CLIMATE ASSESSMENT REPORT

CAUSES FOR HYDROLOGIC EXTREMES IN THE UPPER MISSOURI RIVER BASIN

Prepared for the US Army Corps of Engineers to Address the Increased Frequency of High Flow Events in the Upper Missouri River Basin in Recent Decades

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National Oceanic and Atmospheric Administration

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This assessment is a NOAA response to Missouri River Basin Water Management's, Northwestern Division, U.S. Army Corps of Engineers request for an expert scientific evaluation on why 9 of the 10 highest historic annual runoff years in the Upper Missouri River Basin (UMRB) have occurred since 1970.

The effort combines climate and multi-scale hydrology experts from NOAA's Earth System Research Laboratory's Physical Sciences Division, the University of Colorado-Boulder, and its Cooperative Institute for Research in Environmental Sciences (CIRES) located at the University of Colorado. The team builds upon knowledge of climate variability over the Missouri River Basin derived in part from their 2013 climate assessment titled "Understanding and Explaining Climate Extremes in the Missouri River Basin Associated with the 2011 Flooding". Therein it was noted that nine of the ten highest annual runoff volumes in the UMRB since records began in 1898 have occurred after 1970, and that year-to-year variability in annual runoff has therefore increased dramatically. This report assesses the underlying causes for such proliferation in high runoff events. It first reconciles changes in annual runoff with changes in observed meteorological forcing. The report then presents new analyses, based on land surface modeling, quantifying UMRB runoff sensitivity to various forcings. Using the 2011 extreme flood event as an archetype of the trend to higher runoff, the report diagnoses the impact of antecedent soil moisture, precipitation, temperature, including changes in their seasonality and changes in daily rainfall extremes. The report also examines observed changes in UMRB hydro-climate within a context of current and future impacts due to global warming.

Gavins Point Dam is located on the Missouri River in Nebraska and South Dakota

Water being released at about 105,000 cubic feet per second on June, 5, 2011. Photo credit: Jay Woods, USACE

EXECUTIVE SUMMARY

In 117 years of record-keeping (1898-2014), 9 of the highest 10 annual runoff years in the Upper Missouri River Basin (UMRB) have happened in just the last 40 years (1975-2014). This report provides an assessment of what has occurred to explain such a trend as it relates to known meteorological forcing and new diagnostic results on upper basin runoff sensitivity. *The increased frequency of high runoff years in the past 40 years resulted principally from the land surface response to increased precipitation delivered to the UMRB.* Runoff production is shown to be especially sensitive to two features of the observed meteorological changes during 1975-2014 (relative to 1895-1974):

- A seasonality of wetting that saw the largest percentage increases (+12%) occur during the cold season (October-March).
- A regional wetting that saw the strongest wet trends occur over South Dakota and the eastern one-third of the upper basin (up to +20%).

Precipitation also increased over most of the UMRB during the warm season (April-September), although less significantly (+5%). Also, using a network of approximately 200 meteorological stations that recorded daily precipitation since the beginning of the 20th century, it is shown that more of the annual precipitation has been delivered to the upper basin within very heavy daily events in recent decades. The effect on such changes in the character of extreme daily rainfall was secondary to the runoff sensitivity to increases in annual precipitation overall, however. It is recommended that further analysis be performed to address impacts on changes in the sequencing of rainy days, for example consecutive wet days, which was not examined in this report.

Hydrologic model experiments using a high resolution land surface model known as the Variable Infiltration Capacity (VIC) macroscale model provide evidence for a significant runoff sensitivity to increased moisture delivery into the upper basin. When subjected to the observed meteorological forcings during 1950-2013, the simulated time series of runoff for the UMRB as a whole is in general agreement with observations, characterized by an increase in frequency of high runoff years after 1970 and punctuated by a record high runoff year in 2011. The land surface model simulations thus reproduce key features of the UMRB annual runoff time series as measured at Sioux City, Iowa, including more frequent extremes and a commensurate increase in the year-to-year variability.

