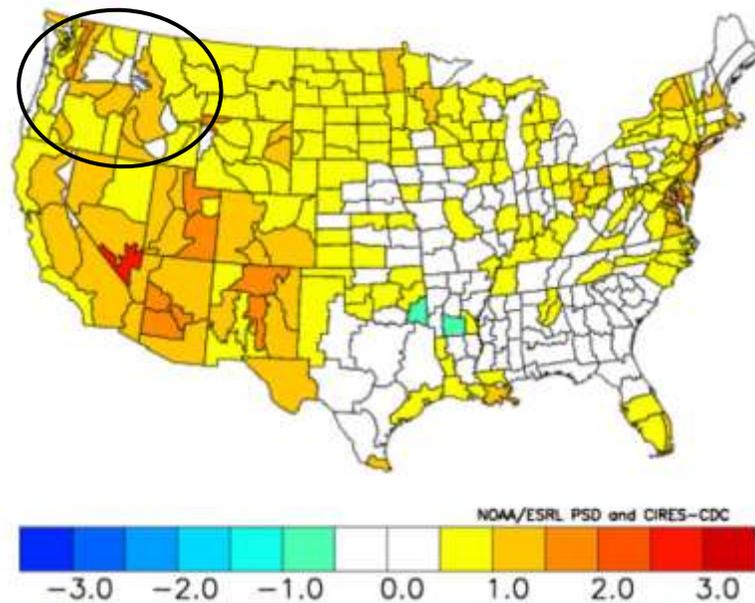
**Figure 2.1.** Linear trends in (a) surface air temperature in Kelvin (b) and precipitation in mm/day over the United States, 1950 – 2000. The Pacific Northwest Region is within the black oval (Wang et al., 2009).

A later study by Westby et al. (2013), using data from the period 1949 – 2011, also presents spatial variation in winter temperature trends for the Pacific Northwest Region for this time period (**Figure 2.2**), however, areas of historic warming and cooling are conflicting with those results presented by Wang et al. (2009). Westby et al. (2013) found a cooling trend in the central portion of the region (eastern Oregon) while increases in winter temperatures were observed in both the furthest east portions and coastal areas. However, the temperature variability presented by Westby et al. (2013) for the Pacific Northwest Region, was noted by the authors to lack statistical significance (95% confidence interval [C.I.]).



**Figure 2.2.** Mean winter (December through February) temperature trends from 1949 – 2011 (K/year). Black contours indicate statistical significance at the 95% confidence level. The Pacific Northwest Region is within the green oval (Westby et al., 2013).

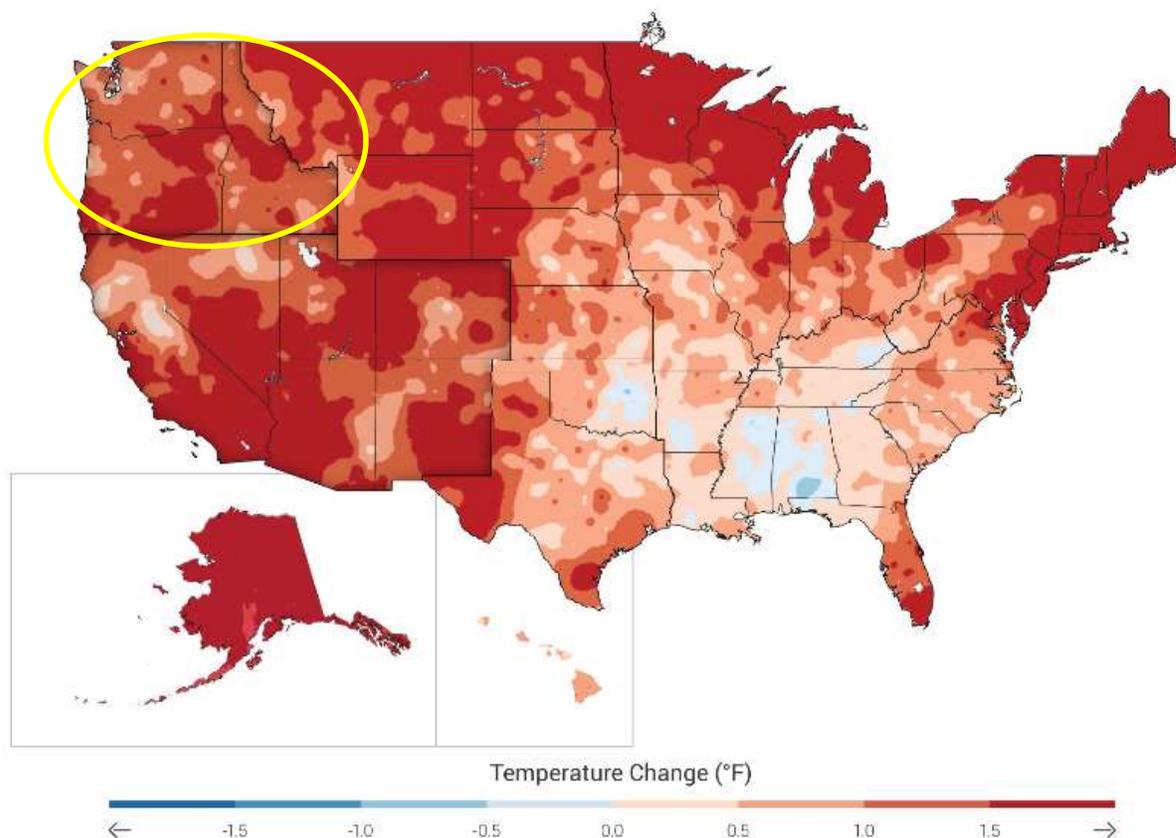
An article by MacDonald (2010) evaluated average annual temperatures over 2001 – 2009 compared to 1895 – 2000. In the Pacific Northwest Region annual temperatures were up to 2 standard deviations above the 20<sup>th</sup> century average (**Figure 2.3**). Details on statistical significance were not provided in the study.



**Figure 2.3.** Composite standardized temperature anomalies for 2001 – 2009 relative to 1895 – 2000. The Pacific Northwest Region is within the black oval (MacDonald, 2010).

Another national study by Tebaldi et al. (2012) evaluated average annual historic decadal changes in temperature. Based on data from 1912 – 2011, temperatures within the states of Idaho, Oregon, and Washington (which the Pacific Northwest Region is primarily within), increased in temperatures at a rate of 0.166 °F (0.092 °C), 0.128°F (0.071 °C), and 0.129°F (0.072 °C) per decade, respectively, with a 95% confidence interval.

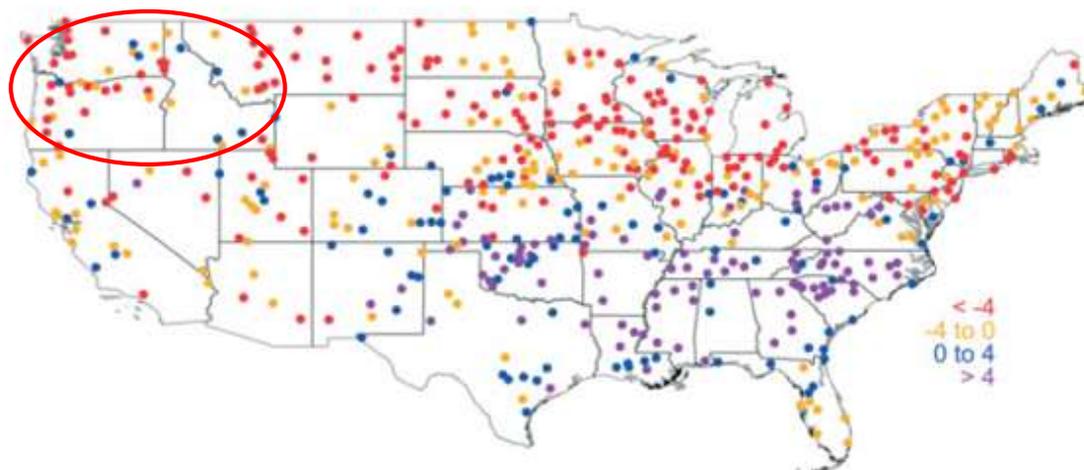
The third NCA report (Mote et al., 2014) presents trends in historical annual average temperatures for the northwestern US. For the northwest region, including the majority of the Pacific Northwest Region, historical data shows a 1.3 °F (0.7 °C) increase of average annual temperatures based on data from 1895 to 2011. Details on statistical significance are not provided. When comparing a recent 22-year span (1991 – 2012) to a historic average (1901 – 1960), temperatures have increased throughout the Pacific Northwest Region up to 2 °F (1.11 °C), as illustrated by **Figure 2.4** (Walsh et al., 2014). This is consistent with an increasing trend in annual average temperatures within the Pacific Northwest Region reported by MacDonald (2010), Tebaldi et al. (2012), and Mote et al. (2014).



**Figure 2.4.** Changes in average temperatures for 1991 – 2012 compared to 1901 – 1960 (Walsh et al., 2014). The Pacific Northwest Region is within the yellow oval.

Extreme temperatures were studied by Grundstein and Dowd (2011). These authors investigated trends in one-day extreme maximum and minimum apparent temperatures across the continental U.S. The study was based on daily temperature data compiled by the National Climatic Data Center (NCDC) for 187 stations across the country for the period 1949 – 2010. Extreme minimum and maximum temperatures were defined as the number of days per month that exceeded the local 85<sup>th</sup> percentile for the one-day maximum and minimum temperatures. For the Pacific Northwest Region, they found a statistically significant (95% C.I.) increasing trend in the number of one-day extreme minimum temperatures for six of ten stations in the region. The authors also found a statistically significant (95% C.I.) increasing trend in the number of one-day extreme maximum temperatures for three of ten stations in the region. No significant trend was found at the other stations in the Pacific Northwest Region.

Schwartz et al. (2013) investigated changes in spring onset for the continental U.S. Their particular focus was on changes in the seasonality of plant growth as dictated by changing temperature regimes. The authors used historical data from over 22,000 stations across the United States, obtained from the NCDC, with periods of record extending through 2010. Their findings indicate that for most of the Pacific Northwest Region, spring onset is occurring earlier, in some cases by more than four days for the current period (2001 – 2010) compared to an earlier baseline reference decade (1951 – 1960) (**Figure 2.5**).

