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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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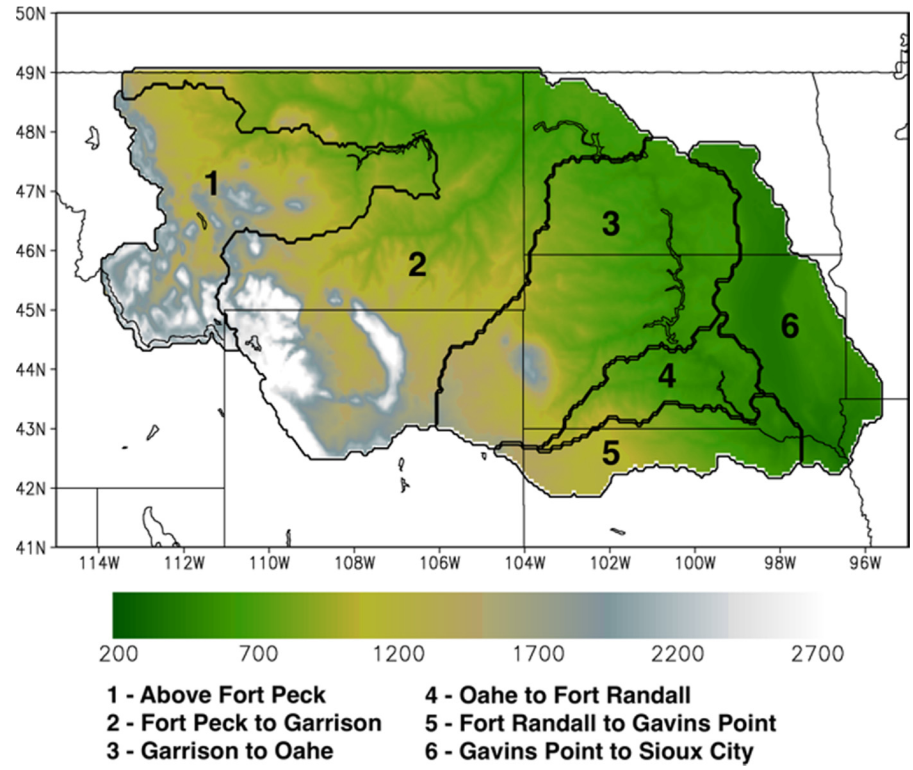

Fig. 1. Upper Missouri River Basin modeling domain with each sub-basin labeled. Shaded is the domain topography (m).

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

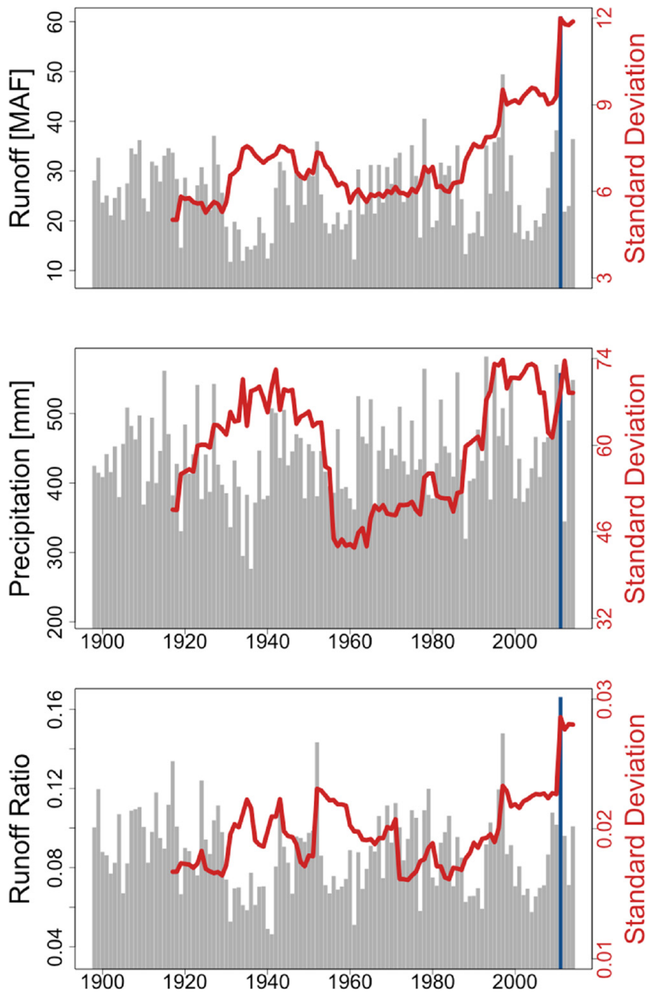

Fig. 2. Time series of water-year (1-October to 30-September) Missouri River streamflow (million acre-feet) above Sioux City, Iowa (top), water-year Missouri River basin precipitation above Sioux City (mm; middle), and water-year runoff ratio (bottom). Time series are 1898–2014. The standard deviation of water-year values for 20-yr moving windows shown in red curves. The value is plotted at the last year of the moving window thus the end-point for the red curve is 2014, and denotes a 1995–2014 period. Streamflow data source is U.S. Army Corps of Engineers (USACE); precipitation data source is PRISM (Daly et al., 1994). Dark-blue bar denote year 2011.

offline mode. With a land surface model that has been calibrated towards UMRB streamflow, we address whether the trend toward more extreme annual streamflow is reconcilable with historical trends in meteorological conditions. Analysis of sub-basin (Fig. 1) streamflow sensitivity through time permits an evaluation of the importance of changes in the seasonality and spatial pattern of moisture delivery.

With respect to our second question, we ask whether extreme values of late spring peak in the seasonal hydrograph at Sioux City might have been foreseen by knowledge of initial land surface conditions on 1-October of the prior year. Salley et al. (2016) showed that higher water-holding capacity soils in parts of the northern Great Plains region can be more resilient to extreme rainfall shifts, in contrast to lower-capacity soils with less buffering ability. It is known that initial information on Snow Water Equivalent (SWE) and soil moisture states can contribute to skillful streamflow prediction (Koster et al., 2010; Reager et al., 2014). Changes in the management of the river and the consumptive-use of water can also be important, though the impact of these effects on the streamflow data has been accounted by the U.S. Army Corps of Engineers (USACE) through the development of naturalized streamflow, developed using a Maintenance Of Variance Extension type 1 (MOVE.1) technique and water-balance approach (e.g. outflow is equal to inflow plus or minus changes in storage and diversions). This naturalized flow is suitable for comparison with our VIC simulations, since it reflects the streamflow that results primarily from natural processes simulated by the model. The result is a time series of monthly 'naturalized' streamflow at Sioux City (Fig. 2) based on recorded diversions and impoundments (USACE, 2006).

In this study, we undertake a systematic analysis of such initial land factors compared to subsequent meteorological factors that evolve during winter and spring. The impact of such land initial states is compared to the control exerted by subsequent meteorological conditions. Finally, we repose this question from a later start date—1-March, consistent with typical water supply forecasts—and explore relevant changes in predictability.

