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Ubiquitous increases in flood magnitude in the Columbia River Basin under climate change

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Abstract. The US and Canada have entered negotiations to modernize the Columbia River Treaty, signed in 1961. Key priorities are balancing flood risk, hydropower production, and improving aquatic ecosystem function while incorporating projected effects of climate change. In support of the US effort, Chegwidden et al. (2017) developed a large-ensemble dataset of past and future daily flows at 396 sites throughout the Columbia River Basin (CRB) and select other watersheds in western Washington and Oregon, generating a large ensemble using state-of-the art climate and hydrologic models. In this study, we use that dataset - the largest now available - to present new analyses of the effects of future climate change on flooding using water year maximum daily flows. For each simulation, flood statistics are estimated from Generalized Extreme Value distributions fit to simulated water year maximum daily flows for 50-year windows of the past (1950-1999) and future (2050-2099) periods. Our results contrast with previous findings: we find that the vast majority of locations in the CRB are estimated to experience an increase in future discharge magnitudes. We show that on the Columbia and Willamette rivers, increases in discharge magnitudes are smallest downstream and grow larger moving upstream. For the Snake River, however, the pattern is reversed, with increases in discharge magnitudes growing larger moving downstream to the confluence with the Salmon River tributary, and then abruptly dropping. We decompose the variation in results attributable to climate and hydrologic factors, finding that climate contributes more variation in larger basins while hydrology contributes more in smaller basins. Equally important for practical applications like flood control rule curves, the seasonal timing of flooding shifts dramatically on some rivers (e.g., on the Snake, 20th century floods occur exclusively in late spring, but by the end of the 21st century some floods occur as early as December) and not at all on others (e.g. the Willamette).

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1 Introduction

Among natural disasters in the Northwest, flooding ranks second behind fire in federal disaster declarations[1] since 1953 despite extensive flood prevention infrastructure. The largest flood in modern times on the Columbia occurred in late spring (May-June) 1948, and obliterated the town of Vanport which lay on an island between Portland, OR and Vancouver, WA, permanently displacing its 18,500 residents[2]. Other disruptive floods in the region include the Heppner flood in 1903, one of the deadliest flash floods in US history (Byrd, 2014); floods on the Chehalis River in both December 2007[3] and January 2009[4] that closed Interstate 5, the main north-south transportation corridor through the Northwest, for several days each time at a cost of several $m per day to freight movement alone; and floods on the Willamette River in February 1996 and April 2019. The timing of typical floods varies widely across the region: low-elevation basins in western Washington and Oregon typically flood in November through February, whereas the snow-dominant basins east of the Cascades more typically flood in spring, even as late as June (Berghuis et al. 2016).

The Columbia River drains much of the Northwest, with the fourth largest annual flow volume in the US and a drainage that includes portions of seven states plus the Canadian province of British Columbia (BC). Its numerous federal and nonfederal dams provide flood protection, hydropower production, navigation, irrigation, and recreation services. A treaty with Canada, signed in 1961, codified joint management of the river's reservoirs (and funded construction of new reservoirs in BC) primarily to provide flood protection and hydropower production[5]. The US and Canada have entered negotiations to update the treaty; the USA's "key objectives include continued, careful management of flood risk; ensuring a reliable and economical power supply; and improving the ecosystem in a modernized Treaty regime." (*ibid.*) Both countries have expressed an intention to include the effects of climate change on flows, and clearly a key aspect of hydrologic change is to inform the treaty negotiations of the influence of climate change on the magnitude of flooding.

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[1] https://www.fema.gov/data-visualization-summary-disaster-declarations-and-grants accessed 8/6/2019
[2] https://www.oregonlive.com/portland/2017/05/vanport_flood_may_30_1948_chan.html accessed 8/6/2019
[3] https://www.seattletimes.com/seattle-news/extensive-flooding-3-confirmed-deaths-hundreds-of-rescues/ accessed 8/6/2019
[4] https://www.seattletimes.com/seattle-news/despite-drying-cooling-trend-flooding-and-road-closures-continue/ accessed 8/6/2019
[5] https://www.state.gov/columbia-river-treaty/ accessed 8/6/2019

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While rising temperatures potentially affect all parts of the hydrologic cycle, in a snowmelt-dominated hydrologic system such as many of the Northwest's rivers, warming directly affects snow accumulation and melt. Observational studies have shown consistent changes toward lower spring snowpack (Mote et al. 2018), earlier spring flow (Stewart et al. 2005), and lower summer flow (Fritze et al. 2011) since the mid-20th century. Observations of trends in flooding in the US have generally failed to find any consistent trends (Lins and Slack 1999; Douglass et al. 2000; Sharma et al. 2018). Sharma et al. (2018) offer several possible explanations, chiefly "decreases in antecedent soil moisture, decreasing storm extent, and decreases in snowmelt". The detection of trends in floods is complicated by the interaction of extreme events and nonstationarity (Serinaldi and Kilsby, 2015). Moreover, as a result of the substantial alteration of rivers to prevent flooding (e.g., by the construction of dams and levees) during the observational period, the best long-term records - i.e., on streams with the least modifications - are on rivers that were not producing sufficiently disruptive floods to lead decision-makers to construct flood protection structures.

To interpret the ambiguous results from observed trends, Hamlet and Lettenmaier (2007) used the Variable Infiltration Capacity (VIC) hydrologic model forced twice with detrended observed daily weather for the period 1916-2003, with about 1°C of temperature difference between the two. They then compared 20- and 100-year flood quantiles for basins at varying sizes in the western US and found a wide range of changes in flood magnitude ranging from large decreases to large increases (+/- 30%). Broadly, the responses depended somewhat on basin winter temperature, with the coldest basins (<-6°C) showing reductions in flood magnitude owing to reduced snowpack, basins with moderate temperatures exhibiting a wide range of changes, and rain-dominant (>5°C) basins showing little change, though the warm basins in coastal areas of Washington, Oregon, and California showed increased flood magnitude.

Modeling work using state-of-the-art hydrologic models has been applied to understand where and how flood magnitudes may change in the future. Tohver et al (2014) found widespread increases in flood magnitudes, especially in temperature-sensitive basins (mainly on the west side of the Cascades), but their approach used monthly GCM output so changes in daily precipitation would not be represented. Salathé et al. (2014) used a single global climate model (GCM), the ECHAM5, linked to a regional climate model to obtain high-resolution (in space and time) driving data for VIC over the period 1970-2069. As did Hamlet and Lettenmaier (2007), they compared the ratio of flood change (2050s vs 1980s) against mean historical winter temperature and found a majority of locations with a higher 100-year flood, in some cases by a factor of 2 or more; while they projected increases in every one of the warmer basins (>0°C), a substantial fraction of colder locations had decreases in flood magnitude.

As noted above and detailed below, Chegwidden et al. (2019) describe the process used to generate the streamflow ensemble used here. In addition, they used analysis of variance (ANOVA) to analyze the different influences of choices of emissions scenario (as a Representative Concentration Pathway - RCP), GCM, downscaling method, and hydrologic model, and how those influences varied spatially across the domain and also seasonally and by hydrologic variable. They found that the RCP and GCM had the largest influence on the range of annual streamflow volume and timing, and hydrologic model had the largest influence on low flows. The hydrologic variables they considered were snowpack (maximum snow water equivalent and date of maximum SWE), annual streamflow volume, centroid timing (the date at which half the water year's flow has passed), and seasonal streamflow volume; primary focus was on centroid timing, annual volume, and minimum 7-day flow. They did not examine maximum daily flow, which is the purpose of this paper.

2 Methods

2.1 Hydrologic modeling data set

To assess changing flood magnitudes under climate change, we analyzed changes in water year maximum daily flows in a large ensemble of streamflow simulations at 396 locations in the CRB (Figure MAP) and select watersheds in western Oregon and Washington (Chegwidden et al., 2017). The simulations were constructed from permutations of modeling decisions on forcing datasets and hydrologic modeling. Specifically, choices included two RCPs (RCP4.5 and RCP8.5), ten GCMs, two methods of downscaling the climate model output to the resolution of the hydrologic models, and four hydrologic model implementations, for a total of 160 permutations. For our analysis, we extracted a more tractable dataset of 40 simulations per location, by only considering simulations with RCP 8.5 and the Multivariate Adaptive Constructed Analogs (MACA) downscaling method (Abatzoglou and Brown, 2012).