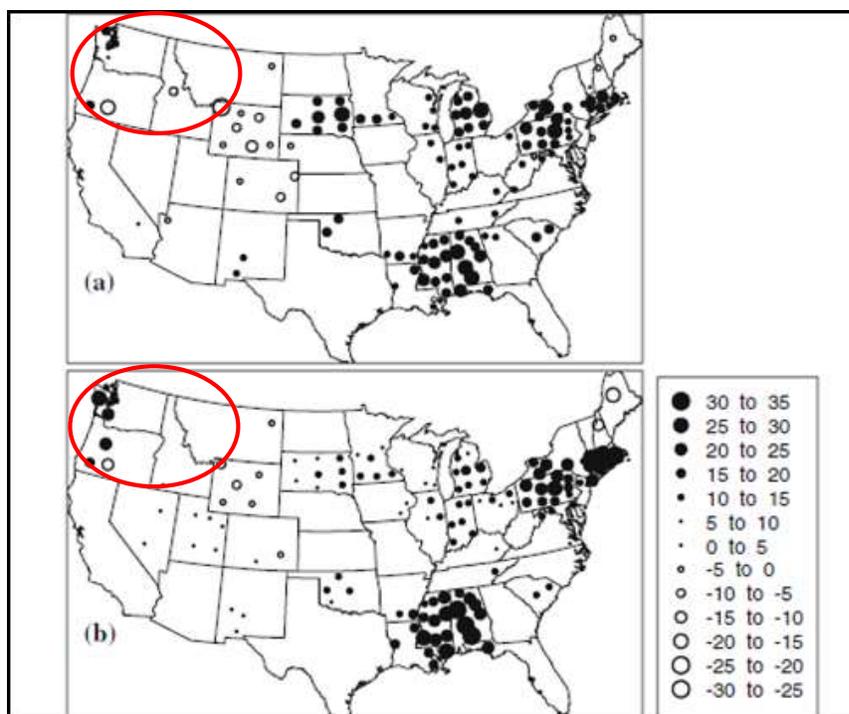


**Figure 2.5.** Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The Pacific Northwest Region is within the red oval (Schwartz et al., 2013).

*Key point: Increasing trends have been identified in the region's temperature data for the 20<sup>th</sup> century for average, minimum, and maximum temperatures. Some spatial variability is observed in the recent peer-reviewed literature related to mean annual temperature; however, there is a strong consensus that the region's coastal area has experienced an overall increase. A few studies note a slight decrease or no trend in the inland areas of the region, but the location of these decreasing trends (or no change) was not consistent amongst the literature presented.*

## 2.2. Precipitation

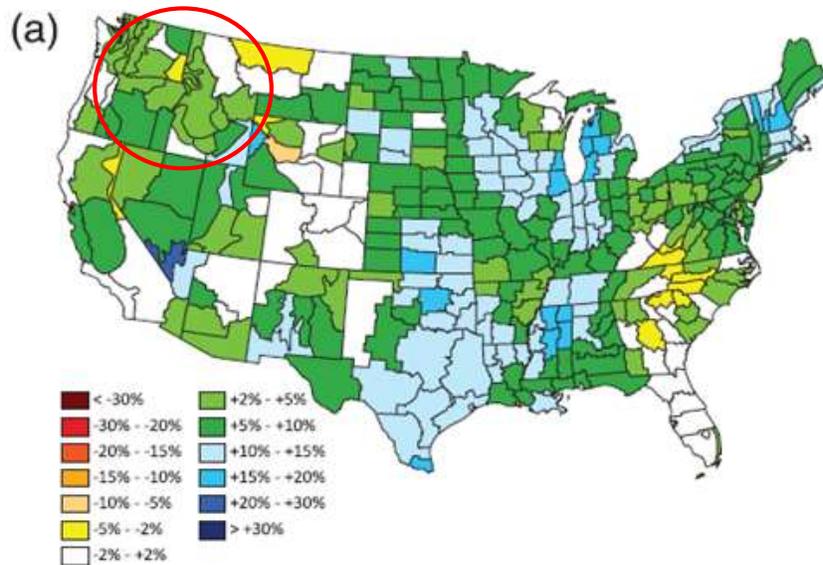
Multiple studies on observed trends in precipitation have identified increasing trends in annual total precipitation; however, trends related to extreme precipitation events for the Pacific Northwest Region were observed to be more variable. One study by Grundstein (2009) identified statistically significant (95% C.I.) increasing trends in soil moisture and precipitation in the western Pacific Northwest Region based on annual data from 1895 to 2006 (**Figure 2.6**). Soil moisture was found to be slightly decreasing annually in the eastern portion of the Pacific Northwest Region. Soil moisture is a function of both supply (precipitation) and demand (ET), and therefore is a proxy for both precipitation and ET. Soil moisture indices are influenced by vegetative and hydrologic conditions.



**Figure 2.6.** Statistically significant linear trends in (a) soil moisture index (unitless) and (b) annual precipitation (cm) for the continental U.S., 1895 – 2006. The Pacific Northwest Region is within the red oval (Grundstein, 2009).

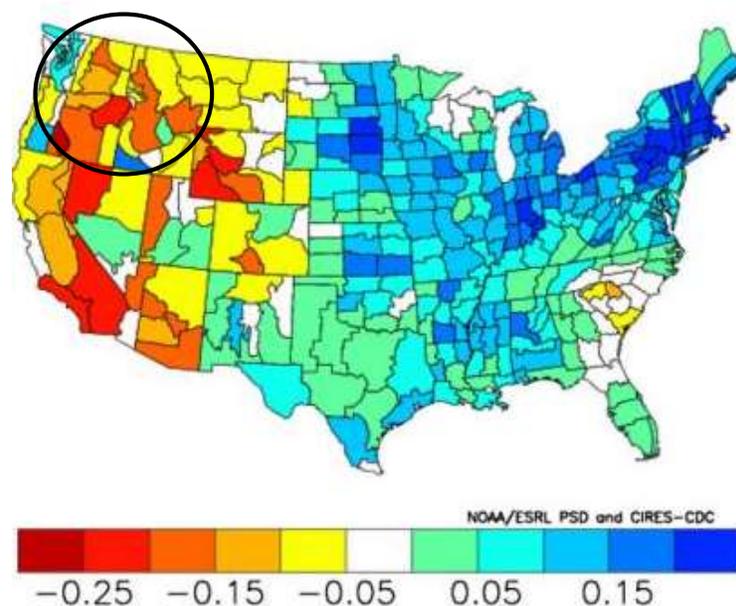
As described in Section 2.1, a similar study by Wang et al. (2009) also focused on historical climate trends across the continental U.S. using gridded climate data and a shorter period of record (1950 – 2000). The authors identified generally positive significant trends in annual precipitation for most of the U.S.; however, for the Pacific Northwest Region, variability was seen within the region for many seasons. For spring, the entire Pacific Northwest Region showed increasing trends in precipitation. In fall, the majority of Pacific Northwest Region showed increasing precipitation trends, with the exception of western Oregon and Washington which showed a decreasing trend. In summer, the Pacific Northwest Region showed an overall increasing precipitation trend; however, the central portion of the region exhibited no trend. Winter showed an overall decrease of historic precipitation trends with the western portion of the region showing significant decreases in precipitation (**Figure 2.1**). The authors do not provide information on statistical significance of the presented observed trends.

A study by McRoberts and Nielsen-Gammon (2011) used a new continuous and homogenous data set to perform precipitation trend analyses for sub-basins across the United States. The extended data period used for the analysis was 1895 – 2009. Linear positive trends in annual precipitation were identified for most of the U.S. (**Figure 2.7**). For the Pacific Northwest Region, results indicate an increasing (+2 to +10% change per century) trend in annual precipitation with the exception of a small area in eastern Washington which exhibits a decreasing trend (-2 to -5% change per century). The authors do not provide information on statistical significance of the presented observed trends.



**Figure 2.7.** Linear trends in annual precipitation, 1895 – 2009, percent change per century. The Pacific Northwest Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

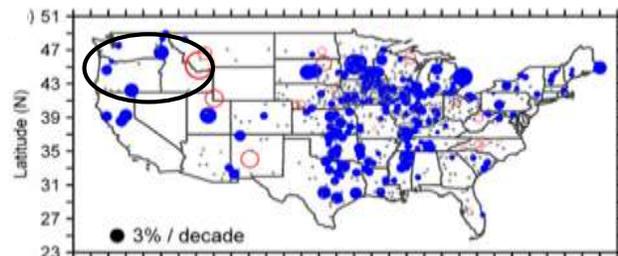
Similarly, a study by MacDonald (2010) evaluated national precipitation from 2001 – 2009 standardized relative to data from 1895 – 2000. These results primarily show a decrease in precipitation within the Pacific Northwest Region with the exception of a few isolated areas in western Oregon, western Washington, and southern Idaho that show an increase (**Figure 2.8**).



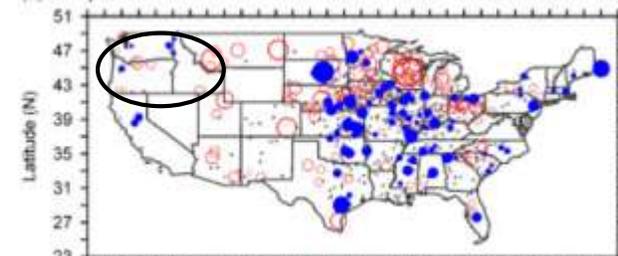
**Figure 2.8.** Standardized precipitation anomalies for 2001 – 2009 relative to 1895 – 2000. The Pacific Northwest Region is within the black oval (MacDonald, 2010).

Pryor et al. (2009) performed statistical analyses on 20<sup>th</sup> century rainfall data to investigate for trends across a range of precipitation metrics. They used data from 643 stations scattered across the continental U.S. For the Pacific Northwest Region, the analysis showed an overall increasing trend in total annual precipitation (though some decrease in the east), a decreasing trend in extreme high precipitation events (90<sup>th</sup> percentile daily) and precipitation intensity, and an increasing trend in the number of precipitation days per year (Figure 2.9 a, b, c, and d). These trends were determined to be significant at the 90% confidence interval. The authors note that the trends identified are not necessarily linear, with an apparent increase in the rate of change in the latter part of the century for most of the trends.

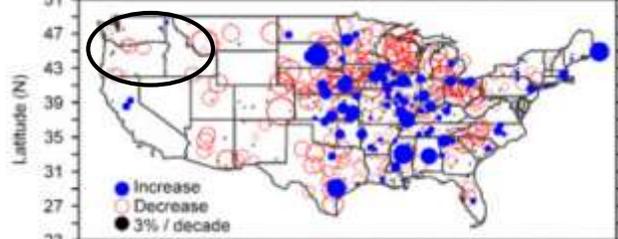
a) Annual precipitation



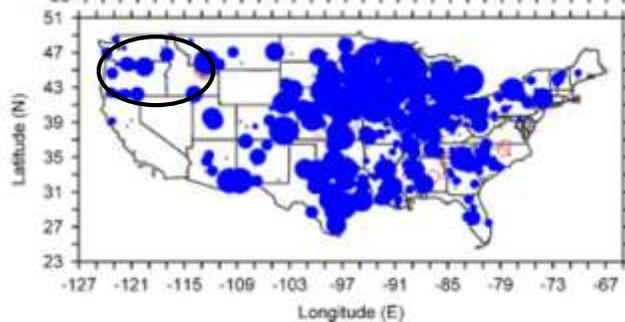
b) 90<sup>th</sup> percentile daily precipitation



c) Precipitation intensity (annual total / number of precipitation days)



d) Number of precipitation days per year



**Figure 2.9.** Historical precipitation trends (20<sup>th</sup> century). (a) annual totals, (b) 90<sup>th</sup> percentile daily, (c) precipitation intensity (annual total/number of precipitation days), and (d) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The Pacific Northwest Region is within the black oval (Pryor et al., 2009).

The third NCA report (Mote et al., 2014) documented trends in observed precipitation for the Pacific Northwest Region. For the study's northwest region, including the majority of the Pacific Northwest Region, the study cites a general increase in precipitation; however, the study also disclaims that observed trends are small relative to natural variability. Additionally, Mote et al. (2014) notes that the direction of trends (increasing vs. decreasing) varies based on geography and season. This finding is consistent with the variability in results reported above. Details on statistical significance are not provided.

