Summary of Projected Changes in Physical Conditions Across the Colville Tribes Study Area

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Prepared by the UW Climate Impacts Group as technical input for The Colville Tribes Natural Resources Climate Change Vulnerability Assessment

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1 INTRODUCTION

The Colville Tribes Natural Resources Climate Change Vulnerability Assessment aims to provide a baseline understanding of how climate change is likely to affect priority species and habitats in the Colville Tribes area of interest (also referred to as the Colville Tribes study area; see Figure 1). Climate impacts on human systems (e.g., health, infrastructure) are not considered in the assessment.

This report, *Summary of Projected Changes in Physical Conditions across the Colville Tribes Study Area*, has been developed by the University of Washington Climate Impacts Group (CIG) as technical input for the vulnerability assessment, summarizing observed and projected climatic changes across the area of interest. The climate-relevant variables explored herein were selected collaboratively by the CIG and Colville Tribes Natural Resources staff because of their expected influence on natural resources vulnerability, and included air temperature, precipitation, snowpack, runoff, streamflow, flooding, and water temperature. Most projected changes in these variables are summarized for mid-century (30-year average around the 2050s) and end of century (30-year average around the 2080s). Expected effects of climate change on landslides and forest disturbances (e.g., wildfire, insects, and disease) are also briefly summarized.

Because this document draws from the breadth of existing datasets and published studies, time periods and spatial scales of the information presented vary. Whenever possible, we provide projections summarized across the Colville Tribes study area (Figure 1). However, some data are only available for broader geographic areas, such as Washington State or the contiguous United States.

Colville Tribes Study Area

The Colville Tribes study area lies in the rain shadow of the Cascade Mountains; consequently, its climate is strongly continental, with hot, dry summers and cold, dry winters. Precipitation is generally in the form of snow during the winter months. This region includes the Okanogan Highlands to the north, Columbia Basin toward the center, and the Blue Mountains to the south. Overall, temperatures are colder at higher elevations and latitudes and warmer at lower elevations and latitudes, such as within the Columbia Basin.

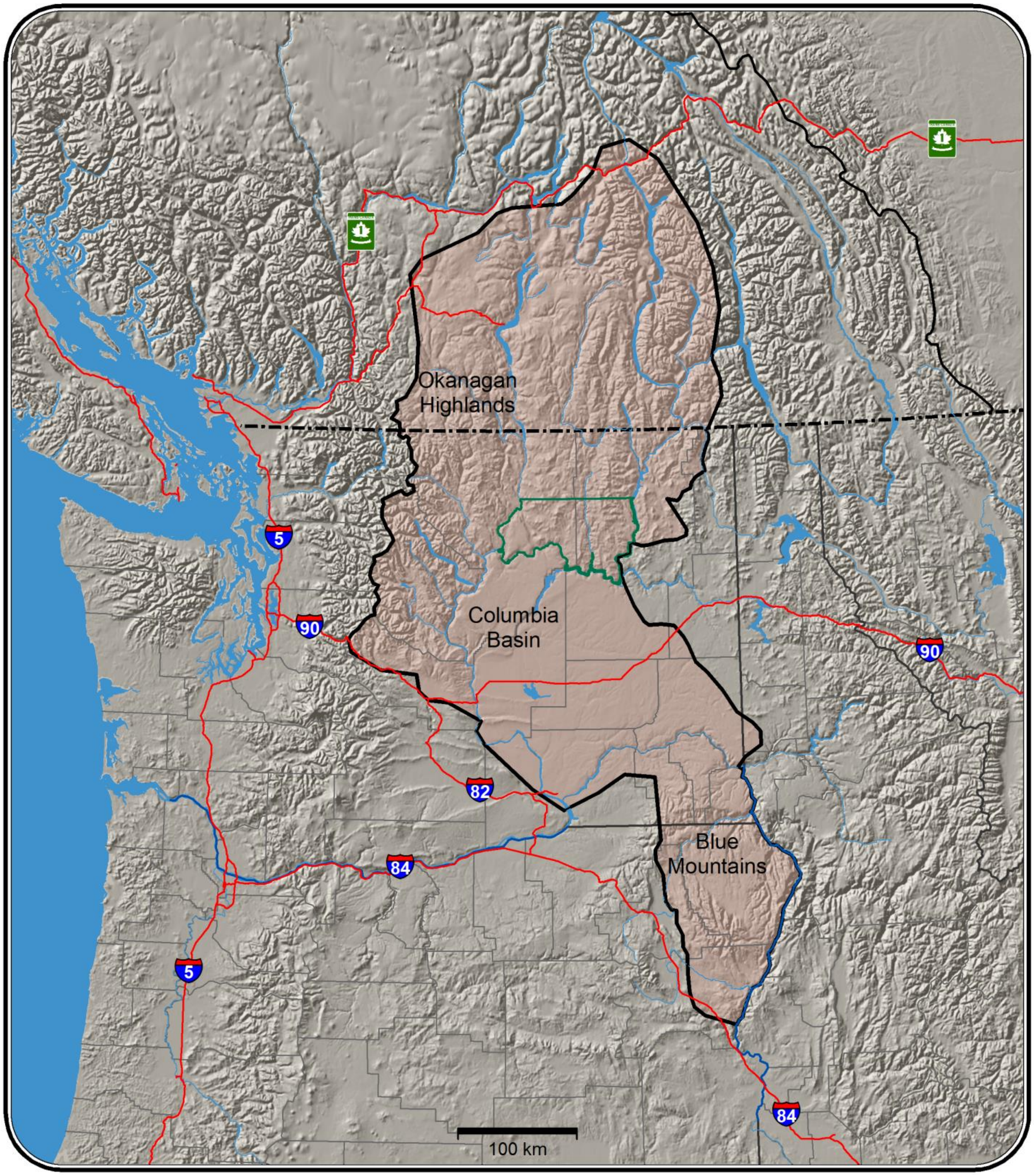

Figure 1. Colville Tribes Natural Resources Climate Change Vulnerability Assessment Study Area (outlined in black) and the Colville Reservation (outlined in green).

2 OBSERVED CLIMATIC TRENDS

Observational data show that climate in the Pacific Northwest is warming and that this trend will likely continue for at least the next century (IPCC 2013). While it can be challenging to attribute exactly how much of this warming is due to rising greenhouse gas (GHG) emissions versus natural variability (see Box 1), there is a high level of certainty that the region will continue to warm in the future due to human-caused climate change (IPCC 2013).

As summarized in a recent synthesis report, *Climate Change Impacts and Adaptation in Washington State: Technical Summaries for Decision Makers* (Snover et al. 2013), observed changes in regional temperature and precipitation include the following[1]:

- Pacific Northwest average annual temperature warmed about +0.72°C between 1895 and 2011, with statistically-significant warming occurring in all seasons except spring (Snover et al. 2013).
- The frost-free season (and the associated growing season) for the Pacific Northwest has lengthened by 35 days (±6 days) from 1895 to 2011 (Kunkel et al. 2013).
- There are no statistically-significant long-term (1895–2011) annual or seasonal trends in Pacific Northwest precipitation (Kunkel et al. 2013, Mote et al. 2013). Trends in heavy precipitation are equally ambiguous; most studies find slightly increasing trends but few are statistically-significant and results are sensitive to the assessed time period and method of analysis.

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[1] Observed trends are summarized here for the Pacific Northwest, rather than the Colville study area, because historical trends for the study area are not currently available.

Box 1. The Role of Climate Variability in Observed Trends and a Changing Climate[*]

In addition to long-term warming caused by human-caused climate change, natural climate variability can also affect Pacific Northwest climate, with impacts to communities and natural resources.

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 generally last for up to a year, typically peaking between December and April; warm phases are referred to as “El Niño” and cool phases as “La Niña”. 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 (Mantua et al. 1997).[2]

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. 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.

The degree to which ENSO and PDO will change in the future as a result of climate change remains unclear. Some studies suggest that climate change may cause a prolonged persistence of El Niño conditions in the equatorial Pacific, although the reasons remain uncertain (Collins 2005, Trenberth and Hoar 1997). Despite this uncertainty, it is generally expected that ENSO and PDO will continue influencing Pacific Northwest climate in the coming decades, sometimes reinforcing or counteracting the effects of human-induced climate change. For example, if PDO were to persist in its cool phase for another decade or two, the long-term global warming trend could be masked in the Pacific Northwest, leading to smaller near-term changes and the possibility of more rapid changes when the PDO returns to warm phase conditions.

[*] *Reproduced from Tohver et al. (2015)*

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[2] This information is based on an analysis of observed 20th Century sea surface temperatures; prior to 1900, the PDO pattern is less persistent. It is unclear which pattern is more indicative of the true behavior of the PDO.

In addition to observed changes in temperature and precipitation, many Pacific Northwest rivers have also experienced shifts in the timing and volume of seasonal streamflow due to long-term changes in temperature, snowpack accumulation, glacial melt, and sedimentation. The vast majority of rivers on the east side of the Cascade Mountains experience peak streamflows in spring or early summer. Some of these rivers have experienced decreased streamflow, most likely due to decreased precipitation at headwaters at higher elevations (Luce et al. 2013). Other important trends that affect regional hydrology include the following:

- April 1 snowpack in the Washington Cascades declined from 15-35% from mid-20th century to 2006, with large declines at low elevations but also with substantial year-to-year variability due to natural variability (Stoelinga et al. 2009, Mote et al. 2008).

- The timing of peak spring streamflow shifted earlier by more than 3 days in 66% of the 241 snowmelt-dominated stream gauges in the Pacific Northwest from 1948–2002 (Stewart et al. 2005).

Although changes in historical stream temperatures within the study area have not yet been summarized, stream temperatures have been shown to have warmed across the Pacific Northwest from 1980-2009 (Isaak et al. 2012). July and August stream temperatures in the Okanagan River can already be stressful for salmonids; further warming could exceed temperatures required for survival of some species, such as Sockeye and Spring Chinook (C. Baldwin, personal communication). Warming stream temperatures in the lower Columbia River could also impede the ability of some migrating salmonids to reach the Okanogan River (see Box 2).

Box 2. Observed Implications of Warming Stream Temperatures in Washington: A Summary of the 2015 Sockeye and Sturgeon Die-off

The drought and unusually hot weather of 2015 caused stream temperatures across the region to increase substantially. This led to particularly warm stream temperatures in the Columbia River and tributaries, which had devastating effects on fish species such as sockeye salmon (*Oncorhynchus nerka)* and white sturgeon (*Acipenser transmontanus)*. Federal and state fisheries biologists estimate that more than 250,000 (about half of the total anticipated run) of Columbia River sockeye salmon died during this event (Harrison 2015). Stream temperatures in the Columbia were measured at 21°C (above the 20°C lethal limit for salmon) for multiple days. It is also estimated that approximately 98% of the sockeye in the Okanogan River died before spawning due to high stream temperatures (C. Baldwin, personal communication).

White sturgeon were also affected by the 2015 drought and hot temperatures. Columbia River water temperature was documented to be warmer than usual (O. Langness, personal communication), stressing these fish. Carcasses from 169 sturgeon were identified by wildlife law enforcement officers during late June and July 2015. Of these, approximately 87% were broodstock, or fish that were over the legal limit (i.e., “oversized”). Most of these individuals were determined to be females in the process of resorption of eggs (atresia) as a result of failure to spawn. By mid-July 2015, the large number of dead broodstock sturgeon prompted regional fishery managers to close down retention fisheries and the catch and release of sturgeon in the Columbia Basin waters upstream of Bonneville Dam, according to Washington Department of Fish and Wildlife (WDFW) staff (O. Langness, personal communication). Information for other areas was not available at the time of this report.

3 PROJECTED CLIMATE CHANGE

To project changes in 21st century climate we used an ensemble of 20 global climate models (GCMs) (see Appendix A) and two scenarios of future GHG emissions. GCMs are used to simulate the physical processes in and between the atmosphere, frozen areas of the earth, and the land surface. The scenarios of future GHG emissions, also referred to as Representative Concentration Pathways (RCPs), apply socio-economic assumptions about future changes in global population, technological advances, and other factors that influence the amount of carbon dioxide and other GHGs emitted into the atmosphere as a result of human activities (Van Vuuren et al. 2011). These scenarios were developed by international climate modeling centers for use by the scientific community to study climate change and potential climate change impacts. Some of the studies that we reference used older emissions scenarios (e.g., B1, A1B, A2, and A1F; Nakicenovic et al. 2000), which are generally similar to the RCP scenarios.

Table 1 and Figure 2 are provided to help the reader understand the scenarios and how they compare to one another.

We used data from the *Integrated Scenarios of the Future Northwest Environment* project to summarize projected changes in climate across the study area.[3] This project uses projections from 20 GCMs (Appendix A) statistically downscaled using the Multivariate Adaptive Constructed Analogs method (Abatzoglou and Brown 2012). We simulated an ensemble of these 20 GCMs for two future GHG scenarios: RCP 4.5 and RCP 8.5 (see Table 1). RCP 4.5 was chosen because it represents a low emissions scenario in which emissions stabilize by mid-century and fall sharply thereafter, whereas RCP 8.5 represents a high emissions scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century.

We also summarize research that applied a regional climate model – the Weather Research and Forecasting (WRF) model (Salathé et al. 2010). Regional climate models are similar to GCMs in how they model physical processes, but differ in that they cover a more limited geography and are usually run at finer spatial resolutions. Regional climate models can model regional weather patterns and local topography better than GCMs, but are computationally intensive to run.

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[3] https://climate.northwestknowledge.net/IntegratedScenarios/index.php

Table 1. Greenhouse gas emissions scenarios used in global and regional climate studies. Table modified from Snover et al. (2013).

IPCC Fifth Assessment Report (2013) scenarios	Comparable IPCC Third and Fourth Assessment Report (2001–2013) scenarios	Scenario characteristics	Related qualitative description
RCP 2.6	No analogue in previous scenarios	An extremely low scenario that reflects aggressive GHG reduction and sequestration efforts	"Very Low"
RCP 4.5	Very close to B1 by 2100, but higher emissions at mid-century	A low scenario in which GHG emissions stabilize by mid-century and fall sharply thereafter	"Low-Medium"
RCP 6.0	Similar to A1B by 2100, but closer to B1 at mid-century	A medium scenario in which GHG emissions increase gradually until stabilizing in the final decades of the 21st century	"Medium"
RCP 8.5	Nearly identical to A1FI[4]	A high scenario that assumes continued increases in GHG emissions until the end of the 21st century	"High"

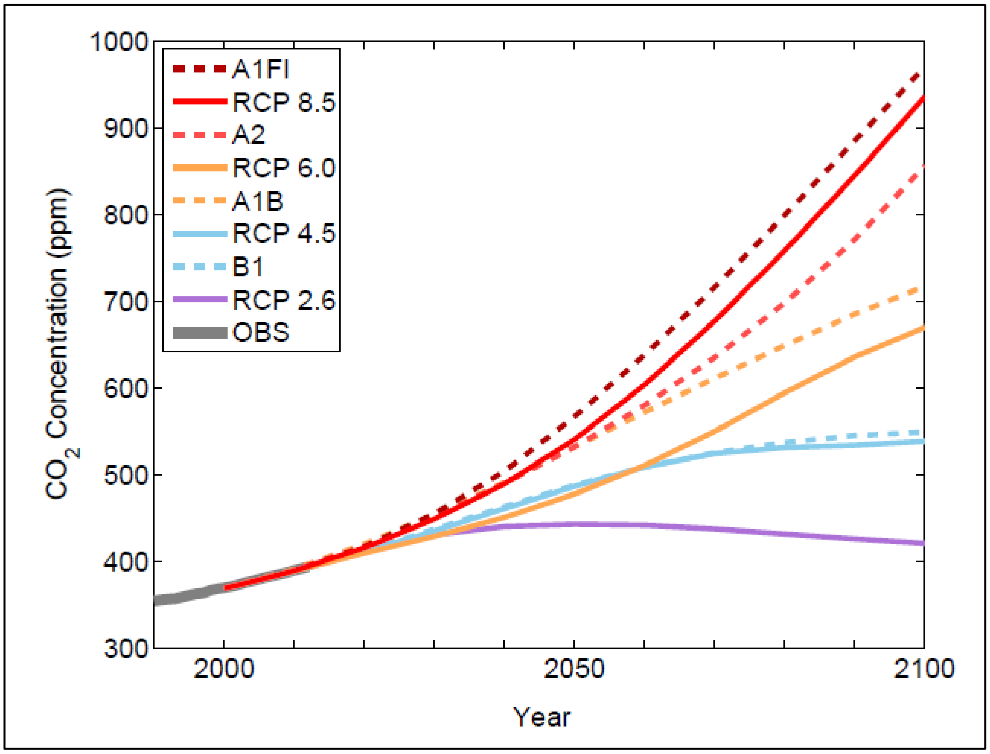

Figure 2. Total carbon concentration in parts per million (ppm) for RCP (solid lines) and SRES (dashed lines) greenhouse gas emissions scenarios for the rest of the century. Figure reproduced from Snover et al. (2013).

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[4] The A2 greenhouse gas scenario is between the RCP 6.0 and 8.5 scenarios, see Figure 2.

3.1 Temperature Change

All climate models project warming in the Pacific Northwest during the 21st century as a result of rising atmospheric GHG concentrations, with the total amount of change dependent on the rate of GHG emissions and the global climate model used (see Table 2) (Kunkel et al. 2013). Within the Colville Tribes study area, temperature changes are most pronounced for seasonal maximum and minimum average temperatures (Table 2, Figures 3-4, and Appendix B).

Table 2. Projected changes in temperature for the Pacific Northwest and the Colville Tribes study area.