The rationale for using a subset of the available data is as follows. First, the time-dependent set of greenhouse gas concentrations in RCP4.5 is fully included in RCP8.5, so any concentration of greenhouse gases on the RCP4.5 path can be converted to a point on RCP8.5 (at a different time). We analyzed results for both RCP8.5 and RCP4.5, and found that to first order the changes in flood magnitude in RCP4.5 were approximately 2/3 those in RCP8.5, which is also roughly the ratio of global temperature change over the period considered (IPCC Summary for Policymakers, 2014). For clarity we show only the results for RCP8.5. Second, we considered only simulations using the MACA downscaling method because of the method's ability to capture the daily GCM-simulated meteorology critical for assessing changes in extremes and its skill in topographically complex regions (Lute et al., 2015). The other downscaling approach used by Chegwidden et al. (2019), the Bias Correction and Statistical Downscaling (BCSD) method (Wood et al. 2004), produces probability distributions of daily precipitation inconsistent with the GCM response to forcings because the method stochastically disaggregates monthly data to daily data based on historical statistical properties of the daily data. This statistical property limits the ability of BCSD to reproduce changes in storm frequency in the future, making it a less attractive choice for daily extreme flow analysis (Hamlet et al. 2010; Guttman et al. 2014).

The GCMs used in this study are the CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, Inmcm4, IPSL-CM5A-MR, and MIROC5. These ten GCMs were chosen primarily for their ability to accurately reproduce observed climate metrics during the historical period mainly of the Northwest US but also at sub-continental and larger scales as assessed in Rupp et al. (2013) and RMJOC (2018). The four hydrologic model implementations included two distinct hydrologic models: the Variable Infiltration Capacity (VIC; Liang et al., 1994) model and the Precipitation Runoff Modeling System (PRMS; Leavesley et al., 1983). VIC and PRMS are process-based, energy balance models and were both run on the same 1/16th degree grid with output saved at a daily time step for the period 1950 to 2099. VIC also included a glacier model (Hamman & Nijssen, 2015). Three unique implementations of VIC were used with independently derived parameter sets (P1, P2, P3) marked by differences in calibrated parameters, calibration methodology, and meteorological and streamflow reference sets. See Chegwidden et al (2019) for details. It is important to note that these hydrologic simulations and calibrations do not include reservoir models.

2.2 Flood magnitude

We assessed changes in flood magnitude in the Columbia River Basin by comparing maximum daily streamflows over a 150-year period (1950-2100). We estimated the 10, 5, 2, and 1% probability of occurrence (commonly referred to as the 10-, 20-, 50-, and 100-year flood, respectively) by fitting generalized extreme value (GEV) probability distributions to simulated water year maximum daily flows for 50-year windows of the past (1950-1999) and future (2050-2099) periods. (We also looked at 30- and 75-year windows, choosing 50 years as a

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balance between sample size favoring longer periods, and nonstationarity considerations favoring shorter periods.) We used Python's scipy.stats.genextreme module (Jones et al., 2001) to fit a Gumbel distribution and estimate flood magnitudes for each return period. We assessed change in flood magnitude as the "discharge ratio" of the estimated future to past floods for a given return period; a ratio greater than 1 indicates an increase in flood magnitudes while a ratio less than 1 indicates a decrease.

We describe how changes in flood magnitude vary by climatic zone across the PNW by using an efficient and internally consistent proxy for climatic zone: the centroid of timing – the day in the water year that half the annual volume of water has passed through the location. The centroid of timing is a metric of snow dominance (e.g., Stewart et al. 2005) which is related to the spatial distribution of temperature and tends to decrease downstream. This temporal proxy of a hydrologic characteristic is effective in the Columbia Basin where most of the precipitation occurs in winter and the relative magnitude and timing of the freshet from the spring thaw is a good indicator of importance of snowmelt to streamflow. An early centroid indicates that rain, which falls predominantly during the cooler, earlier part of the year, is the driver of the peak flows at the location, while a late centroid indicates that snowmelt during later spring months is the prime hydrological driver. We computed the centroid using the 1950-79 simulated years. Note that Chegwidden et al. (2019) also used the *change* in centroid as a hydrologic variable of interest; below, we discuss our results in the context of their findings.

3 Results

3.1 Regional changes in flood ratio

Figure 3 shows the changes in maximum daily discharge for all of the 396 flow locations for different return periods. The horizontal position of each circle represents the centroid of timing. The circles are semi-opaque so overlapping circles lead to a deeper saturation. Each circle represents the average of the ratios of change for the 40 hydrological simulations for that location. (In Figure 5 we will show the full set of points for select locations.) Points on the same river tend to be ordered from more to less snow dominant traveling downstream; strings of circles in a smooth pattern sometimes indicate points on a given river, and a few of these are highlighted in Figure 4.

A striking result in Figure 3 is that the flood magnitude increases (i.e., the discharge ratio exceeds one) at nearly every flow location and return period (though not for every individual climate scenario, as shown in Figure 5).

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Broadly, the patterns are similar across all return periods though with slightly higher ratios for longer return periods, and subsequent figures will show only the 10- and 100-year floods. For the flow locations with centroid <125 or so (i.e. February 2), flood ratios are fairly concentrated about 1.25 for all return periods. For mixed rain-snow basins, roughly delineated by centroids between 125 and 160 (March 8 most years), flood ratios range widely from just below 1 to about 2.4 for the 10-year and 3.2 for 50- and 100-year floods. For the longer return intervals, there is a wide range of projected changes in daily flood at many locations (indicated by the red coloring). This is undoubtedly partly due to the GEV fit extrapolating from 50 to 100 years. Finally, for the basins with flow centroid >160, the ratios have a smaller range, from slightly greater than 1 to a maximum that increases from about 2 for the 10-year, to about 2.75 for 100-year.

To understand better how flood magnitude changes along the length of a river, we focus (Figure 4) on a handful of significant rivers in the region: the mainstem Columbia, Willamette (along with major tributaries the McKenzie and Middle Fork Willamette), and Snake, and also on the Chehalis in southwest Washington (see Introduction). Flow locations are listed in Table 3Rivers in the Appendix. The Columbia River includes the most snow-dominant basins, with a centroid of >190 days (early to mid April) in the Canadian portion of the basin. The flood ratio decreases almost uniformly along the length of the river, from 1.3 for the 10-year and >1.5 for the 100-year in the Canadian portion to just above 1 at the last few points along the river (The Dalles, Bonneville, and Portland). Like the Columbia, the Willamette also has flood ratios that decrease along the length of the river, from 1.7 to 1.35 for both return periods. The McKenzie River (points 15-17), one of the three tributaries that converge at Eugene to form the Willamette, is a highly aquifer-fed river with higher baseflow than is represented in the hydrologic models, though it is unclear how that difference would manifest in the flood statistics.

Surprisingly, the Snake behaves oppositely: flood ratio increases along the length of the river, until the confluence with the Salmon River, which drains a large mountainous area of central Idaho. On parts of the Snake the ratios are as high as 1.4 for 10-year and 1.6 for 100-year. Then after the confluence with the Salmon River, which has much lower change in discharge ratio, the ratios on the Snake drop to about 1.2 for 10-year and about 1.3 for the 100-year. Our hypothesis is that in the Snake above the Salmon River, the tributaries shift from snow-dominant to rain-dominant, so that a single storm can drive large rainfall-driven increases (possibly with a snowmelt component) leading to larger synchronous discharges. The Salmon and Clearwater rivers retain less exposure to such shifts, and dilute the effects of single large storms on flooding. Fully understanding the reasons for this curious behavior would require additional analysis, beyond the scope of this paper.

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Each circle in Figures 3 and 4 represents an average of 40 simulations: 10 GCMs and 4 hydrologic model configurations. To better understand the range in results, Figure 5 shows the discharge ratio for all 40 simulations at each point on the mainstem Columbia. Although the mean flood ratio at the lowest two points is only barely above 1, several ensemble members have ratios less than one, and a few have ratios >1.5. Moving upstream, the range in results increases, as shown also by the color of the dots.