Changes in extreme precipitation events observed in recent historical data have been the focus of a number of studies. Studies of extreme events have focused on the intensity, frequency, and/or duration of such events. Wang and Zhang (2008) used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. For the Pacific Northwest Region, an overall slight decrease in the recurrence of the 20-year daily maximum precipitation event for the period 1977 – 1999 was computed to be three-fourths as likely to occur compared to the same storm type during the period of 1949 – 1976. An exception along the coastal portion of the Pacific Northwest Region was found where the authors observed a slight increase in the occurrence frequency (one to four-thirds) of the 20-year daily maximum precipitation event.

A regional study of extreme precipitation was conducted by Rosenberg et al. (2010). These authors evaluated historical precipitation records and associated probability distributions of precipitation extremes in Washington State for the period 1949 – 2007. Three major metropolitan areas were included in the study: the Puget Sound area, the Vancouver, WA area, and the Spokane, WA area. The authors found little evidence of statistically significant changes in the observed record of extreme precipitation in the study areas, though the Puget Sound region was an exception (increasing).

*Key point: Overall, increasing trends have been identified in the Pacific Northwest Region's annual average precipitation data for the latter half of the 20<sup>th</sup> century, especially in the coastal areas. Note, there is only a moderate consensus across the literature for annual average precipitation trends and this increasing trend is variable depending upon location and season.*

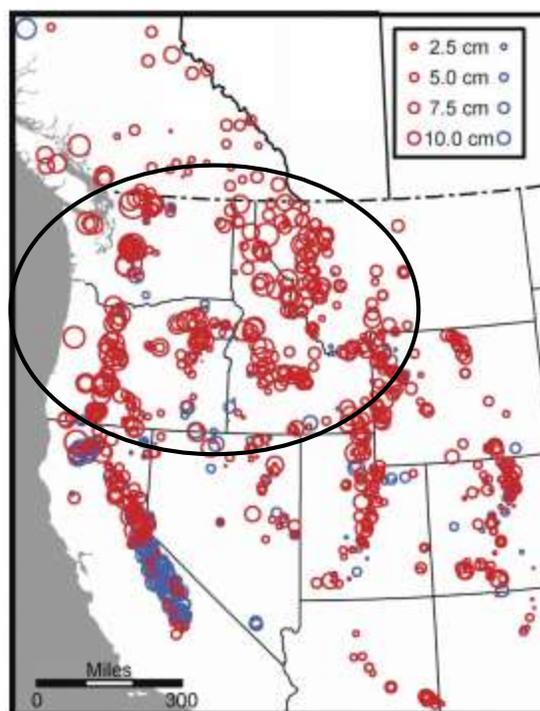
### **2.3. Hydrology**

Studies of trends and nonstationarity in streamflow data collected over the past century have been performed throughout the continental U.S., some of which include the Pacific Northwest Region. A study by Sagarika et al. (2014) evaluated data from 240 unimpaired streamflow stations throughout the U.S. from 1951 – 2010. Statistically significant (90% C.I.) decreasing trends were found for 16 of the 37 stations within the Pacific Northwest Region.

Kalra et al. (2008) performed a study using recorded streamflow data from 639 unimpaired stations to assess trends and step changes in streamflow between 1951 and 2002. These authors found significant (95% C.I.) decreasing trends in streamflow within the Pacific Northwest Region for both the water year and the spring-summer season. No significant trend was identified for the autumn-winter season.

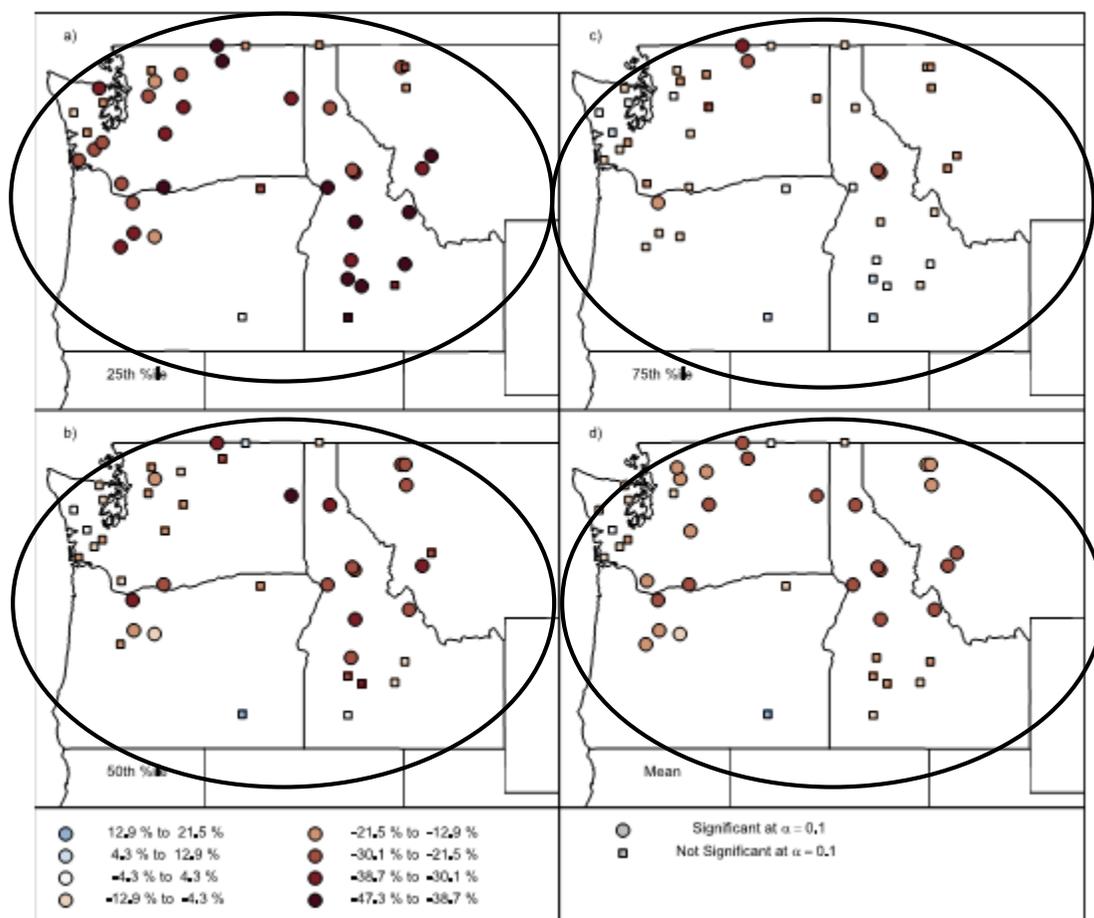
Decreased snowpack, as measured by SWE, is strongly related to the amount of runoff and associated natural inflows to snowpack-supplied watersheds such as those found in the Pacific Northwest Region. Mote (2006) examined historical snow course records in the Pacific Northwest Region over the 1960 – 2002 period of record. These authors found an overall decrease in the amount of 1 April SWE (**Figure 2.10**) ranging from -2.5 cm to -10.0 cm across the Pacific Northwest Region. The authors of this study do not provide information on statistical significance of the presented observed trends.

Similarly, a later study by the same authors focused on the Cascade Mountains of Washington State. The study utilized a period of record of 1950 – 1997 and found similar, but statistically significant (95% C.I.), decreasing trends in 1 April SWE (Mote et al., 2008)



**Figure 2.10.** Trends in observed 1 April SWE over the 1960 – 2002 period of record. Red circles indicate a decrease and blue circles indicate an increase. The Pacific Northwest Region is within the black oval. (Mote, 2006)

Another regional study by Luce and Holden (2009) examined annual streamflow distribution in the Pacific Northwest Region from 1948 to 2006 at 43 gaging stations. Statistically significant (90% C.I.) decreasing trends in the 25<sup>th</sup> percentile of annual flows were found at 72% of the stations (**Figure 2.11**). To a lesser extent, statistically significant trends were found for median and mean annual flow while even fewer stations (five) were found to have observed and significant decreasing trends in the 75<sup>th</sup> percentile of annual flows.



**Figure 2.11.** Changes in (a) 25<sup>th</sup> percentile annual flow (b) 50<sup>th</sup> percentile annual flow (c) 75<sup>th</sup> percentile annual flow (d) mean annual flow. The Pacific Northwest Region is within the black oval (Luce and Holden, 2009).

*Key point: A strong consensus of statistically significant decreasing trends have been identified in the region's streamflow and 1 April SWE data for the latter half of the 20<sup>th</sup> century.*

#### 2.4. Summary of Observed Climate Findings

A number of studies focusing on observed trends in historical temperatures were reviewed for this report. These studies included both national scale studies inclusive of results relevant to the Pacific Northwest Region and regional studies focused more specifically and exclusively on the Pacific Northwest Region. Overall, increasing trends have been identified in the region's temperature data for the 20<sup>th</sup> century for average, minimum, and maximum temperatures. Some spatial variability is observed in the recent peer-reviewed literature related to mean annual temperature; however, there is a strong consensus that the region's coastal area has experienced an overall increase. A few studies note a slight decrease or no observed trend in the more inland areas of the region; however, the location of these decreasing trends (or no trend) was not consistent amongst the literature presented.

Multiple studies on observed trends in precipitation have identified increasing trends in annual total precipitation, especially in the coastal areas. However, when considering all literature reviewed there is only a moderate consensus supporting increasing annual average precipitation trends and this increasing trend is variable depending upon location and season. Observations from the literature presented here found trends related to precipitation extremes to be even more variable than annual average precipitation.

For streamflow, and related climate variables, a strong consensus of statistically significant decreasing trends was identified in the Pacific Northwest Region. Specifically, decreasing trends for annual streamflow and 1 April SWE for the latter half of the 20<sup>th</sup> century were identified by multiple authors. The noted moderate trend of increasing precipitation and a decreasing trend in streamflow are not necessarily contradictory because of the complex feedbacks that exist in the Pacific Northwest's hydrologic system. For example, lower SWE could have a larger impact than increased rainfall on annual streamflow. Also, the region's observed increasing trend in temperature correlates to an increased loss in the water balance due to evaporation which would also impact streamflow.