Variable	Projected Change for the 2050s[5]	Projected Change for the 2080s[6]
Pacific Northwest		
Average annual temperature	+2.4°C for RCP 4.5 and +3.2°C for RCP 8.5 relative to 1950-1999[7]	+2.9°C for RCP 4.5 and +4.8°C for RCP 8.5 relative to 1950-1999[7]
Colville Tribes Study Area		
Average annual temperature	+2.6°C for RCP 4.5 and +3.4°C for RCP 8.5 relative to 1950-1999	+3.3°C for RCP 4.5 and +5.6°C for RCP 8.5 relative to 1950-1999
Maximum summer temperature	+3.5°C for RCP 4.5 and +4.6°C for RCP 8.5 relative to 1970–1999 (Figure 4)	+4.2°C for RCP 4.5 and +7.3°C for RCP 8.5 relative to 1970–1999 (Figure 4)
Minimum winter temperature	+2.8°C for RCP 4.5 and +3.4°C for RCP 8.5 relative to 1970–1999 (Figure 5)	+3.5°C for RCP 4.5 and +5.7°C for RCP 8.5 relative to 1970–1999 (Figure 5)

In addition to average temperatures, we also summarized projected changes in key climatic variables relevant to human health, agriculture, and natural resource management within the Colville Tribes study area. Averaging all climate models for the RCP 8.5 emissions scenario, it is projected that, on average, there will be 14% more consecutive dry days by mid-century and 25% more consecutive dry days by the end of the century. It should be noted that these numbers are annual averages across a 30-year period and that year-to-year variability will also occur.

Another key variable is the number of frost days, defined as the annual count of days when the daily minimum temperature is below 0°C. Frost days are projected to decline by 28% by mid-century and 46% by the end of the century. Similarly, "icing days" are defined as the annual count of days when the daily maximum temperature is below 0°C. Icing days are projected to

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[5] Specifically, "2050s" refers to the 30-year average spanning from 2041 to 2

[6] Specifically, "2080s" refers to the 30-year average spanning from 2070 to 2099.

[7] Snover et al. 2013

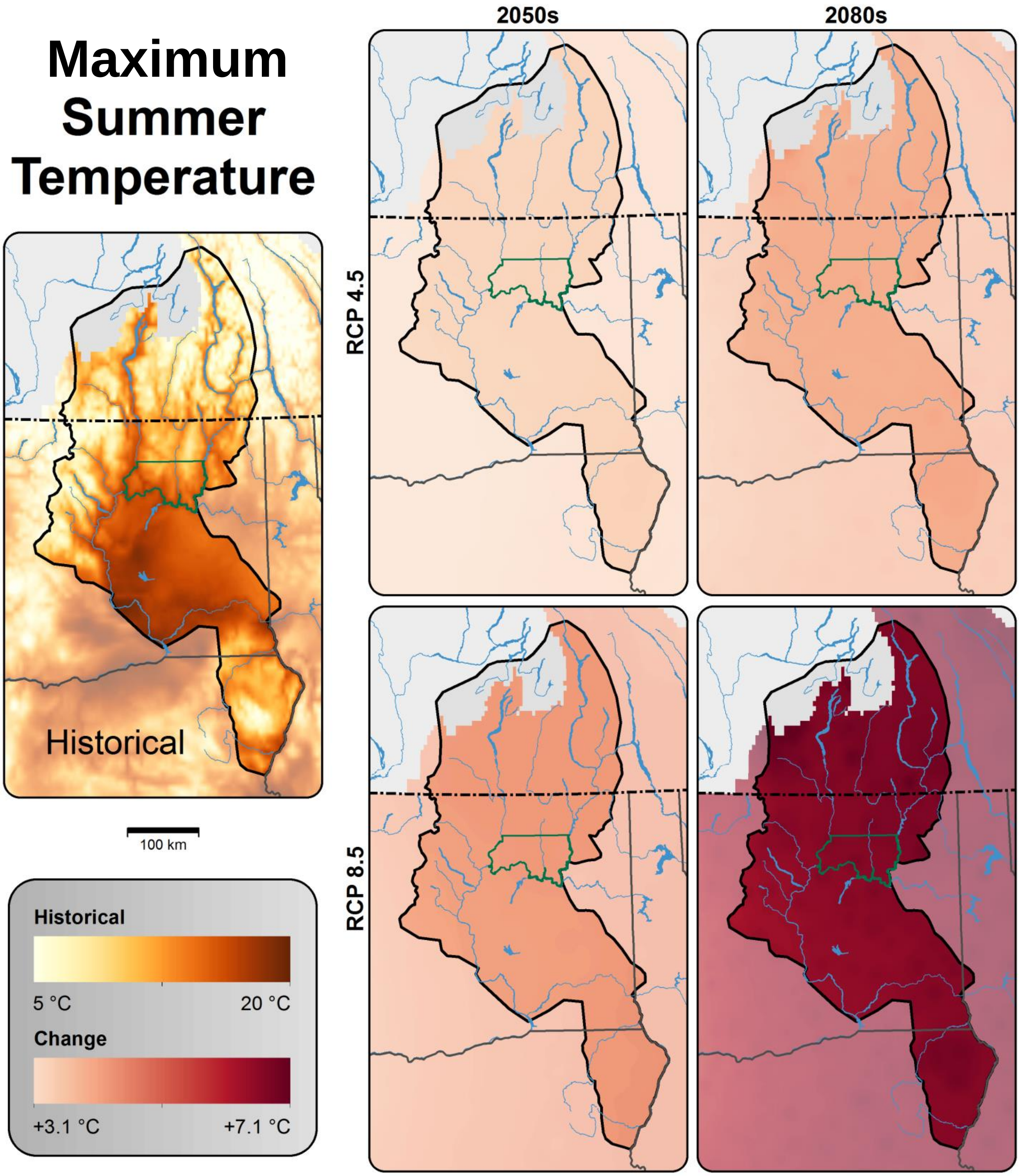

Figure 3. Maximum average summer (June–August) temperature for historical (1970–1999), mid-century (2050s), and end of century (2080s) for two future scenarios (RCP 4.5 (top) and RCP 8.5 (bottom)) across the Colville Tribes study area. Future projection maps represent temperature change from historical conditions. Average summer temperature is projected to rise between +3.5°C (top left) and +4.6°C (bottom left) by the 2050s and between +4.2°C (top right) and +7.3°C (bottom right) by the 2080s. Projected increases in average summer temperature are more pronounced than projected increases in average annual temperature.

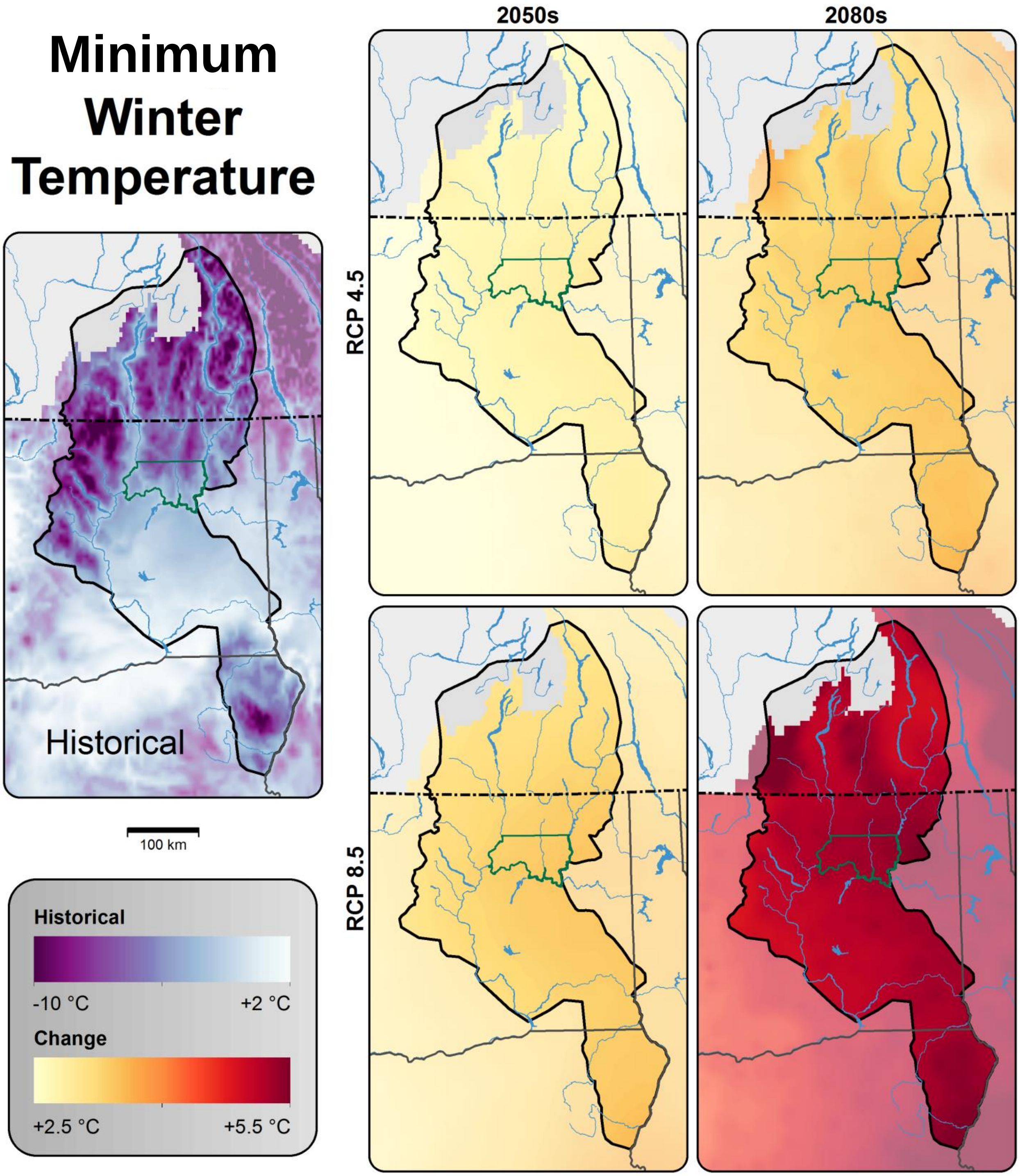

Figure 4. Minimum average winter (December–February) temperature for historical (1970–1999), mid-century (2050s), and end of century (2080s) for two future GHG scenarios (RCP 4.5 (top) and RCP 8.5 (bottom)) across the Colville Tribes study area. Future projection maps represent temperature change relative to historical conditions. Average winter temperature is projected to rise between +2.8°C (top left) and +3.4°C (bottom left) by the 2050s and between +3.5°C (top right) and +5.7°C (bottom right) by the 2080s. Projected increases in average winter temperature are more pronounced than projected increases in average annual temperature.

decline 41% by mid-century and 64% by the end of the century. Growing degree days, used to measure heat accumulation and predict changes in the timing of biological events (i.e., phenology), are projected to increase across the Colville Tribes study area (see Table 3). The number of hot days, defined as the number of days when the average maximum temperature is in the 90th percentile, are projected to increase by 173% by mid-century and 323% by end of the century.

The projected increase in the frequency of hot days is further supported by another study that applied a regional climate model, WRF (Salathé et al. 2010). This study showed that the number of consecutive hot days is projected to increase, especially in southcentral Washington, as illustrated by the size of the red circles in Figure 5. Defining a heat wave as an episode of three or more days where the daily heat index exceeds 32°C, Salathé et al. (2010) estimate that there could be up to three more heat waves each year by mid-century relative to 1970–1999.

Table 3. Projected changes in key climatic variables for the Colville Tribes study area, by mid and end of the century (relative to 1970–1999). Note that growing degree days are reported in the number of days, not the percent change.

Variable	Projected Change	Historical Value (Days)	Average Future Value (Days)	
			2050s	2080s
Consecutive dry days	+14% (2050s) to +25% (2080s)	Not available	Not available	
Frost days	-28% (2050s) to -46% (2080s)	184	134	114
Icing days	-41% (2050s) to -64% (2080s)	Not available	Not available	
Growing degree days (10°C)	+494 more degree days (2050s) to +771 more degree days (2080s)	778	1272	1548
Hot days	+173% (2050s) to +323% (2080s)	12	33	45

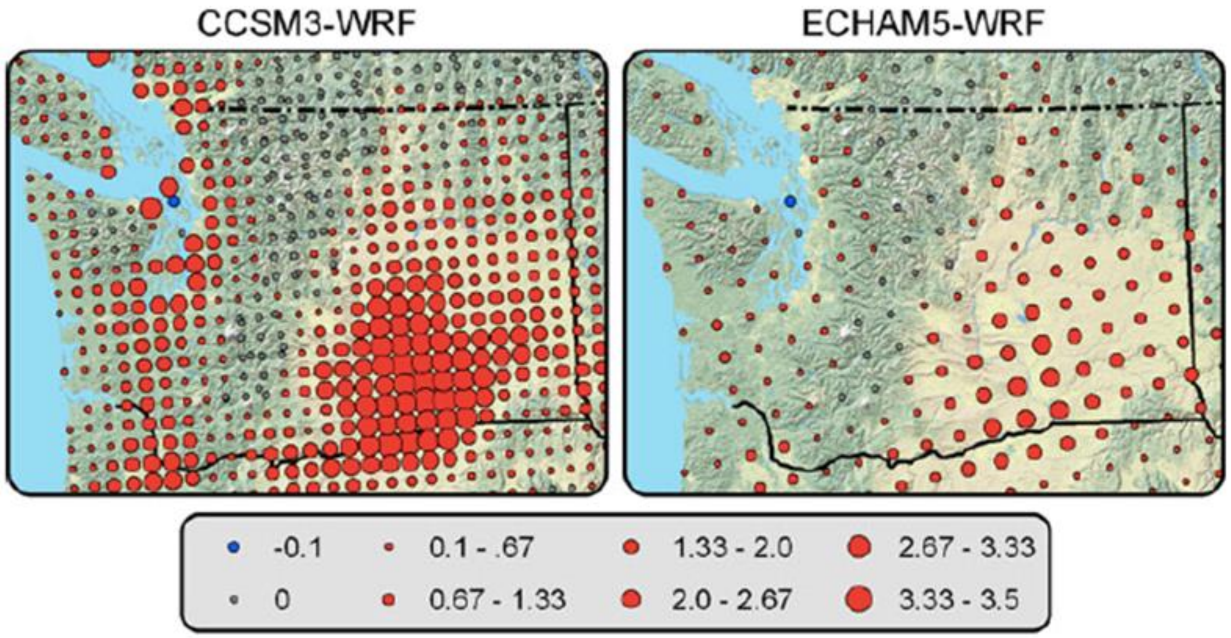

Figure 5. Change in the yearly annual number of heat waves of 3-day duration, as simulated by two versions of a regional climate model (WRF): National Center for Atmospheric Research Community Climate System Model version 3 (CCSM3) (left) and Max Plank Institute, Hamburg, global model (ECHAM5) (right) from 1970–1999 to 2030–2059 for the A1B scenario (a medium scenario in which GHG emissions increase gradually until stabilizing in the final decades of the 21st century). The size of the circles indicates the magnitude of the change and both models agree that southcentral Washington State is projected to have more heat waves. The density of circles reflects differences in the grid spacing used by the two models. Figure reproduced from Salathé et al. (2010).

3.2 Precipitation Change

Average Annual and Seasonal Precipitation

Climate models do not project substantial changes in average annual precipitation across the entire Pacific Northwest. While most models do project modest increases in average annual precipitation as well as winter, spring and fall precipitation, those increases are small relative to the large natural year-to-year variation that characterizes Pacific Northwest precipitation.

Across the Colville Tribes study area, average annual precipitation is projected to increase 6.5% (RCP 4.5) to 7.7% (RCP 8.5) by the end of the century (i.e., 2080s) (see Appendix A). However, precipitation projections differ by season with winter, spring, and autumn projected to become wetter and summer projected to become drier in most locations. Average winter precipitation (December–February) is projected to increase by 12.3% to 17.6% (RCP 8.5) by the end of the century (see Table 4 and Figure 6). By contrast, average summer precipitation (June–August) is projected to decrease by -15.5% to -19.5% (RCP 8.5) by the end of the century (see Table 4 and Figure 7). Precipitation projections for spring and autumn show modest increases (see Appendix C).

Table 4. Projected changes in precipitation for the Colville Tribes study area.

Region and Variable	Projected Change for the 2050s[8]	Projected Change for the 2080s[9]
Average annual precipitation	+4.2% for RCP 4.5 to +5.3% RCP 8.5 relative to 1970–1999	+6.5% for RCP 4.5 to +7.7% RCP 8.5 relative to 1970–1999
Average winter precipitation	+11.1% for RCP 4.5 to 12.6% RCP 8.5 relative to 1970–1999 (Figure 6)	+12.3% for RCP 4.5 to +17.6% for RCP 8.5 relative to 1970–1999 (Figure 6)
Average summer precipitation	-13.5% for RCP 4.5 to -15.5% for RCP 8.5 relative to 1970–1999 (Figure 7)	-9.8% for RCP 4.5 to -19.5% for RCP 8.5 relative to 1970–1999 (Figure 7)

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[8] Specifically, “2050s” refers to the 30-year average spanning from 2041 to 2070.

[9] Specifically, “2080s” refers to the 30-year average spanning from 2070 to 2099.

