Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America

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1. Introduction

The performance of water resources systems is often most sensitive to changes in hydrologic extremes rather than changes in mean conditions. Currently the rising demands on the Columbia River associated with irrigation withdrawals, instream requirements for fish, and hydropower production aggravate the risks associated with low flow events (such as those occurring in water year 2001). Similarly, high flow risks create hazards for built infrastructure and human systems (Hamlet and Lettenmaier 2007) and for natural habitat ecosystems (Mantua *et al*. 2010).

The implications of changing hydrologic extremes in the Pacific Northwest (PNW) due to climate change in the 21st century are extensive and include hydropower production (Hamlet and Lettenmair 1999), flood control operations (Lee *et al*. 2009) instream flow for fish passage (Hamlet *et al*. 2010), and local-scale impacts to instream habitat for fish (Battin *et al*. 2007; Crozier *et al*. 2008; Mantua *et al*. 2010). Thus water resources planning requires quantitative information on changing extreme high or low flows resulting from climate change. In response to this need, this study examines changes in extreme flow statistics in a large number of PNW basins of varying size through an analysis of simulated streamflows for the historical past and for a range of 21st century climate change scenarios associated with the fourth report by the Intergovernmental Panel on Climate Change (IPCC AR4, Chapter 10).

The distinct topography that characterizes the Pacific Northwest (PNW) interacts with atmospheric patterns from the Pacific Ocean to orchestrate the region's climate, and the hydrologic characteristics of rivers. Four major mountain chains carve the landscape of the PNW: the Coast Range in western Oregon, the Olympics in western Washington, the Cascade Range extending from southern Oregon to southern British Columbia and the Rocky Mountains stretching along the eastern limits of the PNW. The region's unique topographic and climatic features give rise to a diverse system of watersheds, dominated by the larger Columbia and Snake River basins on the eastern side of the Cascade Range and various smaller coastal drainages on the western side of the Coast and Cascade

Ranges. The Cascade Range broadly delineates two climatic regions in the PNW: continental in the east and maritime in the west. The region east of the Cascades is characterized by a wider range of seasonal temperatures, typically hot in the summers and cold in the winters. Some areas of this region receive an average annual precipitation of only about 250 mm, with greater snow accumulation at lower elevations than on the west side of the Cascades. Annually, the relatively wet west side of the Cascade Range receives approximately 750 mm of precipitation, with greater precipitation at higher elevations (> 2500 mm) falling as a mix of rain or snow depending on winter temperatures. During the period of October through March the Pacific storm track delivers most of the precipitation in the PNW as rain at warmer, lower elevations or as snow at cooler, higher elevations. The winter precipitation and temperature regimes in the PNW determine both the amount and the timing of flow in the rivers, so shifts in climate alter both streamflow magnitude and timing. Figure 1 shows hydrographs exemplifying the annual streamflow behavior for the three characteristic basins in the PNW as described in Hamlet *et al*. (2005). Regional warming tends to shift snowmelt dominant and transient snow basins towards more rain dominant behavior, increasing winter flows and decreasing summer flows (Mantua *et al*. 2010; Elsner *et al*. 2010; Chapter 5, this report).

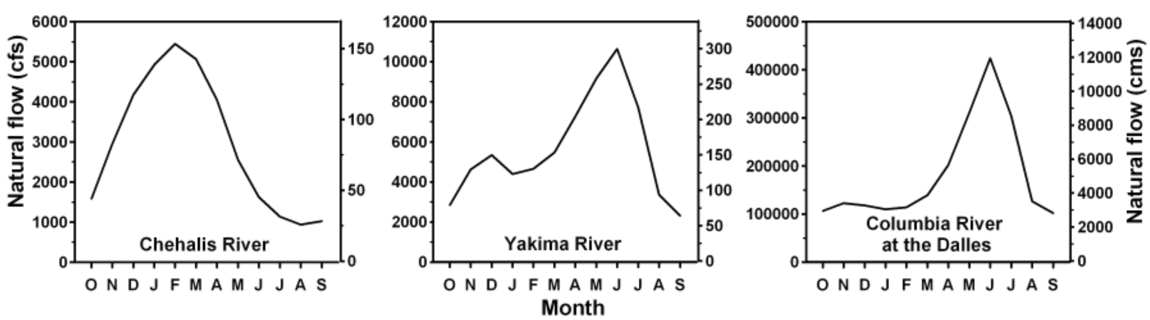

Figure 1: Simulated streamflow hydrographs for three typical basins in the PNW: a) rain dominant, b) transient snow, c) snowmelt dominant.

Mote *et al*. (2005), Hamlet *et al.* (2005, 2007) and Hamlet and Lettenmaier (2007) demonstrated that average winter temperatures for each basin can be used to characterize the behavior of individual basins since wintertime temperature regimes largely govern the primary mechanisms that produce streamflow. Mote *et al.* (2005) and Hamlet *et al.*

(2005) showed that losses of snowpack in the Western U.S. were strongly dependent on mid-winter temperature regimes, and Hamlet *et al*. (2007) and Mantua *et al*. (2010) showed that changes in flood risk could be broadly attributed to mid-winter temperatures in each river basin.