### 3. Projected Climate Trends

While historical data is essential to understanding current and future climate, nonstationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2005). Consequently, the scientific and engineering communities are actively using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed GCMs, are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the Pacific Northwest Region identified in a review of recent peer-reviewed literature. The information presented should be considered an overview, and similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth's climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of "climate futures" so each study's assumed emission scenario(s) are noted. When additional detail is needed, the reader is referred to the specific references cited, including the third NCA which includes not only regional assessments, but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

The USACE vulnerability assessments (<https://corpsclimate.us/rccvar.cfm>) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey,

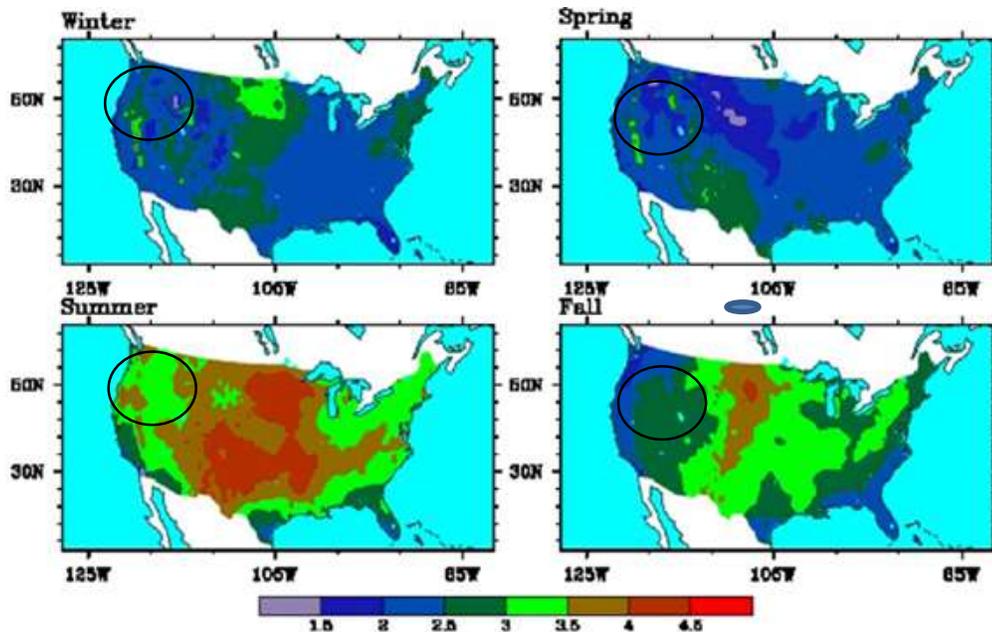
Climate Central, Scripps Oceanographic Institute and Santa Clara University, and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed or basin-scale water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate a moderate consensus in the scientific literature that air temperatures and extreme precipitation events will increase over the next century in the Pacific Northwest Region. A strong consensus was found in the literature that indicates a large increase in maximum temperature extremes. There is much less consensus on the future trending, or lack thereof, of minimum temperature, average annual precipitation, and streamflow in the region. This lack of consensus is likely due to the varied topography of the region and the current ability of GCMs and regional climate models to consistently resolve topographic effects from local climate forcings.

### **3.1. Temperature**

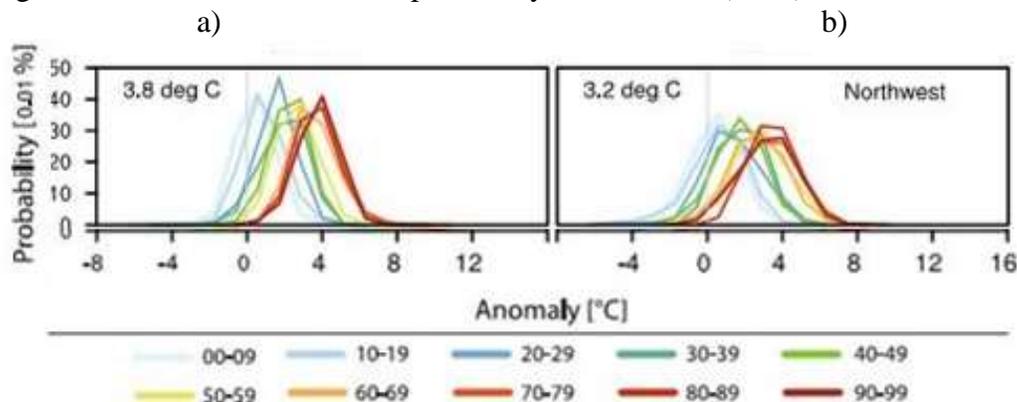
GCMs have been used extensively to project future climate conditions across the country. At a national scale, model projections generally show a significant warming trend throughout the 21<sup>st</sup> century, with a high level of consensus across models and modeling assumptions. Results of studies inclusive of the Pacific Northwest Region typically fall in line with this generalization.

Maximum air temperature projections were investigated by Liu et al. (2013) using a single GCM and assuming an A2 greenhouse gas emissions scenario (worst case) in a national analysis. The results of their study, specific to the Pacific Northwest Region, show a projected increase in winter, spring and fall maximum air temperature of 1.5 – 3 °C (2.7 °F – 5.4 °F) for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (**Figure 3.1**). The results of the study project increases in maximum air temperature from 3.0 to 4.0 °C (5.4 °F – 7.2 °F) for summer temperatures.



**Figure 3.1.** Projected changes in seasonal maximum air temperature, °C, 2055 vs. 1985. The Pacific Northwest Region is within the black oval (Liu et al., 2013).

Similar results are presented by Scherer and Diffenbaugh (2014). These authors applied a multi-member ensemble GCM (nested the International Centre of Theoretical Physics Regional Climate Model 3 [RegCM3] within the National Center for Atmospheric Research [NCAR] Community Climate System Model 3 [CCSM3]), assuming an A1B (middle of the road) emissions scenario, to the continental U.S. For the Pacific Northwest Region, model projections indicate steadily increasing air temperatures throughout the 21<sup>st</sup> century for both summer and winter seasons (**Figure 3.2**). By 2090, projections show an increase of 3.8 °C (6.8 °F) in the summer and 3.2 °C (5.8 °F) in the winter, compared to a 1980 – 2009 baseline period. These results agree well with those described previously for Liu et al. (2013).



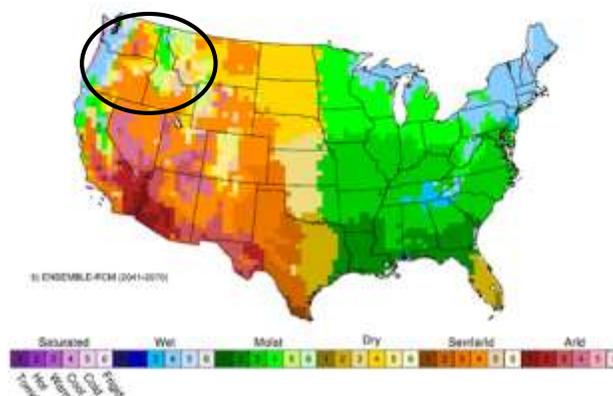
**Figure 3.2.** Probability distributions of GCM projections comparing 1980 – 2009 average to years 2000 – 2100 by decade for the northwest region. Average daily maximum temperature comparison is shown for a) summer months: June – August. Average daily minimum temperature comparison is shown for b) winter months: December – February) (Scherer and Diffenbaugh, 2014).

Elguindi and Grundstein (2013) present results of regional climate modeling of the U.S. focused on the Thornthwaite climate type – a measure of the combination of relative temperature and precipitation projections. For the Pacific Northwest Region, results show little to no shift in the region’s coastal areas while inland areas are projected to have an overall characteristically warmer climate by the period 2041 – 2070 (**Figure 3.3**).

a) Historical observed (1971 – 2000)



b) GCM projections (2041 – 2070)



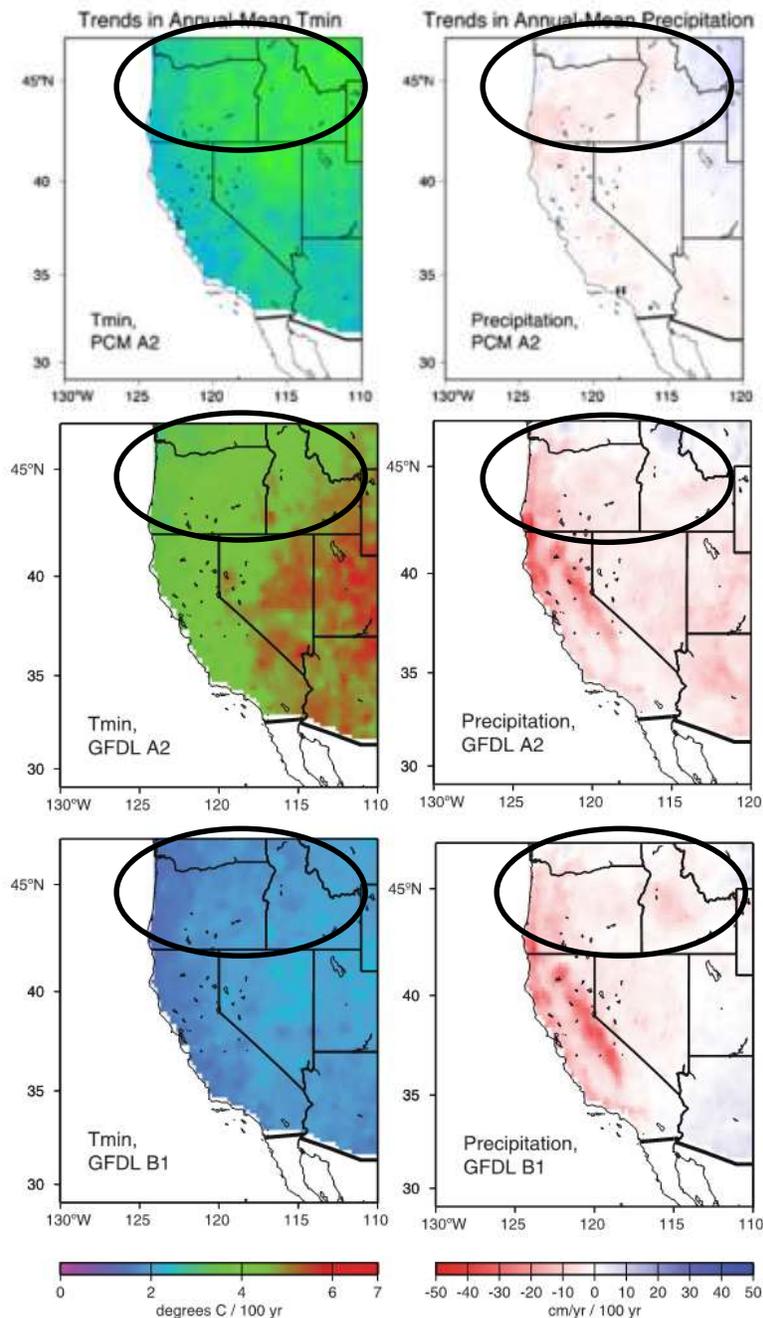
**Figure 3.3.** Revised Thornthwaite climate types projected by regional climate models. The Northwest Region is within the black oval (Elguindi and Grundstein, 2013).

A regional study by Payne et al. (2004) evaluated projected changes in temperature and precipitation (described in Section 3.2) in the Columbia River Basin. A “business as usual” emissions scenario developed by simulations from the Department of Energy and National Center for Atmospheric Research Parallel Climate Model (DOE/NCAR PCM) served as input to a regional climate model. Three different time horizons were used: 2010 – 2039, 2040 – 2069, and 2070 – 2098. The authors found a projected change in average temperature of +0.5 °C (+0.9°F), +1.3 °C (+1.6 °F), and +2.1 °C (+3.8 °F), respectively.

The third NCA (Mote et al., 2014) supports the findings presented above. Climate model projections for the northwest region of the U.S., which is mostly coincident with the Pacific Northwest Region, indicate an increase in annual average temperature over the next century. The NCA report presents a projected temperature increase ranging from 1.8 °C (3.3 °F) to 5.4 °C (9.7 °F) by 2070 to 2099 (relative to a baseline period of 1970 to 1999) with increases projected to be most significant in the summer months. The range in projected increases is the result of modeling various emission scenarios (B1, A1B, A2, etc.).