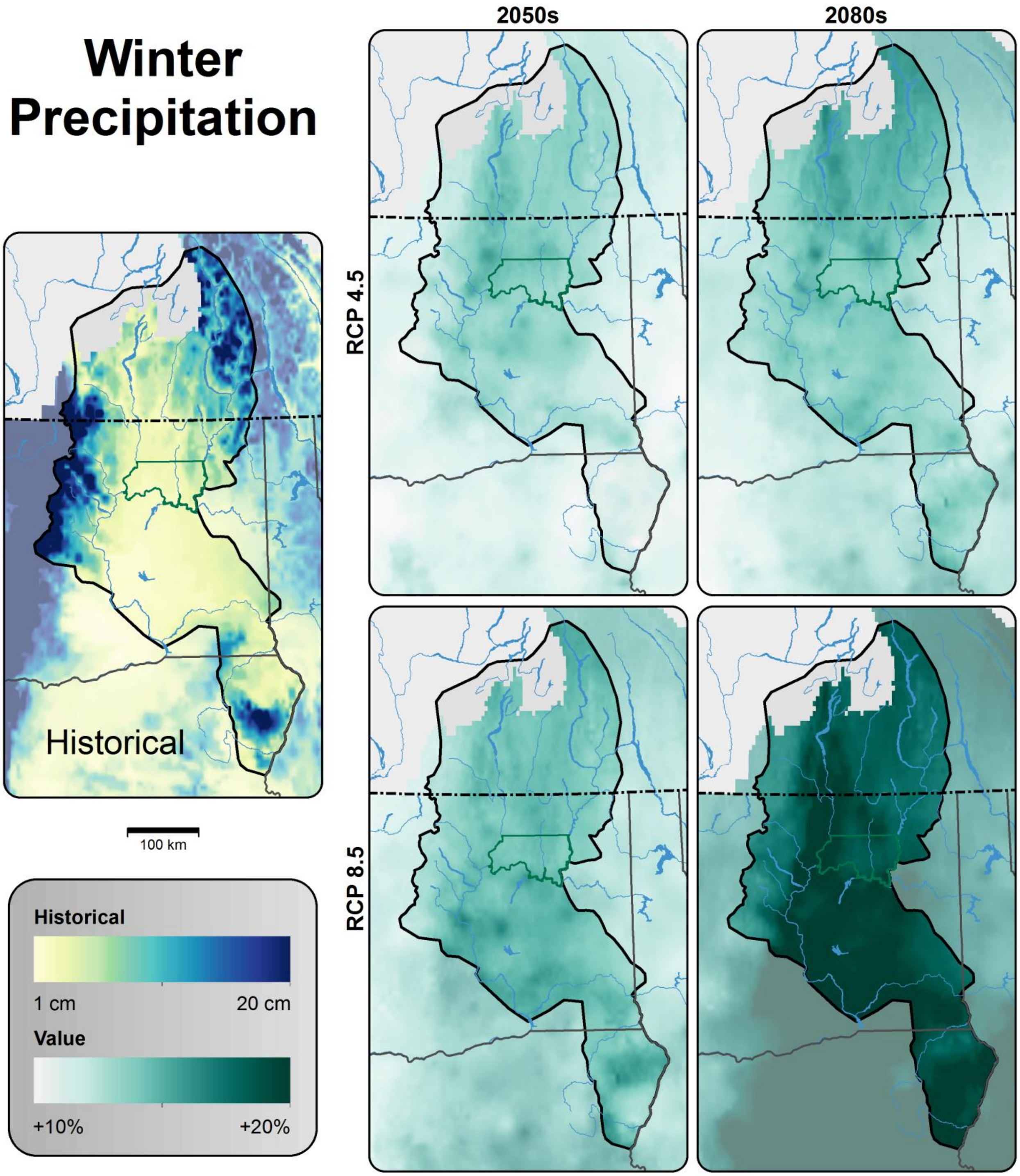

Figure 6. Average winter (December–February) precipitation for historical (1970–1999), mid-century (2050s), and end of century (2080s) for two future scenarios (RCP 4.5 (top) and RCP 8.5 (bottom)) across the Colville Tribes study area. Future projection maps show percent change relative to historical conditions.

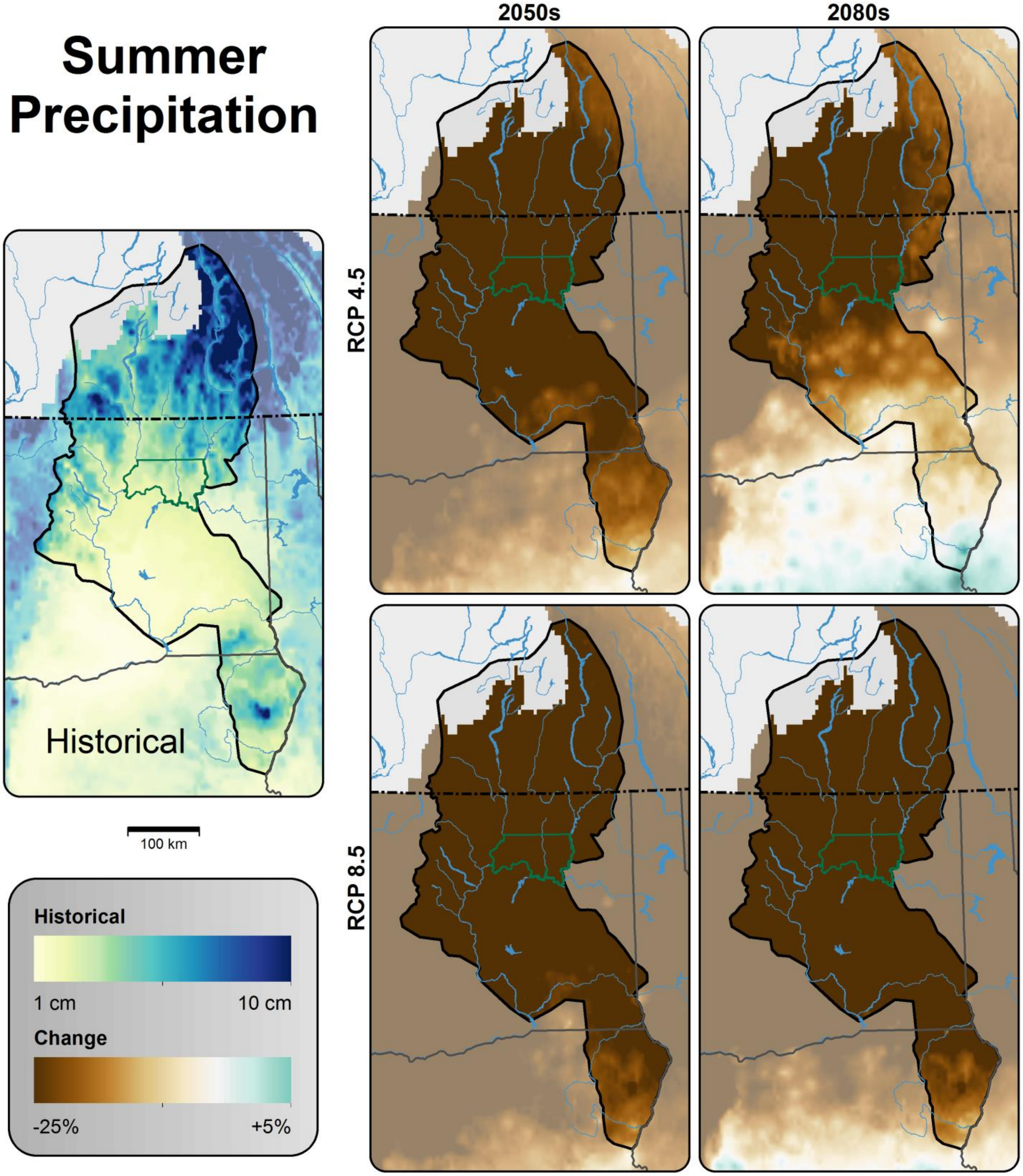

Figure 7. Average summer (June–August) precipitation for historical (1970–1999), mid-century (2050s), and end of century (2080s) for two future scenarios (RCP 4.5 (top) and RCP 8.5 (bottom)) across the Colville Tribes study area. Future projection maps show percent change relative to historical conditions. It should be noted that because only a small amount of precipitation falls during the summer, even small decreases result in a large percentage change.

Extreme Precipitation

Overall, climate models indicate that heavy rainfall events are likely to become more frequent and intense in the Pacific Northwest (Kunkel et al. 2013). Some of these heavy precipitation events may be the result of “atmospheric rivers”: narrow bands of water vapor that can result in heavy precipitation events (Zhu and Newell 1998). However, the impact of atmospheric rivers on precipitation east of the Cascade Mountains is not well known and is a topic of current research. Although GCM projections are not necessarily appropriate to analyze fine-scale changes in climatic variability and extreme precipitation events, regional models like WRF can more reliably simulate some of these changes. As such, Salathé et al. (2010) apply a regional climate model (WRF) for Washington State and project increases in precipitation intensity by mid-century (Figure 8). Specifically, both models (CCSM3-WRF and ECHAM5-WRF) project increases in the fraction of precipitation falling on days with precipitation exceeding the 95th percentile for that location, where the 95th percentile is calculated from the historical simulation. This parameter is also referred to as R95.

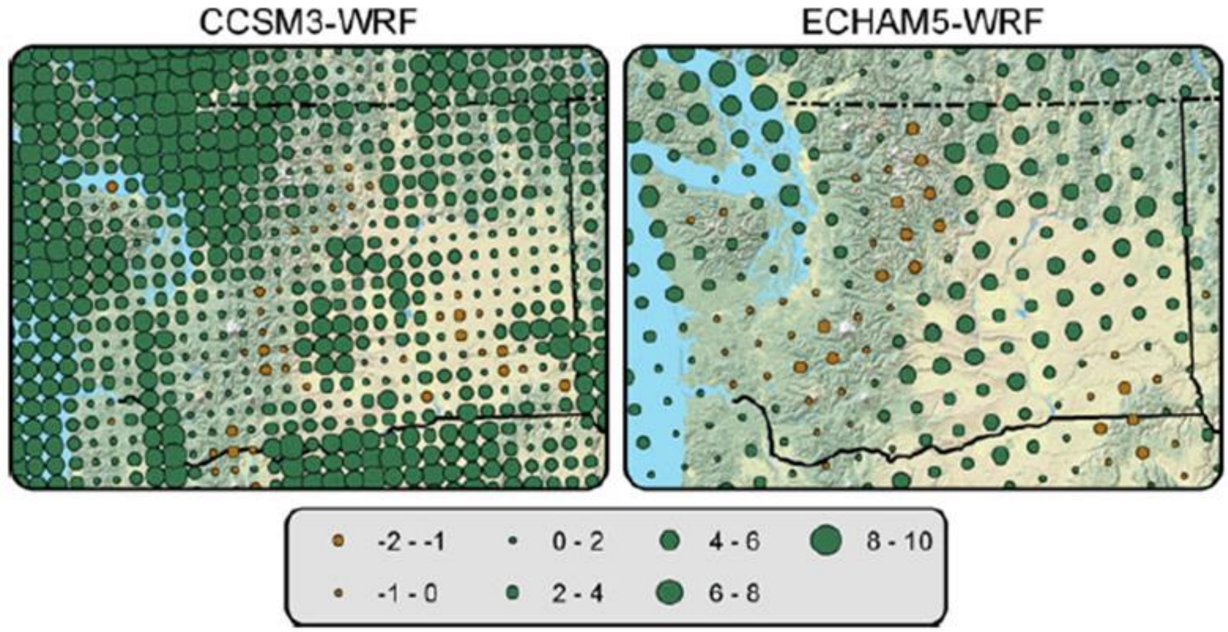

Figure 8. Projected change in heavy rainfall events, as measured by change in the percentage of total precipitation that occurs when daily precipitation exceeds the 20th century 95th percentile (R95) from two regional climate models: CCSM3–WRF (left) and ECHAM5–WRF (right) from 1970–1999 to 2030–2059 for the A1B (medium) emissions scenario. The size of the circles indicates the magnitude of the change; results suggest that portions of the Colville Tribes study area could see large increases in heavy rainfall events (indicated by large circles). The density of the circles reflects differences in the grid spacing used by the two models. Figure reproduced from Salathé et al. (2010).

3.3 Hydrology | Snowpack and Streamflow

Watersheds can generally be defined as being rain-dominated, snow-dominated, or a mix of both (the latter also referred to as transitional, transient, or mixed). Rain-dominated watersheds see heaviest runoff in the fall and winter as precipitation falls predominantly as rain, whereas snow-dominated watersheds see heaviest runoff in the spring or summer when winter precipitation that fell predominantly as snow begins to melt. Transitional watersheds have two peaks in runoff: one in fall/winter (similar to rain-dominated watersheds) and one in spring/summer (similar to snow-dominated watersheds), reflecting precipitation falling as rain early in the rainy season and then turning to snow as temperatures grow colder later in the season (Tohver et al. 2014). The majority of watersheds within the Colville Tribes study area are currently classified as being either snow-dominated or rain-dominated (see Figure 9).

Projected changes in temperature and precipitation will result in a shorter snow season as more precipitation falls as rain and snow melts away earlier in spring. Within the Colville Tribes study area, projected changes in April 1 snow water equivalent (SWE) show large declines, relative to 1970–1999, for both a low-medium (RCP 4.5) and a high emissions scenario (RCP 8.5). The ratio of snow to rain is also projected to decline across the Colville Tribes study area.

- **Average spring snowpack** in Washington State is projected to decline by -56% to -70% by the 2080s (2070–2099, relative to 1916–2006) for a low-medium (B1) and medium GHG scenario (A1B), respectively.[10]
- **April 1 SWE** in the Colville Tribes study area is projected to decline by -41% (RCP 4.5) to -48% (RCP 8.5) for the 2050s, and by -59% (RCP 4.5) to -68% (2080s) for the 2080s.
- **Maximum SWE** in the Colville tribes study area is projected to decline by -21% (RCP 4.5) to -26% (RCP 8.5) by the 2050s, and -24% (RCP 4.5) to -44% (RCP 8.5) by the 2080s (Figure 11).

The consequences of declining snowpack and earlier spring snowmelt depend on the balance of temperature, wintertime rain, and snow accumulation within a watershed. Warmer winter temperatures are expected to cause more winter precipitation to fall as rain rather than snow, which will drive the transition of snow-dominated watersheds to either transitional or rain-dominated. Warmer winter temperatures will also likely contribute to higher winter streamflows and reduced spring snowpack. These changes would result in earlier spring streamflow and lower summer streamflow as warmer temperatures melt snow earlier in the year. Summer streamflows would be reduced both as a function of earlier spring runoff and

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[10] These numbers indicate changes in April 1 Snow Water Equivalent (SWE). SWE is a measure of the total amount of water contained in the snowpack. April 1 is the approximate current timing of peak annual snowpack in the mountains of the Northwest.

higher summer temperatures, which could be compounded by increased evapotranspiration (i.e., the movement of water from plants, water bodies, and soil to the air).

Changes from snow- to transitional- or rain-dominated watersheds are projected to become more pronounced as warming increases. For instance, the ratio of snow to precipitation (as measured by the ratio of snow water equivalent to precipitation) is projected to decline, from 0.4 (RCP 4.5) to 0.37 (RCP 8.5) by the 2050s and 0.37 (RCP 4.5) to 0.28 (RCP 8.5) by the 2080s. A declining ratio of snow to precipitation indicates fewer snow-dominated watersheds and more transitional or rain-dominated watersheds. Historically, watersheds in the Colville Tribes study area have been largely either snow-dominated or rain-dominated, with few transitional watersheds (see Figure 9). However, by the end of the century under the “high” emissions scenario (RCP 8.5), there is a substantial decrease in the number of snow-dominated watersheds and a dramatic increase in the number of rain-dominated watersheds (Figure 9). It should be noted that heavily managed rivers featuring dams or irrigated water systems may be able to mitigate or control some of the changes in streamflow by regulating how much water is stored and released, at least in the short-term.

Additionally, conditions during the summer months are projected to become drier in the Colville Tribes study area. The moisture deficit – the difference between the available water in the soil compared to the soil water holding capacity – during July-September across the Colville Tribes study area is projected to increase by 20% (RCP 4.5) to 24% (RCP 8.5) by the 2050s and 22% (RCP 4.5) to 31% (RCP 8.5) by the 2080s.

Runoff

Projected changes in average annual runoff across the Colville Tribes study area show declines during July of -7% (RCP 4.5) to -9% (RCP 8.5) for mid-century and -9% (RCP 4.5) to -12% (RCP 8.5) by the end of the century. However, like many variables, runoff varies by season; projections for April–September show decreases of -0.05% (RCP 4.5) to -1.4% (RCP 8.5) by mid-century and -1.7% (RCP 4.5) to -6.3% (RCP 8.5) by the end of the century (Figure 12). By contrast, projections for October–March show increases of 23% (RCP 4.5) to 30% (RCP 8.5) by mid-century and 34% (RCP 4.5) to 55% (RCP 8.5) by the end of the century.