Further data analyses and idealized model experimentation identified key aspects of UMRB runoff sensitivity to meteorological forcing. Empirical results on the relationship between historical water-year runoff and observed water-year precipitation paints a picture of the unique characteristics of the UMRB as they pertain to partitioning rainfall into runoff overall. The runoff coefficient—the ratio of total annual runoff to total annual precipitation—for the UMRB is only about 8% indicating less than 1/10th of annual precipitation is realized as runoff. This is in stark contrast to other parts of the country, such as the more humid East and Pacific Northwest where runoff coefficients can be as large as 50% or higher. This appreciable loss of more than 90% of land surface moisture returned to the atmosphere results as a combination of arid-to-semi-arid conditions together with the unique climatological seasonal cycle in the UMRB whereby most of the precipitation falls during late spring/summer—a time when atmospheric demand for moisture is highest and thus most precipitation is lost to evaporation. *As such, the stronger precipitation increases observed over the past several decades during the cold season have been important for the overall water-year runoff increases (+9%) as they occur during a period of low atmospheric evaporative demand, an important feature of the heightened frequency of extreme high runoff years. VIC simulations confirm that cold season precipitation increases were the most relevant meteorological changes contributing to increases in annual runoff and to elevated probability for extreme annual runoff events.*

Conversely, changes in the character of daily rainfall were found to not have a major impact on annual runoff in the UMRB. An observed trend toward more precipitation delivered via extreme daily events, though possibly producing more efficient runoff, was found in VIC experiments to be secondary to the impact of trends in seasonal precipitation. The effect of changes in sequencing of rainy days, including possible changes in consecutive wet days, was not examined in this report. Likewise, changes in temperature during this period did not produce a major impact on annual runoff in the upper basin. UMRB averages for the 1975-2014 period have been ~0.5°C higher than during 1895-1974, with much of the warming occurring during winter. No significant change in statistics of simulated runoff was found to result from the modest recent warming of the UMWB though the warming may have slightly reduced the basin's overall runoff efficiency. *The observed temperature changes to date fail to explain either the increased frequency of high runoff years or the increased year-to-year variability in annual runoff over the upper basin.*

In addition to the importance this report attributes to seasonal patterns in precipitation changes for explaining increased runoff and extreme hydrologic events, it also finds critical amplifying effects triggered by regional patterns of precipitation trends. The greatest cold-season (October-March) precipitation changes occurred in the eastern portions of the UMRB, with greater than 20% increases averaged for 1975-2014 compared to 1895-1974. Land model experiments reveal acute runoff sensitivity to soil moisture in eastern sections of the upper basin, especially in the reach from Gavins Point to Sioux City. High soil moisture content during recent decades in this region is speculated to have appreciably enhanced runoff efficiency. *Higher soil moisture conditions due to wetting in the last 40 years over that mostly unregulated sub-basin has appreciably enhanced its contribution to the upper basin's overall runoff production.*

Further, case study analysis of the extreme 2011 runoff event confirms the importance of regional patterns of initial soil moisture. A virtually perfect storm for high runoff production resulted from the combination of high mountain snow pack, wet cold season conditions creating wet antecedent soils in the eastern prairies above Sioux City that were then subjected to above normal spring rains. Indeed, analysis of observed seasonal and regional rainfall patterns during all three highest runoff years (1978, 1997, and 2011) shows unusually wet fall and early winter conditions focused on the eastern prairies of the upper basin, consistent with the overall multi-decadal trend pattern.

Long-term climate change associated with global warming alone since the early 20th century is unlikely to have contributed significantly to the wetting of the UMRB, nor has it obviously led to the proliferation of high annual runoff years during 1975-2014. Annual precipitation in the upper basin increases by only about 1% in the ensemble average of 40 historical simulations studied herein, *indicating that the vast majority of increases in precipitation has resulted from natural variations in the climate system*. Nonetheless, analysis of predicted runoff statistics for the UMRB based on the extension of those model simulations to the end of the 21st century, under assumption of aggressive carbon emissions (RCP8.5), reveals increased volatility in upper basin annual runoff from year-to-year owing to increases in both extreme high and low runoff events. It is certainly of curiosity that this projected future change of a more volatile hydroclimate in the upper basin bears resemblance to the recent observed trends. Further careful investigation using a larger suite of climate and hydrologic model simulations would nonetheless be warranted to more conclusively assess the plausibility of future conditions. However, the current report argues that different underlying factors are likely operating in the current climate regime, namely cyclical natural hydro-climate variability.