In Section 2, we describe the meteorological data used to drive the land model, provide details of the land surface model including its calibration, appraise its ability to simulate the naturalized Sioux City streamflow during 1950–2013. Section 3 includes results from our ensemble streamflow simulations to diagnose antecedent moisture and atmospheric forcing contributors to streamflow sensitivity. Section 4 explores unique features of the 2011 extreme streamflow, and includes commentary and assessment of the potential for enhanced flooding over the UMRB in future decades.

2. Methods

By making use of a range of observational sources and the Variable Infiltration Capacity (VIC) model (Liang et al., 1994) a series of sensitivity experiments were conducted to identify the important physical mechanisms governing extreme regional streamflow events.

2.1. Model and model calibration

The VIC land surface model was selected in this study, given its successful regional application (e.g. Maurer et al., 2002; Andreadis et al., 2005; Sheffield and Wood, 2008; Livneh et al., 2013) as well as it's physically based structure, important for reconciling key processes that are dynamic through time. Historical hydrologic simulations were driven by the observed meteorological dataset from Livneh et al. (2015). These gridded meteorological data span 64-years from 1950 to 2013, integrating station-based observations of daily precipitation, maximum and minimum temperature, and wind-speed from National Centers for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) reanalysis.

The VIC model includes mosaic land cover to capture sub-grid variability in vegetation classes; statistically represented sub-grid variability in soil moisture storage; baseflow represented as non-linear drainage from the lower soil moisture zone; and elevation bands in topographically complex regions to capture orographic precipitation and lapse temperatures (Nijssen et al., 1997, 2001). Penman-Monteith potential evapotranspiration (Monteith, 1973) is used to dynamically compute evapotranspiration from which components of soil, canopy evaporation and transpiration are estimated based on resistance-terms that are a function of soil and plant stress. VIC computes a full energy and water balance snow model (Andreadis et al., 2009), which simulates both canopy and sub-canopy snowpack evolution.

In this study, the VIC model was built at a $1/16^{\circ}$ (~ 6 km) spatial resolution with soil parameters derived from Livneh et al. (2013; 2015). Numerous previous studies have noted considerable challenges in realistically simulating the hydrology of the arid UMRB (e.g. Xia et al., 2012; Newman et al., 2015) and as such, calibration was required to match simulated and observed hydrograph characteristics. The soil parameters listed in Table 1 were modified during the calibration process with the objective of identifying model parameters that minimize errors between simulated streamflows and naturalized streamflows (described below). Given the large computational expense of daily simulations spanning multiple-decades for the 24,369 grid cells within the UMRB domain, approximately 100 total simulations (sensitivity plus manual calibration adjustments) were performed to arrive at the final parameter set. The pattern of spatial variability for the soil parameters was based on the distribution of observationally based soil bulk density. Bulk density characterizes soil texture, through the porosity, and therefore much of the soil hydraulic properties relevant for hydrologic response.

Daily VIC simulated streamflows are aggregated to monthly values and are then compared to the United States Army Corps of Engineers (USACE) naturalized streamflow. Analyzing extreme streamflows on a monthly time-step has the limitation of dampening any higher-frequency, acute streamflows associated with flooding. USACE conducted an analysis to reconstitute streamflows without the reservoir system for the purposes of determining the impacts of reservoir regulation on streamflow (USACE, 2006). The natural streamflows were calculated by USACE using a program called Mainstem and Tributary Unregulated Flows by which a simple lag-average procedure to route reservoir effects, considering withdrawals, impoundments, and the length of river reaches and their associated attenuation. Results of model performance in comparison to naturalized streamflow can be found in Section 3.

2.2. Sensitivity experiments - contributions of antecedent moisture versus atmospheric forcing

The approach taken in this study is a unique application of Ensemble Streamflow Prediction (ESP) and reverse-ESP applied as a diagnostic tool for an unprecedented extreme flood event. ESP and reverse-ESP (Wood et al., 2016; Wood and Lettenmaier (2008))

Table 1
Calibration parameters used in this study including the infiltration parameter, binf, baseflow parameters Ds, Dsmax, Ws, as well as the thicknesses of soil layers 2 and 3, D2 and D3 respectively.

Parameter	Description
binf	Infiltration curve shape parameter
Ds	Fraction of maximum baseflow where non-linear baseflow occurs
Dsmax	Maximum velocity of baseflow
Ws	Fraction of maximum soil moisture where non-linear baseflow occurs
D2	Thickness of second soil layer
D3	Thickness of third (deepest) soil layer

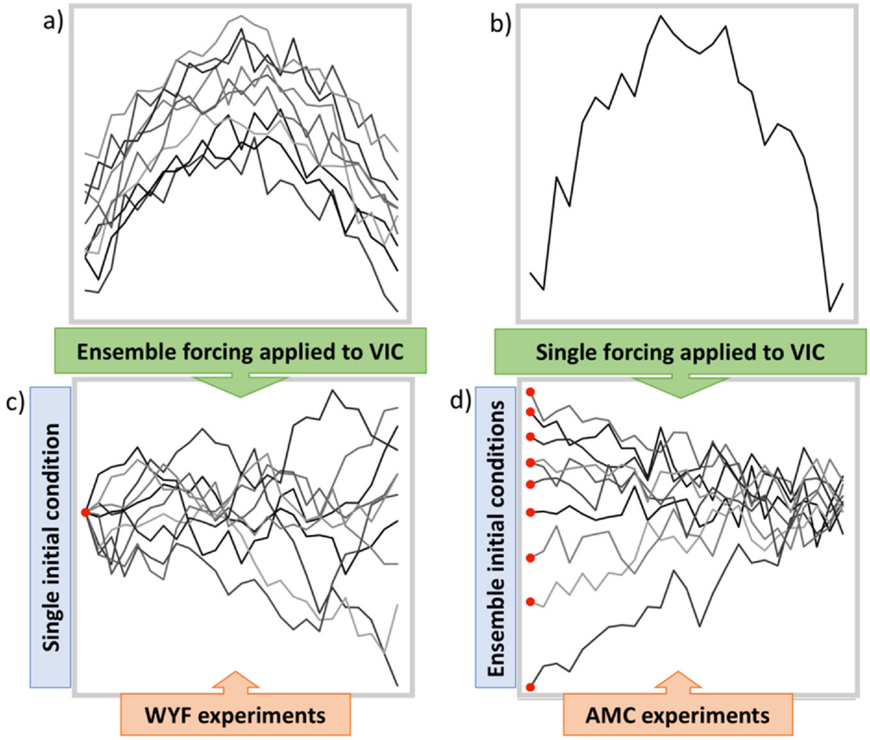

Fig. 3. Idealized schematic of water-year atmospheric forcing (WYF; a & c) and antecedent moisture condition (AMC; b & d) experiments. Panel b is akin to the ESP, while panel d is akin to the reverse-ESP methodology (e.g. from Wood et al., 2016). Top-panels (a & c) represent forcing applied to VIC. Bottom-panels (b & c) represent VIC model evolution, with red dots indicating VIC initial condition(s).

are techniques that use several decades of historical model simulations to diagnose the roles of antecedent moisture and seasonal climate forecasts on streamflow predictability, typically applied to small watersheds. By either an ensemble of seasonal climate forcings (ESP) or an ensemble of the model's initial conditions (reverse-ESP), by which their relative importance on streamflow prediction can be ascertained.