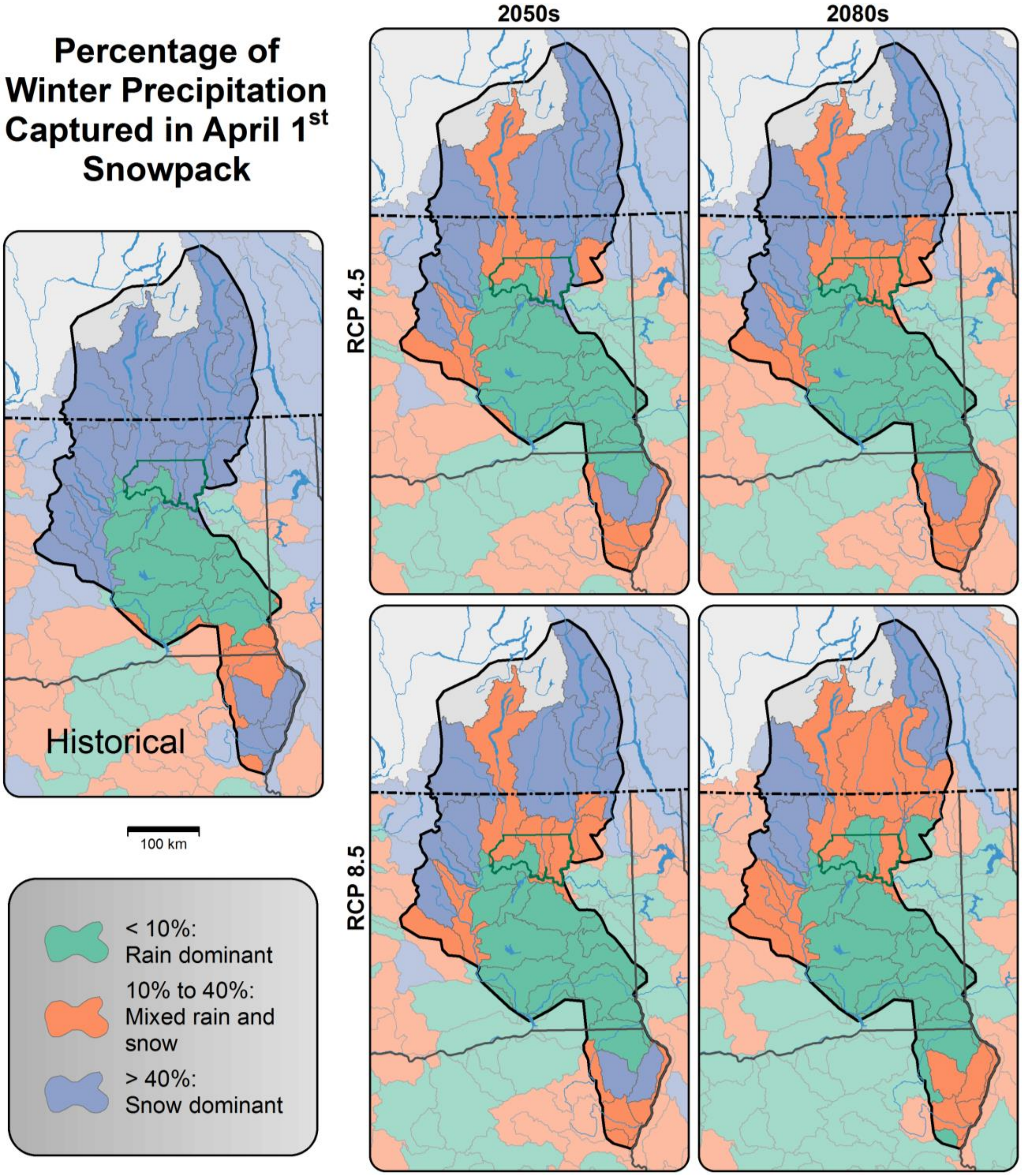

Figure 9. Changing hydrology due to warming temperatures in the Colville Tribes study area. Maps above indicate historical (1970–1999) and future projected watershed classifications, based on the proportion of winter precipitation stored in peak annual snowpack, under a low-medium (RCP 4.5) and high (RCP 8.5) GHG scenarios. Green shading indicates warm (rain-dominant) watersheds, which receive little winter precipitation in the form of snow. In these basins, streamflow peaks during winter months and warming is projected to have less of an effect compared to snow and transition watersheds. Blue shading indicates cold (snow-dominant) watersheds, which receive more than 40% of their winter precipitation as snow. Depending on elevation, these basins are likely to experience increasing winter precipitation as rain and increased winter flows in the future. The orange shading indicates transitional watersheds, which receive between 10% and 40% of their winter precipitation as snow.

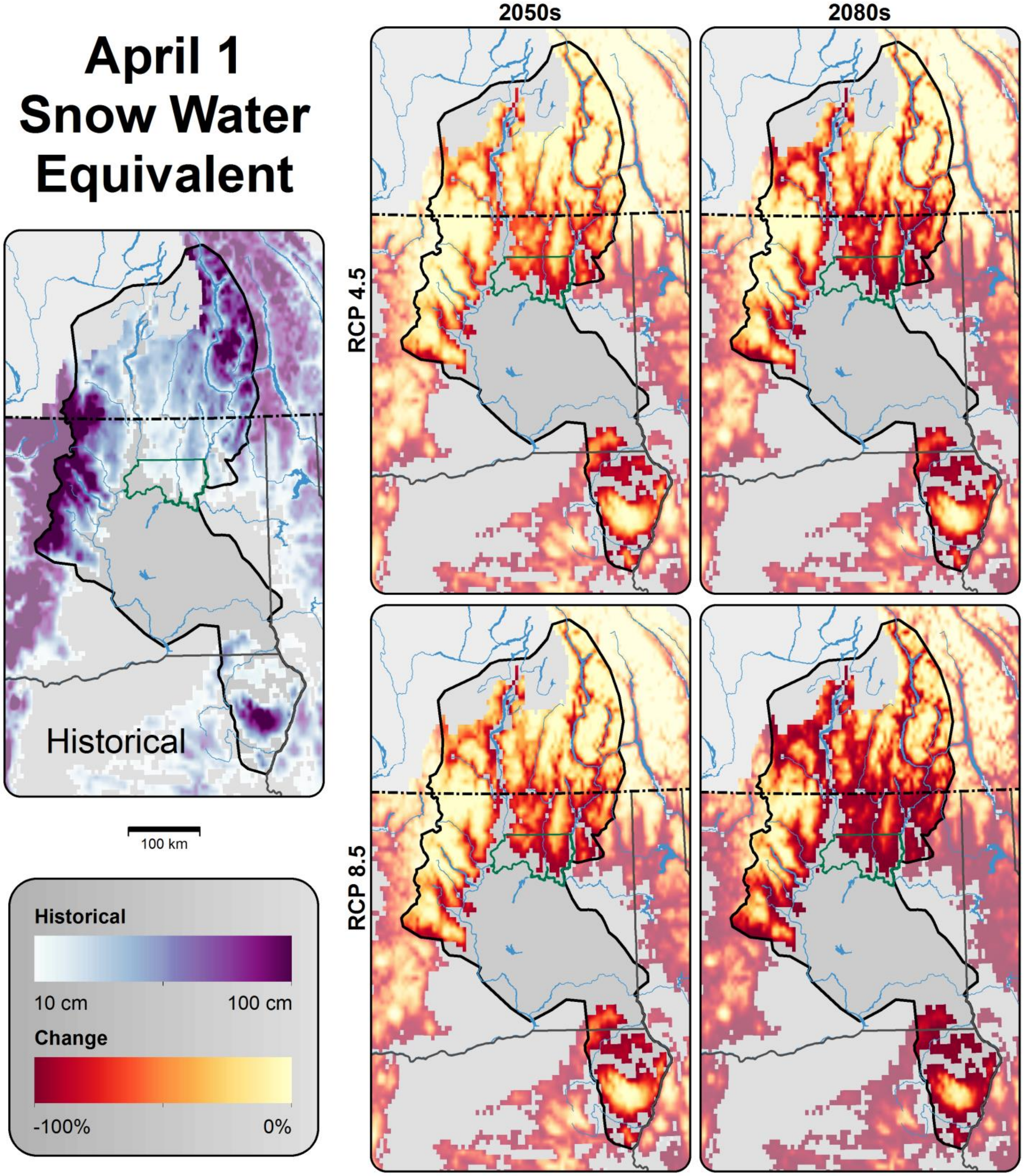

Figure 10. Snow water equivalent (SWE) on April 1 for historical (1970–1999), mid-century (2050s), and end of century (2080s) for two future scenarios (RCP 4.5 (top) and RCP 8.5 (bottom)) across the Colville Tribes study area. Future projection maps show percent change from historical conditions. Generally, areas of the greatest amount of change are found at lower elevations.

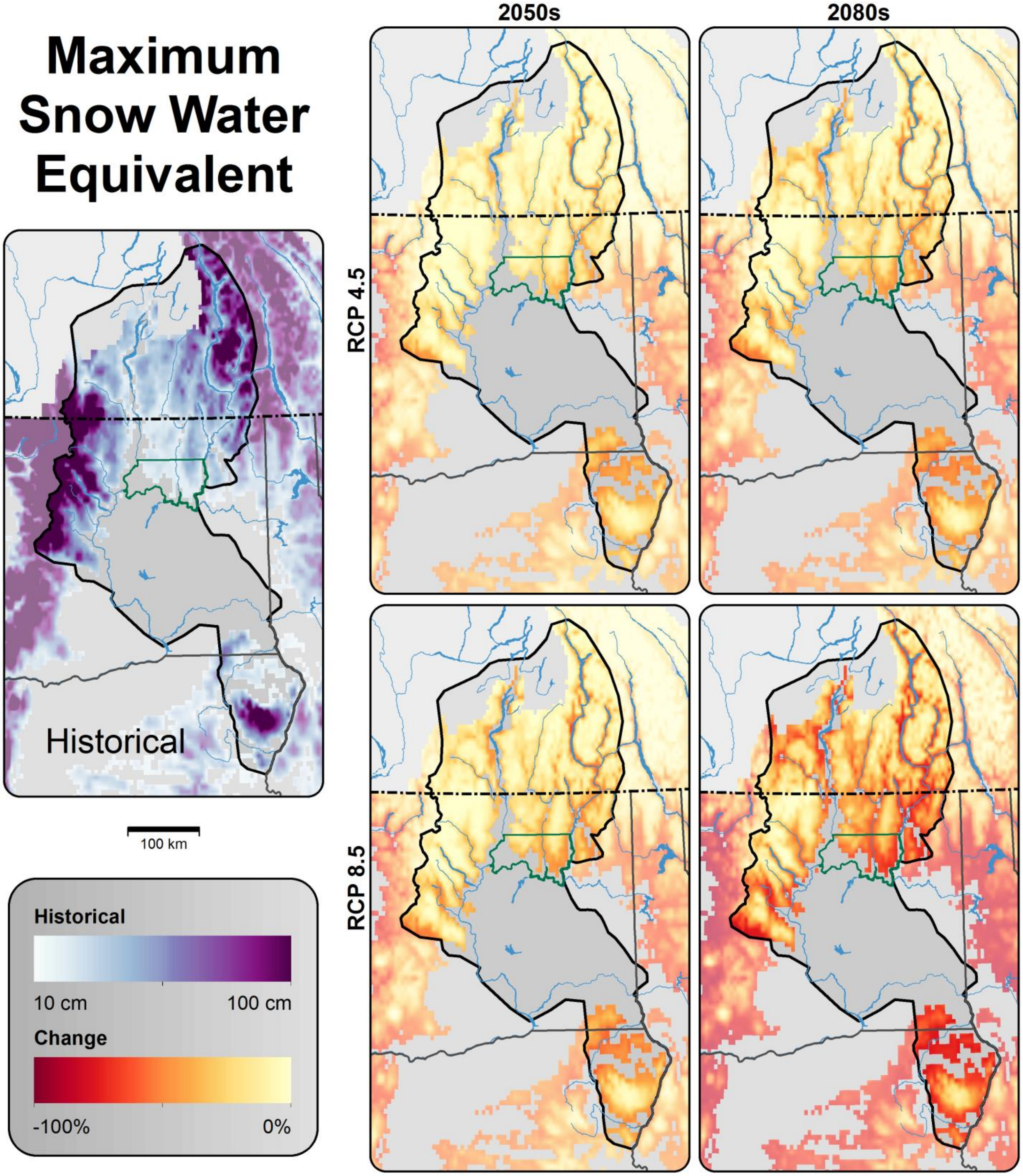

Figure 11. Maximum snow water equivalent (SWE) for historical (1970–1999), mid-century (2050s), and end of century (2080s) for two future scenarios (RCP 4.5 (top) and RCP 8.5 (bottom)) across the Colville Tribes study area. Future projection maps show percent change from historical conditions. Generally, areas that are projected to change the most are at lower elevations and in the southern portion of the Colville Tribes study area.

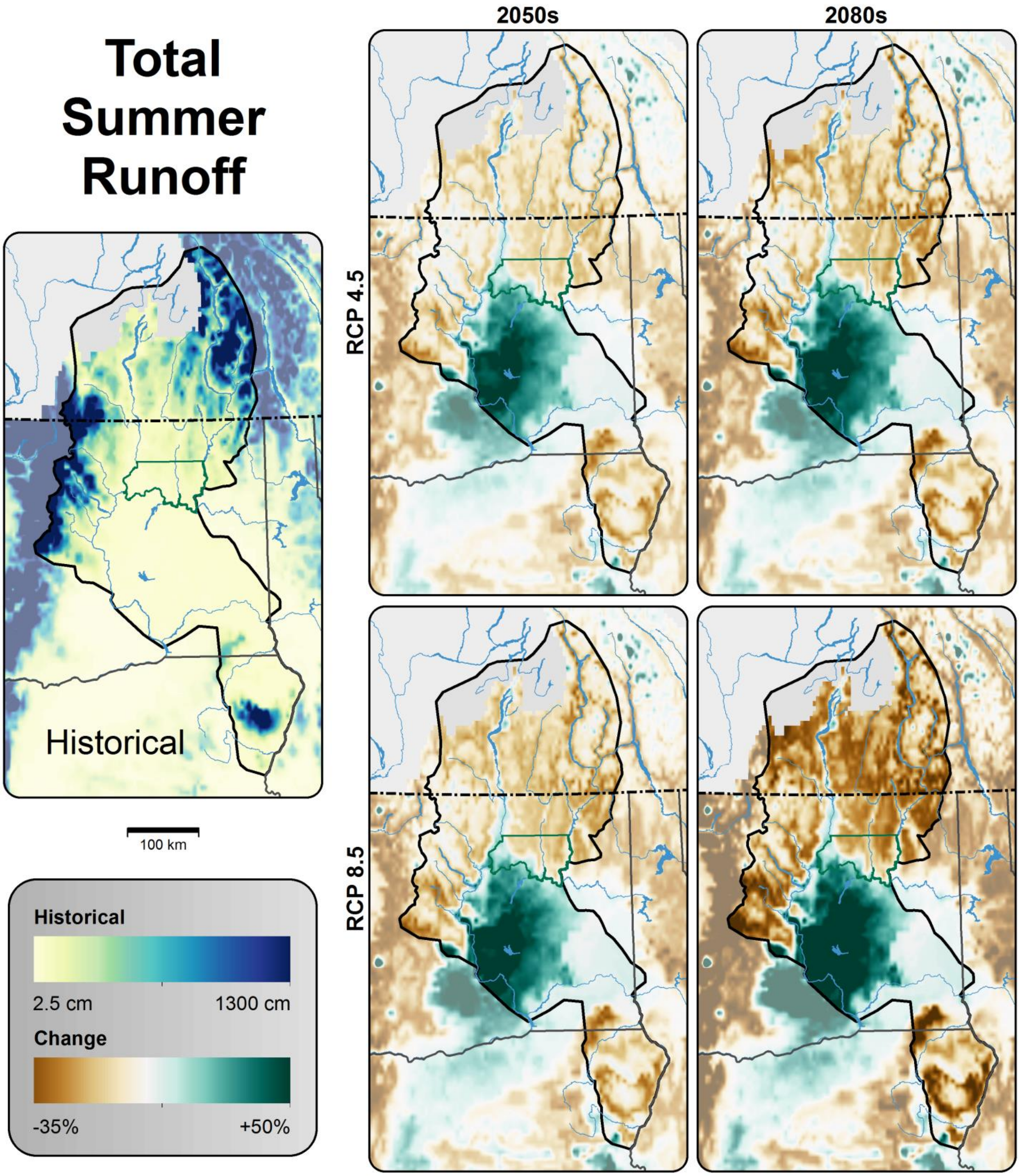

Figure 12. Projected changes in runoff from April to September for historical (1970-1999), mid-century (2050s), and end of century (2080s) for two future scenarios (RCP 4.5 (top) and RCP 8.5 (bottom)) across the Colville study area. Future projection maps show percent change from historical conditions.

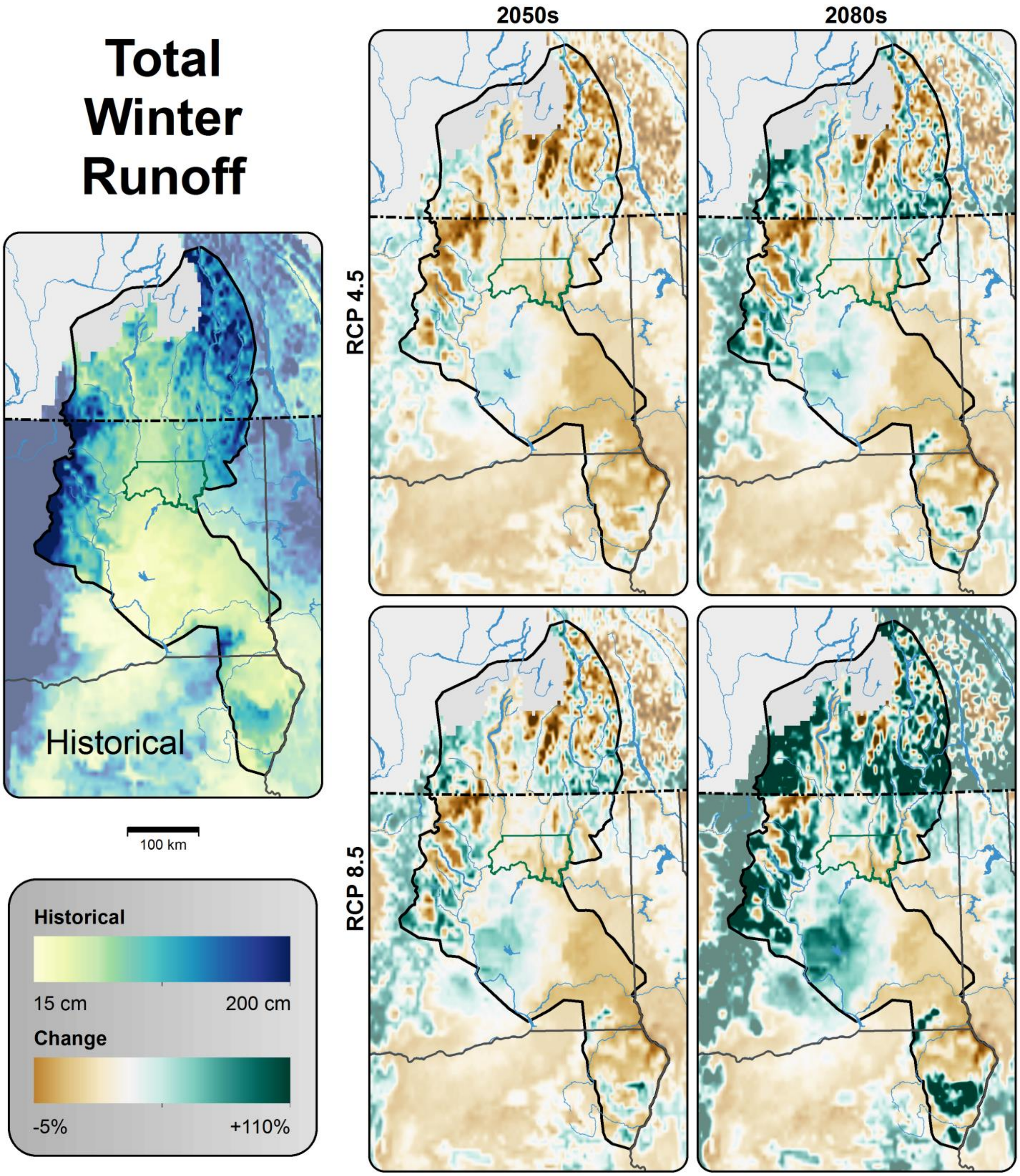

Figure 13. Projected changes in runoff from October to March for historical (1970-1999), mid-century (2050s), and end of century (2080s) for two future scenarios (RCP 4.5 (top) and RCP 8.5 (bottom)) across the Colville study area. Future projection maps show percent change from historical conditions.