1. BACKGROUND

The year-to-year variability of runoff from the UMRB has roughly doubled in the most recent 20-yr window compared to prior decades dating to 1898 (Figure 1). This rise in volatility is a symptom of more than just the single extreme flooding event that occurred in 2011; rather, nine of the ten highest annual runoffs in the UMRB historical record have occurred after 1970. Likewise, for 1 October-30 September totals as shown in Figure 1, 10 of the 13 highest water year runoffs in the UMRB historical record have occurred since 1975. The three highest runoff years (1978, 1997, and 2011) are significantly separated from the remaining sample of high runoff cases. Low runoff years continue to be interspersed, for instance as during the early 21st century drought period. These have not been unusual nor materially different from low runoff conditions during the 1930s and 1950s (Figure 1). Runoff volatility has therefore increased principally due to an increase in the frequency and magnitude of high runoff events.

This assessment builds upon a case study of the 2011 event "*Assessment Report: Understanding the Explaining Climate Extremes in the Missouri River Basin Associated with the 2011 Flooding*" by Hoerling et al. (2013). That report identified key climate conditions that occurred in the UMRB and contributed to record flooding in 2011. The factors immediately responsible for flooding in 2011 were found to be a sequence of events that included antecedent wet conditions, a particularly cold and wet 2010-2011 winter that led to unusually high plains and high mountain snowpack, and record setting rains in late spring. Insights gained from study of 2011 will help inform this assessment of conditions believed to be responsible for a proliferation in high runoff events.

This report will examine historical trends in meteorological conditions that can be conducive for high runoff, especially changes in precipitation and its characteristic patterns of moisture delivery within the upper basin. The efficacy of various drivers will be tested using historical land surface model simulations that quantify upper basin runoff responses to changing meteorological driving through time. To further reveal runoff sensitivity to particular factors and to probe the upper basin's hydrologic dynamics that yield extreme runoff, the 2011 event is revisited as an archetype of the high runoff situations. This report will examine land model runoff responses to various plausible scenarios of land surface and meteorological drivers, many of which were known to operate in 2011 and during the other occurrences of high annual runoff.

2. PURPOSE OF THIS ASSESSMENT REPORT

The principal concern of this report is to better understand the factors responsible for increases in high runoff years during recent decades. Generation of high runoffs over the UMRB as a whole is the focus, and sub-basin scale sensitivity to meteorological forcings that could contribute to high runoffs is also addressed. Different physical processes drive overall UMRB runoff, and have different effects at the sub-basin scale. For example, high mountain snowpack and high plains snowpack both have unique runoff signatures. The headwaters regions of western Montana (above Fort Peck) provide mountain snowmelt driven runoff, with precipitation falling most abundantly in winter/early spring. For the Plains region (below Fort Peck), spring snowmelt, but also moisture from spring rains (April-June) are key, and runoff related to these can be augmented when falling on deep snowpack accumulated during winter. We note that the reach from Gavins Point to Sioux City is largely unregulated, and precipitation falling in that far eastern portion of the UMRB thus cannot be readily controlled before entering the main stem of the Missouri river. This report will examine the contribution of these various sub-basins to the overall upper basin runoff, as measured by the runoff at Sioux City.

This report addresses the underlying causes for the recent proliferation of high runoffs events. The recent period of high runoffs is placed into a historical context of meteorological change over the UMRB. We specifically examine the hydrological response of the upper basin runoff to meteorological forcing since 1950. Physical processes operating in the UMRB that may have caused the escalation in flooding events during recent decades is diagnosed. The questions probed in this report center on clarifying what has occurred in the UMRB, from a perspective of meteorological forcing and hydrologic response relationships, to explain the trend toward high annual runoff. The assessment will be guided by land surface model simulations that depict the interplay of UMRB dynamics and meteorological forcing, evaluating conditions conducive for extreme runoff production.