3.2 Dependence of results on modeling choices

As in Chegwidden et al (2019), we separate the results - here for the three largest rivers - into variations across GCM (Figure 6) and variations across hydrologic model configurations (Figure 7). The ranking of flood ratios by GCM changes substantially between basins and even within a basin, and does not correspond to the changes in seasonal precipitation. For the upper Columbia River, the models with the least warming - inmcm4 and GFDL-ESM2M (Rupp et al 2017) - have almost no change in flood magnitude, but the HadGEM2-ES which warms considerably in summer produces a large decrease in flood magnitude. In the Willamette and Snake Rivers, the range of projected flood changes by different GCMs remains large from the headwaters to the mouth of the river, whereas for the Columbia the range diminishes considerably as one moves downriver.

The variation of results depends less on hydrologic model than on GCM (Figure 7), though the differences across hydrological models are still substantial. For the Willamette, lower Snake, and both upper and lower Columbia, the PRMS model predicts substantially larger increases in flooding than the three calibrations of the VIC model. For the upper Snake, it predicts substantially smaller change than any VIC calibration. While it is perhaps not surprising that the three calibrations of VIC are close to each other, it is striking just how different are the projections from PRMS at most locations on these three rivers. Chegwidden et al. (2019) found that the main contributors to differences in hydrologic variables generally (except low flows) were the climate scenarios (GCM and RCP), consistent with our findings here. (The order of models is similar in the equivalent figure for the 100-year return period, but we elected to show the 10-year figure since the 100-year figure is more difficult to decipher because the symbols overlap with those from other rivers.)

To parse the contributions of climate factors (represented by the GCMs) and hydrologic factors (represented by the hydrologic models), we perform ANOVA on the 40 discharge ratios. The pie charts in Fig. 8 show the proportion of the total variance explained by climate factors and hydrologic factors at different locations. For the

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Willamette River, the role of climate grows more important and the role of hydrologic variability less important going from the confluence of the three major tributaries at Eugene to the mouth. For the Snake and Columbia rivers, climate is responsible for virtually all of the variance in projections in the upper reaches, but only about half at the lowest point, similar to the Willamette. The Willamette basin is much smaller, and a large storm can affect the entire basin on the same day, whereas storms typically take a couple of days to move across the Snake and Columbia (and generally move upstream). With larger and more diverse contributing areas, differences in the rates with which the hydrological models transfer precipitation to the point of interest become more important. Unlike Chegwidden et al. (2019), we did not attempt to isolate the response to anthropogenic forcing from internal climate variability. Though several techniques for separating these two factors have been used (e.g., Hawkins and Sutton, 2009; Rupp et al., 2017; Chegwidden et al., 2019), these techniques are either infeasible with our dataset or we question their suitability for the application to changes in extreme river flows.

3.3 Change in timing

Although in a broad hydrologic sense a flood is a flood regardless of what time of year it occurs, there are potentially significant ecological differences depending on time of year; for example, scouring salmon redds (Goode et al. 2013). Moreover, water management policies are strongly linked to the calendar year (see Discussion). We computed the probability of flooding for (all 40) past and future simulations at all the points on the three rivers (Figure 4) as a function of day of year (Figure 9). For the Willamette, no significant change in timing occurs; however, for the upper Willamette, a single peak in likelihood in February becomes more diffuse, whereas for the lower Willamette, a more diffuse distribution becomes more peaked. For the Snake, all locations see a shift toward earlier floods, consistent with the transition to less snow-dominant and more rain-dominant. Whereas floods were historically concentrated in the period of mid-May to mid-July, the projected future flooding period spans December to June. For the Columbia, the mode in the flood timing shifts earlier by half a month in the upper Columbia to about a month in the lower Columbia. The distribution also broadens with an elongated tail towards winter such that there is low, but non-negligible, probability of floods occurring as early as January. Although the magnitude of the 10- and 100-year flood events in the lower Columbia do not increase much (Figures 4-7), the risk of major flood on any given day decreases, and the likelihood of major flooding in May or April (or even February and March) increases.

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4 Discussion and conclusions

Compared with Salathe et al. (2014), who found decreases in flooding at a substantial number of sites, our results show increases in flood magnitude at nearly every return period and location, which includes about 100 locations not included in their study. They also noted that directly downscaling the GCM outputs leads to a smaller range of results than when running the regional model as an intermediate step. In our study, the MACA statistical downscaling approach preserves much of the daily variability from the GCM, so the primary reason for the difference between our results and theirs is probably the fact that we analyzed 40 scenarios. Some locations, for example the points on the lower Columbia river, had a handful of ensemble members with decreasing flood magnitude. But averaging the entire ensemble nearly always resulted in a increase in flood magnitude. It is possible therefore that their study, repeated with a larger ensemble of hydrologic-climate model combinations, might have found ubiquitous increases in flood magnitude as ours did.

Earlier results (Hamlet and Lettenmaier 2007, Tohver et al. 2014, Salathe et al. 2014) suggested a decrease in flood magnitude in snowmelt-dominated basins like the Columbia, since reduced snowpack reduces the store of water available to be released quickly in a spring flood (like the May-June 1948 Vanport flood). In a subbasin of the Willamette, Surfleet and Tullos (2013) projected decreases in flood magnitude for return periods > 10 years in the Santiam River basin under a high-emissions scenario (SRES A1B, 2070-2099 vs. 1960-2010; 8 GCMs), attributing the decreases to fewer large rain-on-snow events. Our results for the Santiam River show an *increase* of 40% for both 10- and 100-year floods; this result includes rain-on-snow events, since they are represented in VIC, which computes the accumulation of water in the snowpack and determines whether sufficient energy has been provided to create a melt event. Our results point to ubiquitous increases throughout the basin, even on the lower mainstem Columbia. The coldest basins including the headwaters of the Columbia also had some large increases in flood magnitude, suggesting that the former results were missing some key details. It seems likely that any reduction in flood magnitude originating from the warming-induced reduction in spring snowpack is offset by the increased pace of melt (including possibly rain-on-snow events). These results emphasize the necessity of revisiting reservoir rule curves, which are strongly tied to historical hydrographs, and also emphasize that changes in the seasonality of flooding can be dramatically different from the changes in the mean hydrograph. In particular, in the lower Snake and lower Columbia, changes in magnitude of flooding are modest but changes in timing of the earliest quartile of flood events is much larger than the 0.5-1 month shift in the mean hydrograph.

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A strength of our study compared with earlier studies is the use of our large ensemble. Conventional wisdom and evidence from the weather and seasonal climate forecasting realms illustrate the utility of considering ensembles, and that generally the true outcome of a prediction lies near the middle of the ensemble. The spread of results shown in Fig Col suggests that although the likeliest outcome is little change in flood magnitude in the lower Columbia, a prudent risk management strategy would consider the range of possibilities. However, we view the highest outcomes (>50% increase in peak 100-yr flood) as less likely than other individual scenarios, because they are the product of a hydrologic model that may be less suited to calculating the extreme changes in a much warmer world.

Our findings provide an initial indication of how existing flood risk management could respond to a warming climate. Reservoir management is guided by rule curves which are intended to reflect the changing priorities and risks during the year. For example, reservoirs used for flood control have rule curves that require reservoir levels to be lowered when approaching the time of year when flood likelihood increases, and reservoir levels may be raised as the likelihood decreases. For the Willamette, we found little change in the distribution of timing of flood events, which indicate that with the state of the science today, reservoir rule curves may need to be altered as to magnitude of flooding (which our results indicate will increase by 30-40%) but not timing; a reservoir model would be required for complete understanding of how flood risk (magnitude and timing) will actually change. For the Snake, larger shifts in the timing imply a need to completely rethink the existing rule curves. For the Columbia, the mode in flood timing shifts earlier by half a month in the upper Columbia to about a month in the low Columbia. The distribution also broadens, with an elongated tail towards winter such that there is low, but non-negligible, probability of floods occurring as early as January. These changes in timing imply a need for moderate alteration of rule curves for reservoirs in the Canadian portion of the Columbia Basin.

Our results should not be taken as a precise prediction of flood magnitude change but rather as the best available projections given the current state of the science. Two important factors need to be taken into account in interpreting our results: first, in using RCP8.5, we selected the most extreme emissions scenario. If efforts to stabilize the climate before 2050 are successful, the flood magnitudes shown here will undoubtedly be smaller (our analysis suggests most of the locations would see a change in flood magnitude about 1/3 smaller, for RCP4.5; e.g., a ratio of 1.3 (30% increase) for RCP8.5 would correspond to a ratio of 1.2 for RCP4.5).