In this report, following methods developed by Hamlet *et al.* (2007) and Mantua *et al.* (2010) we assess changes in extreme streamflow statistics at 297 locations (Chapter 8, this report) using daily streamflow projections for future scenarios. Projections of temperature (T) and precipitation (P) from regionally downscaled Global Climate Models (GCMs) drive the hydrological models used to produce the streamflows at a daily time step (Chapter 5, this report). The two regional downscaling approaches used in these analyses, the "composite delta" and "hybrid delta" methods, are described in detail in Chapter 4 (this report).

2. Approach/Methods

2.1. VIC model output

The hydrologic model, Variable Infiltration Capacity (VIC), implemented at the spatial resolution of 1/16th degree latitude and longitude, generated the daily runoff and base flows used to calculate daily streamflow for this study (see Chapter 5, this report; Hamlet 2005). To drive the VIC model, a historical (1915-2006) input dataset, including the variables of daily precipitation, maximum and minimum daily temperatures and windspeed, was developed as described in Chapter 3 (this report). The IPCC AR4 report (2007) archived datasets from Global Climate Models (GCMs) under numerous greenhouse gas (GHG) emissions scenarios. To calculate future streamflows for this report, the VIC model processed input datasets of future conditions derived from two methods of downscaling GCMs into regional datasets under two emissions scenarios. The first downscaling approach uses the delta method, where monthly perturbations are calculated from multi-model means of future conditions and then applied to the historical record (Elsner *et al*. 2010). Chapter 4 of this report describes the second approach, the hybrid delta method, to statistically downscale 10 GCMs for the A1B (medium) and 9

GCMs for the B1 (low) emissions scenarios. Resulting streamflow scenarios were evaluated for three future time periods: 2020s, 2040s, 2080s, and two emissions scenarios to produce an ensemble of 66 scenarios, 6 for the delta method and 60 for the hybrid delta method. Because there are 19 realizations for each future time period (10 for A1B and 9 for B1)), an uncertainty analysis of the change in streamflow statistics is straightforward to produce. For example, the uncertainty in the future flood magnitude can be approximated for each site by comparing the range of estimates projected for a given return frequency from the ten downscaled models.

2.2. Extreme flow statistics & basin classification

Applying the delta and the hybrid delta methods, Elsner *et al.* (Chapter 5, this report) generated the daily streamflows used here to calculate extreme flow statistics for four time periods: the historical (1915-2006) and three future intervals (2020s, 2040s, 2080s). The annual maximum streamflow time series for each time period and basin were ranked, assigned a plotting position using an unbiased quantile estimator, and fitted to the Generalized Extreme Value distribution using the L-moments method (Wang 1997; Hosking and Wallis 1993; Hosking 1990). Flood magnitudes with 20-year, 50-year and 100-year return frequencies were estimated for each basin and time period from the fitted probability distributions. These methods are described in more detail by Hamlet and Lettenmaier (2007) and Mantua *et al*. (2010). In a similar approach, the GEV distributions were used to estimate the 7-day consecutive lowest flow with a return frequency of 10-years (7Q10) for each basin and time period. From these we computed the ratio of the magnitudes (historical versus model/scenario/time interval combinations) for each flow statistic.

The air temperature fields of the historical period for each downscaled dataset were used to calculate the average temperatures during the winter months of December, January and February (DJF). The DJF for each basin in this study was estimated to classify individual catchment's winter temperature regime. Although basin temperatures and their effects on snow and runoff timing is in fact a continuum, Hamlet *et al.* (2007) broadly characterized snowmelt dominant basins as those with DJF < -6 ^{o}C, transient basins as those with DJF between -6 ^{o}C and 5 ^{o}C, and rain dominant basins those with a DJF exceeding 5 ^{o}C. Each site was classified based on the month of peak flow historically and used to characterize the sensitivity of each basin to increased temperatures by comparing mid-winter temperature regimes to the change in magnitude of the 20-year and 100-year return flood events.

3. Key Findings/Discussion

As discussed in Chapter 5 (this report), the Columbia basin shifts towards more rain dominant behavior as the region's temperatures warm, which creates changes in both flood and low flow statistics that vary with mid-winter temperatures and other factors. These changes are related primarily to changes in snowpack and associated effective basin area during extreme precipitation events (Hamlet and Lettenmaier 2007). Figure 2 shows the maps of the shifting characterizations of these basins, measured as the ratio of April 1 snowpack to October-March total precipitation, as time progresses through the 21st century under the A1B and B1 scenarios. The topmost map illustrates the spatial distribution of basin types for the historical period (1970-1999). Historically, snowmelt dominant basins prevail in the northern PNW, the headwaters of the Columbia River basin, extending south into the east side of Cascades in Washington and the higher elevation basins of the Rockies in Idaho and northern Montana. Transient basins predominate where mid-winter temperatures fluctuate around 0^{o} C at mid-elevations of the Cascades and Rockies, in central Washington and Oregon and in southern and western Idaho. Rain-dominant basins are confined to the coastal stretches in Washington and Oregon, west of the Cascades and Coast ranges, and in large swathes of warmer regions in central and southern Oregon and smaller patches in southeast Washington and southwest Idaho.

In projections for the 21st century, future warming results in a progressive shift from snow dominant to transient basins and from transient basins to rain dominant basins (lower panels of Figure 2). Furthermore, this shift in basin characterization occurs at a faster rate for the A1B than for the B1 scenarios, because the rate of warming is faster. By the 2080s for the A1B scenario, there is a complete loss of snowmelt dominant basins in the Cascades and the Rockies in the U.S., and only a few transient basins remain at higher elevations. This shift in basin type has implications for the timing of peak flows since the mechanism driving the flows is changing under warmer conditions.

