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Impacts of climate change on the seasonality of extremes in the Columbia River Basin

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Abstract

The impacts of climate change on the seasonality of extremes i.e. both high and low flows in the Columbia River basin were analyzed using three seasonality indices, namely the seasonality ratio (SR), weighted mean occurrence day (WMOD) and weighted persistence (WP). These indices reflect the streamflow regime, timing and variability in timing of extreme events respectively. The three indices were estimated from: **(1)** observed streamflow; **(2)** simulated streamflow using simulated inputs from ten combinations of CMIP5 inputs for the future climate (2040–2070) including the pathway RCP4.5 **(3)** simulated streamflow using simulated inputs from ten combinations of CMIP5 inputs for the future climate (2040–2070) including the pathway RCP8.5. The hydrological model was calibrated at 1/16 latitude-longitude resolution and the simulated streamflow was routed to the subbasin outlets of interest. These three cases are compared to assess the effects of forcing by different climate models and different pathways on the three indices. The results showed significant differences between three cases indicating a shift in streamflow regime and timing of extreme events such as high and low flows in the Columbia River Basin. The persistence of high flows are similar in all cases. The results will help to understand the effects of climate change on three important seasonality properties: regime, timing and persistence and associated errors.

Multi-model Averaging of 10 Climate Forcing Data

In this study multiple model outputs from 10 GCMs are combined using a weighted averaging method. In this method, the weights are distributed over each model grid cell (1/16) and estimated based on the performance of each model over the reference historical period. In other words, the inverse of the error variance of each model's output for each model cell is used to estimate the weight for that cell. It should be noted that the total of weights are equal to 1 for each cell (first method) or for all models (second method).

$$p(M_j|D) = \frac{1/\sigma_{\varepsilon j}^2}{\sum_{i=1}^{k} 1/\sigma_{\varepsilon i}^2} \quad (1)$$

$$\sigma_{\varepsilon j} = \sum_{t=1}^{n} \left(P_{t,j}^{sim} - P_{t,j}^{obj}\right)^2 \quad (2)$$

$$P_{MM_t} = \sum_{j=1}^{k} p_j * P_{t,j}^{sim} \quad (3)$$

where M_j is the climate model *j*, *D* is the calibration period (here 1950-2005), σ_ε is the model error variance, *k* is the number of climate models, $P_{t,j}^{sim}$ is the simulated precipitation at time *t* for climate model *j* and $P_{t,j}^{obj}$ is the observed precipitation.

Three Seasonality Indices for Streamflow

The Seasonality Ratio (*SR*): This index reveals the streamflow characteristics in summer and winter periods. The definitions of extremes (high or low flow) and the seasons (months for winter and summer) are crucial for the *SR* results as the underlying hydrological processes for summer and winter streamflows are different. In this study we focus on high flows and use the 90% exceedence probability (Q_{90}) as a threshold for defining summer high flow (Q_{90s}) and winter high flow (Q_{90w}). The *SR* index is calculated as the ratio of Q_{90s} and Q_{90w} (Eq 4)

$$SR = \frac{Q_{90s}}{Q_{90w}} \quad (4)$$

A value of *SR* greater than one indicates the presence of a winter high flow regime and a value smaller than one indicates the presence of a summer high flow regime.

Weighted Mean Occurrence Day (*WMOD*)

The days at which the discharge is above the Q_{90} threshold are transformed into Julian dates D_i, i.e. the day of the year ranging from 1 to 365 in regular years and 1 to 366 in leap years. The day number of each high flow event (D_i) is weighted by the inverse high flow value ($1/Q_i$) on the same day to address the severity of a high flow event as well as its occurrence day. The weighted mean day of occurrence is estimated first in radians to represent the annual cycle correctly. Otherwise, a simple averaging of high flow occurrences in winter months, e.g. January and December, can lead to a large error in the results. The weighted mean of Cartesian coordinates x_θ and y_θ of a total of high flow days *i* is defined as

$$x_\theta = \sum_i \frac{cos\left(\frac{D_i}{Q_i}\frac{2\pi}{365}\right)}{Q_i^{-1}} \qquad y_\theta = \sum_i \frac{sin\left(\frac{D_i}{Q_i}\frac{2\pi}{365}\right)}{Q_i^{-1}} \quad (5)$$