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The second important factor in interpreting our results is that the actual river system in the Northwest includes many dams, a majority of which have flood control as a primary (or one of a few top) objective. As a result, actual flows (and the changes in flow) at a given point in the river would be altered by reservoir management. Translating these changes in flood magnitude into actual changes would require a reservoir model for the basin or subbasin of relevance. One could then compute optimal rule curves for the major flood control reservoirs (perhaps time-evolving every couple of decades, to reflect the likely changes in scientific understanding and emissions trajectory). Even without that additional analysis, however, our results stress that the magnitude and/or timing of flood events will change throughout the basin. In other words, what worked for flood control in the past will not work as well in the future.

This study may have some utility in framing and quantifying the possible changes in flood risk as the Columbia River Treaty is in renegotiation, but further work would be needed to assign probabilities to future flood magnitude. Such work includes (a) understanding whether the PRMS projections of much larger change are reliable, (b) applying different statistical and/or dynamical downscaling methods, and (c) using a more sophisticated approach to evaluating extremes in a nonstationary climate (as advocated by Serinaldi and Kilsby, 2015). Furthermore, a new generation of GCM outputs (CMIP6, Eyring et al. 2016) already has data available from over 25 GCMs; in the near future, it would be feasible to apply a newer multi-model hydrologic modeling approaches (e.g., Clark et al., 2015) to the new generation of GCMs, though perhaps no significant changes would result. Nonetheless, with current knowledge the fact that very few locations would see a decrease in flood risk under any climate/hydrologic scenario is a strong statement of the need to update all aspects of flood preparation: the definition of N-year (especially 100-year) return period flows, flood plain mapping, and reservoir rule curves, to name a few. Moreover, the challenges that the renegotiated Columbia River Treaty faces in accounting for climate change now appear to include the necessity of incorporating the likely increase in flood risk throughout the region.

Code/data availability. The data used here are available at https://zenodo.org/record/854763.

Author contribution. L. Queen performed all analyses, wrote portions of the text, and edited the document. P. Mote guided the analysis and wrote much of the text. D. Rupp guided the analysis and edited the document. O. Chegwidden generated the underlying dataset, guided the analysis, provided assistance with programming, and commented on the text. B. Nijssen generated the underlying dataset and commented on the text.

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Competing interests. The authors declare no competing interests.

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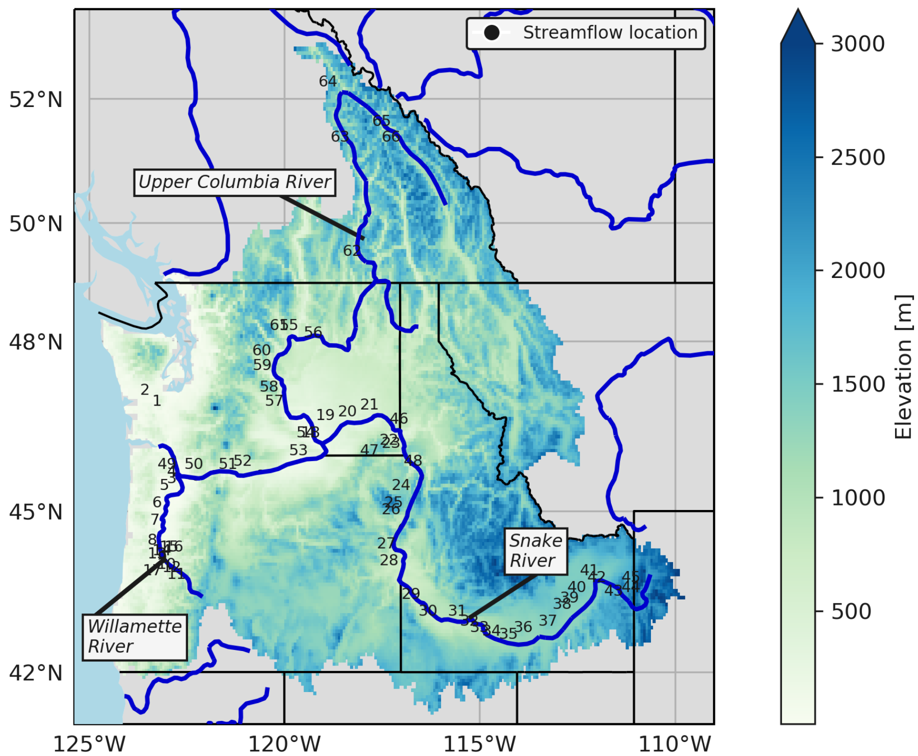

Figure captions

Figure 1. Domain of hydrologic simulations used in this paper, with colors indicating elevation of each grid cell, major rivers highlighted in blue, and numbers indicating locations of streamflow points highlighted in Figures 4-9, and Table 1. See Chegwidden et al. (2017, 2019) for all streamflow locations plotted in Figure 3. Digital elevation data are in the public domain, obtained from https://www2.usgs.gov/science/cite-view.php?cite=1530

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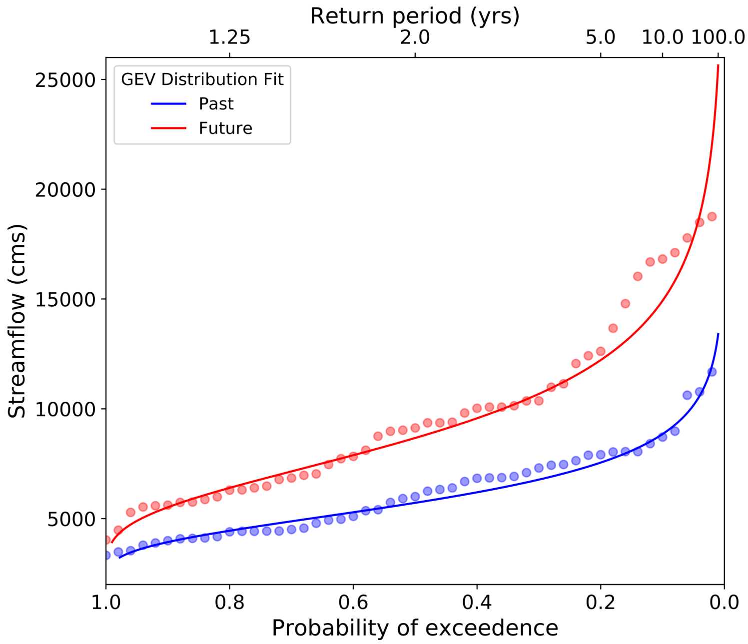
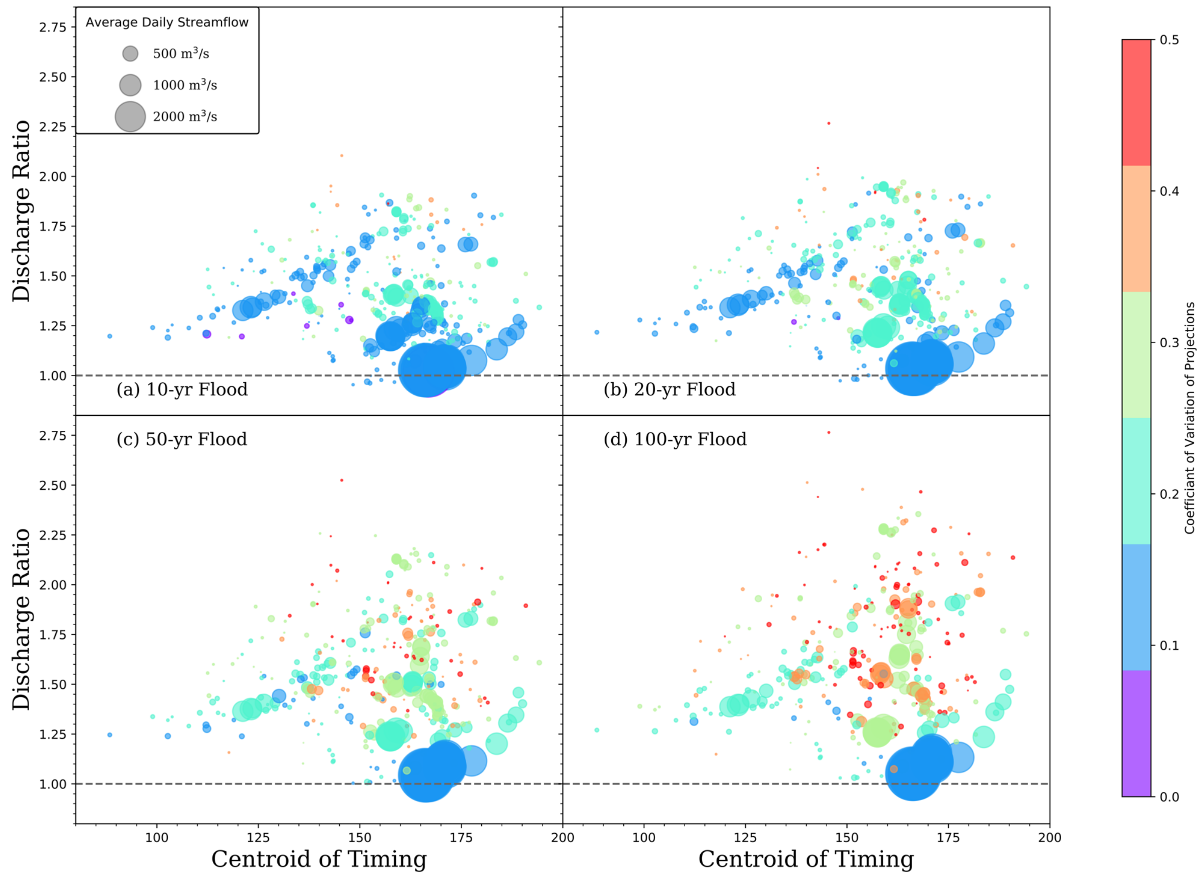