Floods

To estimate changes in the likelihood of future flooding events, we summarized peak flow projections for eight sites within the Colville Tribes study area (Appendices D and E). These sites include Kettle River near Ferry, Kettle River near Laurier, Okanogan River at Malott, Okanogan River at Tonasket, Sanpoil River AB 13 Mile Creek Near Republic, West Fork Sanpoil River near Republic, Similkameen River at Oroville, and Similkameen River near Nighthawk. These site locations were selected from a larger study area that was used for the *Pacific Northwest Hydroclimate Scenarios Project* (2860).[11] We chose these eight streamflow sites because they were geographically dispersed across the north and central portion of the Colville Tribes study area and had available data. Additional sites are also available.

Peak flow (as measured in cubic feet per second) was projected at each site for 20, 50, 100-year flooding events for historical (1916–2006) and future (2020s, 2040s, and 2080s) time periods and for two GHG scenarios (A1B and B1) (Appendix D). Of these eight sites, all show increased likelihood of 100-year flood by the 2080s under a medium (A1B) emissions scenario. This may be partly due to warming temperatures, declining snowpack, and increasing heavy precipitation events. Furthermore, warming temperatures will lead to rising snowlines, which could increase the area of a watershed with winter rain runoff. If this occurs it would increase the risk of winter flooding during storms because more water would be channeled into streams and rivers instead of being stored as snow. Increased likelihood of flooding events will also likely have impacts on water crossing structures, such as culverts (see Box 3).

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[11] http://warm.atmos.washington.edu/2860/

Box 3. Implications of Climate-Driven Hydrologic Shifts on Culverts

Washington Department of Fish & Wildlife (WDFW) conducted a study that explored how climate-related changes to stream channel morphology could be incorporated into the design of water crossing structures, such as culverts (WDFW 2016).[12] Water crossing structures are important because if not designed or constructed adequately, they can create barriers to fish movement (Price et al. 2010, Chelgren and Dunham 2015). For example, improperly designed or constructed culverts can become barriers by leading to sediment aggradation at a culvert's inlet, stream bed scour at a culvert's outlet, and high flow velocity in the culvert. The consequences to fish populations associated with barriers at road crossings include the loss of habitat for various life history stages (Beechie et al. 2006, Sheer and Steel 2006), genetic isolation (Rieman and Dunham 2000, Wofford et al. 2005, Neville et al. 2009), inaccessibility to refuge habitats during disturbance events or warm water episodes (Lambereti et al. 1991, Reeves et al. 1995, Dunham et al. 1997), and local extirpation (Winston et al. 1991, Kruse et al. 2001). Climate change will likely compound these problems by increasing the frequency and intensity of heavy rain events, which may increase sediment loads and ultimately lead to wider and shallower stream channels requiring wider culverts (WDFW 2016).

WDFW estimated that in 2015, "there may be as many as 35,000 culverts currently blocking or impeding fish passage statewide" (D. Price, WDFW, personal communication, as noted in WDFW 2016). In response to the current number of fish barriers and the anticipated impacts of climate change, WDFW conducted a study that projected changes in stream bankfull width and 100-year flooding events. WDFW (2016) found that 80% of the sites they modeled are projected to have an increase in bankfull discharge, leading to increased stream width. However, a large portion of the Columbia Plateau is projected to have a decrease in bankfull discharge. Overall, changes in bankfull width varied by elevation, with large increases occurring at high elevations in the North Cascades and decreases projected to occur in the Columbia Basin. Nevertheless, this study illustrates that most culverts are undersized for future projections and studies such as this can be used to help prioritize when and where upgrades are needed.

3.4 Stream Temperatures

Stream temperatures are an important factor in the quality of Pacific Northwest aquatic habitat and health of fish species, such as salmon. When exposed to warmer water temperatures, salmon become more susceptible to pathogens, suffer higher mortality, and stop or slow their migration (Mantua et al. 2009).

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[12] http://wdfw.wa.gov/publications/01867/

Climate change is projected to increase water temperatures in all watersheds within the Colville Tribes study area, to some extent. To evaluate the magnitude of temperature change, we used future projections for mean stream temperatures during August from the NorWeST database (Isaak et al. 2016) (see Table 5, Figure 14, and Appendix F). Overall, stream temperatures are projected to warm the most at lower elevations, within the downstream portions of watersheds where rivers slow down, and where streams widen and encounter warmer air temperatures. The most dramatic projected changes are 1) a reduction in the number of streams with August temperatures below 8°C and 2) an increase in the number of streams with August temperatures above 20°C, a potentially lethal temperature for some fish species (Mantua et al. 2009). Across the U.S. portion of the Colville Tribes study area, it is evident that some of the tributaries of the larger streams are projected to warm the most (Figure 14 and Appendix F). Also significant is the high number of streams projected to exceed 20°C by the 2050s. The length of time that rivers exceed thermal thresholds for salmon is also projected to increase as a result of warming air temperatures (Mantua et al. 2010).

Table 5. Projected change in stream temperatures for the month of August for the U.S. portion of the Colville Tribes study area by mid- and late-century (relative to 1993–2011), based on a medium (A1B) GHG scenario. Changes are shown as the percent change in the number of streams falling within categories of stream temperatures (e.g., percent change in the number of streams with temperatures below 8°C). Data from NorWeST, available at: https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html.

Stream temperature (°C)	Percent change (2040s)	Percent change (2080s)
< 8	-36	-52
8 – 10	-27	-43
10 – 12	-18	-30
12 – 14	-8	-18
14 – 16	-21	-24
16 – 18	+36	+20
18 – 20	+8	+50
> 20	+267	+429

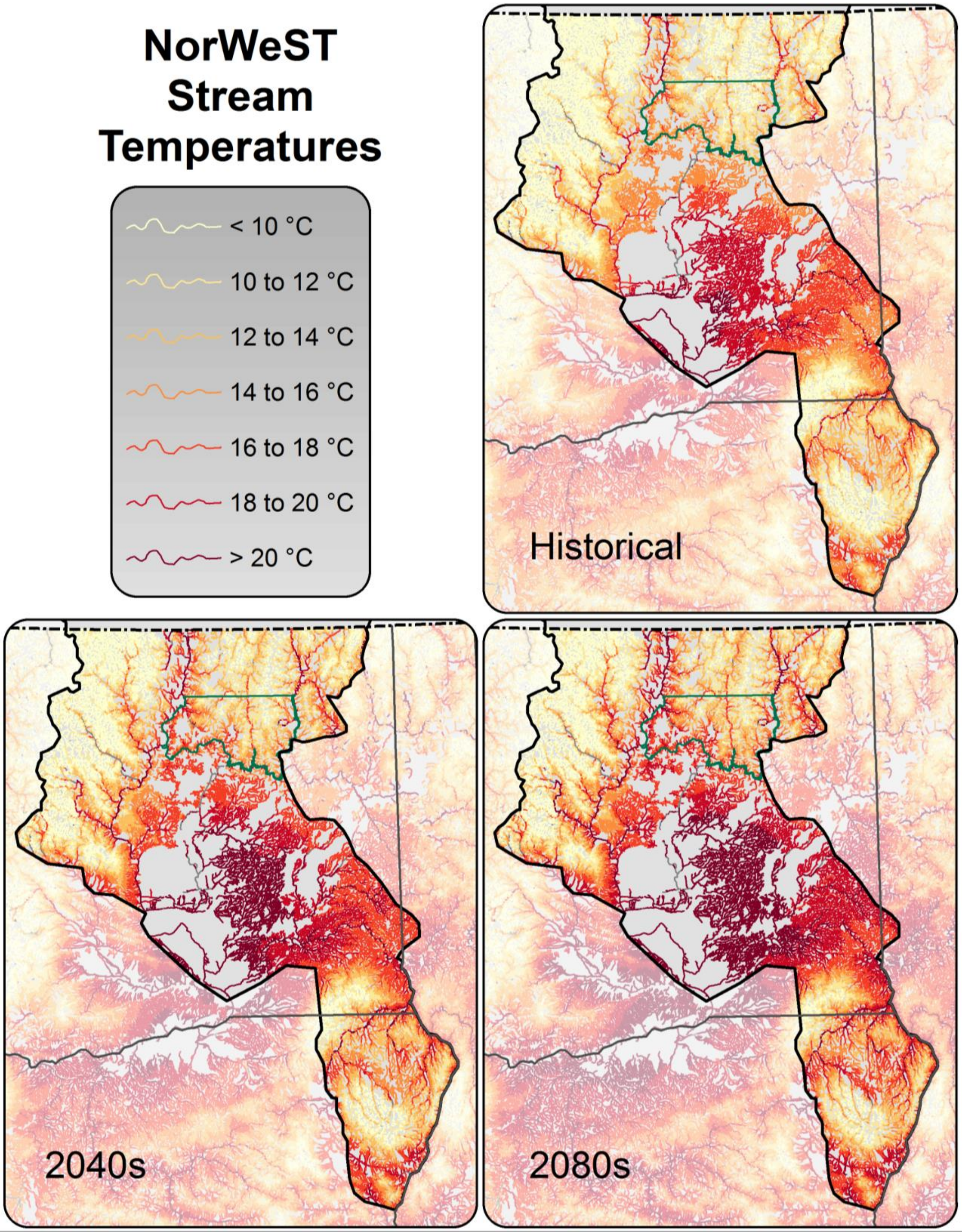

Figure 14. Maps of historical (1993–2011) average August stream temperatures (top) and projected stream temperatures modeled for mid-century (2040s) (bottom, left) and end-of-century (2080s) (bottom, right) based on August air temperatures under a medium (A1B) GHG scenario for the U.S. portion of the Colville Tribes study area. Source: NorWest project (http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml). For larger map panels see Appendix F.

4 LANDSLIDES

The location and size of landslides depends on several factors, including precipitation duration and intensity, antecedent soil moisture, soil types, slope gradients, runoff patterns, land cover, and land-use. Landslide location and size are also important determinants of the amount of sediment delivered to bodies of water, such as rivers and lakes. Intense or prolonged rain events or rapid snow or ice melt that substantially increase soil moisture can initiate landslides and debris flows (Baum et al. 1998, Brooks et al. 2004, Crozier 1986). Although the majority of landslides in the Pacific Northwest occur on the west side of the Cascades during the rainy season (October–May) (Baum et al. 2007), landslides can occur in areas where average December precipitation is higher than 15 cm (MacArthur et al. 2012). Areas that receive intense precipitation, especially during the already wet season, and that have steep topography are at increased risk of landslides. Mapping these locations may provide critical insight into predicting future risk because landslides usually occur in the same area or near the same area as in the past (Raymond et al. 2014).

The most direct mechanism by which climate change may influence future landslide risk is through increased seasonal (fall and winter) precipitation, an increase in the frequency and duration of extreme precipitation, and a transition of precipitation falling as snow to rain. However, these effects will differ by elevation, with greater changes projected at higher elevations (Raymond et al. 2014). A reduction in snowpack and increased soil moisture at high elevation sites (Hamlet et al. 2013) may also compounding landslide risk at high elevations. Although projected changes in landslide risk due to climate change are currently unavailable for the Colville Tribes study area, Raymond et al. (2014) provide a more thorough discussion of this issue for the North Cascades.

5 CLIMATE-INDUCED DISTURBANCES

Climate change is likely to affect the frequency, intensity, size, and locations of disturbances such as wildfire and insect and disease outbreaks. Such changes have the potential to transform entire ecosystems (e.g., Westerling et al. 2011). For example, historical area burned across the western US has increased over the last century and is strongly linked with changes in climate (Littell et al. 2009). It has been estimated that human-caused climate change contributed to an additional 4.2 million hectares of forest fire area in the western US during 1984–2015, nearly doubling the forest fire area expected without climate change (Abatzoglou and Williams 2016). Although future projections assume a static relationship between climate and fire, the projected future increase in area burned is due to projected declines in summer precipitation and warmer summer temperatures, which reduce the moisture content of fuels. Compounding this effect is earlier snowmelt, which is expected to bring an earlier start of the fire season. Wildfires and landslides can also deliver significant amounts of sediment into streams, which can have negative effects on fish populations by smothering eggs and inundating spawning gravels.

Different modeling approaches project varying amounts of increased area burned in the future. For example, one set of fire models projects an increase to 300,000 hectares in the 2020s, 500,000 million hectares in the 2040s, and 800,000 hectares in the 2080s, under a medium emissions scenario (A1B) compared to the median annual area burned in the Northwest during 1916-2006 (estimated to be 200,000 hectares) (Littell et al. 2010).

Another set of models projects +76% to +310% increases in annual area burned for the Northwest by 2070–2099 relative to 1971–2000 under a high emissions scenario (A2) (Rogers et al. 2011). However, increases in area burned are projected to vary across the region. For instance, in forested Northwest ecosystems (e.g., Western and Eastern Cascades, Okanogan Highlands, and Blue Mountains), annual area burned is projected to increase by a factor of 3.8 by the 2040s, compared to 1980–2006, under a medium (A1B) emissions scenario. This means that there would be 3.8 times as much area burned in the future as compared to the historical average, but individual ecoregions vary. For example, in the Okanogan Highlands the historical average of area burned is 54,000 hectares, and by the 2040s this is projected increase to +87,000 hectares. By contrast, the historical average of area burned in the Blue Mountains is 24,000 hectares and this is projected to increase to 224,410 hectares by the 2040s. In non-forested areas, such as the Columbia Basin and Palouse Prairie, annual area burned is projected to increase on average by about a factor of 2.2 (Littell et al. 2010).

Overall, it is likely that more area will burn in the future and that some areas that have recently burned may burn again (see Box 4). Changes in precipitation patterns may also affect the presence and dominance of non-native vegetation, which may further increase fire frequency. For instance, wildfires are currently limited by a lack of ignitions during the fire season and by a lack of continuous fuels in some locations in non-forested areas (i.e., shrublands). Increased biomass buildup of non-native grasses such as cheatgrass (*Bromus tectorum*) could promote the spread of fires in the future. Invasive species like cheatgrass displace native bunch grasses and can mature earlier in the season; by dying and drying out earlier in the fire season compared to native grasses, such species increase the risk of fires (S. Sears, personal communication).

Climate change is also expected to increase the risk of forest health issues caused by insects and diseases. For example, historically, mountain pine beetle (*Dendroctonus ponderosae*) outbreaks have typically occurred at low to mid-elevations in the Washington Cascades where historical temperatures have been suitable for the insects’ habitat. As temperatures warm, areas of thermal suitability for mountain pine beetle could move upward in elevation compared to their current distribution (Littell et al. 2010). This species is also projected to move northward and to increase the number of reproductive cycles it completes within one year (Carroll et al. 2003). However, the future suitable area for mountain pine beetle in Washington State may decrease overall as temperatures rise (Littell et al. 2010). Nevertheless, it is expected that outbreaks of species will continue to be a major concern. Additional insect species that could see changes in their abundance and distribution in the future include other bark beetles (Douglas-fir beetle (*Dendroctonus pseudotsuqae*), fir engraver beetle (*Scolytus ventralis*); western balsam bark beetle (*Dryocoetes confuses*), and spruce beetle (*Dendroctonus* *rufipennis*)), defoliators (western spruce budworm (*Choristoneura occidentalis*), Douglas-fir needle midge (*Contarinia pseudotsugae*)), and branch and terminal insects (balsam woolly adelgid (*Adelges piceae*)).

As temperatures warm, precipitation changes, and there are fewer cold periods, outbreaks in forest pathogens could also see changes in their distributions, frequencies, and intensities. Examples include white pine blister rust (*Cronartium ribicola*), root rot disease (*Armillaria* and *Phellinus weirii)*, yellow-cedar decline, *Cytospora* canker of alder, dwarf mistletoes (*Arceuthobium* spp.), sudden oak death, swiss needle cast, larch needle cast, sphaeropsis tip blight, and others.

Box 4. Recent Fire Activity on the Colville Reservation

Although individual fire years have not been attributed to climate change, the 2014 and 2015 fire years were particularly severe and may provide insight into what the future may hold. The 2014 wildfire season was record-setting for Washington State, with the Carlton Complex fire burning 255,000 acres and representing the largest wildfire in State history. With over 65% of this area being burned within a 9-hour period, this fire has been identified as an extreme climate-driven event (S. Prichard, personal communication). However, regional drought led to 2015 surpassing 2014 in area burned and fire suppression costs. During the 2015 fire season, the 218,000-acre North Star Fire burned a total of 165,000 acres on the Colville Reservation, representing the largest fire on Trust lands in recent history. Starting just one day after the North Star Fire, the Tunk Block fire started to the west of the Colville Reservation and burned 165,947 acres. This fire was extremely fast-moving, mostly burning through grass and shrub-steppe vegetation. Since 2000, it is estimated that approximately 467,000 acres have burned on the Colville Reservation (L. Cawston, personal communication).

Severe wildfire seasons have now occurred in 2003, 2006, 2012, 2014 and 2015. Warmer and potentially drier summers will undoubtedly increase the likelihood of large, high-severity fire events in the future. Compounding this increased risk is a century of fire suppression and substantial increases in forest area and density within the region (Hessburg et al. 2015, 2016). Consequently, the region could experience rapid shifts in vegetation type, such as from forest to savanna or grassland; however, it is important to note that not all vegetation types will respond similarly and that although many forests are fire adapted (e.g., mature ponderosa pine forests), many may not survive severe fires.