We use 2011 as a case study for diagnosing the importance of the antecedent moisture conditions (AMC) versus water-year atmospheric forcing (WYF) on extreme streamflow in the UMRB. Parallel VIC sensitivity experiments were performed by shuffling either AMCs at the start of each water-year (1-October), or the evolution of atmospheric forcing variables throughout the water-year (1-October to 30-September); see Fig. 3 for an idealized schematic of the experiment design. The AMCs were obtained from the historical calibrated VIC simulation (1950–2013), e.g. a control simulation in which AMC conditions—total column soil moisture and snow water equivalent—were saved at the start of each water-year (WY) on 1-October of the preceding calendar year, representing our best estimate of moisture conditions priming hydrologic response for the subsequent WY. Time period means centered on 1-October show that initial conditions starting on 1-October are representative of the start of the WY. WYFs are simply the historical observed precipitation and temperature sequences for each historical WY, 1950–2013. The parallel experiments are summarized as follows:

2.2.1. AMC experiments

Application of a specific year of WYF to all historical AMCs to quantify the influence of AMC on extreme streamflow, involving:

- Reverse-ESP experiment
- Model simulations for a one year duration, initialized with the soil moisture and snow water equivalent antecedent conditions from the calibration run for 1-October from each of the historical 64 years, 1950–2013;
- Each simulation year forced with the 2011 WY atmospheric conditions (i.e. 1950 AMC forced with 2011 WYF, 1952 AMC forced with 2011 WYF, …, 2013 AMC forced with 2011 WYF).

2.2.2. WYF experiments

Application of a specific year AMC to all historical years WYF to quantify the influence of WYF on extreme streamflow:

- ESP experiment
- Model simulations for a one year duration, initialized with the 2011 AMC conditions, e.g. the start of the 2011 WY is 1-October 2010;

- Each simulation year forced with the atmospheric conditions from all other WYs (i.e. 2011 AMC forced with 1950 WYF, 2011 AMC forced with 1951 WYF, …, 2011 AMC forced with 2013 WYF).

By holding either the 2011 AMC or WYF constant, the experiments isolate antecedent moisture (i.e. AMC) versus subsequent WY atmospheric (i.e. WYF) contributions to the 2011 extreme streamflow event.

2.3. Community Earth System Model (CESM) ensemble

A 40-member historical transient simulation of the NCAR Community Earth System Model version 1 (CESM1; Kay et al., 2015) is used to contrast historical streamflow variability with future projections. These “All-Forcings” simulations span 1920–2005, and use RCP8.5 for 2006-2100. Importantly, an ensemble of 40 model simulations is available, such that the central tendency (mean) of all model simulations (n = 40) can provide an estimate of the externally forced climate change, while the spread among the simulations reveals effects of unforced internal variability. Using this ensemble, the likelihood of extreme streamflow events in the future can be estimated, as well as providing a general overview of future hydroclimatology.

3. Results

3.1. VIC model performance

Evaluation of historical simulations with naturalized streamflow provides an important measure of performance from which to conduct idealized experiments. A common evaluation metric is the Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970), while we also analyze others including the annual and monthly Pearson correlation, as well as the ratio of model-to-observed monthly standard deviation—a measure of how well the model simulates variability, particularly important when simulating alternative climate scenarios. Hydrologic modeling challenges have been well-documented over the UMRB region by numerous studies with a class of comparable models. Both Xia et al. (2012) and Newman et al. (2015) conduct national-scale hydrologic assessments and highlight the UMRB and Great Plains as regions with the among lowest NSEs, typically less than 0.3, across a range of models.

The 64-year monthly hydrograph of naturalized streamflow at Sioux City, IA and streamflow from the UMRB produced by the calibrated VIC model are compared in Fig. 4. The model captures the seasonal timing of peak streamflow, and achieves a NSE of 0.59, which is deemed as satisfactory (Moriasi et al., 2007), although VIC does not capture early spring streamflow events that are present in the naturalized record.

Further analysis of the inter-annual variability of simulated streamflow demonstrates a 0.90 and 0.81 correlation between naturalized VIC streamflow at annual and monthly intervals, respectively. Perhaps most important for validating the model’s ability to replicate streamflow variability, the ratio of model-to-observed monthly standard deviation is 0.99. Additionally, when analyzing

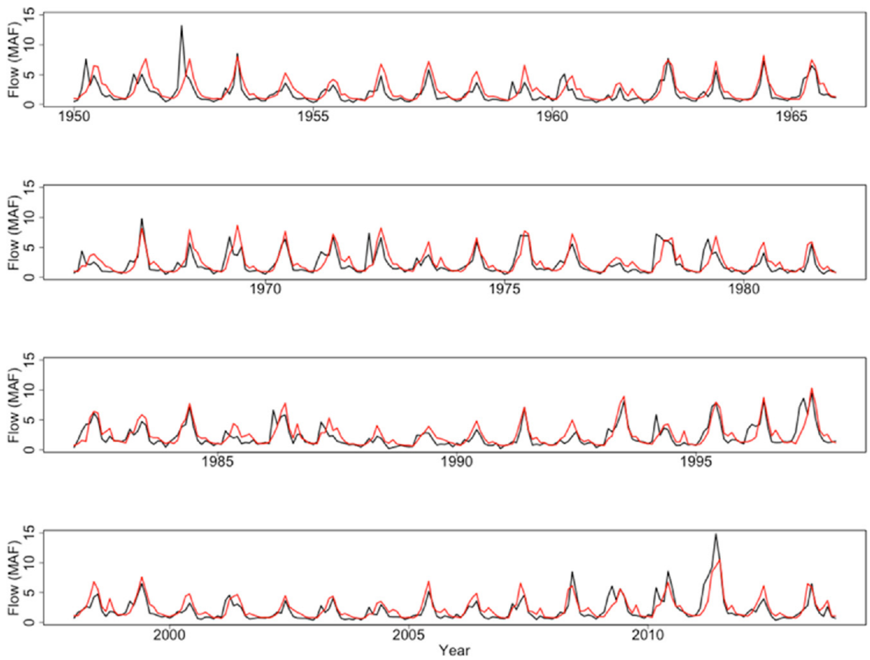

Fig. 4. Model validation over a 64-year historical period. Monthly hydrograph from 1950 to 2013 for the naturalized streamflow (black) and VIC (red), units of streamflow are million acre-feet (MAF). Notable skill metrics include: NSE of 0.59, correlation of 0.81, and model-to-observed ratio of standard deviation is 0.99.