Figure 2. Generalized Extreme Value fit of annual maximum daily flow from 50 years of simulation using output from one GCM (HadGEM2-ES), one hydrologic model (PRMS), for the Willamette River at Portland. Red and blue dots/ lines indicate the annual values and GEV fit for the 1950-99 'past' and 2050-99 'future' periods.



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476 **Figure 3**. Discharge ratios (future:past) versus centroid of timing (day on which 50% of water-year flow has
477 passed, an indicator of snow dominance) for all 396 locations and four return periods. For each location, the
478 average of 40 ensemble member ratios calculated from GEV distribution fitting from 50-year windows for the
479 future (2050-2099) and past (1950-1999) time periods is shown. Points are sized by average daily streamflow and
480 colored by the coefficient of variation of the 40 ratios.

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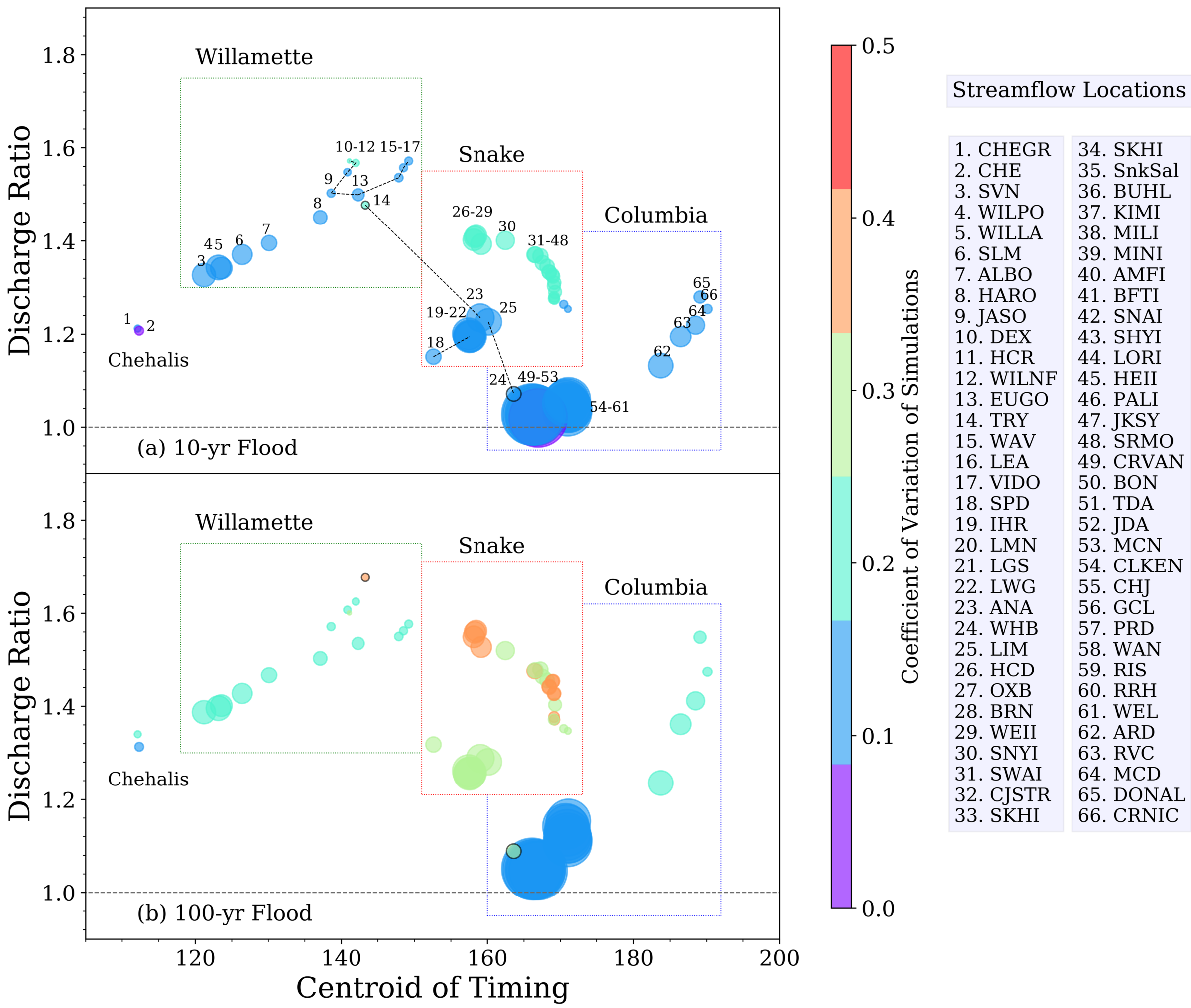

Figure 4. As in Figure 3 but only for points on the indicated rivers. Dashed lines indicate tributaries: 9-12 are on the Middle Fork Willamette, 15-17 on the McKenzie; tributaries of the Snake are the Grand Ronde (14), Clearwater (17) and Salmon (24). In the lower panel, the Grand Ronde and Salmon are clearly distinguished by a black circle around their perimeter. Table 1 translates the codes in the legend into named locations and shows the numerical values represented in the figure. As is evident from both snow-dominance and size, locations are ordered downstream to upstream from left to right for each river.