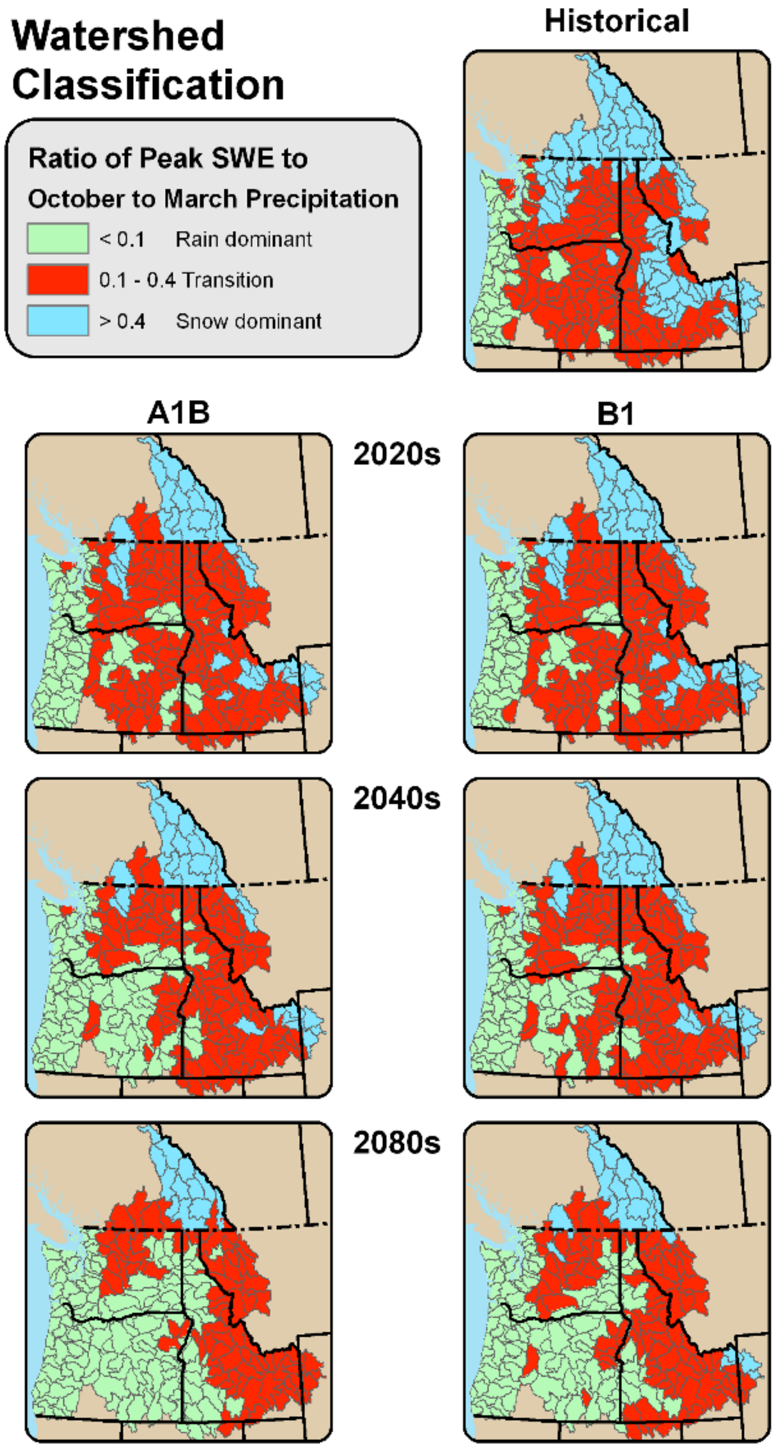

Figure 2: Ratio of April 1 SWE to total March-October precipitation for the historical period (1916-2006), for the A1B scenario (left panel), and for the B1 scenario (right panel) at three future time periods (2020s, 2040s, 2080s).

3.1. Changes in Flood Risk

Maps of the entire PNW region indicating changes in flood risk magnitudes are paired with scatterplots characterizing each basin's DJF and shifts in flood frequency for the 20-year (Figures 3 and 4) and 100-year events (Figures 5 and 6). Overall, the entire region is projected to undergo elevated flood magnitudes under the hybrid delta models, with the exception of a few snowmelt dominant basins in the Cascades. Notably, these results diverge considerably from those projected by the composite delta models used in this study and in Mantua *et al.* (2010). This discrepancy is attributable to the differences in spatial variability of average changes depicted by the two downscaling methods. The composite delta method applies a constant change in temperature and precipitation over the entire domain, whereas the hybrid delta method improves the spatial distribution of climatic shifts (see chapter 4 of this report for detailed description of downscaling methods). Thus, the projections generated from the hybrid delta downscaling capture greater increases in winter precipitation in the headwaters of the Columbia Basin and higher temperatures variably over the entire domain. Higher winter temperatures and precipitation regimes create the conditions favoring elevated flood risk in snowmelt basins.