3. METHODOLOGY

A. OBSERVATIONAL DATA AND ANALYSIS

We utilize 198 meteorological stations to describe observed precipitation variability in the UMRB during 1901-2014 as based on the Global Historical Climatology Network-Daily (GHCN-D) archives (Menne et al., 2012). We require that a given station have at least 100 years of non-missing daily observations during 1901-2014. Trends in precipitation are calculated at the station level by computing the simple difference in averages (1975-2014) minus (1901-1974). The recent 40-yr period captures the epoch of increased frequency of high runoff. We also utilize the monthly gridded PRISM analyses, available from 1901-2014 at 4 km resolution (Daly et al. 1994).

B. LAND SURFACE MODEL AND EXPERIMENTS

The land surface model used in this study is the Variable Infiltration Capacity (VIC) model (Liang et al., 1994). VIC is a physically-based, fully distributed, water and energy balance model. As described by Shukla et al. (2014) and Gao et al. (2010), the VIC model has been widely used at the regional and global scale and has been demonstrated to accurately capture the hydrology of different regimes (Nijssen et al., 2001; Maurer et al., 2002). Full details of the VIC model implementation can be found in Appendix A.1.

4. OBSERVED HYDROCLIMATE CHANGES OVER THE UPPER MISSOURI RIVER BASIN SINCE 1901

A. HISTORICAL RUNOFF AND PRECIPITATION

The time series of water-year (1 October-30 September) UMRB runoff above Sioux City, Iowa is characterized by an increase in the magnitude of high runoff years in recent decades (Figure 1, top). Ten of the thirteen highest runoff years have occurred after 1970. The three highest runoff years during 2011, 1997, and 1978 far exceed the next highest ranked years in the record, with totals of 60.7, 49.0, and 40.1 million-acre-feet (maf) respectively (61.0, 49.0, 40.6 are their respective calendar year totals). These record-setting values compare to a climatological average water-year runoff of 25.3*maf*, and a standard deviation of 7.9*maf*. Owing to the recent proliferation of high runoff years, the year-to-year variability has nearly doubled in the recent 20-year period compared to the early and mid 20th century.

The time series of water-year precipitation falling in the UMRB is also characterized by a wetter era in recent decades (Figure 1, bottom). For the historical period as a whole, the climatological average water-year precipitation falling over the entire catchment of the UMRB is 437*mm* (17.2"), with a standard deviation of 60.6 *mm* (2.39"). Eight of the ten wettest years have occurred after 1970. However, the ranking of wettest years does not align exactly with the ranking of highest runoff years. This suggests the role of upper basin dynamics in mediating the atmospheric forcing, including sensitivity to seasonal and spatial patterns of rainfall, the sequencing of wet and dry years, and runoff sensitivity to rainfall-event intensity, to mention a few possible factors.

The UMRB is characterized by a low runoff coefficient (only ~8% compared to other basins east of the Mississippi exceeding 50%), a common attribute of large basins that highlights the role of dynamics including effects of elevation, slope, vegetation, and soil types which all have a bearing on infiltration and runoff. The climatological average water-year precipitation falling over the entire catchment of the UMRB equates to a maximum potential runoff yield of 301*maf*. Given that the actual annual runoff is only 25.3*maf*, the runoff coefficient is 8.4%. This low efficiency is likely also related to unique features of the seasonal cycle of precipitation in the UMRB (see Figure 2 and 3), with the majority of moisture delivered in late spring/summer at a time of high atmospheric evaporative demand. The exception is over the western portion of the UMRB where the mountain snowmelt dominated runoff is more efficient in generating runoff than are the more widespread prairie rains of late spring and summer. In that sense, it is plausible that seasonality of changes in precipitation would be important for understanding UMRB runoff change, and also for understanding the changed likelihood in extreme runoff events. Subsequent analysis will therefore examine such seasonal structures of climate trends and their hydrologic consequences.