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7 GLOSSARY[13]

100-year flood
A flood or storm that has a 1% probability of occurring in any given year. The 100-year flood zone is the extent of the area of a flood that has a 1% chance of occurring or being exceeded in a given year.

Adaptation
Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects.

Climate change
Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system. [See also global change]

Climate variability
Natural changes in climate that fall within the observed range of extremes for a particular region, as measured by temperature, precipitation, and frequency of events. Drivers of climate variability include the El Niño Southern Oscillation and other phenomena.

Drought
A period of abnormally dry weather marked by little or no rain that lasts long enough to cause water shortage for people and natural systems.

El Niño-Southern Oscillation
A natural variability in ocean water surface pressure that causes periodic changes in ocean surface temperatures in the tropical Pacific ocean. El Niño Southern Oscillation (ENSO) has two phases: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific. Each phase generally lasts for 6 to 18 months. ENSO events occur irregularly, roughly every 3 to 7 years. The extremes of this climate pattern's oscillations cause extreme weather (such as floods and droughts) in many regions of the world.

Emissions scenarios
Quantitative illustrations of how the release of different amounts of climate altering gases and particles into the atmosphere from human and natural sources will produce different future climate conditions. Scenarios are developed using a wide range of assumptions about population growth, economic and technological development, and other factors.

Evapotranspiration
Evaporation of water from soil and plant leaves.

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[13] Glossary adapted from http://www.globalchange.gov/climate-change/glossary

Extreme precipitation event
An episode of abnormally high rain or snow. The definition of "extreme" is a statistical concept that varies depending on location, season, and length of the historical record.

Frost-free season
The time period between the last occurrence of an air temperature of 32°F in spring and the first occurrence of 32°F in the subsequent fall.

Global Climate Models (GCM)
Mathematical models that simulate the physics, chemistry, and biology that influence the climate system.

Greenhouse gases (GHG)
Gases that absorb heat in the atmosphere near the Earth's surface, preventing it from escaping into space. If the atmospheric concentrations of these gases rise, the average temperature of the lower atmosphere will gradually increase, a phenomenon known as the greenhouse effect. Greenhouse gases include, for example, carbon dioxide, water vapor, and methane.

Heat wave
A period of abnormally hot weather lasting days to weeks.

Heavy precipitation event
An episode of abnormally high rain or snow. The definition of "extreme" is a statistical concept that varies depending on location, season, and length of the historical record.

Pathogen
Microorganisms (such as a bacteria or viruses) that causes disease.

Phenology
The pattern of seasonal life cycle events in plants and animals, such as timing of blooming, hibernation, and migration.

Risk
Risks are threats to life, health and safety, the environment, economic well-being, and other things of value. Risks are often evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).

Scenario
Sets of assumptions used to help understand potential future conditions such as population growth, land use, and sea level rise. Scenarios are neither predictions nor forecasts. Scenarios are commonly used for planning purposes.

Snow water equivalent (SWE)
The amount of water held in a volume of snow, which depends on the density of the snow and other factors.

Snowpack
Snow that accumulates over the winter, and slowly melts to release water in spring and summer.

Uncertainty
An expression of the degree to which future climate is unknown. Uncertainty about the future climate arises from the complexity of the climate system and the ability of models to represent it, as well as the inability to predict the decisions that society will make. There is also uncertainty about how climate change, in combination with other stressors, will affect people and natural systems.

Vulnerability
The degree to which physical, biological, and socio-economic systems are susceptible to and unable to cope with adverse impacts of climate change.

Vulnerability assessment
An analysis of the degree to which a system is susceptible to or unable to cope with the adverse effects of climate change.

8 APPENDICES

Appendix A

Climate data from 20 Coupled Model Inter-Comparison Project 5 models were used for this report. These models were chosen because they have daily output for meteorological variables of interest and were selected by the Integrated Scenarios of the Future Northwest Environment project (see climate.northwestknowledge.net/IntegratedScenarios).

Model Name	Model Country	Model Agency
bcc-csm1-1	China	Beijing Climate Center, China Meteorological Administration
bcc-csm1-1-m	China	Beijing Climate Center, China Meteorological Administration
BNU-ESM	China	College of Global Change and Earth System Science, Beijing Normal University, China
CanESM2	Canada	Canadian Centre for Climate Modeling and Analysis
CCSM4	USA	National Center of Atmospheric Research, USA
CNRM-CM5	France	National Centre of Meteorological Research, France
CSIRO-Mk3-6-0	Australia	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia
GFDL-ESM2M	USA	NOAA Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2G	USA	NOAA Geophysical Fluid Dynamics Laboratory, USA
HadGEM2-ES	United Kingdom	Met Office Hadley Center, UK
HadGEM2-CC	United Kingdom	Met Office Hadley Center, UK
inmcm4	Russia	Institute for Numerical Mathematics, Russia
IPSL-CM5A-LR	France	Institut Pierre Simon Laplace, France
IPSL-CM5A-MR	France	Institut Pierre Simon Laplace, France
IPSL-CM5B-LR	France	Institut Pierre Simon Laplace, France
MIROC5	Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies,and Japan Agency for Marine-Earth Science and Technology

MIROC-ESM	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC-ESM-CHEM	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MRI-CGCM3	Japan	Meteorological Research Institute, Japan
NorESM1-M	Norway	Norwegian Climate Center, Norway

Appendix B

Projected changes in temperature for the Colville Tribes study area, by mid- and late-century (relative to 1970–1999), based on medium (RCP 4.5) and high (RCP 8.5) carbon emissions scenarios.

Variable	RCP	Timeframe	Projected change
Annual average temperature	4.5	2050s	+2.6°C
Annual average temperature	4.5	2080s	+3.3°C
Annual average temperature	8.5	2050s	+3.4°C
Annual average temperature	8.5	2080s	+5.6°C
Maximum annual average temperature	4.5	2050s	+2.7°C
Maximum annual average temperature	4.5	2080s	+3.4°C
Maximum annual average temperature	8.5	2050s	+3.4°C
Maximum annual average temperature	8.5	2080s	+5.6°C
Maximum average temperature, June-Aug	4.5	2050s	+3.5°C
Maximum average temperature, June-Aug	4.5	2080s	+4.2°C
Maximum average temperature, June-Aug	8.5	2050s	+4.6°C
Maximum average temperature, June-Aug	8.5	2080s	+7.3°C
Minimum annual average temperature	4.5	2050s	+2.6°C
Minimum annual average temperature	4.5	2080s	+3.3°C
Minimum annual average temperature	8.5	2050s	+3.3°C
Minimum annual average temperature	8.5	2080s	+5.6°C
Minimum average temperature, Dec-Feb	4.5	2050s	+2.8°C
Minimum average temperature, Dec-Feb	4.5	2080s	+3.5°C
Minimum average temperature, Dec-Feb	8.5	2050s	+3.4°C
Minimum average temperature, Dec-Feb	8.5	2080s	+5.7°C

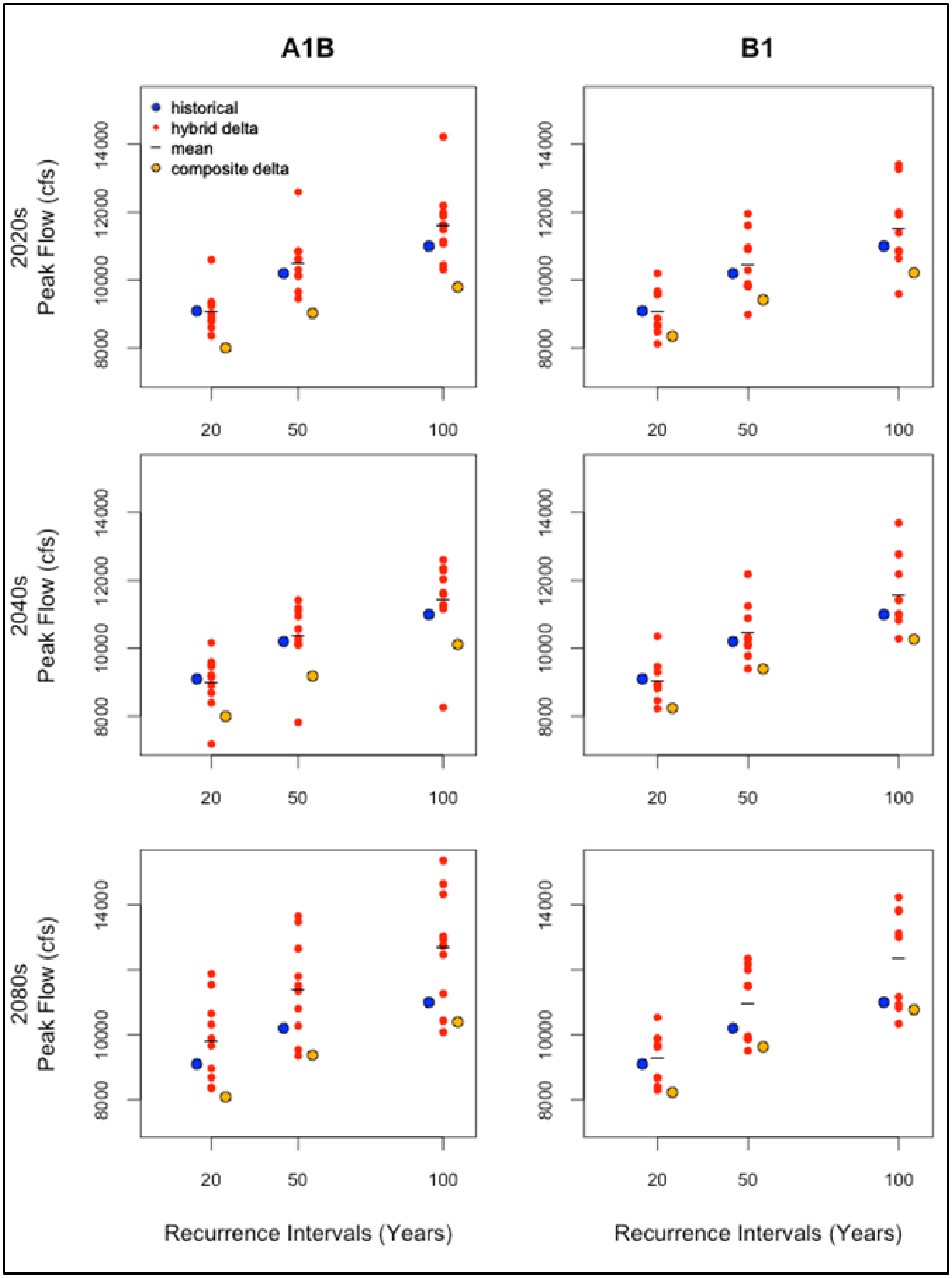
Appendix C

Projected changes in precipitation for the Colville Tribes study area, by mid- and late-century (relative to 1970-1999), based on medium (RCP 4.5) and high (RCP 8.5) carbon emissions scenarios.

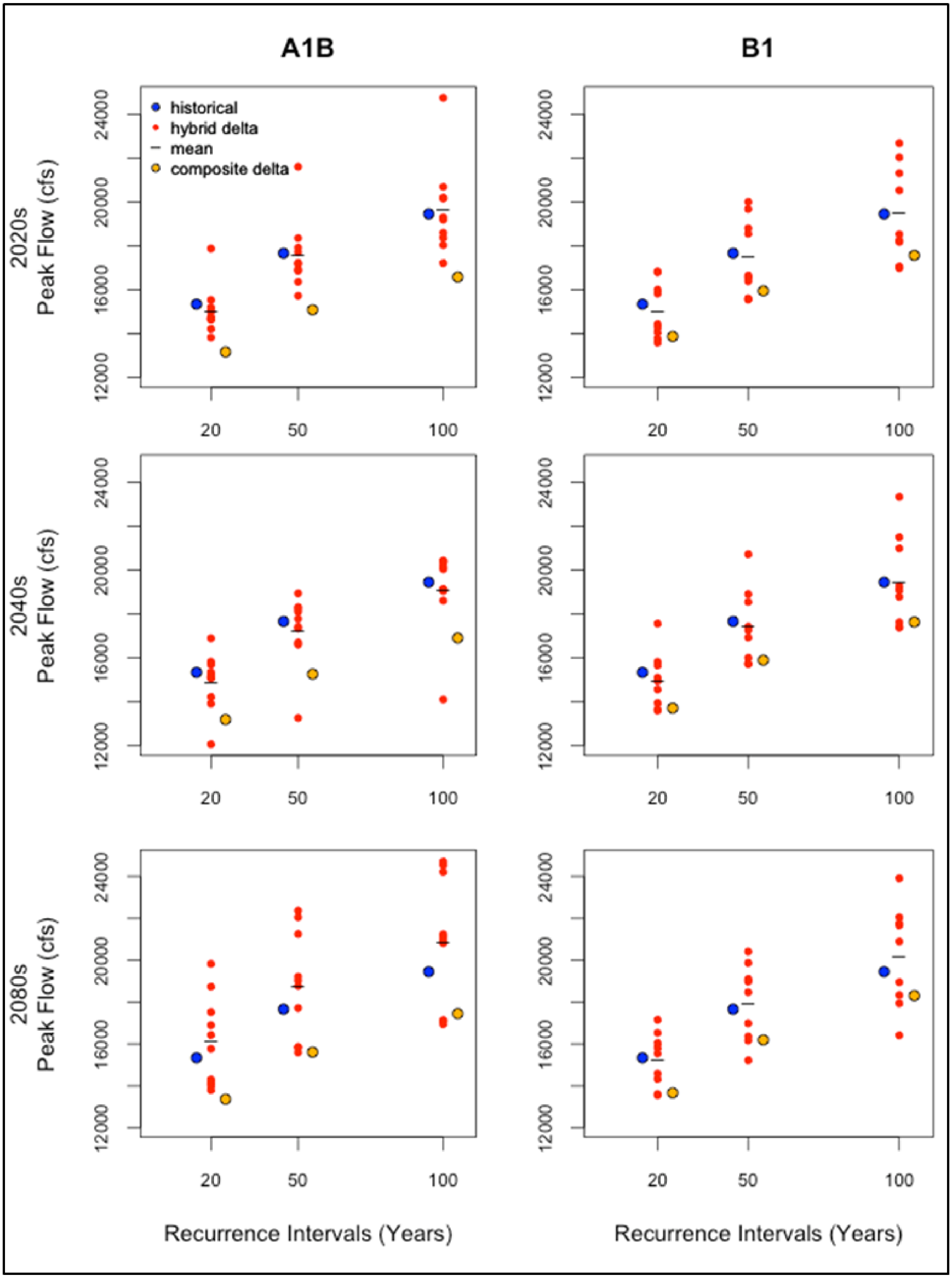
Variable	RCP	Timeframe	Projected change
Average annual precipitation	4.5	2050s	+4.2%
Average annual precipitation	4.5	2080s	+6.5%
Average annual precipitation	8.5	2050s	+5.3%
Average annual precipitation	8.5	2080s	+7.7%
Average winter precipitation	4.5	2050s	+11.1%
Average winter precipitation	4.5	2080s	+12.3%
Average winter precipitation	8.5	2050s	+12.6%
Average winter precipitation	8.5	2080s	+17.6%
Average summer precipitation	4.5	2050s	-13.5%
Average summer precipitation	4.5	2080s	-9.8%
Average summer precipitation	8.5	2050s	-15.5%
Average summer precipitation	8.5	2080s	-19.5%
Average spring precipitation	4.5	2050s	+5.1%
Average spring precipitation	4.5	2080s	+5.7%
Average spring precipitation	8.5	2050s	+7.7%
Average spring precipitation	8.5	2080s	+8.8%
Average autumn precipitation	4.5	2050s	+5.5%
Average autumn precipitation	4.5	2080s	+10.5%
Average autumn precipitation	8.5	2050s	+6.8%
Average autumn precipitation	8.5	2080s	+11.2%

Appendix D

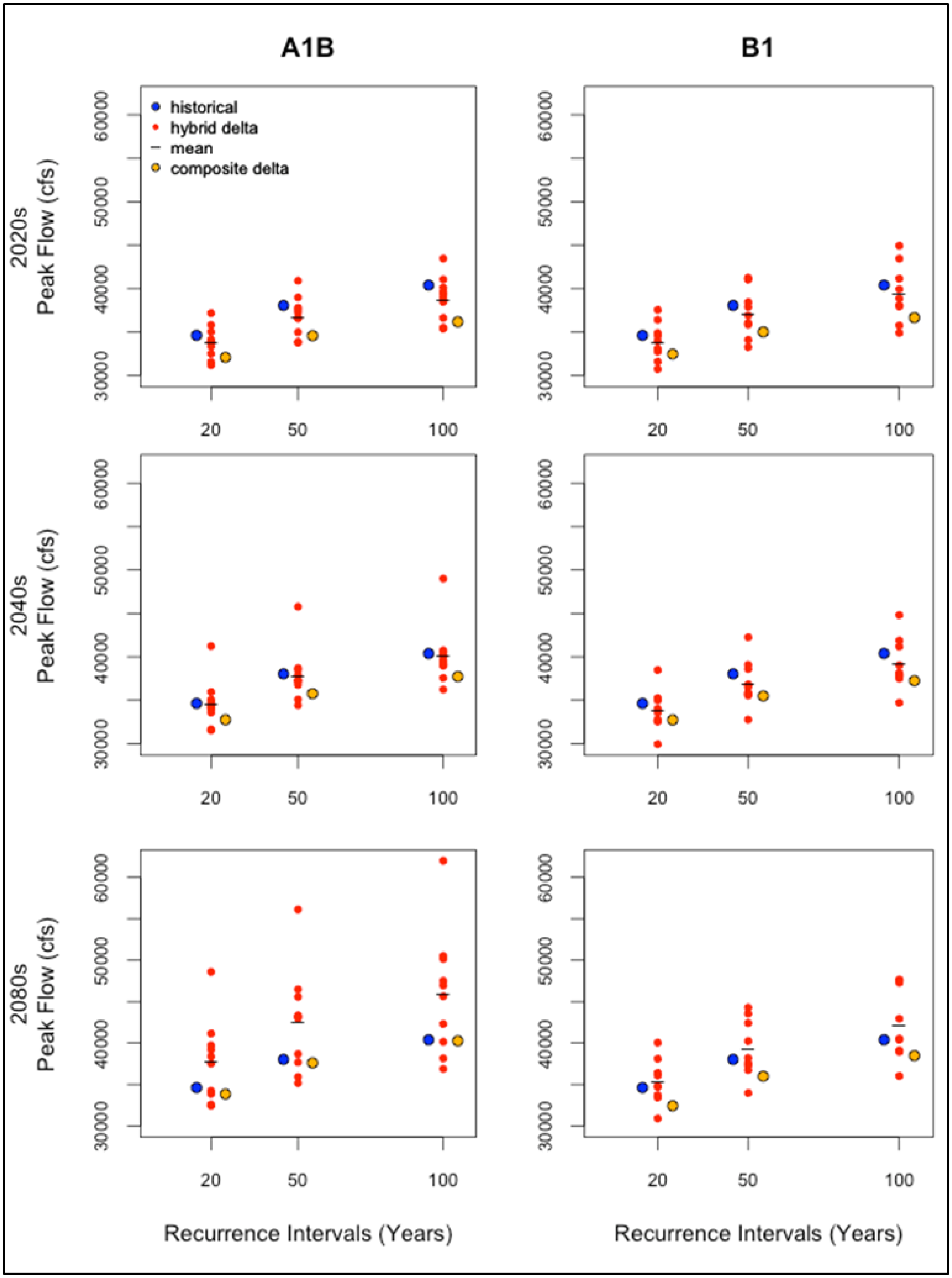
Projected changes in peak flows (as measured in cubic feet per second [cfs]) for historical (1916–2006) and future (2020s, 2040s, 2080s) time periods for eight sites within the Colville Tribes study area and for two future scenarios (A1B [medium] and B1 [low/medium]). Peak flow projections at 20, 50, and 100-year return intervals were generated using the Variable Infiltration Capacity hydrologic model and two downscaling techniques: hybrid delta and composite delta. Blue circles show simulated historical value, red circles show the range of values for hybrid delta simulations (horizontal line shows the ensemble average), and the orange circles show the value for the composite delta simulations. More information on site selection can be found with the report text and for more information on the data and figures please see http://warm.atmos.washington.edu/2860/.