Related Figures 4 and 6 show scatterplots of the change in flood magnitude for the 20 and 100-year flooding events, respectively, as a function of mid-winter temperature regimes. These paired figures with the maps, relate the month of peak flows and average winter temperatures for each basin with the shifts in flood magnitudes. Most basins fall above the 1:1 ratio, indicating a rise in projected flood magnitudes across all winter temperature regimes, with the exception of a few of the basins near or below freezing temperatures. These results are consistent with the projections of increased winter precipitation and temperatures generated by the hybrid delta downscaling. Further exacerbations of flood risk in the future could arise from the soil saturation accompanying a projected rise in spring storm intensity (Salathé 2006) and possible enlargements in contributing basin area as warming increases later in the 21st century (Hamlet *et al.* 2007).

Basins identified as transient, characterized by a mixed runoff of rain and snow, are projected to be the most sensitive to warming temperatures. These basins are found at higher elevations in coastal mountains (western Cascades, Olympic and Coast Ranges) and at lower elevations in the cooler, continental mountains (Rocky Mountains and eastern Cascades). Transient basins typically have a double-peaked hydrographs (Figure 1, center hydrograph), with one peak greater than the other depending on seasonal inputs to streamflow. Warmer transient basins with peak flows occurring in the winter months are located where precipitation falling as rain seasonally peaks in the winter; whereas cooler, transient basins with elevated runoff inputs during the spring or early summer have a greater contribution of snowmelt to streamflows.

Under a warmer future climate, the greater proportion of winter precipitation falling as rain, rather than snow, will intensify winter flood risk for warmer transient basins. This trend is depicted spatially in the 20 and 100-year flood ratio maps (Figures 3 and 5) showing an overlap in the locations of warmer, transient basins with a progressive increase in flood risk through the 21st century. Likewise, the corresponding scatterplots of flood magnitude ratio and DJF temperatures (Figures 4 and 6) capture this trend, showing elevated future flood magnitudes for all transient basins with winter temperatures above freezing and maintaining peak flows in the winter. However, the response of transient basins to warming temperatures is complex, because it is contingent not only on the type and timing of precipitation events, but also on the balance of snow accumulation and change in contributing basin size. If the DJF of the basin is on the cooler spectrum of the winter temperature range, -6 ^{o}C to -3 ^{o}C, then the decline in seasonal snow accumulation tends to lower the flood risk in the spring and early summer (as for some snowmelt dominant watersheds). Whereas the flood risk of transient basins characterized by warmer DJFs (> -3 ^{o}C) tends to increase despite losses of antecedent snowpack, primarily because the area of the contributing watershed is enlarged with additional warming due to an elevational shift in the snow line (Hamlet *et al.* 2007).

The flood risk in rain dominant basins do not respond as quickly as the transient basins, although increases in winter precipitation do elevate the risk of flooding in winter later in the century. Figures 3 and 5 show that the flood risk for rain dominant basins in the western part of the region and in central Oregon increases slower and less intensely than the transient basins.

