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Understanding the 2011 Upper Missouri River Basin floods in the context of a changing climate

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ABSTRACT

Study Region: Upper Missouri River Basin.
Study Focus: The semi-arid Upper Missouri River Basin (UMRB) has experienced notable volatility in high and low streamflow extremes in recent decades, punctuated by the record 2011 flood. This study provides a new perspective into the relative importance of precipitation and antecedent moisture conditions in driving extreme streamflow. Ensemble streamflow simulations demonstrate that precipitation is largely the dominant driver for high streamflows. Applying the observed atmospheric forcing in 2011 with initial conditions of antecedent hydrologic conditions from 64 historic years consistently produces large streamflow events exceeding the 85th percentile of historical peak flows. This study attributes the individual roles of atmospheric conditions and antecedent soil moisture on extreme streamflow production. It uses a novel modeling framework that provides a greater understanding for the role that heterogeneity in basin-scale hydrologic features have in extreme streamflow generation.
New hydrologic insights for the region: A detailed analysis of the record 2011 flood event shows that streamflow generated over the region's easternmost sub-basin is acutely sensitive to antecedent moisture. Yet, the 2011 record streamflow cannot be explained by a single factor or as the result of long-term trends, with the basin responding to several independent factors; significantly high ($p < 0.05$) antecedent moisture and significant cold-season precipitation. Perhaps most importantly was the record-setting May precipitation, which limited the ability of ensemble streamflow simulations initialized on 1-March from reliably predicting the record June streamflows. The recent volatility of UMRB streamflow may be a harbinger of future decades based on our analysis of climate projections that indicate increased hydroclimate variability by the latter half of the 21st century.

1. Introduction

The year-to-year variability of annual streamflow in the Upper Missouri River Basin (UMRB; Fig. 1) has roughly doubled in the most recent 20-yr window compared to prior decades dating to 1898 (Fig. 2). This rise in volatility —with nine of the ten highest annual streamflows in the UMRB historical record occurring after 1970 - was capped by the record 2011 flood event. A central motivation for this study is the fact that while the 2011 water-year precipitation was not the highest historical total since 1898 (Fig. 2, middle-panel), 2011 did produce the highest streamflow totals. This fact alone implies that particular aspects of moisture

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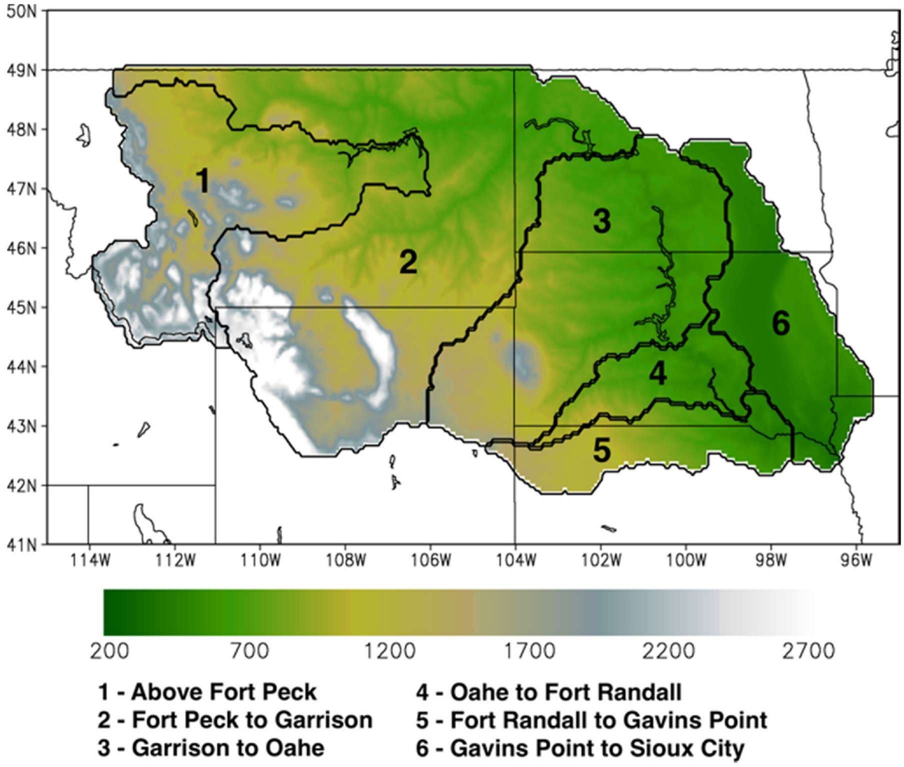

Fig. 1. Upper Missouri River Basin modeling domain with each sub-basin labeled. Shaded is the domain topography (m).

delivery in 2011, both temporally and spatially, were uniquely effective in generating the extreme UMRB streamflow. Further highlighting the uniqueness of 2011 was the record high runoff ratio for the period of record (Fig. 2, bottom-panel), in which 2011 runoff ratio (the coefficient of annual streamflow to annual precipitation) of 0.165 was nearly double the climatological mean (0.086).

Better understanding of flood drivers can inform preparedness efforts and mitigate associated high costs (Smith and Matthews, 2015). This paper aims to quantify the importance of key mechanisms responsible for individual extreme high annual streamflow events and explore whether the major flood event could have been anticipated on the basis of meteorology, antecedent moisture conditions, and historical trends in these quantities.

We ask what factors principally control the occurrence of high streamflow in the UMRB, the seasonal peak of which occurs in late spring. Hoerling et al. (2013) explored the relationship between UMRB flooding and oceanic conditions using a large ensemble of General Circulation Model (GCM) simulations. They found high runoff to be correlated with a Pacific-wide La Nina pattern. However, even perfect foresight of the sea surface temperature (SST) conditions and the La Nina conditions revealed only a modest (10%) increase in the likelihood for high regional precipitation, concluding that ocean conditions were not an appreciable contributing factor.

Here, we go beyond Hoerling et al. (2013) and attribute the local flooding to local mechanisms including land surface conditions using high-resolution land surface model simulations driven by historically observed meteorology.

Our analysis poses the problem of streamflow variability as a forcing-response problem by asking: 1) Are atmospheric conditions the principal driver for variability in annual UMRB streamflow from 1950 to 2013? and 2) Can we reasonably foresee extreme streamflow events from the prior year's land-surface conditions? Overall, the key contributions of addressing these questions will be quantify the mechanisms driving extreme land surface responses, and assess the predictability of high streamflow situations over the UMRB in particular. The unique application of an ensemble technique to isolate and diagnose contributing factors to an extreme event for a major river basin like the UMRB is viewed as a method having more general application to other river basins.

In the context of our first question, we ask whether the historical sequence of daily precipitation, maximum and minimum surface temperatures were the principal drivers for the overall variability in annual UMRB streamflow. A variety of factors are known to contribute to surface streamflow production, including: meteorology, antecedent moisture conditions, land-use, land-cover and soil texture. Meteorological factors are often cited as dictating large-scale moisture delivery, year-to-year streamflow variability and long-term trends (e.g. Stone et al., 2003). Land use can affect local surface runoff conveyance to streams, with vegetation cover, sedimentation, channeling, urbanization, among the factors influencing the efficiency of converting atmospheric moisture delivery into streamflow (e.g. Pegg et al., 2003).

We use historically observed meteorological conditions to force the land surface moisture states and streamflow production in an