Even small changes in the efficiency by which precipitation is converted to runoff could significantly alter UMRB runoff and the likelihood of extreme events. For instance, increases in temperature and the implied heightened evaporative demand could reduce UMRB runoff production. Hoerling et al. (2013) had found a -0.5 correlation between decadal variations in UMRB runoff and average temperatures, and to the extent that such temperature regimes are not strongly linked to rainfall regimes, then temperature could act as an independent mediator for the conversion of rainfall to runoff. The correlation results imply that warm epochs would yield less runoff than cold epochs, assuming identical rainfall statistics, as a symptom of reduced runoff efficiency. Subsequent analysis will argue that the modest warming which has occurred across the UMRB over recent decades may have already acted to reduce runoff efficiency slightly, and an assessment of climate projections will suggest a more substantial impact of a much warmer future climate on UMRB runoff efficiency (see Section 6). So while the increase in precipitation can be directly linked to an increase in runoff, the same cannot be said for temperature. The increase in temperature across the UMRB reduces the runoff efficiency, producing less runoff from the same amount of precipitation.

Despite the low runoff coefficient, year-to-year variations in rainfall are critical drivers of the year-to-year variations in UMRB runoff, including the occurrences of extreme runoff years. This is established from hydrologic model simulations discussed in following sections. It is also implied by results of empirical analysis of the elasticity of runoff to rainfall variability on interannual time scales, which suggests an acute sensitivity to precipitation in the UMRB. The rainfall elasticity of UMRB runoff is the ratio of the change in mean annual runoff to the proportional change in mean annual precipitation. For runoff, the coefficient of variability is 31% (7.9*maf*/25.3*maf*). For annual rainfall, the coefficient of variability is 14% (60.6*mm*/437*mm;* 2.39″/17.2″). The elasticity is therefore about 2, i.e. the rate of change in runoff for a unit rate of change in precipitation. Implying an amplified response of UMRB runoff whereby an incremental change in rainfall would result in a two-fold increase in runoff.

B. ANNUAL AND SEASONAL CHANGES IN CLIMATE

Notable changes in precipitation and temperature have occurred in the UMRB during recent decades. To appreciate the magnitude of these, we begin by summarizing the climatology defined as the long-term average of the historical record since 1895. Figure 3 shows the climatological precipitation over the entire upper basin for overlapping 3-month seasons. The wet season is spring/summer for most of the UMRB, except over the high elevation west that largely accumulates as mountain snowpack, which