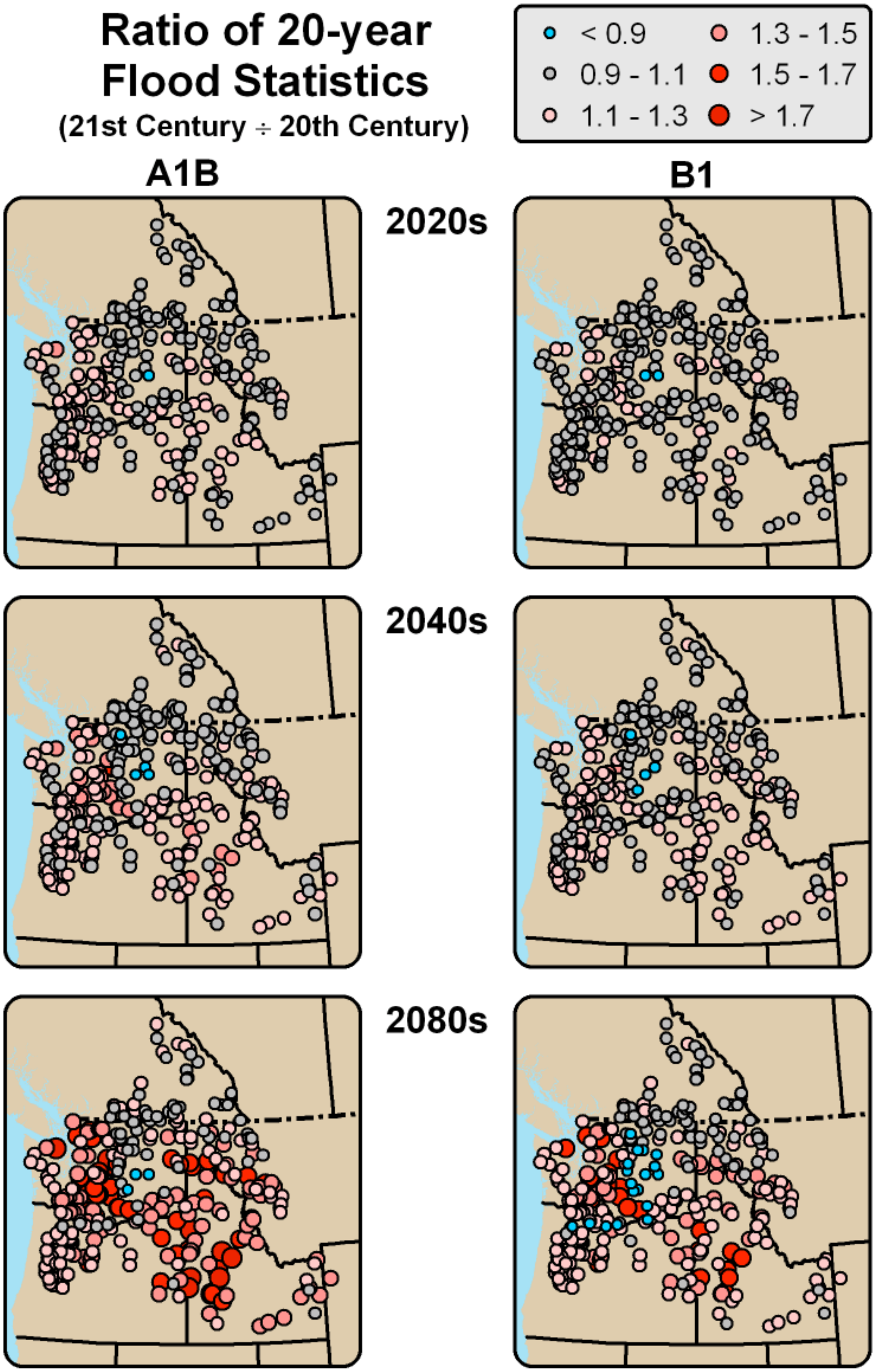

Figure 3: Maps of the ratio of the 20-year flood magnitude (future/ historical) for three future time intervals, under two scenarios. (Higher ratios indicate more intense flooding events projected for the future).

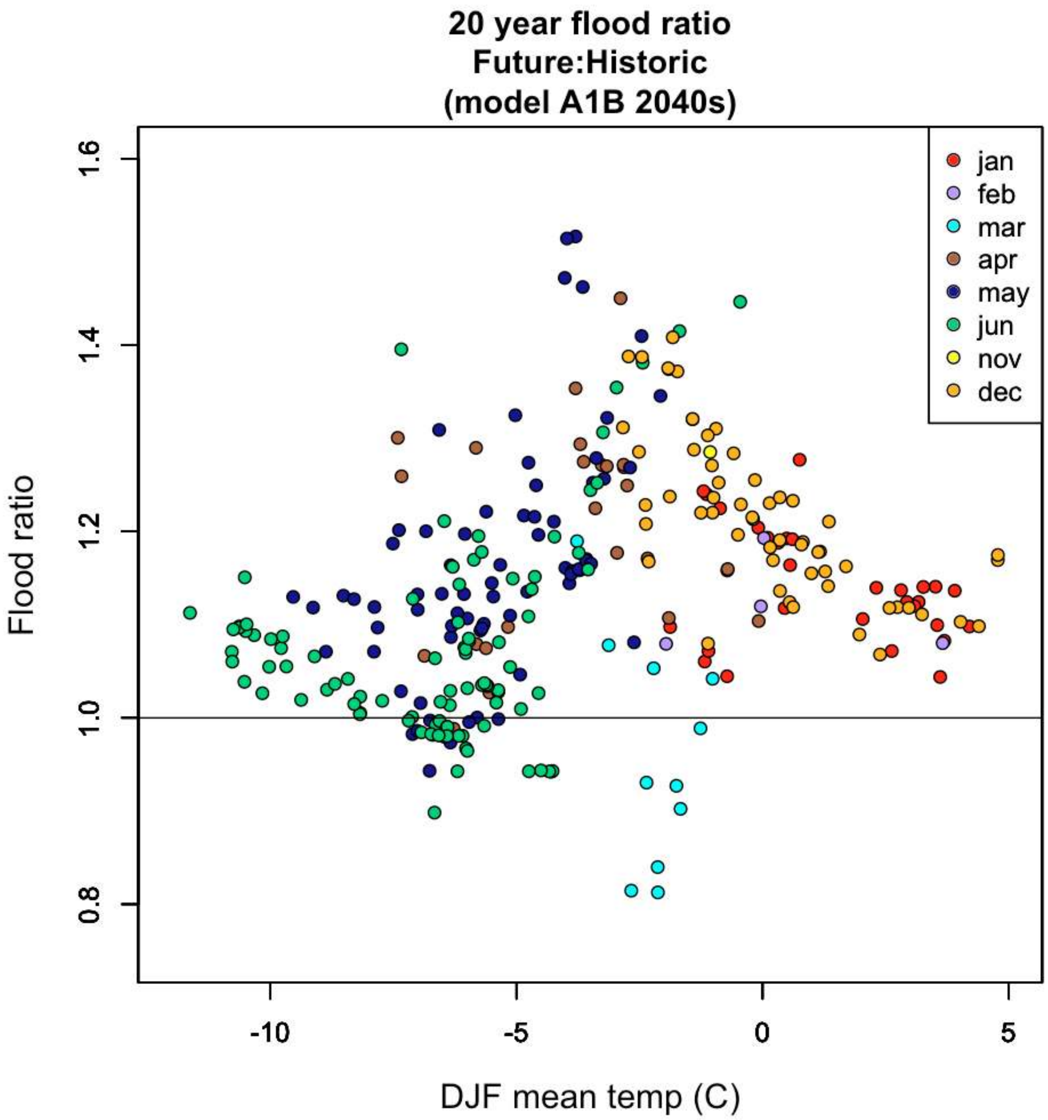

Figure 4: Plots of the mean winter temperature and flood magnitude ratio of the projected future and historical 20-year floods for each basin. Colors of dots indicate month of historical flood occurrence.