The directional angle (θ) is then estimated by

$$\theta = \arctan\left(\frac{y_\theta}{x_\theta}\right) \qquad \text{1st and 4th quadrants: } x_\theta>0$$

$$\theta = \arctan\left(\frac{y_\theta}{x_\theta}\right) + \pi \qquad \text{2nd and 3rd quadrants: } x_\theta<0 \quad (6)$$

The values of θ can vary from 0 to 2π, where a zero value indicates the 1st of January, $\pi/2$ represents the 1st of April, pi represents the 1st of July and $3\pi/2$ represents the 1st of October. The main advantage of using circular statistics is that it allows us to correctly average high flow occurrences in the winter half-year period. The *WMOD* is then obtained by back-transforming the weighted mean angle to a Julian date:

$$WMOD = \theta \frac{365}{2\pi} \quad (7)$$

Weighted Persistence (*WP*)

$$WP = \sqrt{x_\theta^2 + y_\theta^2} \quad (8)$$

The dimensionless *WP* indicates the variability in timing of high flows, where a value of 1 indicates that high flow events occurred on exactly the same day of the year (high persistence) and a value of zero indicates that high flow events are uniformly distributed over the year (no persistence).

Study Area: Columbia River Basin

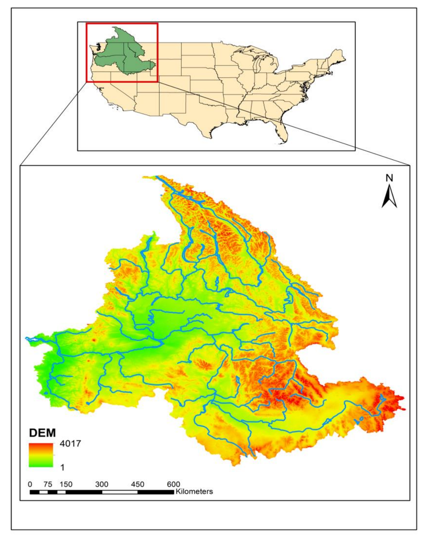

Fig 1 Study Area

Basin area: 567.000 km^2 (seven states-85% and part of British Columbia-15%)

Climate: Varies from moist, maritime conditions in the western parts of the basin to semi-arid and arid conditions in the south-eastern part.

Precipitation:

- Strong control of topography on precipitation.
- 2500 mm/year along the crest of Washington Cascades
- 1000-1800 mm/year in the northern Rocky Mountains, the west slope of the continental divide
- 200-400 mm/year in Columbia Plateau in Washington and Snake River Plain