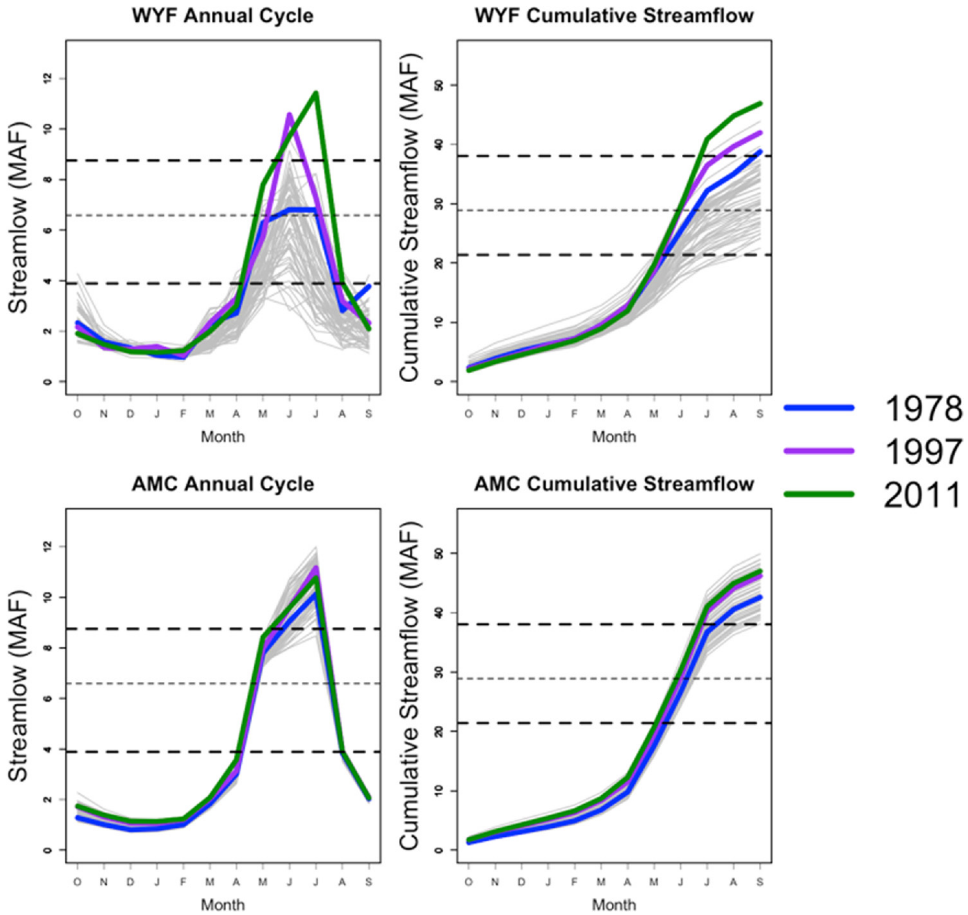

Fig. 5. Annual cycle (a) and cumulative streamflow totals (b) for WYF experiment starting on 1-October, units are million acre-feet (MAF). Annual cycle (c) and cumulative streamflow totals (d) for AMC experiments starting on 1-October, units are MAF. All WYF experiments are begun from the same 1-October 2010 antecedent moisture state. All AMC experiments are subjected to the same 1-October 2010 – 30 September 2011 meteorological forcing. Bold and colored lines represent the three highest streamflow years on record; 1978 (blue), 1997 (purple) and 2011 (green). Dashed lines represent the 5^{th}, 50^{th} (i.e. median) and 95^{th} percentiles from the control simulation of annual peak streamflow in (a) and (c) and of annual total streamflow in (b) and (d).

VIC's capability to capture the naturalized extreme high streamflow annual events (years 1975, 1978, 1986, 1993, 1995, 1996, 1997, 2010 and 2011), seven of the nine extreme naturalized streamflow years were ranked accordingly in VIC's extreme streamflow years. In summary, the fidelity of model portrayals of monthly and annual variability, as well as capturing top ranking extreme events, lends confidence in this calibrated version of VIC to simulate key sensitivity to known meteorological forcing from which we can proceed to explore sensitivities to idealized forcings.

3.2. Antecedent moisture conditions and water-year forcing experiments

The WYF experiments reveal that the 2011 WY forcing uniquely produces the most extreme UMRB streamflow both in terms of peak and cumulative values relative to all other historical water-year atmospheric forcings (Fig. 5). This occurs even though the WY precipitation observed in 2011 was not the highest historical total since 1898 (Fig. 2, bottom-panel). This implies that additional features of moisture delivery in 2011, including its temporal and spatial patterns were uniquely effective in generating the extreme UMRB streamflow. Nonetheless, high historical streamflow WYs are all typically among the largest precipitation years with the WYF experiments revealing statistically significant correlations between water year precipitation with peak streamflows (0.64, $p < 0.05$) and cumulative water-year streamflow (0.83, $p < 0.05$).

The AMC experiments (Fig. 5c and d) show that antecedent moisture conditions on 1-October 2010 did not yield the greatest streamflow relative to other historical years. A significant sample of other 1-October soil moisture conditions, had they occurred in 2010, would have led to an even larger record streamflow that water year. In this context, the 2011 flood could have been conceivably more severe than it was on the basis of antecedent moisture. It is further evident that the sensitivity to historical antecedent moisture is much less than the sensitivity to historical WY meteorological forcings (compare Fig. 5a/b and c/d). All VIC simulations in the AMC ensemble yield a peak streamflow of greater than 8 million acre-feet (MAF) (> the 86^{th} percentile in the control simulation),