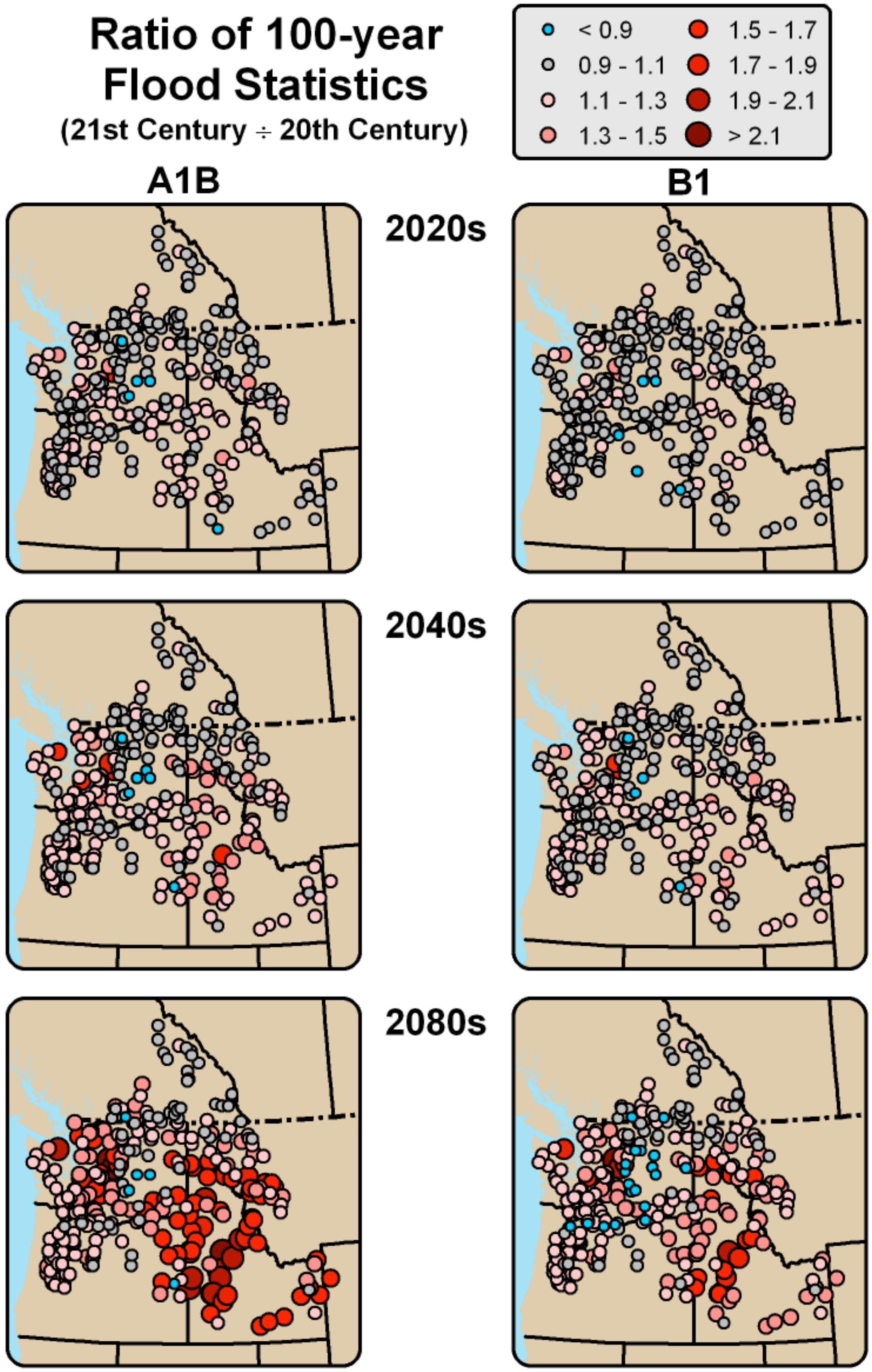

Figure 5: Maps of the ratio of the 100-year flood magnitude (future/ historical) for three future time intervals, under two scenarios. (Higher ratios indicate more intense flooding events projected for the future).

