9-2014

Impacts of Climate Change on the Seasonality of Extremes in the Columbia River Basin

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The impacts of climate change on the seasonality of extremes i.e., high flow 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 CMP5 inputs for the future climate (2040–2070) including the pathway RCP8.5 (3) simulated streamflow using simulated inputs from ten combinations of CMP5 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.

### 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 ($Q_{90}$) and winter high flow ($Q_{90}$). The SR index is calculated as the ratio of $Q_{90}$ and $Q_{90}$ (Eq 4)

$$SR = \frac{Q_{90}}{Q_{90}}$$

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 date. 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 $x_p$ and $y_p$ of a total of high flow days $i$ is defined as

$$x_p = \frac{\sum_i \cos \left( \theta_q \right)}{\sum_i \cos \left( \theta_q \right)}$$

$$y_p = \frac{\sum_i \sin \left( \theta_q \right)}{\sum_i \sin \left( \theta_q \right)}$$

The directional angle ($\theta$) is then estimated by

$$\theta = \arctan \left( \frac{y}{x} \right)$$

1st and 4th quadrants: $x_p > 0$

2nd and 3rd quadrants: $x_p < 0$

The values of $\theta$ can vary from 0 to 2π, where a zero value indicates the 1st of January, 12:00 p.m., or represents the 1st of April, 12:00 p.m., or the 1st of October, 12:00 p.m. 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:

$$WMOD = \frac{365}{2\pi} \theta$$

#### Weighted Persistence (WP)

$$WP = \sqrt{x_p^2 + y_p^2}$$

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).

### Results: Seasonality of observed streamflow

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.

### Acknowledgment

Partial financial support for this study was provided by the DOE-BPA (cooperative agreement 00053182).