In a study by Kunkel et al. (2010), two different downscaled GCMs were applied to the continental U.S., assuming high greenhouse gas emissions scenarios (A2 and A1F), with a focus on summer heat wave occurrence and intensity. For the Pacific Northwest Region, projections indicate a 2.5 to 8 °C (4.5 to 14.4 °F) increase in three-day heat wave temperatures and a 0 to 75-day increase in the annual number of heat wave days for a 2090 planning horizon compared to a recent historical baseline. Generally, increased three-day heat wave temperatures and annual number of heat wave days are greater in the eastern portion of the region (i.e., Idaho).

A regional study by Dettinger (2012) evaluated trends in annual minimum temperature and annual mean precipitation (the latter of which is discussed in Section 3.2) for the western United States using results from National Oceanic and Atmospheric Administration (NOAA's) Geophysical Fluid Dynamics Laboratory (GFDL) coupled ocean atmospheric GCM model and National Center for Atmospheric Research's Parallel Climate Model (PCM1) simulating the A2 (middle-of-the-road) and B1 (low) emissions scenarios over the 21<sup>st</sup> century. While this study focused on impacts to the Lake Tahoe vicinity, results presented include the southern portion of the Pacific Northwest Region. Results from this analysis show an increasing trend in annual average minimum temperature for all models and associated emissions scenarios (**Figure 3.4**).

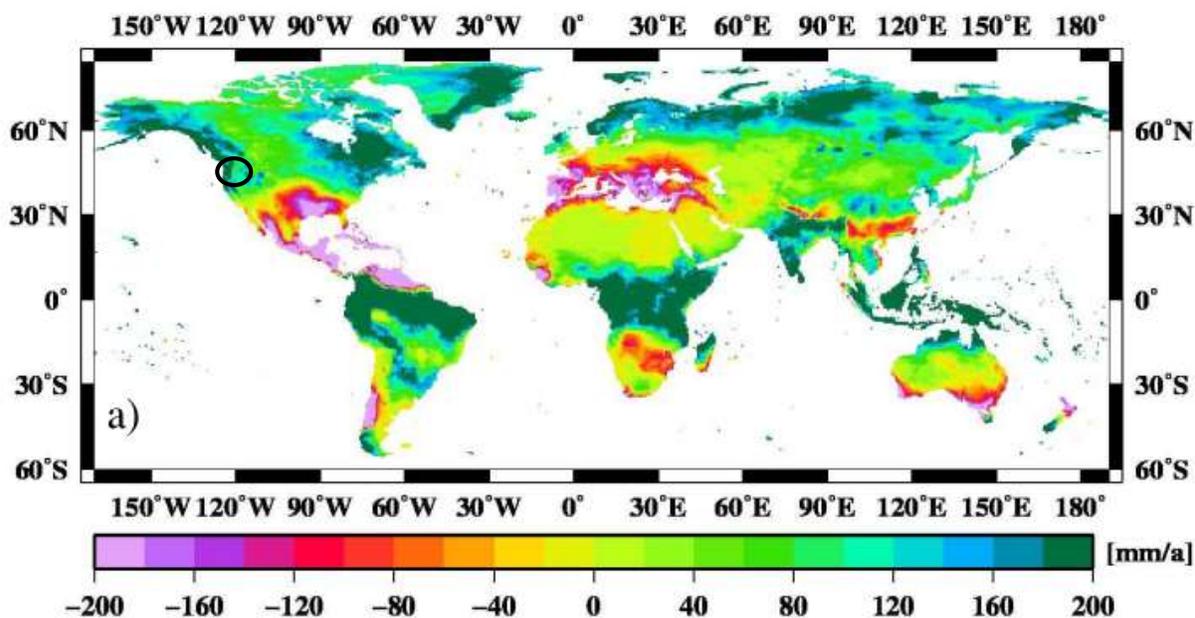


**Figure 3.4.** Downscaled temperature (left) and precipitation (right) trends for the 21<sup>st</sup> century under the A2 and B1 emissions scenarios from the GFDL and PCM1. The Pacific Northwest Region is within the black oval (Dettinger, 2012).

*Key point: Strong consensus exists in the literature that maximum temperature extremes in the study region show an increasing trend over the next century. A moderate consensus was found supporting an increasing trend in annual average temperature and minimum temperature extremes.*

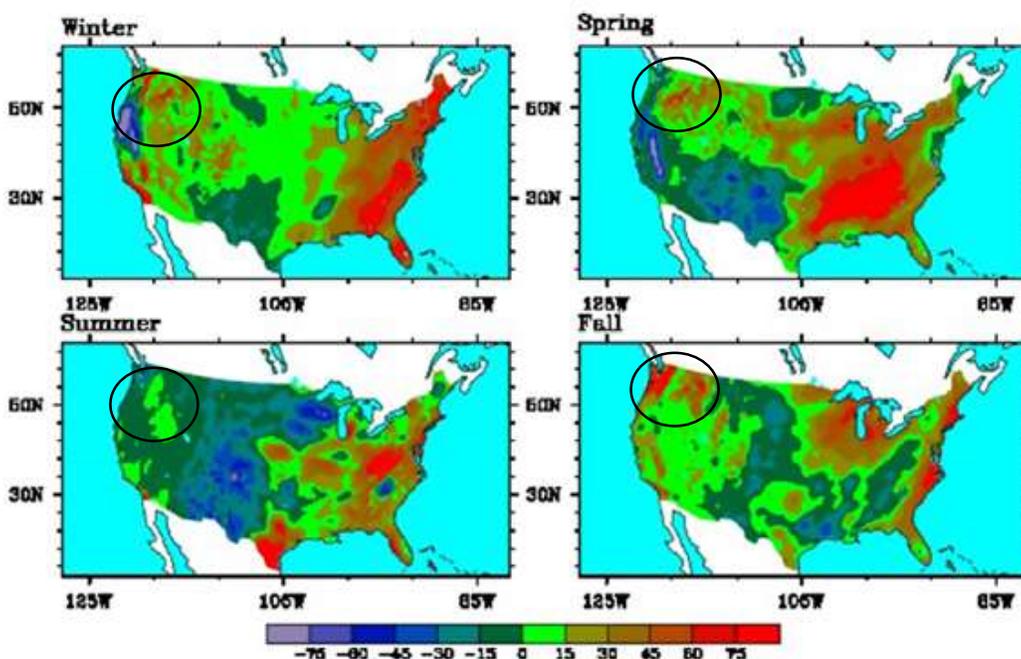
### 3.2. Precipitation

In line with projections for the rest of the country, projections of future changes in precipitation in the Pacific Northwest Region are variable and generally lacking in consensus among studies or across models. From a global analysis using three GCM projections, Hagemann et al. (2013) projects an increase in annual precipitation ranging between 120 and 200 mm per year for the Pacific Northwest Region with the largest increases occurring in the western coastal areas of the region (**Figure 3.5**).



**Figure 3.5.** Projected (2071 – 2100) changes in annual precipitation compared to baseline, 1971 – 2000, conditions, mm/year. The Pacific Northwest Region is within the black oval (Hagemann et al., 2013).

The Liu et al. (2013) study of the U.S., described above, quantified increases in winter and fall precipitation associated with a 2041 – 2070 planning horizon, relative to a recent historical baseline (1971 – 2000, centered around 1985), for the northwestern U.S., including the Pacific Northwest Region (**Figure 3.6**). Decreases in precipitation are projected for summer and spring in the coastal areas of the Pacific Northwest Region while inland areas to the east are projected to increase.

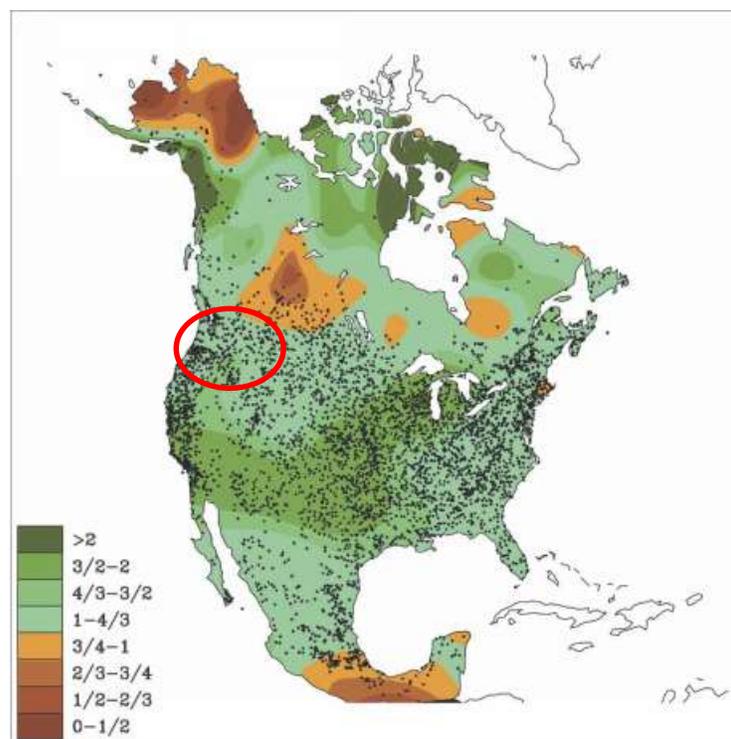


**Figure 3.6.** Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The Pacific Northwest Region is within the black oval (Liu et al., 2013).

As discussed in Section 3.1, a study by Dettinger (2012) simulated projected trends in annual mean precipitation over the 21<sup>st</sup> century based on two regionally downscaled model results with two emissions scenarios, results presented include the southern portion of the Pacific Northwest Region (Oregon and the majority of Idaho). For the Pacific Northwest Region specifically, no change, or a slight decrease in annual mean precipitation are projected for the 21<sup>st</sup> century, as is shown in **Figure 3.4**.

A regional study by Payne et al. (2004), described above in Section 3.1, also evaluated projected changes in precipitation in the Columbia River Basin. Three different time horizons were analyzed: 2010 – 2039, 2040 – 2069, and 2070 – 2098. The authors found a projected change in average winter precipitation of -3, +5, and +1%, respectively.

Future projections of extreme events, including storm events and droughts, are the subject of studies by Wang and Zhang (2008) and Rosenberg et al. (2010). The first authors used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. The GCMs used by Wang and Zhang (2008) were forced with the Intergovernmental Panel on Climate Change (IPCC) high emissions scenario (A2) to quantify a slight increase in the recurrence (one to four-thirds times) of the current 20-year 24-hour storm event for their future planning horizon (2050 – 2099) in the Pacific Northwest Region (**Figure 3.7**).



**Figure 3.7.** Projected risk of current 20-year, 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The Pacific Northwest Region is within the red oval (Wang and Zhang, 2008).