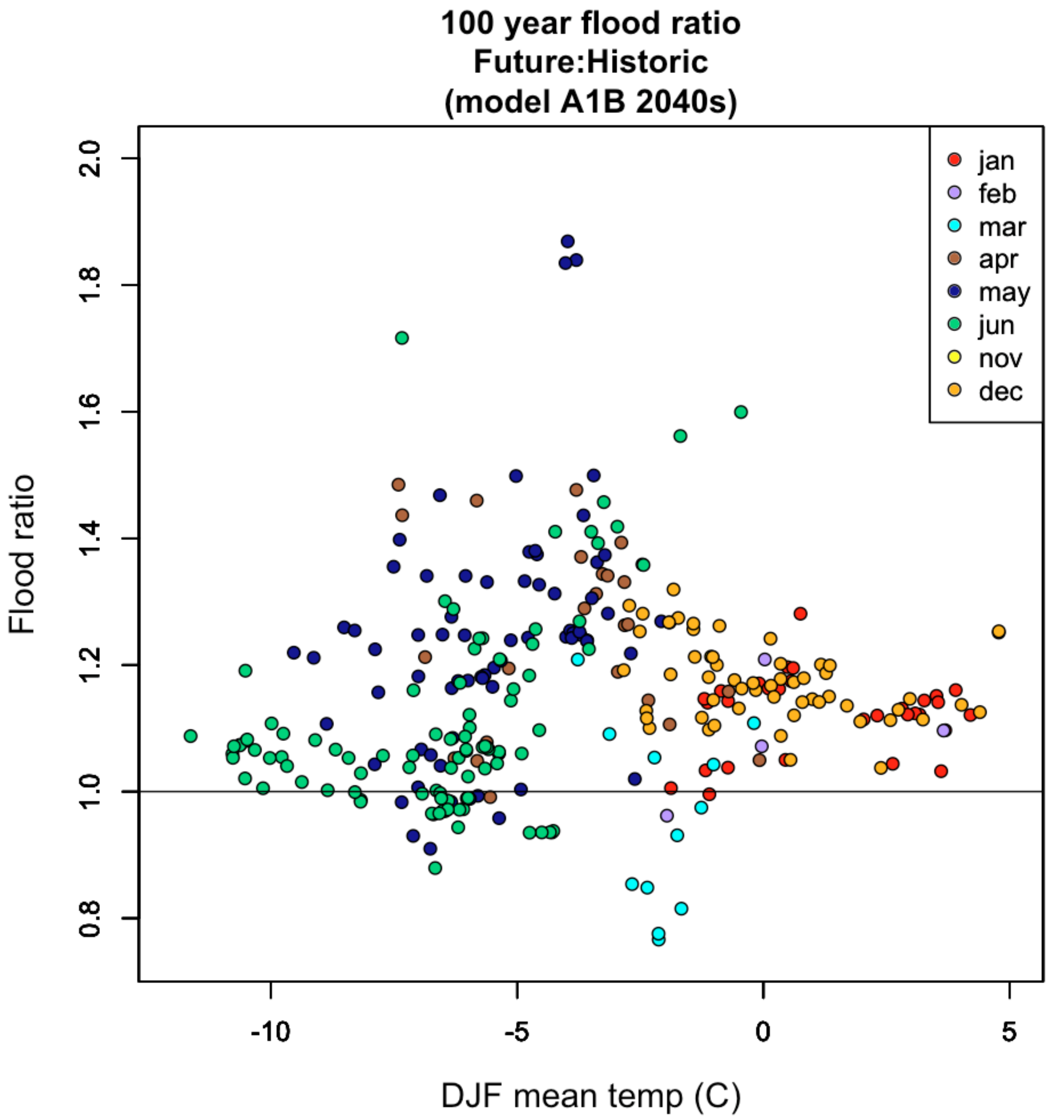

Figure 6: Plots of the mean winter temperature and flood magnitude ratio of the projected future and the historical 100-year floods for each basin. Colors of dots indicate month of historical flood occurrence.

3.2. Changes in Low flow Risk

Low flow, 7Q10, values are projected to decrease (i.e. increasing low flow risk) most strongly in rain dominant and transient basins (Figure 7). This pattern is particularly prominent in the lower elevation basins of the eastern Cascades and the mid to lower elevation basins in the western Cascades and in the Olympic Peninsula and the lower elevations on the west slopes of the Rockies. These results support the hypothesis that the intensity of the low flows will rise with increasing temperatures and evapotranspiration, which reduces the soil water moisture and late summer baseflows. Unlike transient and rain dominant basins, the changes in low flow regimes projected for snowmelt dominant basins are relatively insensitive to increased temperatures. These basins, which include many tributaries in the Columbia and the Snake basins, demonstrate relatively small decreases in 7Q10. Some of the coldest sites located in the interior of Columbia basin and at the headwaters of both the Columbia and Snake basins demonstrate increases for the in 7Q10 statistics associated with warming (Figure 7). One explanation for the relatively small changes or increases in 7Q10 statistics for snowmelt basins is that the lowest flows in these coldest basins often occur in the winter when water is trapped as snow. As temperatures warm, shifting these basins to an increasingly transient behavior, and more precipitation falls as rain in the winter months, 7Q10 values may actually rise somewhat for the coldest basins.