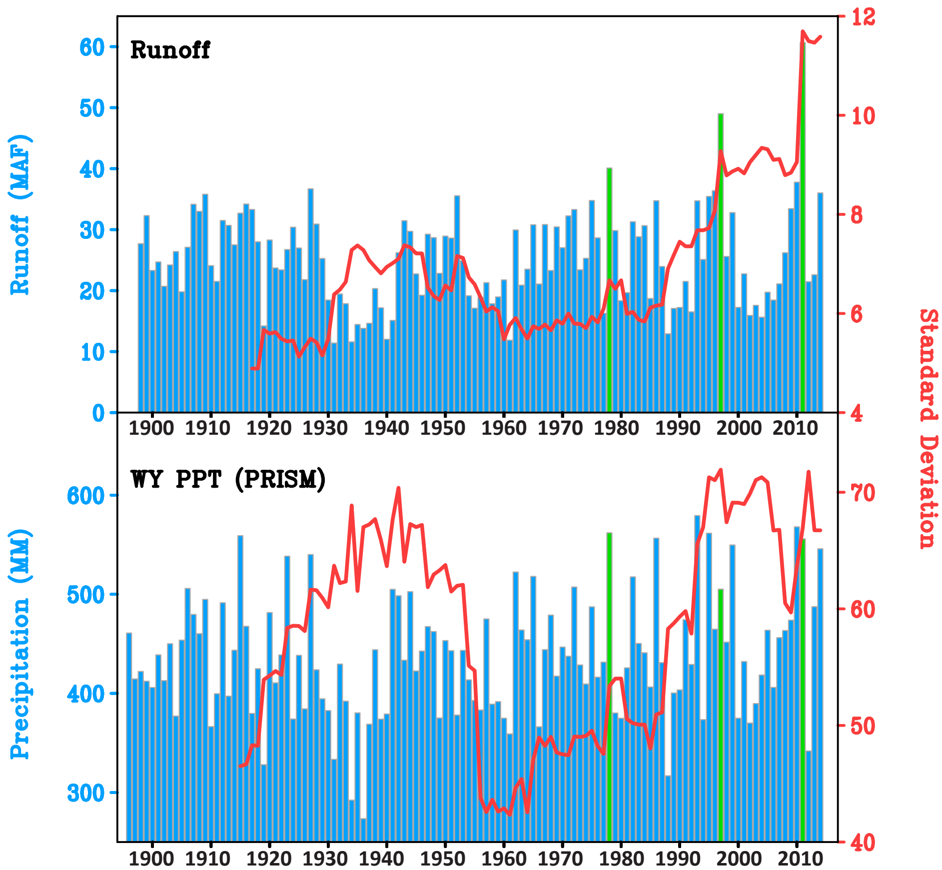


Figure 1. Upper Missouri River Basin Runoff and Precipitation

Time series of water-year (1 October-30 September) Missouri River runoff (million acre-feet) above Sioux City, Iowa for 1898-2014 (top), and water-year precipitation average for the upper basin above Sioux City (mm; bottom). Green bars highlight the 3 highest runoff years in the record. A measure of the year-to-year volatility is shown in the red curves that plot standard deviation of water-year values for 20-yr moving windows. Streamflow at Sioux City from USACE; precipitation is PRISM.

has a late winter/early spring precipitation peak (see Figure 2). Precipitation totals during the May-July season, the wettest 90-day period of the year, are between 150*mm* – 250*mm* (5.9" – 9.8"). That compares to mostly less than 50*mm* (~2") falling during the December-February season, the driest 90-day period of the annual cycle, excepting the Rocky Mountain headwaters region where over 250*mm* (9.8") falls. Further analysis of the annual cycle appears in Hoerling et al. 2013.

We calculate the observed changes in climate as differences between the recent 40-yr period (1975-2014) relative to the prior 80-yr period (1895-1974). Figure 4 shows that precipitation has increased during most seasons, with the largest increases (as % of climatology) occurring during fall (OND) and spring (MAM). The magnitude of the greatest increases has been 20% - 30% of the 1895-1974 climatological means.

Precipitation has generally declined during the normally dry winter (DJF) while relatively little change has occurred during the normally wet summer (JJA). The spatial pattern of rainfall trends shows the largest percentile increases occurring over eastern portions of the upper basin in autumn (SON), and over northwestern portions of the UMRB in spring (MAM).

Figures 5 through 7 show observed changes in maximum, minimum, and daily averaged surface air temperature, respectively. Warming has prevailed in the upper basin during all seasons. The greatest temperature changes have occurred in the northern-most reaches of the UMRB, and the strongest warming rates have occurred during winter. The increases have been somewhat larger for minimum compared to maximum temperatures, with more than 2°C warming (1975-2014 compared to 1895-1974) over Montana and the Dakotas in winter.