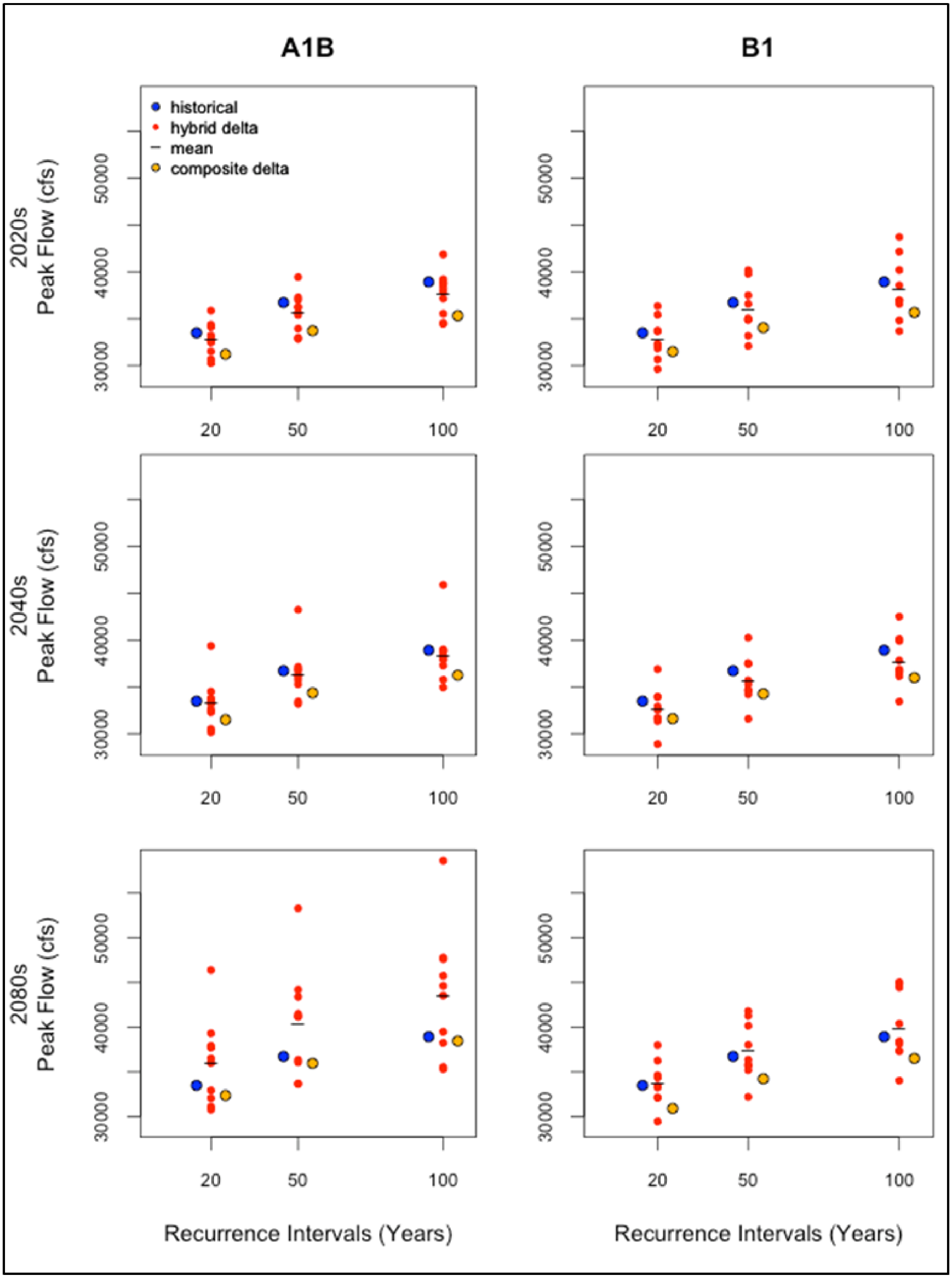
Projected peak flow for KETTLE RIVER NEAR FERRY (site number 6025, USGS ID [12401500](https://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=12401500)).



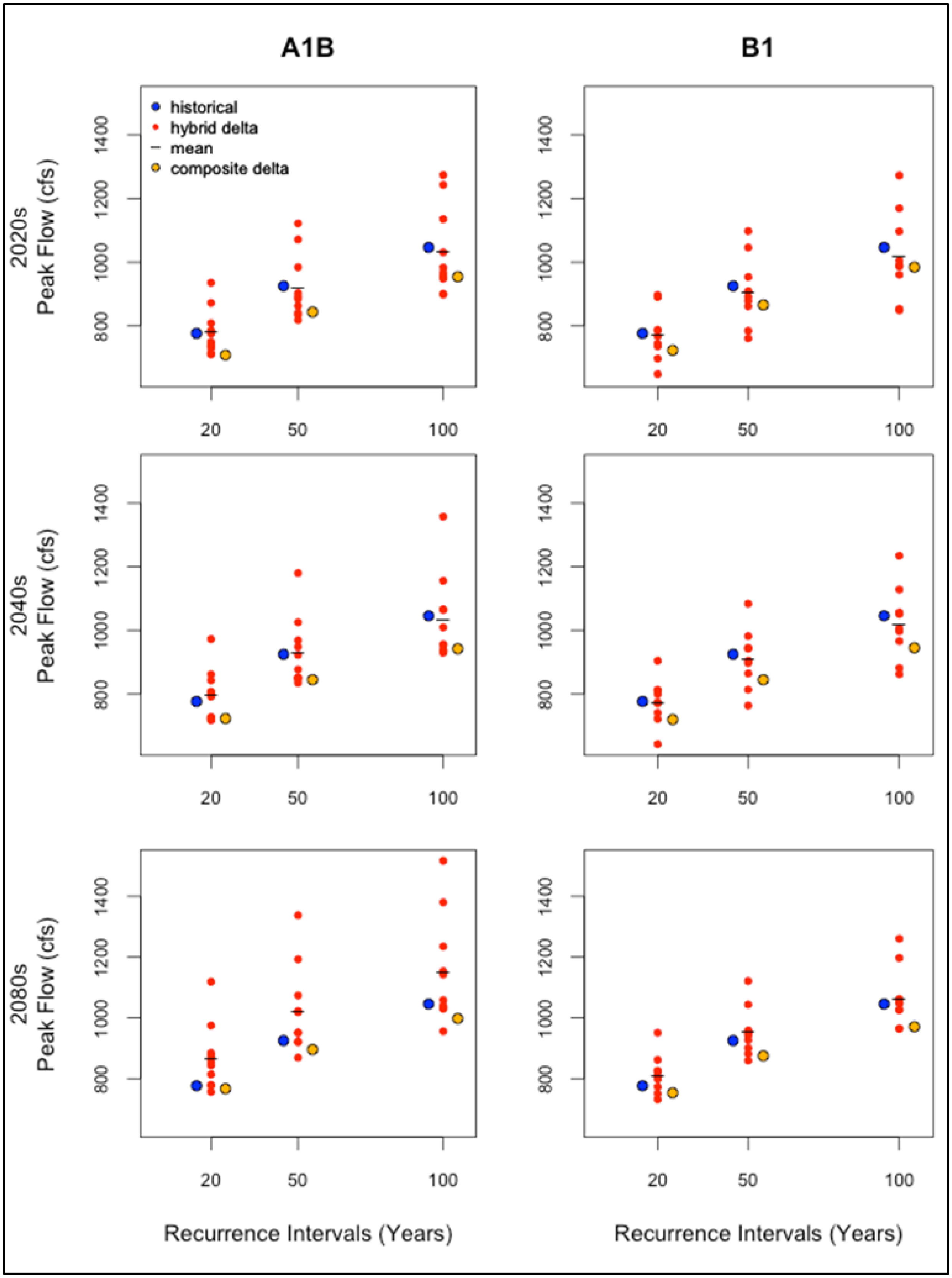
Projected peak flow for KETTLE RIVER NEAR LAURIER (site number 6026, USGS ID 12404500).



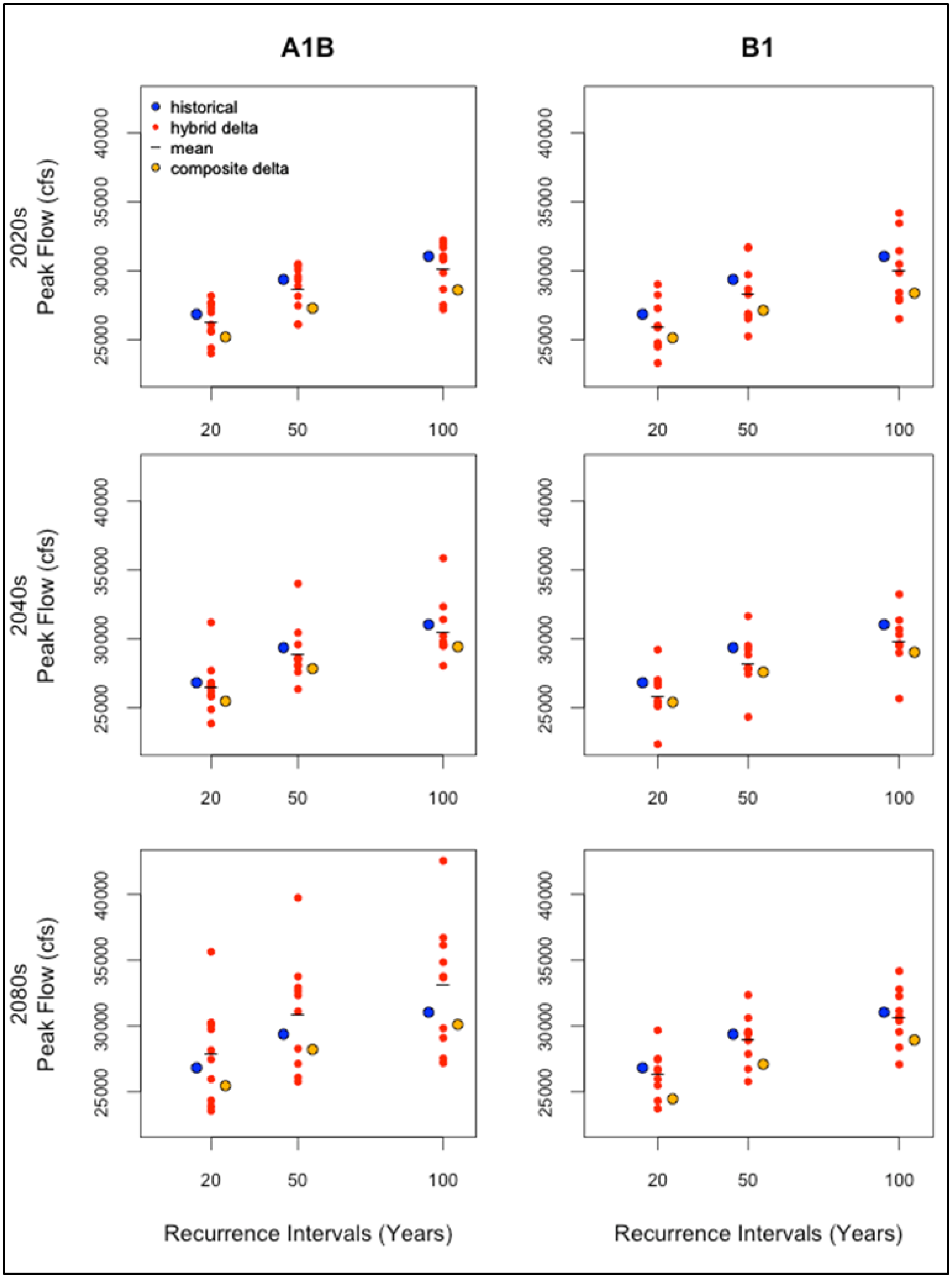
Projected peak flow for OKANOGAN RIVER AT MALOTT (site number 6039, USGS ID 12447200).



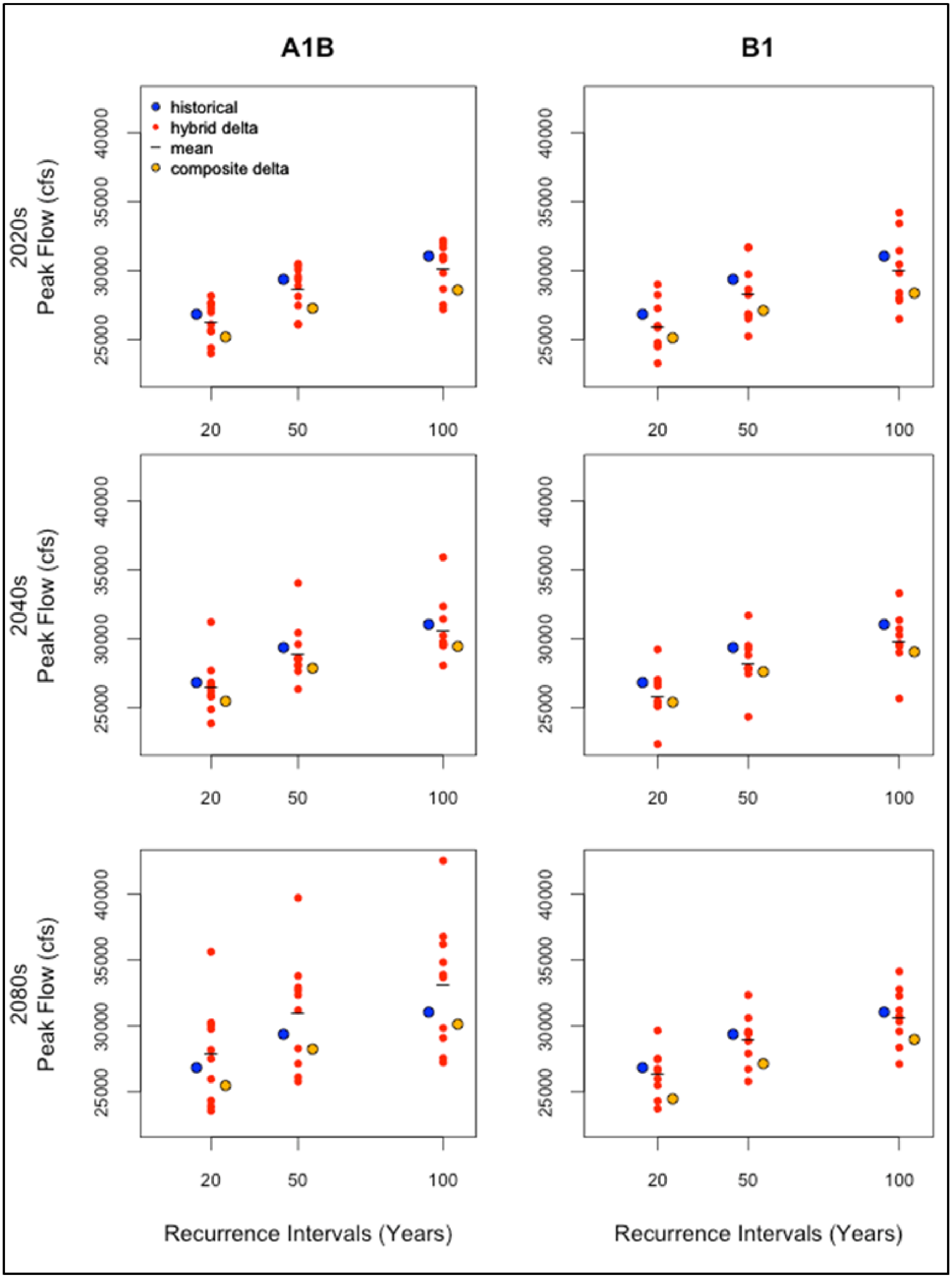
Projected peak flow for OKANOGAN RIVER AT TONASKET (site number 6038, USGS ID [12445000](12445000)).