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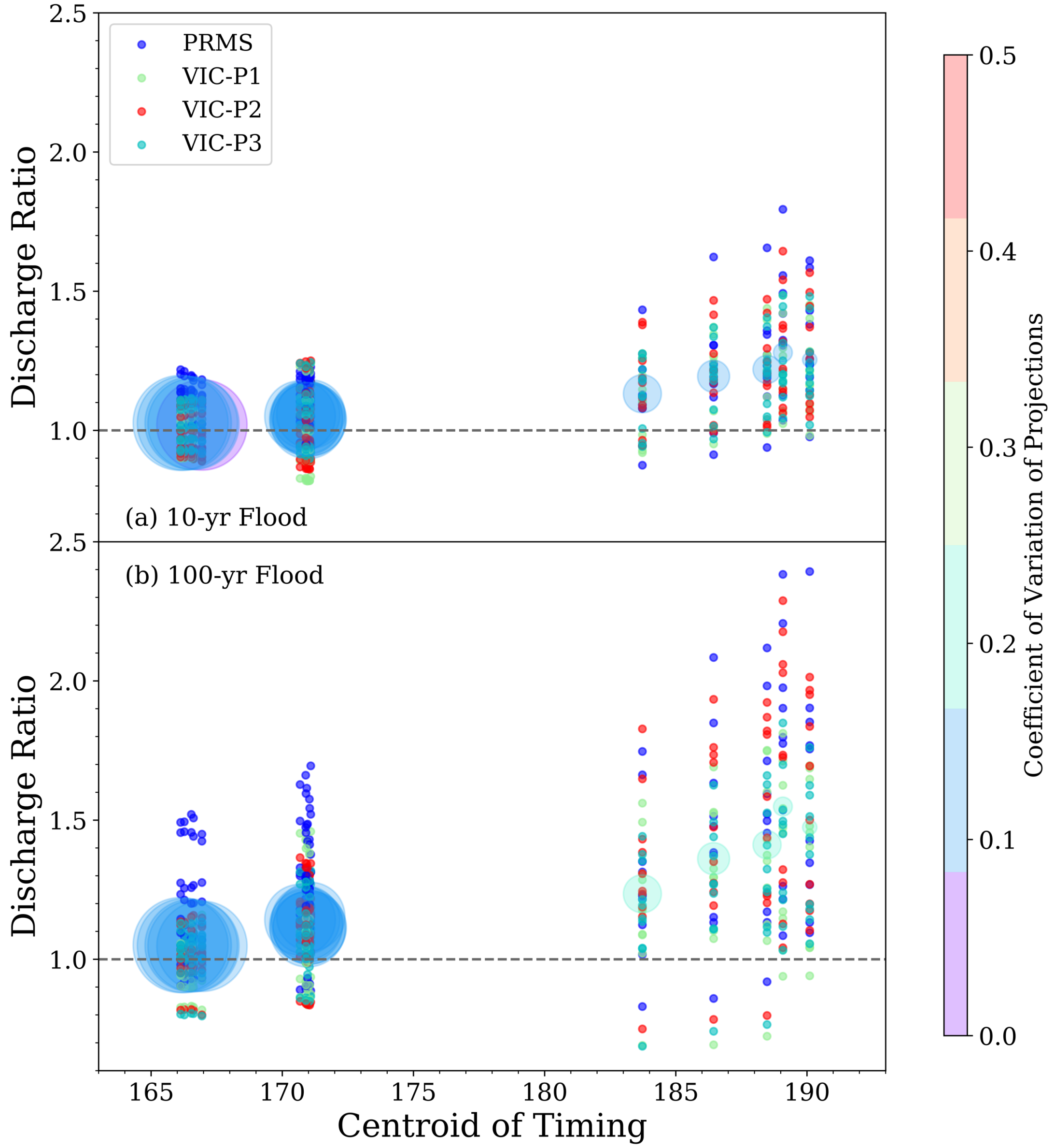

Figure 5. Averaged (large circles) and individual ensemble member (small colored circles) discharge ratios for simulated streamflow locations along the mainstem Columbia River for the 10-year (top) and 100-year (bottom) return periods. As shown in the legend, the color of the dots distinguishes results by hydrologic model setup.

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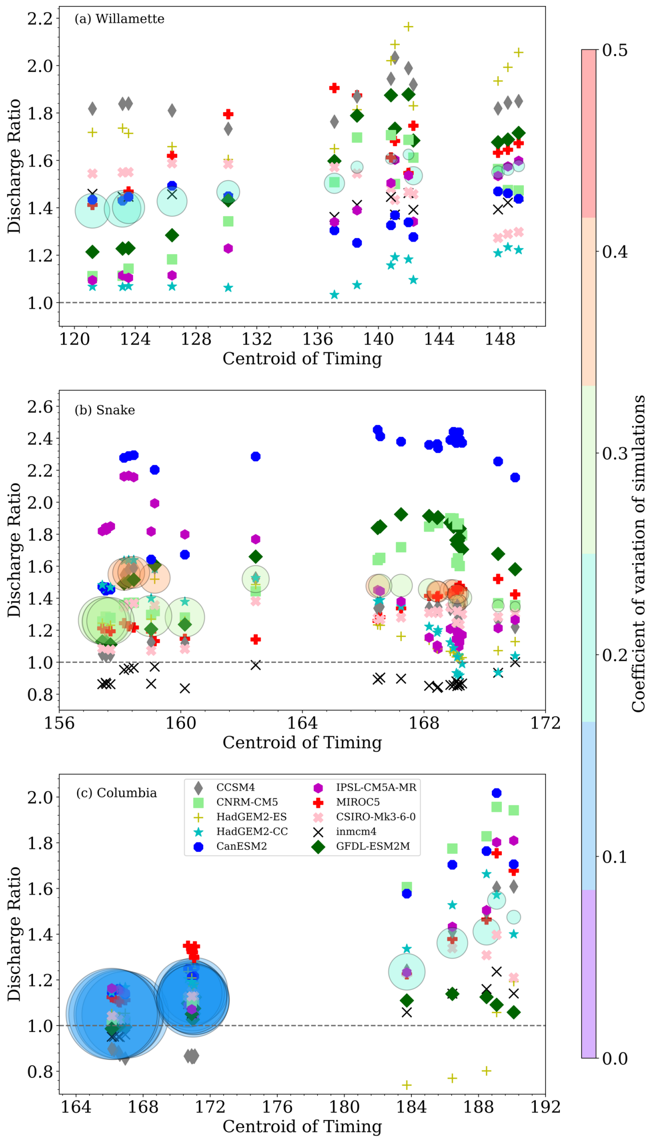

492 **Figure 6.** Average ratios of all 40 ensemble members (large circles) and the average of 4 hydrologic model
493 results for each GCM (symbols), shown for simulated streamflow locations along the Willamette (top), Snake
494 (middle), and the mainstem Columbia (bottom) for 100-year return periods. GCMs are ordered in the legend
495 by their ranking in Rupp et al. (2017), representing their ability to simulate Northwest climate.

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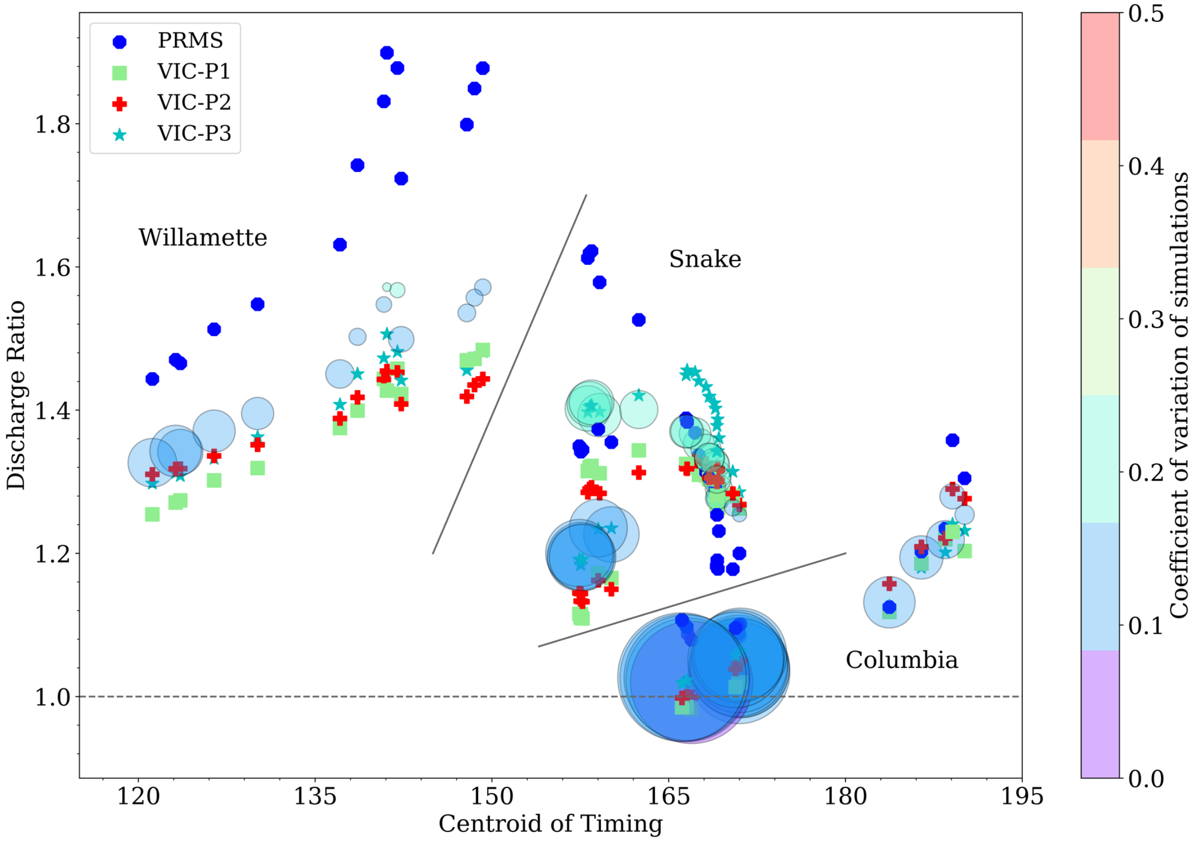

Figure 7: as in Figure 6 but averaged by hydrologic model, for 10-year return period, and combined into one panel.