Results: Seasonality of observed streamflow

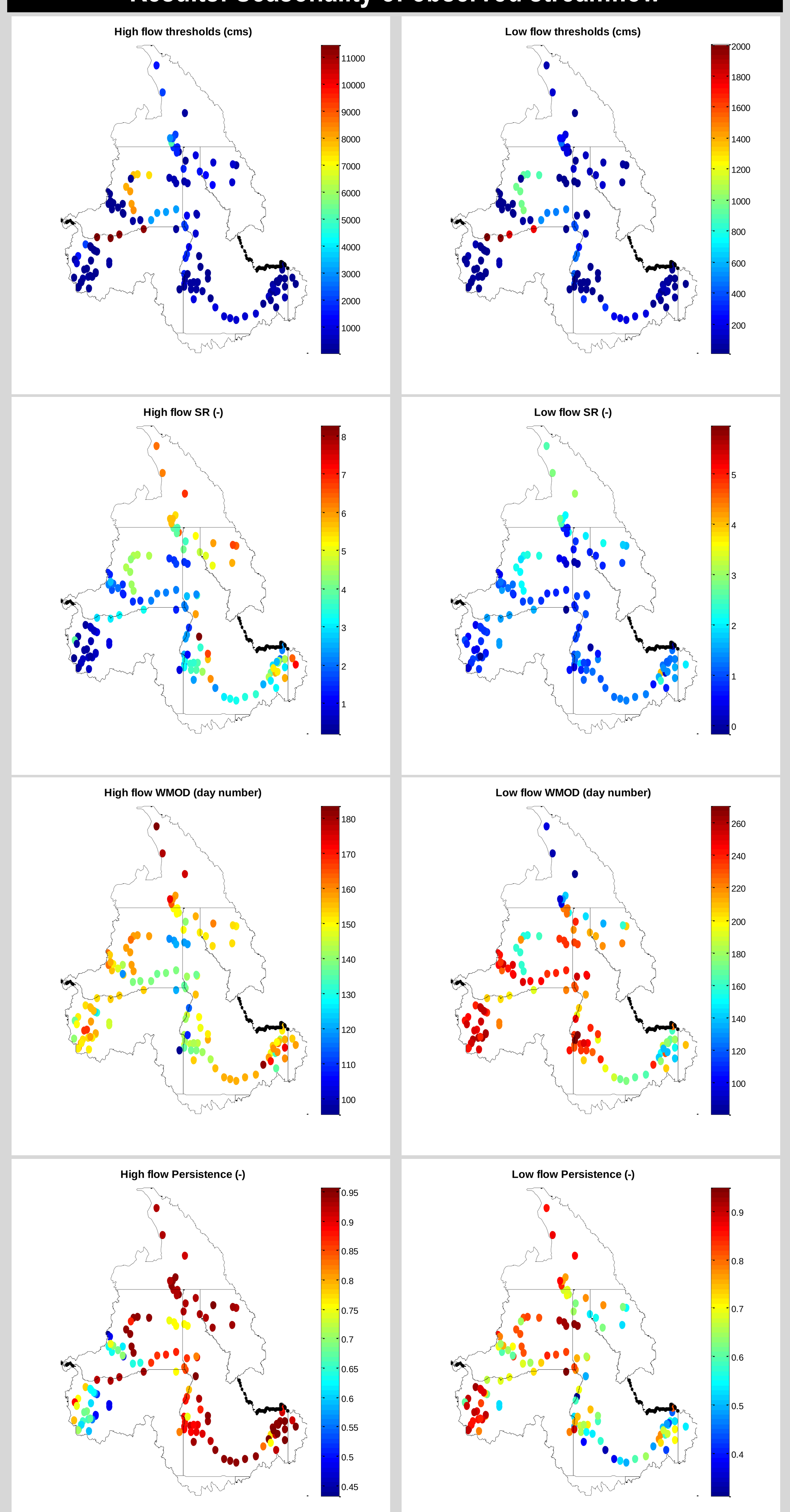

Fig 2 Seasonality characteristics of observed high and low flows

Results: Climate change impacts on high flows (Q90)

Table 1 Seasonality indices based on observed and simulated streamflows on six naturalized flow points over Columbia River Basin

White_Bird	***SR***	***WP***	***WMOD***		**Revelstoke**	***SR***	***WP***	***WMOD***
obs	6.4	0.95	154		obs	6.0	0.93	178
MACA45	12.9	0.98	167		MACA45	4.3	0.98	190
MACA85	15.3	0.98	169		MACA85	4.9	0.98	186
Orofino					**Waneta**			
obs	3.9	0.91	142		obs	4.2	0.93	149
MACA45	8.8	0.98	159		MACA45	9.4	0.98	157
MACA85	8.8	0.98	161		MACA85	8.1	0.98	158
Noxon					**Payette**			
obs	5.3	0.94	150		obs	3.7	0.90	142
MACA45	11.4	0.98	160		MACA45	8.1	0.97	152
MACA85	11.9	0.98	163		MACA85	7.5	0.97	156

- ➢ High flows occur between mid-April and June: ~day 100th and 180 respectively in Fig 2
- ➢ Winter low flows are observed in snow dominated northern and southeastern CRB where precipitation is kept as snow or ice in winter (Fig 2).
- ➢ High flow persistence is increasing in all six locations by 2040s (Table 1)
- ➢ No significant difference was found between RCP45 and 85 for *WP*
- ➢ SR is increasing in all locations except for Revelstoke
- ➢ Weighted mean high flow occurrence day (WMOD) is about ten day late as compared to observed WMOD of high flows. The delay is 20 days in Orofino by 2040s based on RCP85 scenario

Conclusion

In this study, three seasonality indices are used to reflect on streamflow regimes in CRB. These indices are useful to analyze the observed characteristics of streamflow: timing, regime and persistence of an extreme event.

The user can define the event based on high and low flow thresholds e.g. Q10 and Q90 for low flows and high flows.

Based on the future changes in WP, no significant differences between WP estimated from observed and simulated streamflows are expected. The persistence of high flows in CRB is usually above 0.7 in eastern CRB. This indicates a high persistence in occurrence of high flows. However, the weighted mean occurrence day of high flows (Q90) is expected to be late (about two weeks) in the future as compared to observed conditions.

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