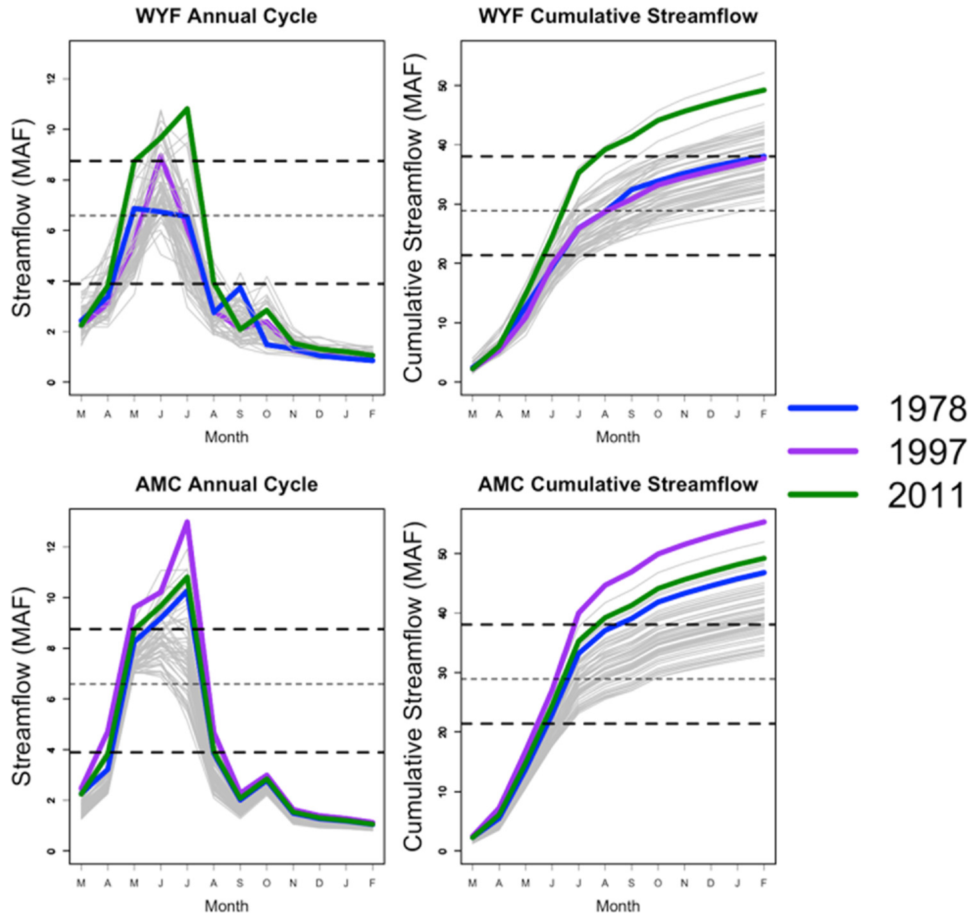

Fig. 6. Annual cycle (a) and cumulative streamflow totals (b) for WYF experiment starting on 1-March, units are million acre-feet (MAF). Annual cycle (c) and cumulative streamflow totals (d) for AMC experiments starting on 1-March, units are MAF. All WYF experiments are begun from the same 1-March 2011 antecedent moisture state. All AMC experiments are subjected to the same 1-March 2011 to 29-February 2012 meteorological forcing. Bold and colored lines represent the three highest streamflow years on record; 1978 (blue), 1997 (purple) and 2011 (green). Dashed lines represent the 5^{th}, 50^{th} (i.e. median) and 95^{th} percentiles from the control simulation of annual peak streamflow in (a) and (c) and of annual total streamflow in (b) and (d).

compared with just 8-out-of-64 (12.5%) years in the WYF experiments above 8 MAF. This marked increase in peak streamflow confirms that the 2011 atmospheric forcing is the distinguishing feature responsible for the extreme streamflow.

Nevertheless, a strong correlation between the antecedent moisture and both peak streamflow (0.795) and the cumulative annual streamflow total (0.876) is found. These positive, statistically significant correlations ($p < 0.05$) confirm that antecedent moisture at least partially drives the streamflow for the following year. The result affirms the widely accepted idea that precipitation falling on a nearly saturated soil column becomes streamflow more readily than on a less saturated column, and can hence contribute to large streamflow events.

Overall, these experiments consistently indicate that years other than 2011 had antecedent moisture conditions capable of driving an even greater flood event than was observed, albeit those years did not receive the same large precipitation as was observed in 2011. The antecedent moisture states alone were insufficient to identify the high historical streamflow years, while we clearly show that the notably wet meteorological conditions were essential in producing the very high streamflow, regardless of the land-surface moisture. This experimental framework establishes quantitative evidence of the leading role of meteorological forcing in streamflow generation for the 2011 event. As an overall synthesis of driving factors, the VIC results indicate an incidental combination of anomalously wet antecedent moisture conditions with subsequent very wet meteorology setting up a near-optimal spatial and temporal moisture delivery.

Although 1-October is a valuable time to anticipate spring streamflows, most forecasts typically do not begin until March. Hence an analogous set of simulations to the above were conducted, initialized on 1-March, to characterize the importance of WYF and AMC on extreme streamflow from a more realistic forecast date. Relative to Figs. 5 and 6 shows increased importance of antecedent moisture for both the AMC and WYF experiments. Among these, the WYF experiment in Fig. 6a is most akin to an operational forecast, where the 1-March 2011 AMCs initialize an ensemble of hydrologic simulations using WYFs from all years. Importantly, the relatively wet 2011 AMC produces an entire ensemble of simulations with peak streamflow above the historical median, indicating

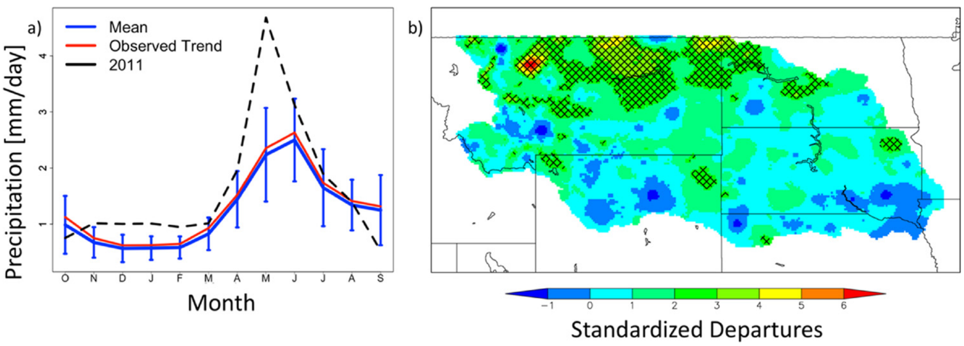

Fig. 7. a) The annual cycle of mean precipitation for the total basin (blue) with error bars indicating one standard-deviation (1950–2013). The black-dashed line denotes the 2011 water-year precipitation and the solid-red line denotes the annual cycle modified by the observed seasonal trends. b) Cold-season precipitation anomaly for 2011 (1-October 2010 to 31-March 2011) with differences from the 1950–2013 mean normalized by the standard deviation, cross-hatched area indicates significant at the 95% level.

that a large streamflow peak was inevitable in 2011, much more so than the larger spread in the 1-October initialization (Fig. 5a; the same can be said when contrasting Fig. 6b with Fig. 5b). Yet, because the record precipitation anomaly occurred after the 1-March initialization, i.e. in May 2011 (See Fig. 7a, next section), the AMC on 1-March 2011 did not drive all traces towards record streamflow levels.