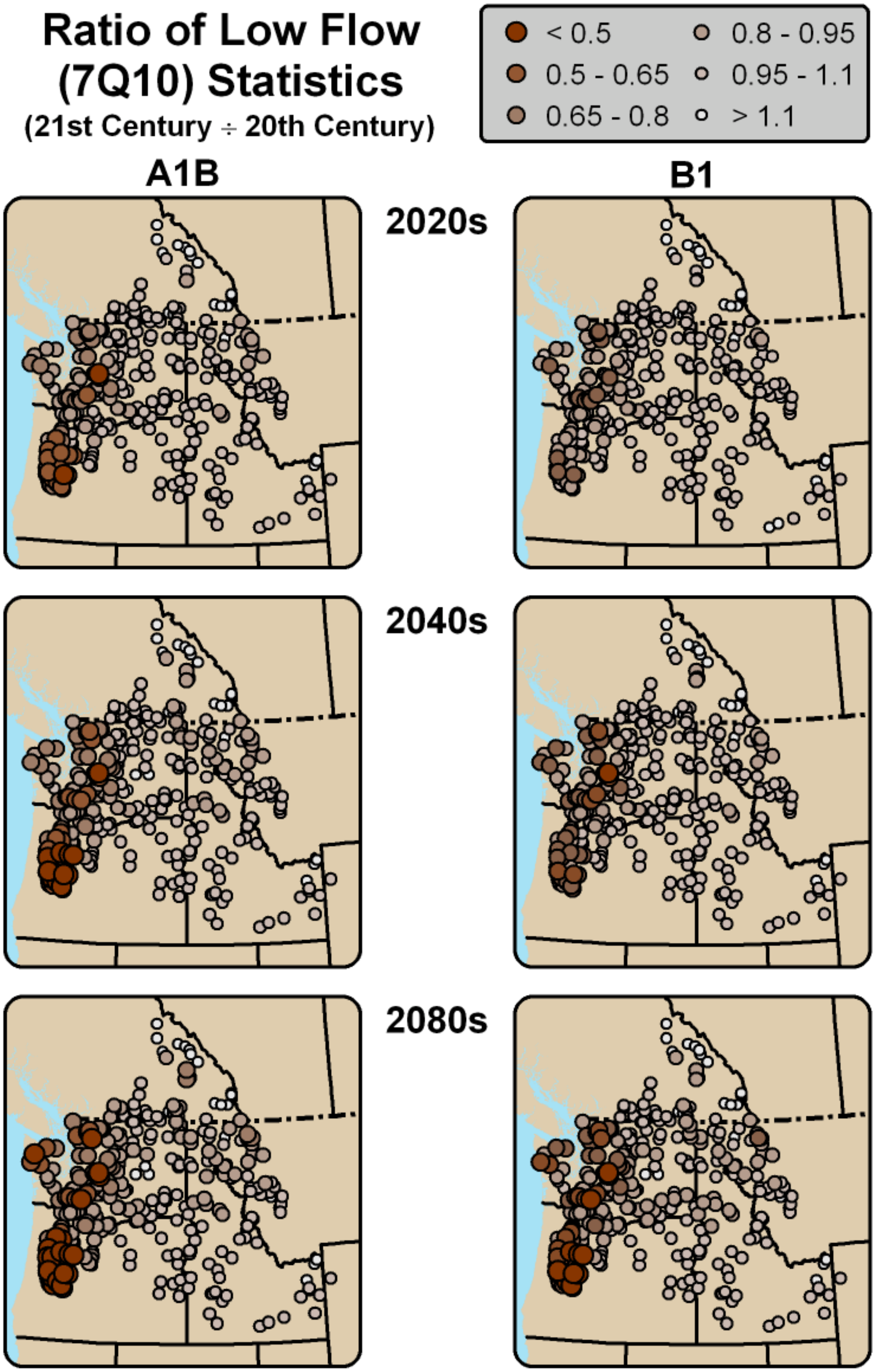

Figure 7: Maps of the ratio of 7Q10 low flow magnitudes (future/historical) for 3 future time intervals, under 2 scenarios. (Lower ratios indicate more intense low flow extremes in the future)

4. Research Gaps

Many of the larger basins contributing to the Columbia River basin are regulated by dam operations and other watershed management practices. Among the limitations of determining extreme flow risks using the methods applied here are the exclusion of management operations. The routed streamflows used to calculate these statistics do not consider the effects of management on flows, so this assessment reports only natural flood and low flow risks. Although the simulated streamflows do not represent absolute values of the actual flows in many of these watersheds, it is important to observe the relative streamflows (historical to future). The strength of these analyses lies in what the models indicate is the historical relative to the future simulated streamflows. Another restriction inherent in these models is the lack of incorporation of potential geomorphological changes in these watersheds, which may affect the hydraulic capacity of river channels and resulting flood inundation for a given flow rate

5. Conclusions

The overall response of the Columbia River basin to warmer temperatures projected in the future is a general shift in the primary mechanism of streamflow inputs from snowmelt to transient snow and rainfall dominant behavior. The most sensitive watersheds to this widespread shift in basin type are those found at mid-elevations, where small increases in average winter temperatures can produce increased runoff production in response to precipitation inputs. The comprehensive conversion in basin type provokes a shift in the timing and quantity of peak flows and base flows. These patterns of change in transient basins are exacerbated by projected seasonal shifts in precipitation that deliver more precipitation in winter and less in summer. As more precipitation falls in the wintertime as rainfall for transient basins, the winter peak flows are projected to increase and summer flows are projected to decrease as less snowmelt contributes to streamflow.

The projected changes in extreme flow risks are dependent on the responses of basins to the future warming. Flood risk increases for mid-elevation basins with higher snowlines, greater rainfall contributions to streamflow, and increased precipitation at the time of year when flooding occurs. Snow and rainfall dominant basins, by comparison remain relatively insensitive to greater flood risks with future warming, although some exceptions are apparent in the coldest basins in BC, which are projected to experience large increases in winter snowpack and peak streamflows The low flow risk, likewise, is projected to rise most prominently for the transient basins since the summertime flows will diminish due to the combined effects of reduced snowmelt runoff, projected decreases in summer precipitation, and projected increases in evaporation that reduce residual soil moisture in late summer.

These varied responses of the Columbia River basins have many implications for future water resources planning and management. The change in magnitude and timing of flood and low flow risks for sensitive basins needs to be considered in the design and operation of flood control infrastructure. Such changes will, in turn, affect other water resources objectives such as water supply for irrigation and municipal needs and hydropower production. Maintaining minimum flows for fish passage is likely to become increasingly difficult over much of the region due to declining baseflows in summer. Likewise the combined effects of lower baseflows and increasing air temperatures is likely to intensify impacts related to stream temperatures in the summer with reductions in habitat suitable for cold water fish species (Mantua *et al.* 2010).

6. References

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