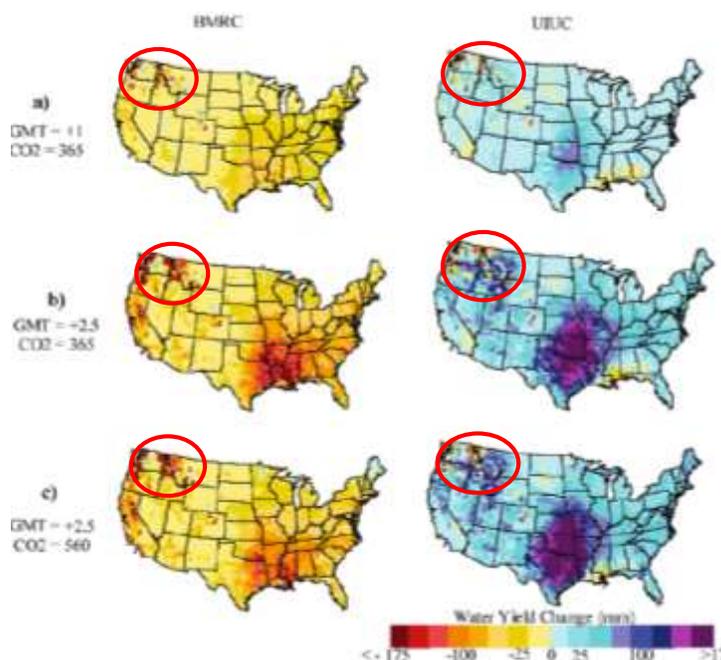
Rosenberg et al. (2010) evaluated projected regional changes in extreme precipitation under the A2 and A1B emission scenarios. Three major metropolitan areas were included in the study: the Puget Sound region, the Vancouver, WA region, and the Spokane region. These authors utilized two regional climate models and found that, generally, extreme precipitation is projected to increase throughout the state by 2050 but noted that the magnitude of the changes differed depending on model and region. Details on statistical significance are not provided.

The third NCA (Mote et al., 2014) reported varying projections in annual average precipitation depending upon emissions scenario. Climate model projections for the northwest region of the U.S., which is mostly coincident with the Pacific Northwest Region, indicate a range of -11% to +12% by 2059 and a range of -10% to +18% by 2099. Similar variability with respect to selected emissions scenario was reported for projections that consider seasonality. The third NCA did report a slight increase in extreme daily precipitation on the order of 0 to 20%.

*Key point: Strong consensus exists in the literature that the intensity and frequency of extreme storm events will increase in the future for the Pacific Northwest Region. Low consensus exists with respect to projected changes in total annual precipitation for the region. Future projected changes in annual average precipitation varied in magnitude (increasing or decreasing) depending upon location(s), season(s), climate model(s), and emissions scenario(s) considered in a particular study.*

### 3.3. Hydrology

A number of global and national scale studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro-scale hydrologic models. These studies include projections of potential hydrologic changes in the northwestern United States. Thomson et al. (2005) applied two GCMs, across a range of varying input assumptions, in combination with the macro-scale Hydrologic Unit Model to quantify potential changes in water yield (considered to be a surrogate for streamflow) across the United States. Results are presented for both continuous spatial profiles across the country (**Figure 3.8**). For the Pacific Northwest Region, and most of the United States, contradictory results are generated by the two GCMs. For the same set of input assumptions, one model predicts moderate decreases in water yield, the other projects moderate increases in water yield.

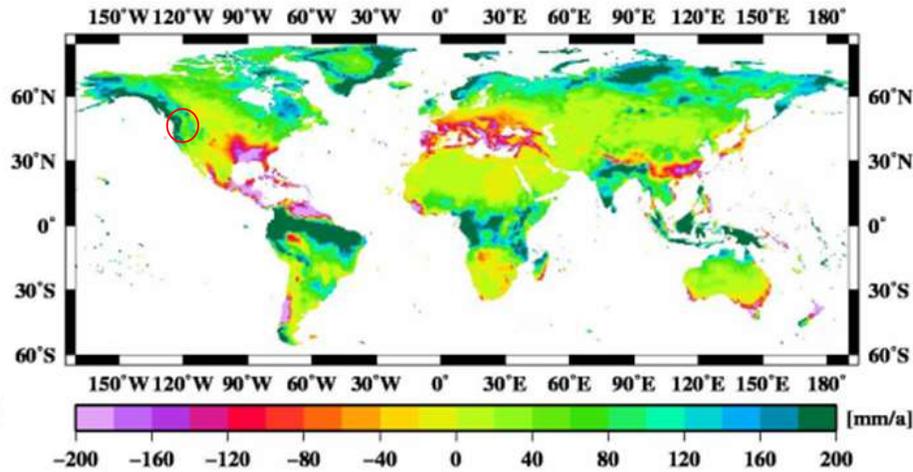


**Figure 3.8.** Projected change in water yield (from historical baseline), under various climate change scenarios based on two GCM projections. The Pacific Northwest Region is within the red oval (Thomson et al., 2005).

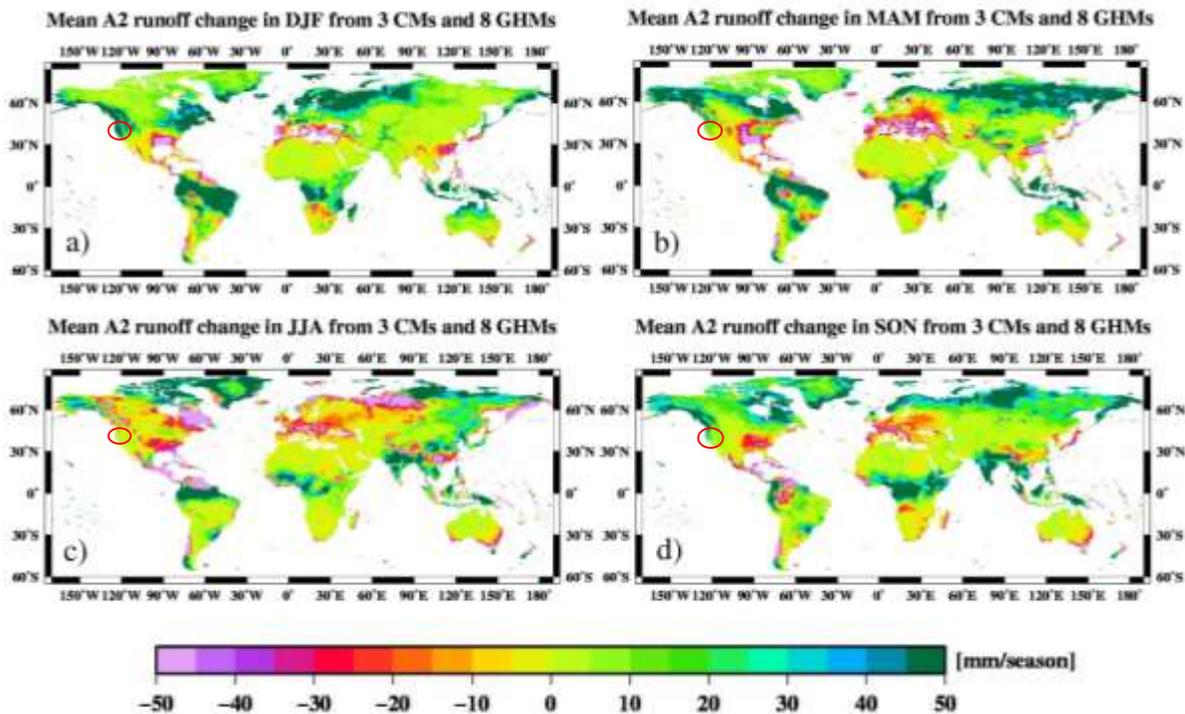
The results presented by Thomson et al. (2005), described above, highlight the significant uncertainties associated with global climate modeling, particularly with respect to hydrologic parameters. Additional uncertainty is generated when these climate models are combined with hydrologic models that carry their own uncertainty. This comparison and quantification of uncertainty is the subject of a 2013 study by Hagemann et al. In this study, the authors apply three GCMs, across two emission scenarios to seed eight different hydrologic models for projecting precipitation, ET, and runoff on a global scale. Their findings, in agreement with CDMSmith (2012) indicate that the uncertainty associated with macro-scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections from Hagemann et al. (2013), for the Pacific Northwest Region show an overall increase in runoff by up to 200 mm per year for their future planning horizon (2071 – 2100) compared to the recent historical baseline (1971 – 2000) (**Figure 3.9**), assuming an A2 emissions

scenario. The largest increases are expected to occur in coastal areas. Seasonally, runoff increases are projected to be greatest in winter, compared with more moderate increases in the spring, summer, and fall (Figure 3.10).

### Runoff change from 3 GCMs & 8 GHMs, 2071–2100 vs. 1971–2000

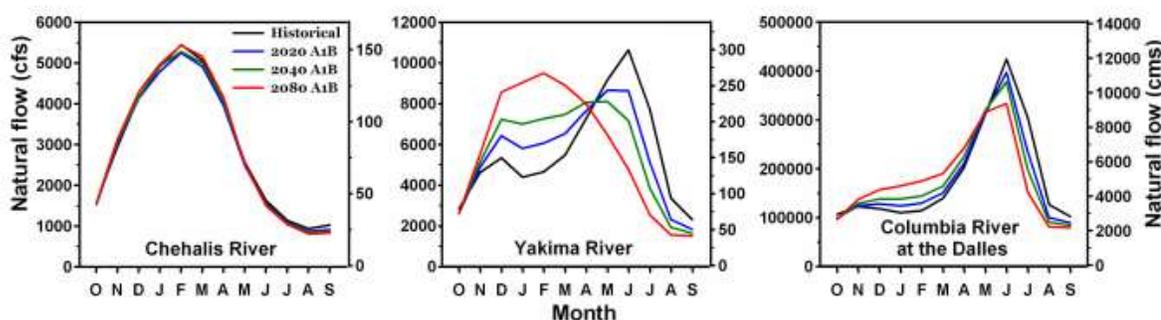


**Figure 3.9.** Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Pacific Northwest Region is within the red oval (Hagemann et al., 2013).



**Figure 3.10.** Ensemble seasonal (a. winter b. spring c. summer d. fall) mean runoff projections (mm/season) for A2 greenhouse gas emissions scenario, changes in seasonal runoff, 2071 – 2100 vs. 1971 – 2000. The Pacific Northwest Region is within the red oval (Hagemann et al., 2013)