Fig. 6c shows the application of the 2011 forcing to all AMCs initialized on 1-March. Since peak streamflow occurs only 3 months after initialization, the persistence of AMCs produced a larger spread in peak streamflow among ensemble members, relative to Fig. 5c. Recalling that 8 MAF corresponded with the 86th percentile in the control, we note that for the AMC experiments, 8 MAF became the 0th percentile for 1-October initializations (63 of 63 simulations exceed 8 MAF) and the 33rd percentile in 1-March initializations (42 of 63 exceed 8 MAF). When analyzing peak streamflow changes regardless of the experiment or start date, the 5th, 50th and 95th percentiles all increase (not shown). Notably, the AMC experiments yield 57.4% (October start) and 9.5% (March start) increases in peak streamflow over their WYF counterparts. Percent increases in the 5th percentile is larger than those of the 95th percentile, together with the increases in the median, this highlights a shift and a skewing of the probability distribution of the peak streamflows. Overall, the large differences in hydrologic response between WYF and AMC experiments initialized on 1-October become less pronounced for the 1-March experiments, leading to the conclusion that knowledge of antecedent moisture becomes as vital as knowledge of atmospheric states are shorter lead times.

Using 1-March as an antecedent moisture condition in WYF experiments, the 2011 water-year stands out in this ensemble and was only surpassed by the 1995 water-year forcing, whereas the 2011 water-year streamflow was the largest streamflow in the 1-October initializations. For context, the 1-March initialization of the AMC experiments had three other antecedent moisture states (1969, 1972 and 1997) producing greater streamflow than was observed in 2011; compared to nine (1951, 1952, 1966, 1973, 1983, 1987, 1994, 1996 and 1998) producing greater streamflow than in 2011 when using 1-October. As opposed to the 1-October initializations, both WYF and ACM experiments with 1-March initializations have a statistically significant change in variability of annual peak streamflow.

4. Discussion

The prior results reveal that an extreme streamflow year in the UMRB does not necessarily result from an initial state having the wettest antecedent moisture conditions or a WY meteorological state having the most precipitation. Rather, a combination of both is most typically involved, which when convolved, produces an extreme hydrologic event. Using the record-setting 2011 UMRB flood event as an example, we further explore the conditions that led to the 2011 event and identify its drivers.

4.1. Unique hydrologic features of the 2011 event

The 2011 WY precipitation exhibited a 36.7% increase in cold-season precipitation relative to climatology, while also being above average for most of the spring and early summer (Fig. 7a), with record precipitation in May. Fig. 7b shows the extent of the UMRB anomalous precipitation for the cold-season of the 2011 WY (1-October 2010 to 31-March 2011), with 18.7% of the domain showing statistically significant high cold-season precipitation ($p < 0.05$). Furthermore, 49.5% of the domain had precipitation that was greater than 1 standard deviation above the mean and 89.7% of the domain experienced above average precipitation during the 2011 WY cold-season.

To isolate the importance of atmospheric versus antecedent moisture drivers, we bin the observed streamflows into four regimes based on basin wide means of observed precipitation and VIC-simulated antecedent moisture states associated with 1-October conditions (i.e. ASM simulation initialization states) into four groups: 1) above-average precipitation and above-average antecedent moisture, 2) above-average precipitation and below-average antecedent moisture, 3) below-average precipitation and above-average antecedent moisture, and 4) below-average precipitation and below-average antecedent moisture. The separation of the annual

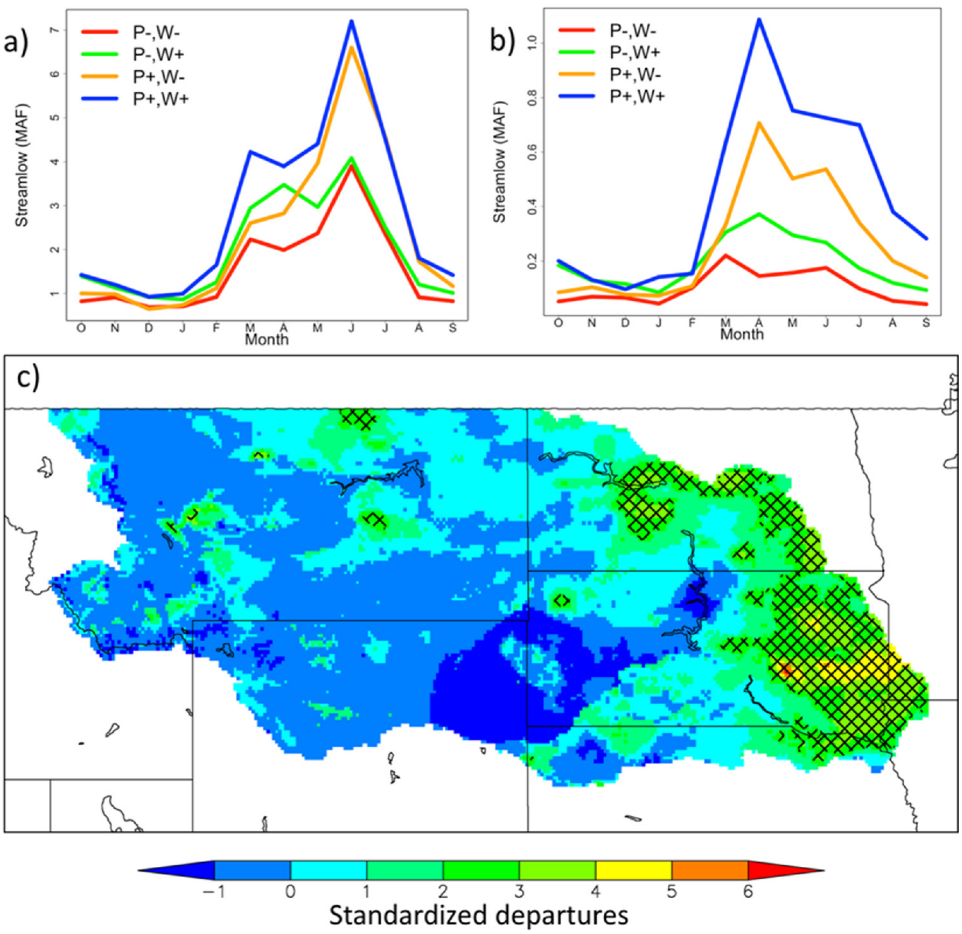

Fig. 8. a) Annual cycles of the four precipitation-soil wetness regimes for naturalized streamflow for the entire UMRB; b) Annual cycles of the four precipitation-soil wetness regimes for the Gavins Point to Sioux City sub-basin, units of streamflow are MAF; c) Soil moisture conditions at the start of the 2011 water-year on 1-October 2010, differences from the mean are normalized by the standard deviation, cross-hatched area indicates statistical significance, $p = 0.05$. For panels a and b, the binning procedure is described in section 4.1.

hydrographs for the four bins (Fig. 8a) demonstrates distinct streamflow behavior among these regimes. The above-average precipitation years produce greater streamflow than below-average precipitation years, and antecedent moisture tends to play only a muted role. It follows that all nine extreme streamflow events (previously listed) since 1975 had above-average precipitation. By contrast, only five had above-average soil wetness, including 2011.