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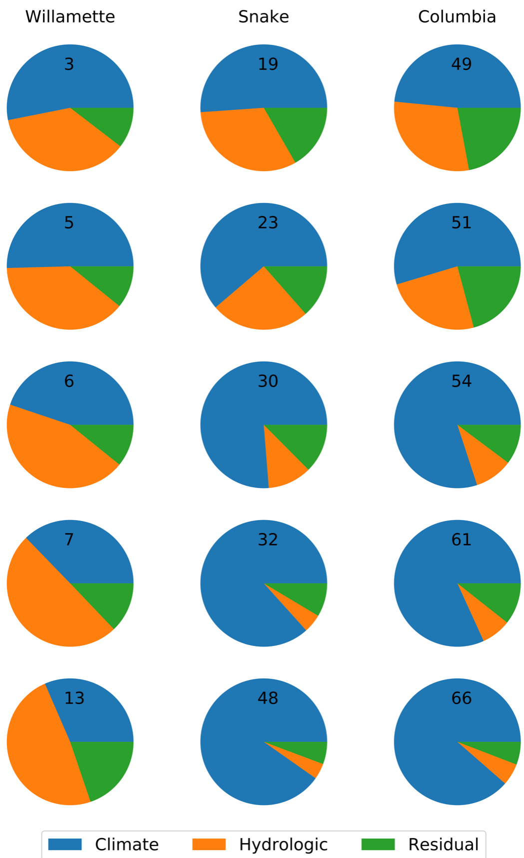

500 **Figure 8**. ANOVA results for select locations on the indicated rivers, for climate and hydrologic factors (and the
501 residual). Charts are numbered to correspond with their location in Figure 4, with the most-downstream location
502 at the top.

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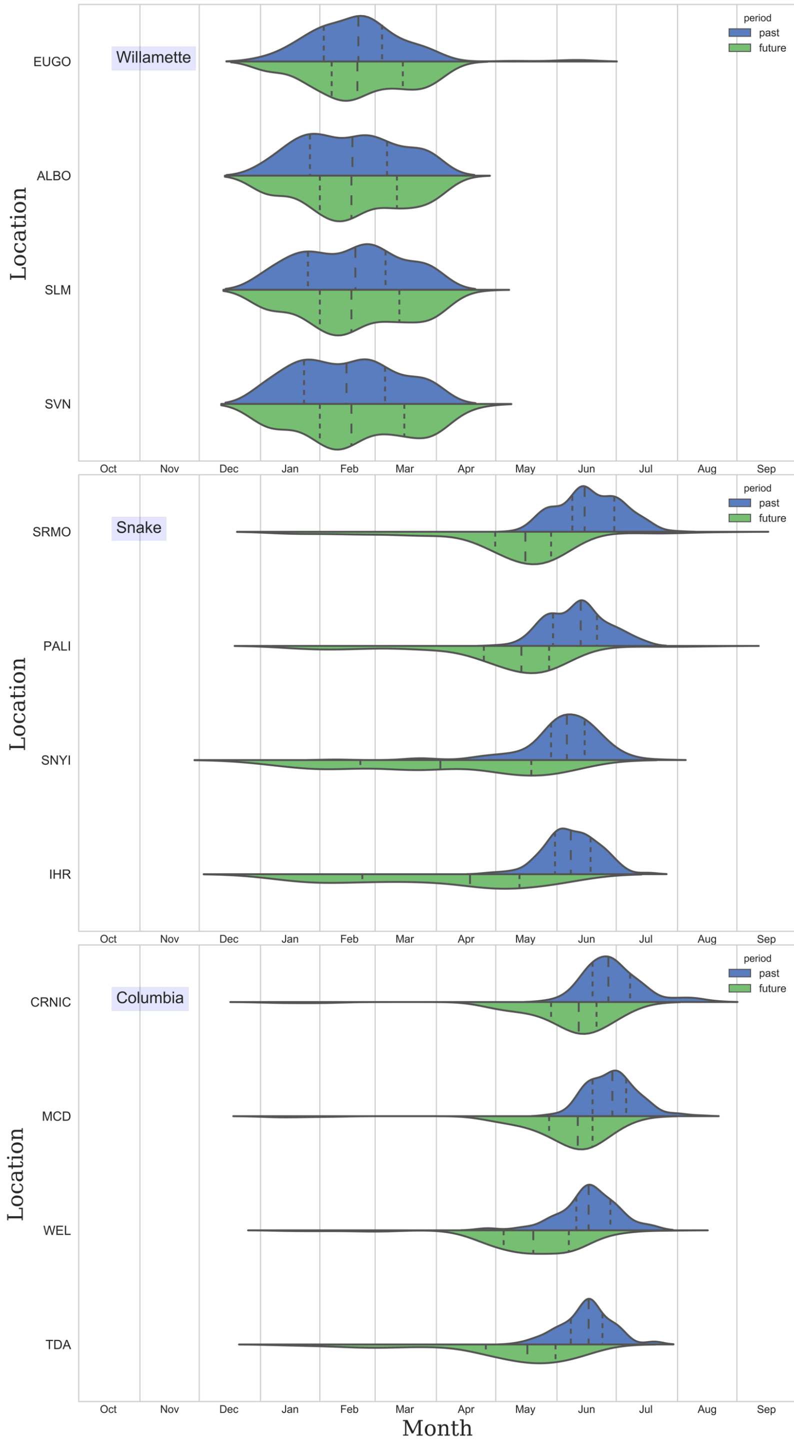

Figure 9. Statistical representations of the variation through the water year of the timing of flood events. For each of the 40 simulations, the dates of the 5 highest flows in the 50-year past (blue) and future (green) windows are tallied, and the resulting distributions smoothed. Long dashed lines indicate median date, short dashed lines the lowest and highest quartiles.

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Table 1 Information about locations featured in this paper - location, river, and discharge ratios

			10-year flood discharge ratios				100-year flood discharge ratios			
River	**UW Key**	**Description**	**Avg.**	**Coeff. of Var.**	**Min**	**Max**	**Avg.**	**Coeff. of Var.**	**Min**	**Max**
Chehalis	CHEGR	Chehalis R nr Grand Mount	1.21	0.09	1.03	1.42	1.34	0.18	0.87	2.07
Chehalis	CHE	Chehalis R at Porter	1.21	0.08	1.03	1.40	1.31	0.16	0.91	1.89
Willamette	SVN	T.W. Sullivan	1.33	0.09	1.07	1.64	1.39	0.22	0.87	2.39
Willamette	WILPO	Portland	1.34	0.09	1.08	1.69	1.40	0.23	0.86	2.47
Willamette	WILLA	Newberg	1.34	0.09	1.09	1.66	1.40	0.22	0.88	2.44
Willamette	SLM	Salem	1.37	0.09	1.10	1.70	1.43	0.22	0.84	2.52
Willamette	ALBO	Albany	1.40	0.09	1.11	1.73	1.47	0.20	0.89	2.40
Willamette	HARO	Harrisburg	1.45	0.10	1.18	1.86	1.50	0.22	0.88	2.37
Willamette	JASO	Middle fork @ Jasper	1.50	0.14	1.20	2.13	1.57	0.23	0.93	2.68
Willamette	DEX	Dexter	1.55	0.16	1.17	2.33	1.61	0.22	1.05	2.67
Willamette	HCR	Hills Creek	1.57	0.18	1.15	2.46	1.60	0.25	1.10	3.18
Willamette	WILNF	Oakridge	1.57	0.18	1.16	2.45	1.63	0.24	1.09	2.88
Willamette	EUGO	WR at Eugene (NWP)	1.50	0.12	1.26	2.04	1.54	0.22	0.88	2.57
Willamette	WAV	Walterville	1.54	0.13	1.29	2.13	1.55	0.18	1.04	2.23
Willamette	LEA	Leaburg	1.56	0.14	1.28	2.23	1.56	0.18	1.05	2.34
Willamette	VIDO	McKenzie nr Vida	1.57	0.15	1.28	2.32	1.58	0.19	1.02	2.41
Willamette	COT	Cottage Grove	1.25	0.11	0.97	1.69	1.39	0.29	0.78	2.38