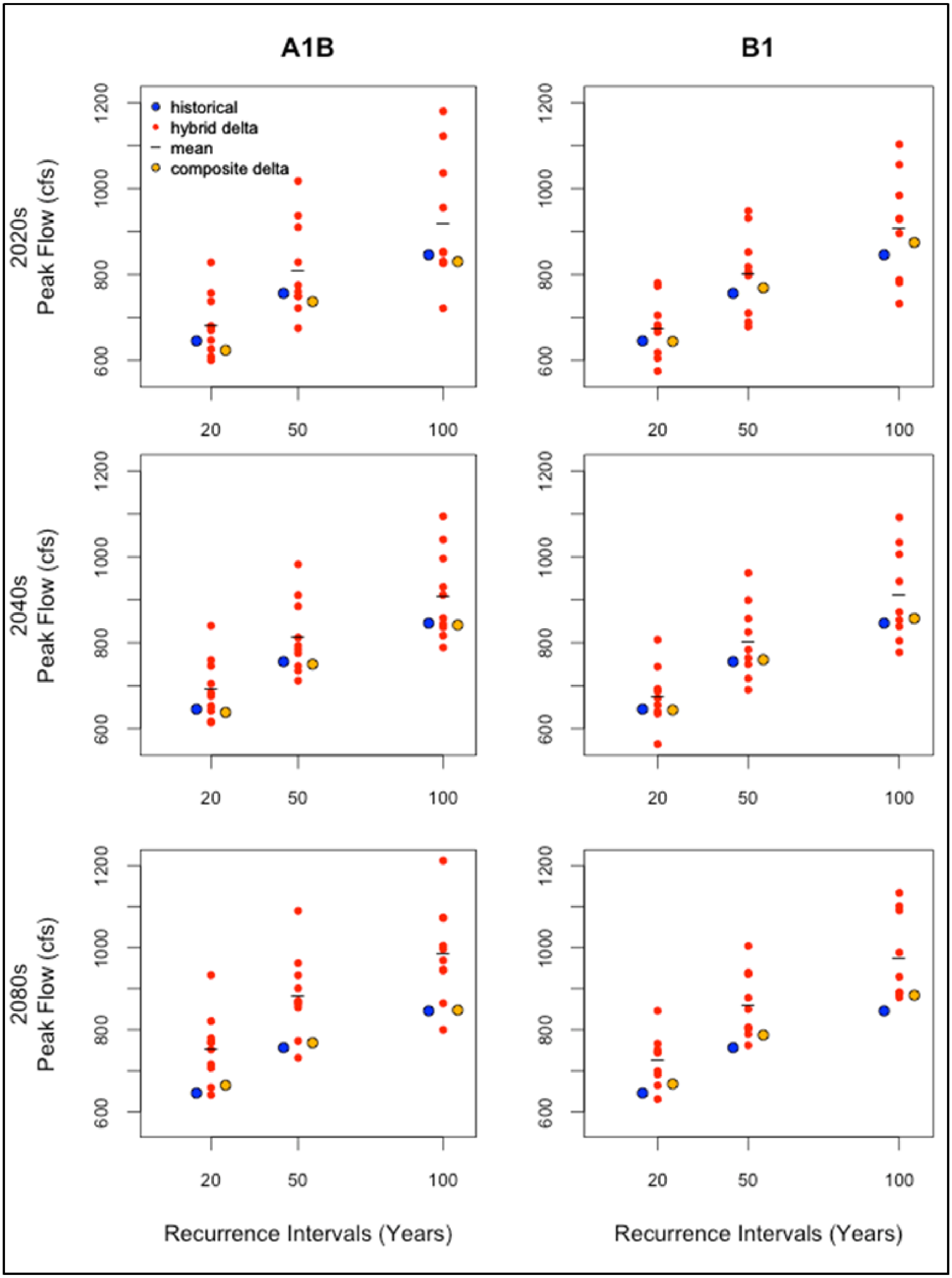
Projected peak flow for SANPOIL RIVER AB 13 MILE CREEK NEAR REPUBLIC (site number 6032, USGS ID 12433890).



Projected peak flow for SIMILKAMEEN RIVER AT OROVILLE (site number 6037, USGS ID 12443600).



Projected peak flow for SIMILKAMEEN RIVER NEAR NIGHTHAWK (site number 6002, USGS ID 12442500).



Projected peak flow for WEST FORK SANPOIL RIVER NEAR REPUBIC (site number 6033 USGS ID 12434110).

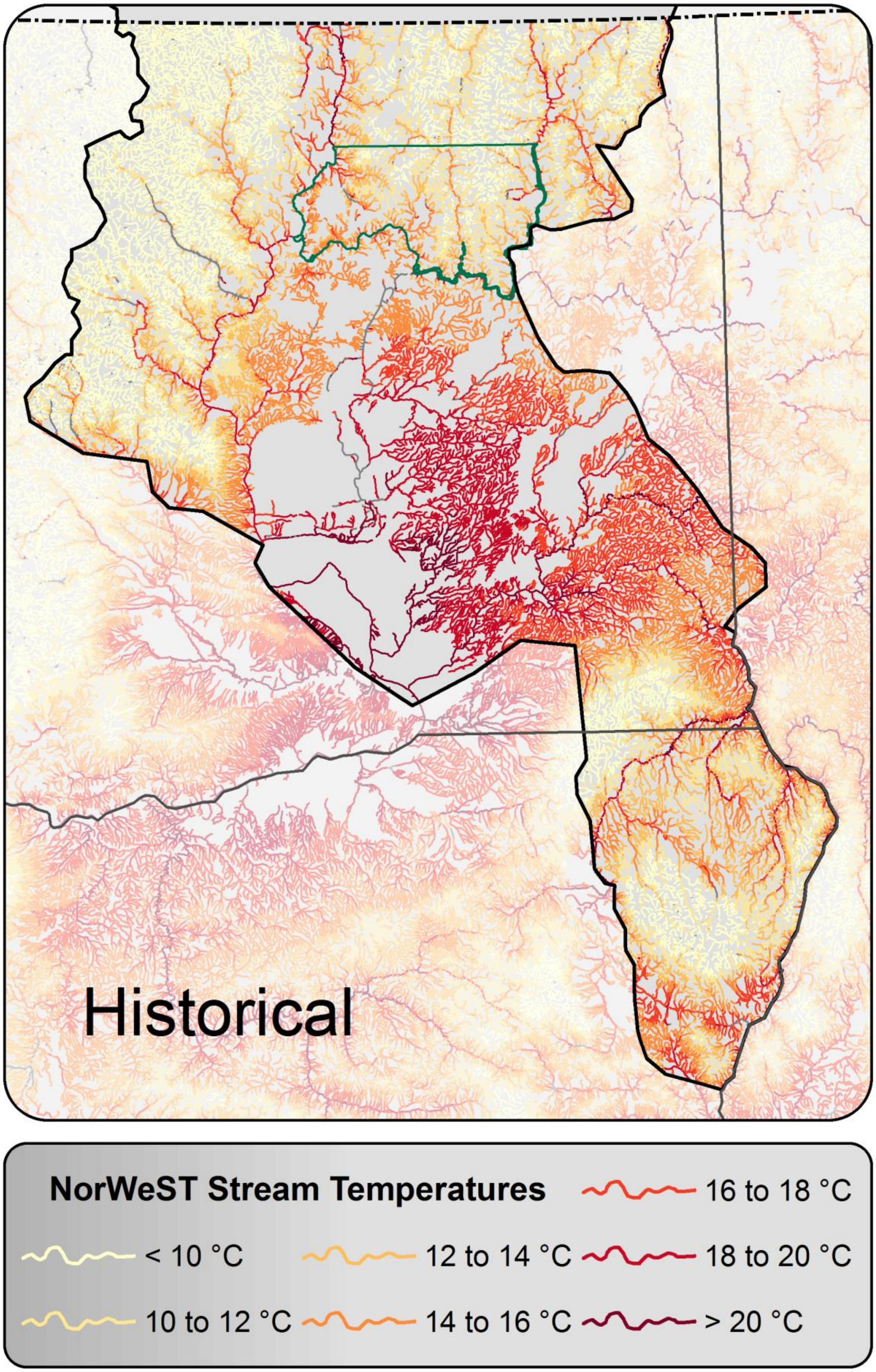
Appendix E

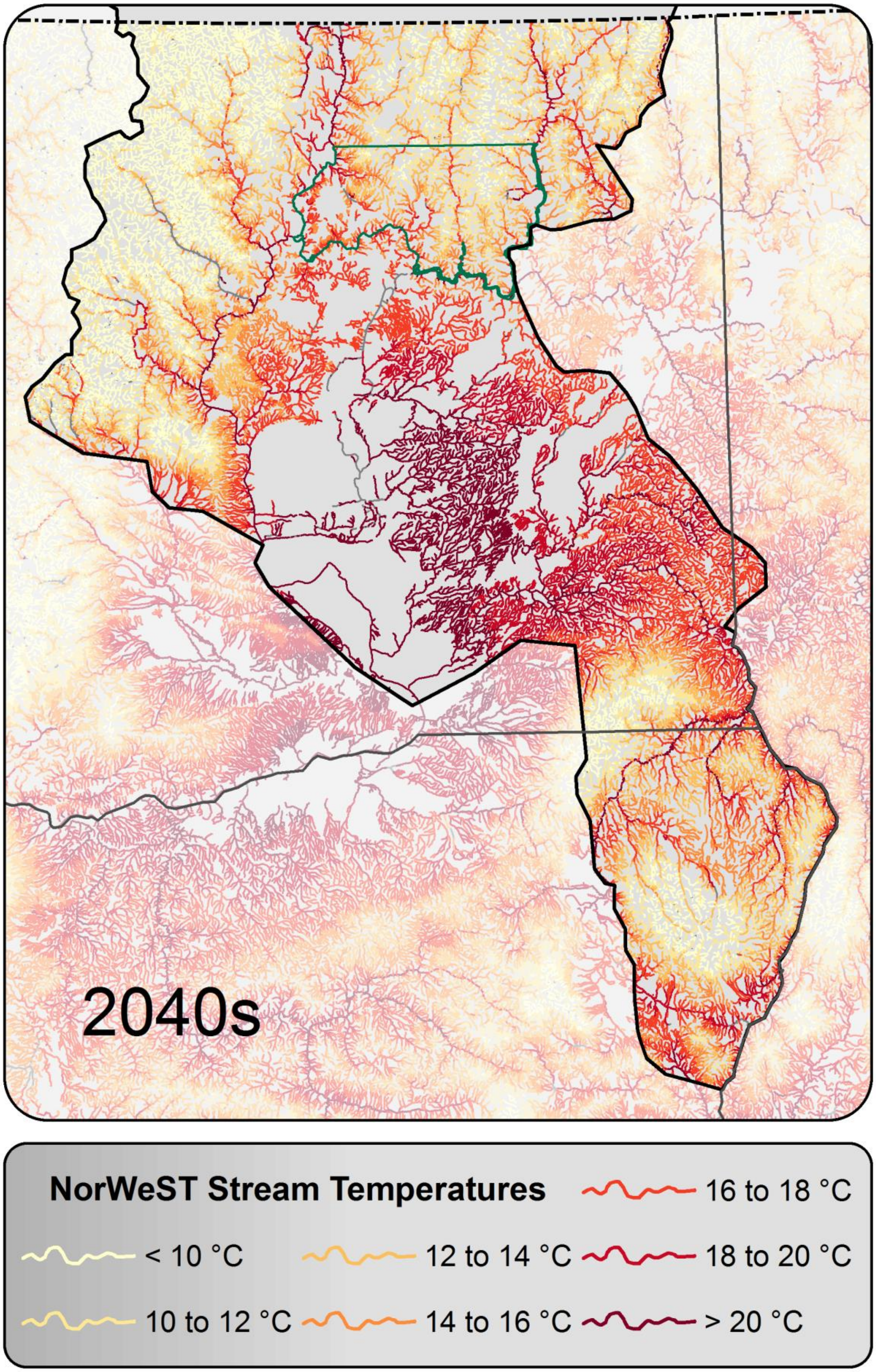
Summarized future projections for 100-year flooding risk for eight sites within the Colville Tribes study area for the A1B (medium) carbon emissions scenario for the 2020s, 2040s, and 2080s. The relative change in 100-year flooding was estimated by considering the ensemble average of all future projections at that given location and time period. For site location and more information, see: http://warm.atmos.washington.edu/2860/.

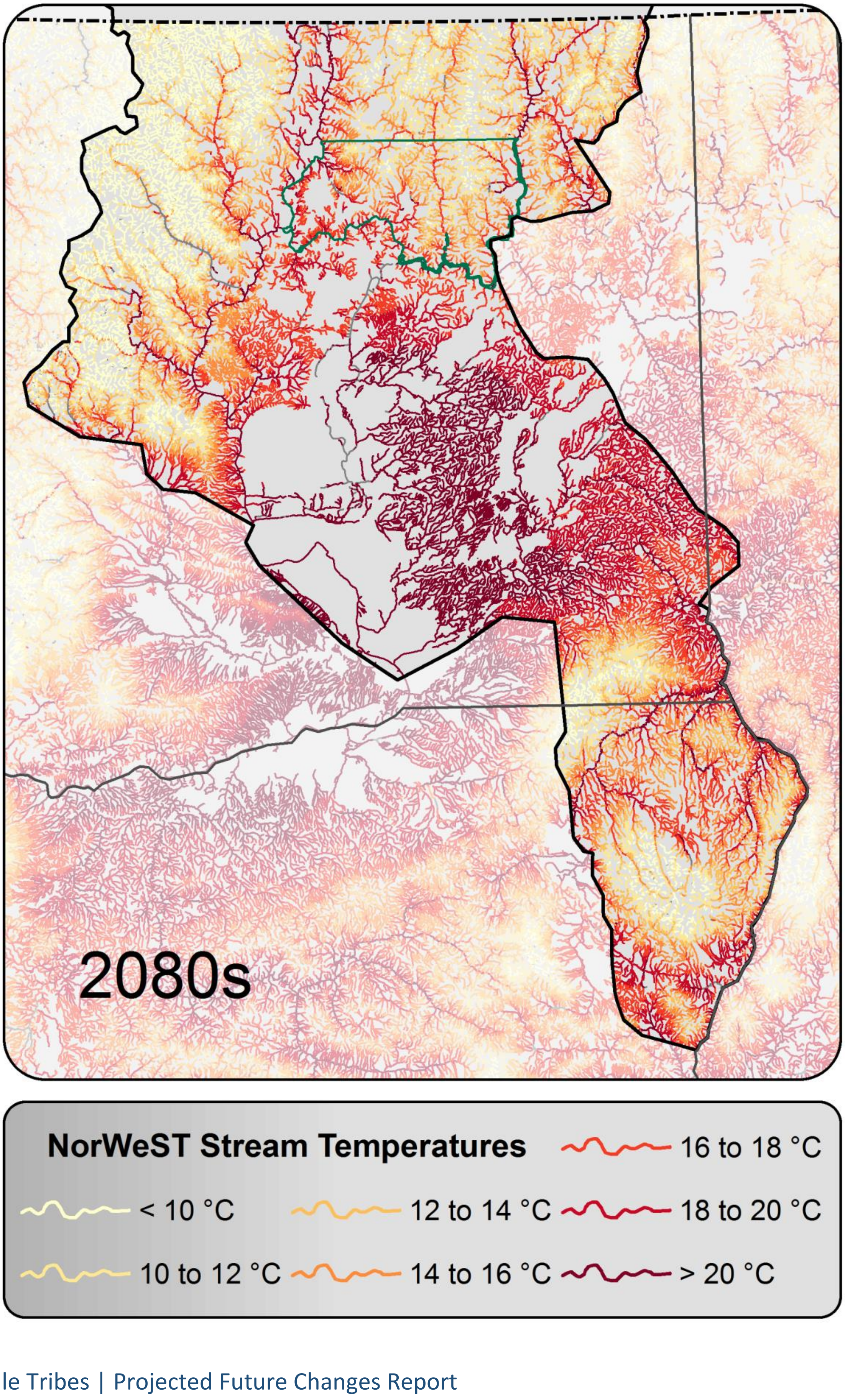
Variable	Timeframe	100-year floods
KETTLE RIVER NEAR FERRY	2020	+ flooding
	2040	+ flooding
	2080	+ flooding
KETTLE RIVER NEAR LAURIER	2020	No change
	2040	- flooding
	2080	+ flooding
OKANOGAN RIVER AT MALOTT	2020	- flooding
	2040	No change
	2080	+ flooding
OKANOGAN RIVER AT TONASKET	2020	- flooding
	2040	No change
	2080	+ flooding
SANPOIL RIVER AB 13 MILE CREEK NEAR REPUBLIC	2020	No change
	2040	No change
	2080	+ flooding
SIMILKAMEEN RIVER AT OROVILLE	2020	- flooding
	2040	- flooding
	2080	+ flooding
SIMILKAMEEN RIVER NEAR NIGHTHAWK	2020	- flooding
	2040	- flooding
	2080	+ flooding
WEST FORK SANPOIL RIVER NEAR REPUBIC	2020	+ flooding
	2040	+ flooding
	2080	+ flooding

Appendix F

Enlarged maps of historical (1993–2011) average August stream temperatures (top) and projected stream temperatures modeled for mid-century (2040s) and end-of-century (2080s) using August air temperatures under the A1B (medium) GHG scenario for the U.S. portion of the Colville Tribes study area. Source: NorWest (http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml).


Historical
NorWeST Stream Temperatures
< 10 °C
10 to 12 °C
12 to 14 °C
14 to 16 °C
16 to 18 °C
18 to 20 °C
> 20 °C


2040s
NorWeST Stream Temperatures
< 10 °C
10 to 12 °C
12 to 14 °C
14 to 16 °C
16 to 18 °C
18 to 20 °C
> 20 °C


2080s
NorWeST Stream Temperatures
< 10 °C
10 to 12 °C
12 to 14 °C
14 to 16 °C
16 to 18 °C
18 to 20 °C
> 20 °C