This regime discrimination is generally shared for each of all UMRB sub-basins (Fig. 1), with the notable exception of the reach between Gavins Point and Sioux City (sub-basin #6). This sub-basin exhibits far greater sensitivity (Fig. 8b) to antecedent moisture conditions than the other five sub-basins with a more even spread across groupings relative to those shown Fig. 8a. We find an almost 50% increase in streamflow between the above and below-average antecedent moisture regimes for the above-average precipitation case—by far the largest difference of any sub-basin. It is worth remarking that the Gavins Point to Sioux City sub-basin is the least regulated sub-basin the UMRB system, and hence the most vulnerable to flood impacts.

Given its importance, we further explore the degree to which the 2011 WY antecedent moisture was anomalous relative to the 1950–2013 mean. We find a large coherent region of significantly wet soils present in the Gavins Point to Sioux City sub-basin (Fig. 8c) at the start of the 2011 WY. This interesting coincidence is worth highlighting, i.e. that the region where streamflow is most sensitive to antecedent moisture, in fact experienced anomalously wet conditions in 2011, contributing to high streamflow production during that respective WY. It should be of note that the Gavins Point to Sioux City sub-basin saw an increase of almost 124% in streamflow production during the 2011 WY, relative to the 1950–2013 climatology.

Anomalous cold-season precipitation can act to “prime” the land-surface for heightened streamflow efficiency during spring and summer through increased soil wetness underlying seasonal snow cover. This condition promotes greater streamflow and less infiltration during warm-season snowmelt and precipitation events. We expect this seasonal land-surface moisture storage (i.e. memory) to be more prevalent for years with anomalous cold-season precipitation given the energy-limitation during this time that enable wet anomalies to therefore persist. This priming of the land-surface was further highlighted by the record-high runoff ratio in the 2011 water-year (Fig. 2, bottom-panel).

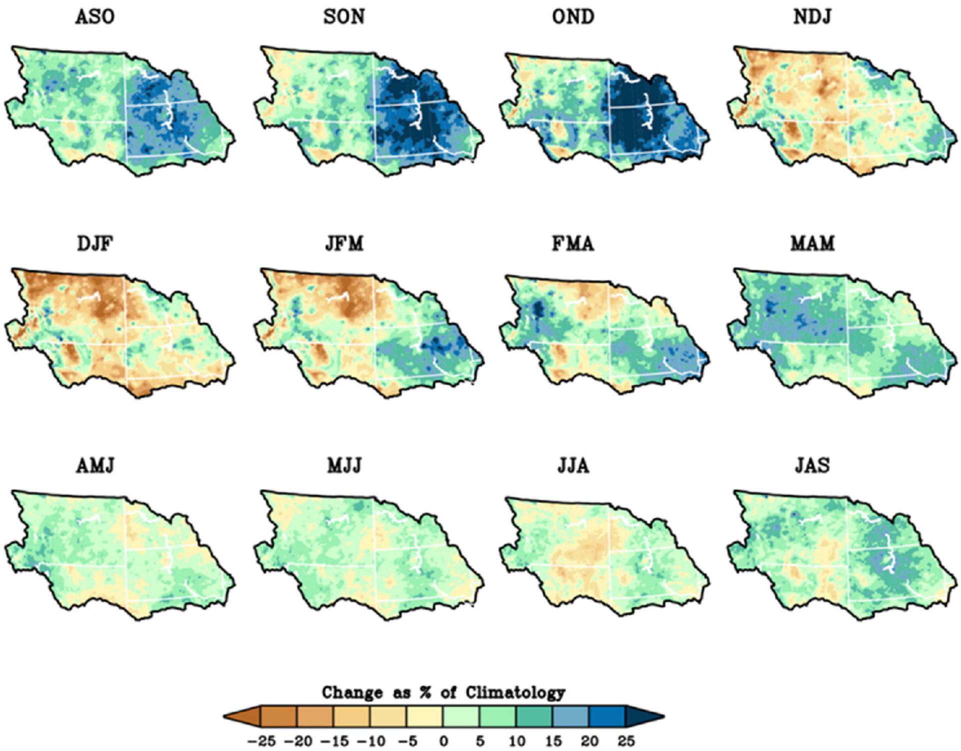

Fig. 9. Recent observed changes in seasonal precipitation (% of climatology) calculated as the difference (1975–2014) minus (1895–1974). Precipitation data source is PRISM.

4.2. Trends and likelihood of flooding under a future climate

To address the question of extremes in the background of an underlying trend; we examine observationally based trends and modeled evolution of UMRB precipitation and temperature in a future climate.

Utilizing the monthly gridded PRISM (Parameter-elevation Regressions on Independent Slopes Model) analyses, for the period 1895–2014 at 4 km resolution (Daly et al., 1994), we are able to ascertain seasonal trends in precipitation. For the UMRB, Fig. 9 shows the changes in seasonal precipitation since 1895. Averaged over the UMRB as a whole, cold-season (Oct. to Mar.) precipitation has been observed to increase by 11.9% (2.52 mm/mon). There are distinct spatial patterns to the cold-season increase especially, with the magnitude of wet trends being most intense over the central and eastern portion of the UMRB. Notably, the increases in the eastern portion of the basin may act exacerbate the role of the Gavins Point to Sioux City sub-basin that was noted to be acutely sensitive to antecedent moisture conditions.

Additionally, we extended seasonal trends in precipitation and applied them to the observed meteorology (Fig. 7a, red-line) and reran VIC with this modified precipitation. The resulting hydrograph analysis (not shown) showed modest increases in streamflow but did not approach streamflows on the order of the observed (or VIC modeled) 2011 event. This confirms that the 2011 event falls outside of the historical trend and cannot be exclusively explained based on long-term trends in precipitation.

The CESM1 ensemble of historical simulations and their future extensions under a scenario of aggressive GHG emissions (RCP8.5; Taylor et al., 2012) are examined to assess potential changing extremes in a future hydroclimate. Modest increases in WY precipitation are projected together with dramatic increases in temperature. Importantly, there is considerable spread in the rainfall changes among individual runs, such that multi-decadal periods could have rainfall regimes much different from the modest wet signal of the ensemble mean. Conversely, the warming signal becomes much larger than the intrinsic variability of temperature among ensemble members by the early-mid 21st century, indicative of a robust change.

Steady warming of the basin—nearly 4 °C warmer than current climate by 2050—appears to contribute to a modest downward streamflow trend. This decline is seen despite the overall increase in precipitation. We interpret the streamflow declines as a response to increased evaporative demands that overwhelm the increase in precipitation by the latter half of the 21st century. In concert with our result, Vano et al. (2012) notes that in the neighboring Upper Colorado River basin that stream is expected to decline by 2–9% per degree Celsius increase.