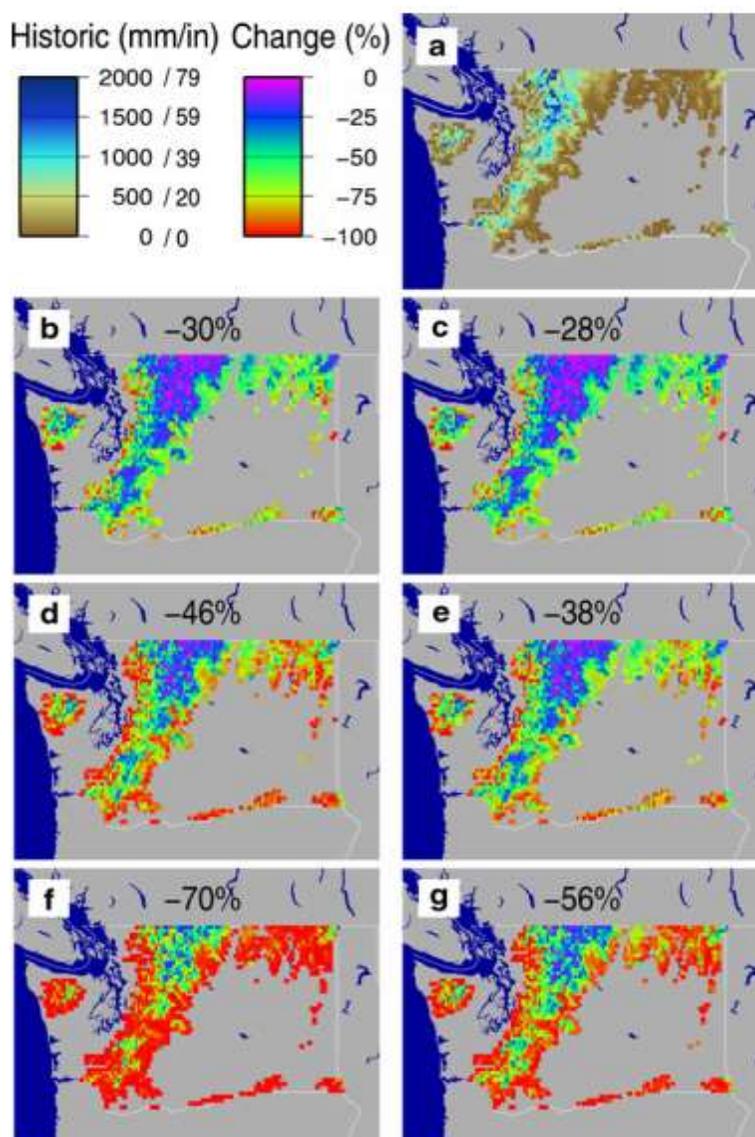
The Climate Impacts Group (University of Washing) published The Washington Climate Change Impacts Assessment in 2009. This report compiled and averaged the results from 20 different GCMs for two different emissions scenarios, A1B (medium) and B1 (low), across three planning horizons: the 2020s, 2040s, and 2080s. Six regional climate change scenarios were developed from this work (2 emissions scenarios x 3 planning horizons) which served as input to the widely used Variable Infiltration Capacity hydrologic model. The study's authors made a point to distinguish results across the varied geography of Washington and the Pacific Northwest Region. Chapter 3 (Elsner et al., 2009) focused on the assessment of projected changes due to climate change on hydrology and water resources of the region. For evaluating projected changes in streamflow three surrogate watersheds were utilized by the authors. The Chehalis River is representative of rain-dominant watersheds characteristic of western Washington, the Yakima River is representative of transient watersheds (mix between and rain- and snow-dominant), and the Columbia River is representative of snow-dominant watersheds. **Figure 3.11** shows the projected average monthly streamflow for each of these surrogate watersheds. The smallest change is projected for rain-dominant watersheds while transient and snow-dominant watersheds are projected to experience both shifts in the timing of annual peaks and amount of monthly streamflow.



**Figure 3.11.** Projected average monthly streamflow for rain-dominant (Chehalis River), transient (Yakima River), and snow-dominant (Columbia River) watersheds. (Elsner et al., 2009).

Döll and Zhang (2010) present similar results in their global modeling study focused on climate change impacts on ecologically relevant flow indices. As above, these authors used a combination of GCMs and a macro-scale hydrologic model (WaterGap) to project hydrology across a coarse spatial resolution (0.5 degree x 0.5 degree grid). They used two different GCMs simulating two bracketing emission scenarios (A2 and B2). Globally, they quantified a shift of peak flow by at least one month (earlier) for one third of the global land area, a significant increase in mean annual flow for approximately half of the land area, and a significant decrease in mean annual flow for approximately one quarter of the land area. Only small differences between the two emissions scenarios were noted. They demonstrate that climate change is expected to have as much, or more, of an impact to ecologically relevant flow characteristics as dams and withdrawals over the next century. For the Pacific Northwest Region, projections show mild (relative to global results) impacts to both low and average annual flows. The projected magnitude of change (increasing or decreasing) in average annual runoff varies depending upon assumed future emissions scenario and model; however, projected low flows are consistently observed to decrease in the future regardless of model or emissions scenario.

Elsner et al. (2009), described above, evaluated projected changes in SWE in the Columbia River watershed in Washington State. These authors found that 1 April SWE is projected to decrease between 38 and 46% by mid-century when compared to a baseline of 1917 – 2006 (**Figure 3.12**). Decreased snowpack, as measured by snow water equivalent (SWE), is strongly related to the amount of runoff and associated natural inflows to snowpack supplied rivers such as the Columbia River headwaters.



**Figure 3.12.** Summary of projected percent change in 1 April SWE. (a) Historical 1 April SWE (1917 – 2006) (b), (c) Projected change in 1 April SWE for the 2020s (A1B and B1 scenarios, respectively). (d), (e) Projected change in 1 April SWE for the 2040s (A1B and B1 scenarios, respectively). (f), (g) Projected change in 1 April SWE for the 2080s (A1B and B1 scenarios, respectively). Percent changes represent spatially averaged changes across Washington State (Elsner et al., 2010).

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*Key point: Low consensus exists with respect to projected changes in hydrology for the region. Future projected changes in hydrologic parameters (e.g., runoff, streamflow, SWE) varied in magnitude (increasing or decreasing) depending upon location(s), climate model(s), and emissions scenario(s) considered in a particular study.*

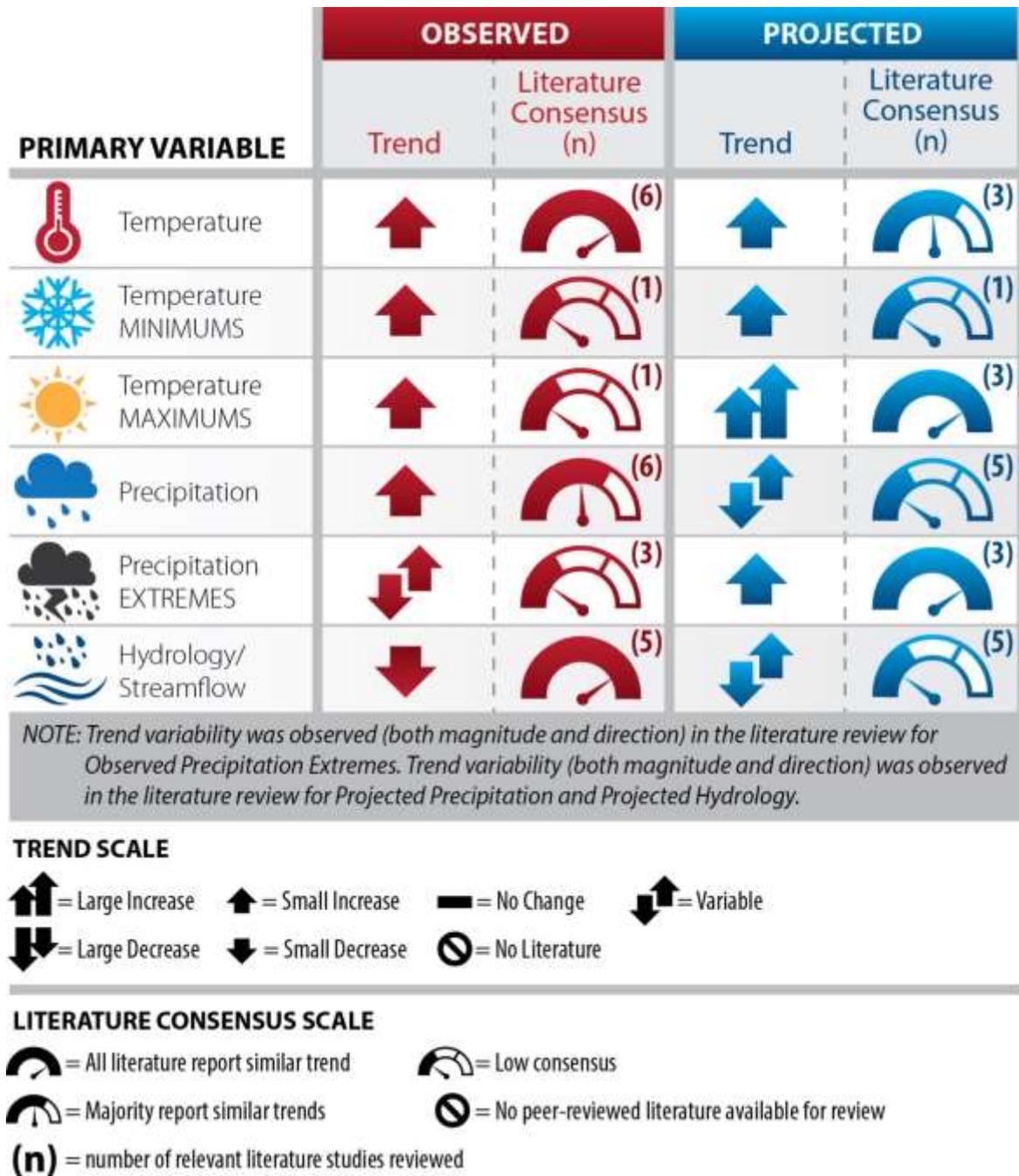
### **3.4. Summary of Future Climate Projection Findings**

There is moderate consensus in the literature that annual average air temperatures will increase in the Pacific Northwest Region, and throughout the country, over the next century. The largest increases are projected for the summer months. A strong consensus is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long-term future compared to the recent past.

Projections of precipitation and streamflow in the study basin are less certain than those associated with air temperature. Results of the studies reviewed here are roughly evenly split with respect to projected increases versus decreases in future annual precipitation. There is, however, a strong consensus among the reviewed studies that future storm events in the region will be more intense and more frequent compared to the recent past.

Similarly, clear consensus is lacking in the hydrologic projection literature. For example, projections generated by coupling GCMs with macro-scale hydrologic models in some cases indicate little change in future streamflows but in other cases indicate a potential increase in runoff in the study region. This lack of consensus across the literature is likely due to the varied topography of the region and the current ability of GCMs and regional climate models to consistently resolve topographic effects from local climate forcings.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in **Figure 3.13**.



**Figure 3.13.** Summary matrix of observed and projected climate trends and literary consensus.

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## 4. Business Line Vulnerabilities

The Pacific Northwest Region encompasses Washington State, the majority of Oregon and Idaho, the western part of Montana, and a small pocket of Wyoming. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE's missions, a set of primary USACE business lines were identified. They include:

- Navigation
- Flood Risk Management
- Water Supply
- Ecosystem Restoration
- Hydropower
- Recreation
- Emergency Management
- Regulatory
- Military Programs

Navigation is an important mission of USACE in the Pacific Northwest Region. By the middle of the century, the frequency and intensity of large storm events and associated flooding are expected to increase. In addition, the region may experience increases in ambient air temperature and a broader range of extremes in water availability, which has implications for water levels and thus the ability for vessels to navigate and dock at ports.

USACE implements flood risk management projects in the region to limit flooding. Increased precipitation event frequency and intensity are predicted for the region. This may cause increased runoff and may cause flash floods if the storms are intense. Flood risk management projects may be very important for reducing the residual flooding impacts due to extreme storm events, which are predicted to be more frequent and intense.

USACE also maintains and operates several fresh water supplies to maintain water quality in the region. Streamflow variability along with the contrast between increasing mean air temperatures and the increased frequency and magnitude of heat waves will make managing competing water needs a challenge, especially when water demand is high and water supply is low.

While this report does not highlight the impacts of sea level change, changes in coastal conditions can have impacts which penetrate to inland water bodies. Sea levels along the Pacific Northwest coastline of the United States are projected to increase and may exacerbate salt water intrusion into freshwater water supply. Tools and information related to sea level change can be found on the USACE Responses to Climate Change website (USACE, 2014).