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			10-year flood discharge ratios				100-year flood discharge ratios			
River	UW Key	Description	Avg.	Coeff. of Var.	Min	Max	Avg.	Coeff. of Var.	Min	Max
Snake	IHR	Ice Harbor	1.20	0.13	0.92	1.75	1.26	0.28	0.79	2.84
Snake	LMN	Lower Monumental	1.20	0.13	0.92	1.76	1.26	0.28	0.78	2.77
Snake	LGS	Little Goose	1.19	0.13	0.92	1.77	1.26	0.28	0.78	2.83
Snake	LWG	Lower Granite	1.19	0.13	0.92	1.77	1.25	0.29	0.78	2.89
Snake	ANA	Anatone	1.24	0.14	0.95	1.74	1.29	0.29	0.78	2.84
Snake	LIM	Lime Point	1.23	0.14	0.94	1.73	1.28	0.30	0.76	2.81
Snake	HCD	Hells Canyon	1.40	0.18	1.01	2.11	1.55	0.38	0.87	3.62
Snake	OXB	Oxbow	1.41	0.18	1.01	2.11	1.56	0.38	0.86	3.65
Snake	BRN	Brownlee Dam	1.41	0.18	1.01	2.12	1.56	0.37	0.86	3.63
Snake	WEII	Weiser,ID	1.39	0.18	1.02	2.09	1.53	0.35	0.86	3.28
Snake	SNYI	Nyssa, OR	1.40	0.18	1.04	2.16	1.52	0.33	0.89	3.21
Snake	SWAI	Murphy, ID	1.37	0.19	0.98	2.09	1.48	0.33	0.84	3.24
Snake	CJSTR	CJ Strike Dam	1.37	0.19	0.97	2.08	1.48	0.32	0.86	3.08
Snake	SKHI	King Hill, ID	1.37	0.19	0.96	2.08	1.48	0.32	0.85	2.84
Snake	SNKBLWLSALMON	Hagerman, ID	1.35	0.18	0.93	2.05	1.46	0.31	0.83	2.66
Snake	BUHL	Buhl, ID	1.35	0.19	0.91	2.05	1.46	0.32	0.73	2.54
Snake	KIMI	Kimberly, ID	1.33	0.19	0.89	2.03	1.44	0.33	0.74	2.47
Snake	MILI	Milner, ID	1.33	0.19	0.88	2.04	1.44	0.34	0.73	2.52

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River	UW Key	Description	Avg.	Coeff. of Var.	Min	Max	Avg.	Coeff. of Var.	Min	Max
Snake	MINI	Minidoka, ID	1.33	0.19	0.86	2.02	1.45	0.33	0.70	2.53
Snake	AMFI	Neeley American Falls	1.32	0.19	0.85	1.99	1.45	0.34	0.67	2.69
Snake	BFTI	nr Blackfoot, ID	1.31	0.19	0.84	1.96	1.43	0.34	0.67	2.72
Snake	SNAI	nr Blackfoot, ID	1.30	0.19	0.84	1.95	1.43	0.34	0.67	2.69
Snake	SHYI	Shelley, ID	1.29	0.18	0.84	1.92	1.40	0.33	0.69	2.62
Snake	LORI	Lorenzo, ID	1.28	0.19	0.86	1.91	1.38	0.34	0.69	2.52
Snake	HEII	Heise, ID	1.28	0.18	0.86	1.91	1.37	0.33	0.70	2.53
Snake	PALI	Irwin Palisades	1.28	0.19	0.87	1.95	1.37	0.34	0.71	2.60
Snake	JKSY	Jackson, WY	1.26	0.15	0.89	1.73	1.35	0.30	0.80	2.46
Snake	SRMO	Moose, WY	1.25	0.13	0.91	1.59	1.35	0.25	0.83	2.34
Grand Ronde	TRY	Troy	1.48	0.19	1.09	2.55	1.68	0.34	1.01	4.38
Salmon	WHB	White Bird	1.07	0.13	0.83	1.57	1.09	0.33	0.72	2.81
Columbia	CRVAN	Vancouver	1.03	0.09	0.90	1.22	1.05	0.13	0.80	1.49
Columbia	BON	Bonneville	1.03	0.09	0.90	1.21	1.05	0.13	0.80	1.49
Columbia	TDA	The Dalles	1.03	0.08	0.90	1.20	1.05	0.13	0.81	1.52
Columbia	JDA	John Day	1.02	0.08	0.90	1.19	1.05	0.13	0.80	1.51
Columbia	MCN	McNary Dam	1.02	0.08	0.89	1.18	1.05	0.13	0.80	1.45
Columbia	CLKEN	Clover Island @ Kennewick	1.03	0.10	0.82	1.22	1.11	0.14	0.84	1.49

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			10-year flood discharge ratios				100-year flood discharge ratios			
River	UW Key	Description	Avg.	Coeff. of Var.	Min	Max	Avg.	Coeff. of Var.	Min	Max
Columbia	CHJ	Chief Joseph	1.06	0.11	0.83	1.25	1.15	0.15	0.85	1.70
Columbia	GCL	Grand Coulee	1.06	0.11	0.83	1.25	1.14	0.14	0.84	1.66
Columbia	PRD	Priest Rapids	1.04	0.10	0.82	1.22	1.11	0.13	0.84	1.54
Columbia	WAN	Wanapum	1.04	0.10	0.82	1.22	1.11	0.14	0.84	1.58
Columbia	RIS	Rock Island	1.04	0.10	0.82	1.23	1.12	0.14	0.84	1.60
Columbia	RRH	Rocky Reach	1.05	0.10	0.83	1.23	1.13	0.14	0.84	1.61
Columbia	WEL	Wells Dam	1.05	0.10	0.83	1.24	1.14	0.14	0.85	1.63
Columbia	ARD	Hugh Keenleyside (Arrow)	1.13	0.12	0.87	1.43	1.24	0.21	0.69	1.83
Columbia	RVC	Revelstoke	1.19	0.12	0.91	1.62	1.36	0.23	0.69	2.08
Columbia	MCD	Mica Dam	1.22	0.12	0.94	1.66	1.41	0.24	0.72	2.12
Columbia	DONAL	Donald	1.28	0.14	1.02	1.79	1.55	0.25	0.94	2.38
Columbia	CRNIC	Nicholson	1.25	0.13	0.98	1.61	1.47	0.23	0.94	2.39
Clearwater	SPD	Spalding, ID	1.15	0.15	0.85	1.78	1.32	0.30	0.80	2.63
Clearwater	DWR	Dworshak Dam, ID	1.14	0.12	0.86	1.55	1.30	0.24	0.89	2.22
Santiam	JFFO	Santiam R nr Jefferson	1.40	0.10	1.14	1.81	1.41	0.25	0.81	2.27
Kootenay	COR	Corra Linn Dam, BC	1.08	0.12	0.85	1.31	1.15	0.16	0.79	1.67
Kootenai	LIB	Libby Dam, MT	1.17	0.14	0.92	1.52	1.32	0.22	0.85	2.01
Kootenay	BFE	Bonner's Ferry, ID	1.13	0.13	0.89	1.45	1.26	0.20	0.83	2.02

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Hydrology and Earth System Sciences
Discussions

			10-year flood discharge ratios				100-year flood discharge ratios			
River	UW Key	Description	Avg.	Coeff. of Var.	Min	Max	Avg.	Coeff. of Var.	Min	Max
Pend Oreille	ALF	Albeni Falls, ID	1.26	0.14	0.96	1.68	1.65	0.30	1.02	2.97
Flathead	CFM	Columbia Falls, MT	1.24	0.13	0.94	1.63	1.65	0.26	1.01	3.19
Flathead	HGH	Hungry Horse Dam, MT	1.30	0.13	1.04	1.70	1.78	0.29	1.16	3.56
Yakima	KIOW	Yakima, WA	1.82	0.21	1.35	3.11	2.28	0.30	1.57	4.39