Despite the overall decline in streamflow generation in the UMRB in CESM1, the frequency of very high annual streamflow events increases, consistent with the large variability in simulated streamflow. Fig. 10 compares histograms of the exceedances in annual streamflow above the 90th percentile (50 MAF) of all years simulated by CESM1. The analysis is divided into three 40-year time slices, one for the early 20th century (top), one for near-current climate (middle), and one for the end of the 21st century (bottom).

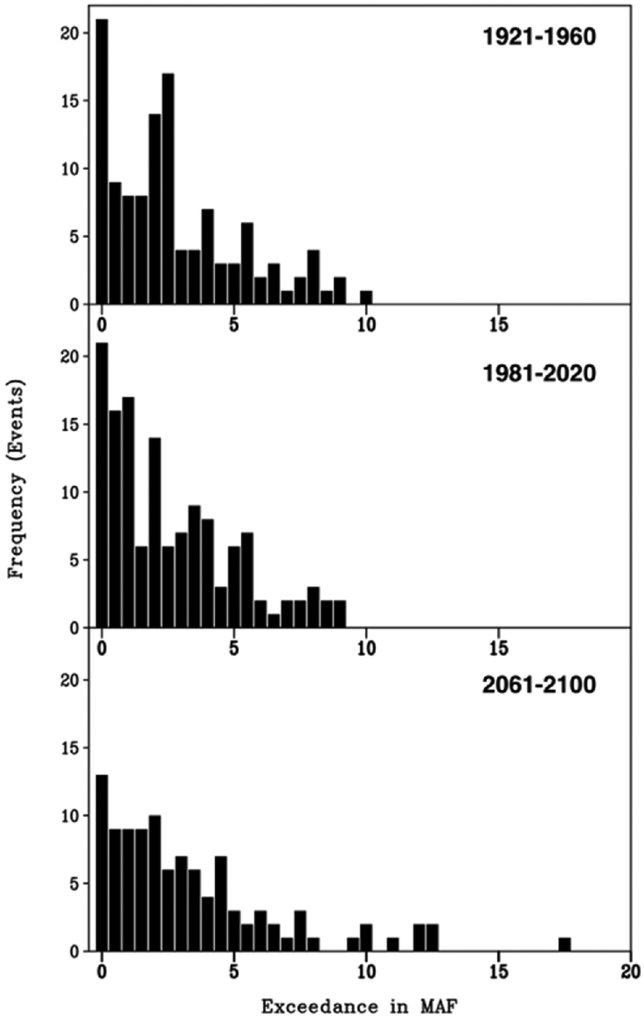

Fig. 10. Histograms of simulated water-year streamflow exceedances above the 90th percentile for 1921–1960 (top), 1981–2020 (middle), and 2061–2100; derived from the 40-member CESM1 historical simulations and projections using the RCP8.5 emissions scenario. The 90th percentile threshold value of 50 MAF is plotted as 0 on the horizontal, and was calculated from the 1921-60 period. There were between 120–140 exceedance events in each epoch, albeit the most extreme departures appear in the latest period.

Numerous extreme event exceedances are present in the statistics of streamflow at the end of the 21st century that are unprecedented relative to earlier periods. Also of note, a similar change in low streamflow water-year statistics is also found to occur in the CESM1 ensemble (not shown), with extreme low streamflow years in the late 21st century becoming more prevalent. Overall, the projections paint a hydroclimate of the UMRB in which annual streamflows become considerably more volatile owing to human-induced climate change.

5. Conclusions

Ensemble sensitivity experiments were used to quantify the roles of antecedent moisture conditions, and subsequent meteorological forcing in generating extreme annual streamflow in the UMRB. High annual streamflow was largely governed by high water-year precipitation, an unsurprising result that is generally expected in major river basins. However, an important effect of antecedent moisture conditions was also uncovered. When above average precipitation occurred, antecedent moisture had relatively minor impact on peak streamflow production for central and western sub-basins. Yet, in the lowest reach of the UMRB (Gavins Point to Sioux City), a marked sensitivity to antecedent moisture conditions was demonstrated. This sensitivity was especially engaged in 2011 when the hydrologic simulation experiments and observations indicate that region experienced heighten streamflow efficiency and contributed an unusually large fraction to the overall UMRB streamflow. Given the challenges associated with seasonal weather prediction, identification of regions sensitive to antecedent moisture conditions such as the Gavins Point to Sioux City reach can potentially aid in prediction of extreme streamflow events.

To better understand extreme streamflow in the UMRB, a detailed analysis of the 2011 record high streamflow event was conducted. The extreme streamflow was principally due to high, though not record, values of precipitation delivered to the basin during the water year. This meteorological factor was considerably more important for generating high streamflow than the high 1-October 2010 antecedent moisture conditions. However, a combination of these conditions was likely necessary to achieve the record setting streamflow. Repeating the experimentation from 1-March indicated that knowledge of antecedent spring soil moisture conditions was sufficient to predict above-median peak streamflows that year, yet with considerable spread across ensemble members. Our results suggest that the 2011 extreme event and others like it could not have been well anticipated based on knowledge of regional antecedent moisture alone. Nonetheless, this paper's identification of a Gavins Point-Sioux City sub-basin streamflow contribution related to high soil moisture sensitivity indicates some promise for potential predictability.

In the backdrop of the record 2011 streamflow, this paper also addressed the question of extreme streamflow events in the background of a changing climate, particularly striking given that nine of the highest 10 streamflow years since 1898 have occurred post-1970. Observational trends highlight increased cold-season precipitation (Oct. to Mar.) in the UMRB, most notably in the eastern portion of the basin that exhibits sensitivity to antecedent moisture conditions. Yet, the extreme 2011 event could not have been foreseen on the basis of such long-term trend information alone. Instead, the analysis indicates that the 2011 extreme flood was an acute event that arose from a combination of unusual, if not extreme, land surface and meteorological forcings of that water year. We also placed the increased frequency of extreme UMRB streamflow events in to a context of human-induced climate change with indications for an increased frequency in the latter half of the 21st century, even while projections of strong surface warming acts to reduce annual mean streamflow in the basin.

This study uses ensemble land-surface model experimentation in a new way to diagnose the mechanisms responsible for extreme annual streamflow production in the UMRB. Sensitivities identified could aid in the prediction of extreme streamflow events in the UMRB at least in a probabilistic sense. They also motivate a need to better monitor soil moisture conditions across the basin, insofar as such conditions may be a tractable means of harvesting predictability. Prediction of water year precipitation in the UMRB is currently understood to be limited, though any advances will be especially critical since it is the main driver of annual streamflow variability. We would also add that the methods employed here may be useful for understanding extreme streamflow events in other major river basins. Beyond developing improved predictive capacity on seasonal to inter-annual timescales, better understanding streamflow sensitivities to land-surface and meteorological drivers will be key in advancing knowledge on the probable hydroclimatology in future climates beyond the UMRB.

Conflict of interest

We declare that there is no conflict of interest associated with this manuscript.

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