USACE implements ecosystem restoration projects in the Pacific Northwest Region. Increased ambient air temperatures and heat wave days, will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air and water temperatures are

associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies.

Increased storm intensities and frequencies may pose complications to planning for ecosystem needs and lead to variation in flows. This may be particularly true during dry years, when water demands for conflicting uses may outweigh water supply.

Thousands of mega-watts (MW) of hydropower are generated in the Pacific Northwest Region. By the end of the century, large storm events are expected to increase in the region, which may be beneficial for the region's hydropower plants, as flooding and increased river flows may lead to increased power generation. However, in extreme cases excess flooding may present some operational issues at these project sites. Conversely, there may also be times during any given year where flows and reservoir levels are reduced due to high temperatures and drought conditions, which diminish the amount of power that may be generated by the hydropower plants.

Recreational facilities in the Pacific Northwest Region offer several benefits to visitors as well as positive economic impacts. Extended heat wave duration and increased heat wave temperatures along with the increased frequency and intensity of extreme storm events have the potential to decrease the number of visitors to USACE's recreational facilities. Periods of extreme high heat poses human health concerns and higher water temperatures can result in algal blooms and other water quality issues which may cause health risks for those involved in aquatic activities. An increase in extreme storm events may make recreational activity difficult, dangerous, or impossible.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency managers and assigned staff in each region and subregion that are able to quickly mobilize. Extreme storm events are capable of creating emergency situations in which USACE would be needed to provide assistance in the Pacific Northwest Region. These types of storms are capable of intense precipitation and winds. Since these may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

USACE's regulatory mission has a serious commitment to protecting aquatic resources while allowing for reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulations or an increase in the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services include the rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. The interrelationships between business lines must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt. **Figure 4.1** summarizes the projected climate trends and impacts on each of the USACE business lines.

CLIMATE VARIABLE	VULNERABILITY
 Increased Ambient Temperatures	<p>Air temperatures are expected to increase 1.8-5.4°C (3.2-9.7°F) by the end of the century, and are expected to create the following vulnerabilities on the business lines in the region:</p> <ul style="list-style-type: none"> <li>• Loss of vegetation from increased periods of heat and variable streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed.</li> <li>• Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system.</li> <li>• Variable flows, have implications for maintaining water levels in the rivers and lakes.</li> <li>• Risk of wildfires during hot and dry conditions may cause an increased risk of wildfires, especially in heavily forested and dry areas. Flora and fauna that are not drought resistant can also be impacted by longer drought conditions, which may reduce opportunities for recreational wildlife viewing.</li> </ul> <p><b>BUSINESS LINES IMPACTED:</b>       </p>
 Increased Maximum Temperatures	<p>Air temperature extremes are expected to increase 2.5-8°C (4.5-14.4°F) by the end of the century, with the number of heat wave days per year increasing by up to 75 days. This is expected to create the following vulnerabilities on business lines in the region:</p> <ul style="list-style-type: none"> <li>• Increased water temperatures leading to water quality concerns, particularly for the dissolved oxygen (DO) levels, growth of nuisance algal blooms and influence on wildlife and supporting food supplies.</li> <li>• Increased evapotranspiration.</li> <li>• Increased human health risk from extended heat waves, impacting recreational visitors and increasing the need for emergency management.</li> </ul> <p><b>BUSINESS LINES IMPACTED:</b>       </p>
 Increased Storm Intensity and Frequency	<p>Extreme storm events may become more frequent and intense over the coming century which are expected to influence the following vulnerabilities on business lines in the region:</p> <ul style="list-style-type: none"> <li>• Increased runoff during an event, which may carry pollutants to receiving water bodies, decreasing water quality.</li> <li>• Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns.</li> <li>• Change in engineering design standards to accommodate new extreme storms magnitudes.</li> <li>• Increased flash flooding, which may have negative consequences for all infrastructure, habitats, and people in the area.</li> </ul> <p><b>BUSINESS LINES IMPACTED:</b>       </p>
 Streamflow Variability	<p>Streamflow may have more variability in the region. Runoff may increase up to 200mm/yr especially in coastal regions and in the winter. The region may also experience low flows and a change in the timing of the peak flow by the end of the century. This may result in:</p> <ul style="list-style-type: none"> <li>• Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality.</li> <li>• Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns.</li> <li>• Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area.</li> <li>• Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system.</li> <li>• Decrease in flows may result from periods of drought and reduced streamflow has implications for maintaining water levels in the rivers.</li> </ul> <p><b>BUSINESS LINES IMPACTED:</b>       </p>
 Sea Level Rise	<p>Sea level rise may exacerbate saltwater intrusion into fresh water supplies.</p> <p><b>BUSINESS LINES IMPACTED:</b> </p>

*NOTE: The Regulatory and Military Program business lines may be impacted by all climate variables.*

 = Navigation  = Flood Risk Management  = Ecosystem Restoration  = Hydropower  = Recreation  = Water Supply  = Emergency Management

**Figure 4.1.** Summary of projected climate trends and impacts on USACE business lines

**Appendix A: References Climate/Hydrology Summary Table**

References	Observed								Projected												
	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	
CDM Smith (2012)																					
Dettinger MD (2012)											X	X		X							
Döll P, Zhang J (2010)																X					
Elguindi N, Grundstein A (2013)											X			X							X
Elsner et al (2009)																X					
Grundstein A (2009)				X				X													
Grundstein A, Dowd J (2011)	X	X	X																		
Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, Hanasaki N, Heinke J, Ludwig F, Voss F, Wiltshire AJ (2013)														X		X					
Kalra A, Piechota TC, Davies R, Tootle GA (2008)						X															
Kunkel KE, Liang X-Z, Zhu J (2010)											X		X								
Liu Y, Goodrick SL, Stanturf JA (2013)											X		X	X	X						
Luce CH, Holden ZA (2009)						X															
MacDonald GM (2010)	X			X																	
McRoberts DB, Nielsen-Gammon JW (2011)				X																	
Milly PC, Dunne KA, Vecchia AV (2005)											X										
Mote P, A., Snover K, Capalbo S, Eigenbrode SD, Glick P, Littell J, Raymondi R, Reeder S (2014)	X			X							X			X	X						
Mote P, Hamlet A, Salathé E (2008)						X															
Mote PW (2006)						X															
Payne JT, Wood AW, Hamlet AF, Palmer RN, Lettenmaier DP (2004)											X			X							
Pryor SC, Howe JA, Kunkel KE (2009)				X	X																
Rosenberg E, Keys P, Booth D, Hartley D, Burkey J, Steinemann A, Lettenmaier D (2010)				X	X									X	X						
Sagarika S, Kalra A, Ahmad S (2014)						X															
Scherer M, Diffenbaugh N (2014)											X		X								
Schwartz MD, Ault TR, Betancourt JL (2013)	X							X													
Tebaldi C, Adams-Smith D, Heller N (2012)	X																				
Thomson AM, Brown RA, Rosenberg NJ, Srinivasan R, Izaurralde RC (2005)																X					
USACE (2014)																X					
Walsh J, Wuebble D, Hayhoe K, Kossin J, Kunkel K, Stephens G, Thorne P, Vose R, ..., Kennedy J, Somerville R (2014)	X																				
Wang H, Schubert S, Suarez M, Chen J, Hoerling M, Kumar A, Pegion P (2009)	X			X																	
Wang J, Zhang X (2008)				X	X									X	X						
Westby RM, Lee Y-Y, Black RX (2013)	X	X																			

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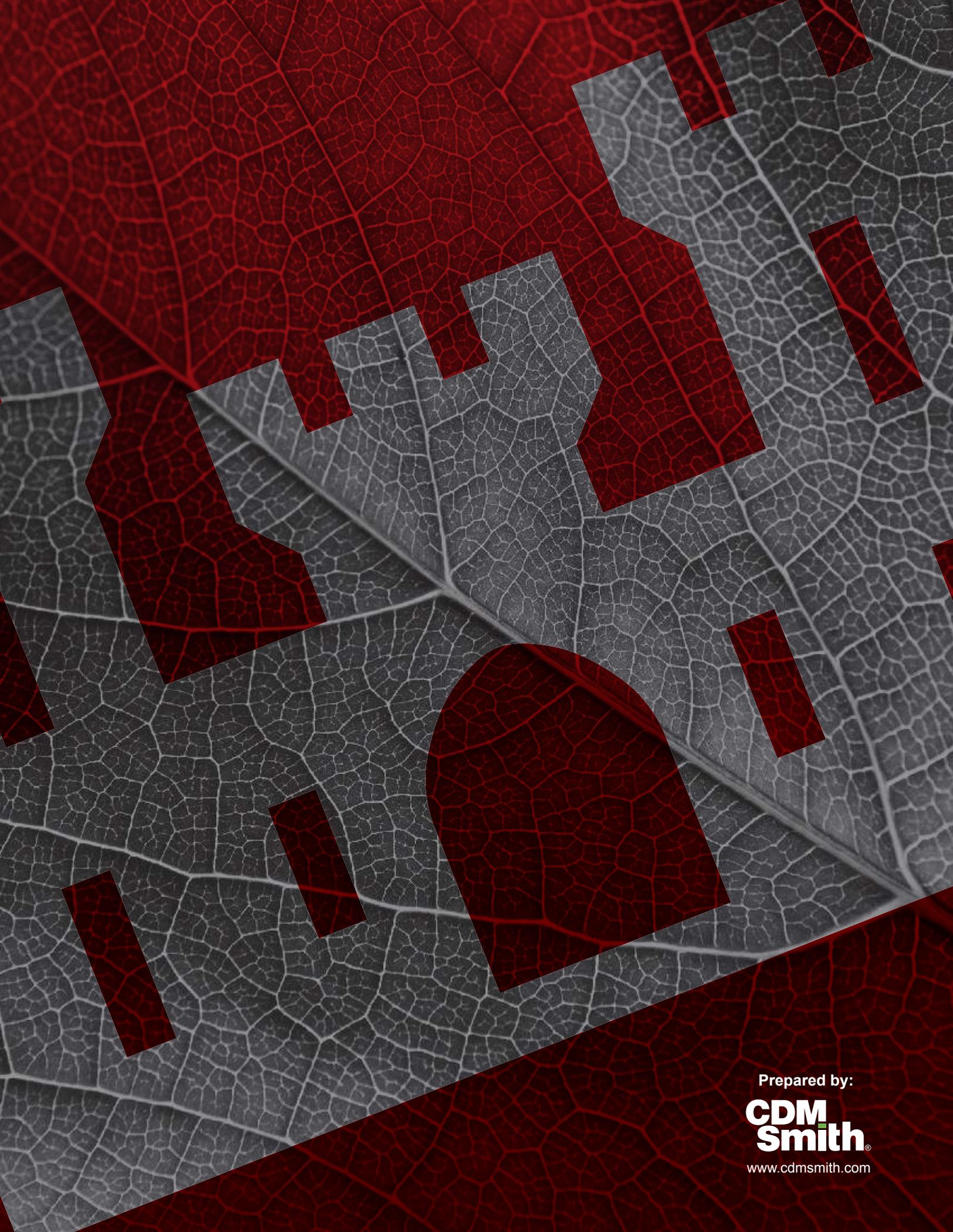
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Prepared by:

**CDM  
Smith**<sup>®</sup>

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