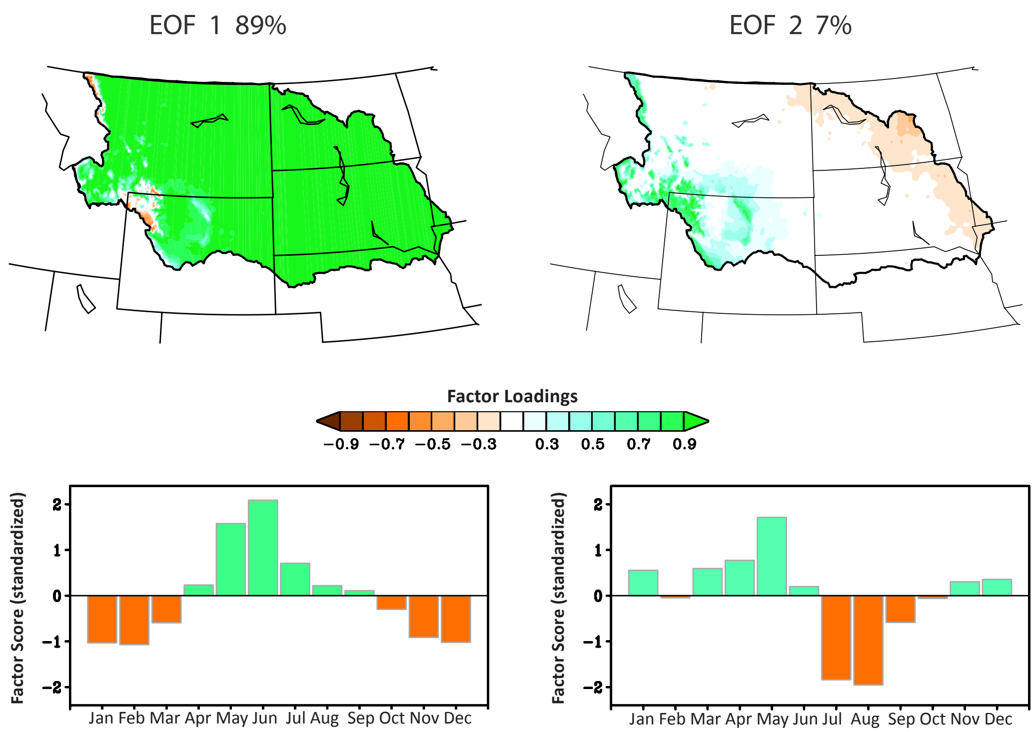


Figure 2. Upper Basin Climatological Precipitation

The statistical pattern of observed monthly climatological precipitation using the method of Empirical Orthogonal Function (EOF) analysis. The spatial plot shows the leading pattern (89% of variance of the seasonal cycle; left) and the second dominant pattern (7% of the seasonal cycle; right) of the climatological UMRB precipitation. The time series of these empirical patterns are shown in the lower panels. These reveal the monthly dependence of precipitation delivery into the upper basin being strongest in May-July for most of the basin, and in the cold season for the Rockies. Data source is PRISM.

Figure 3. Upper Basin Seasonal Precipitation

The observed climatological seasonal cycle of precipitation 1895-2012 (mm). Precipitation data source is PRISM.

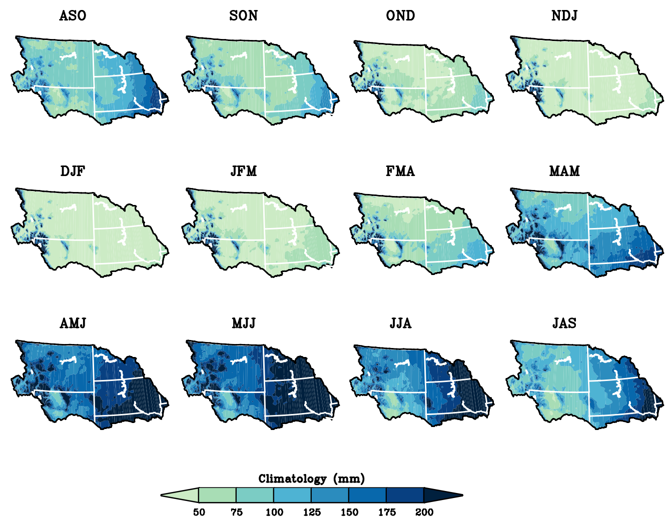


Figure 4. Upper Basin Change in Seasonal Precipitation

The observed change in seasonal precipitation (% of climatology) calculated as the difference (1975-2014) minus (1895-1974). Precipitation data source is PRISM.

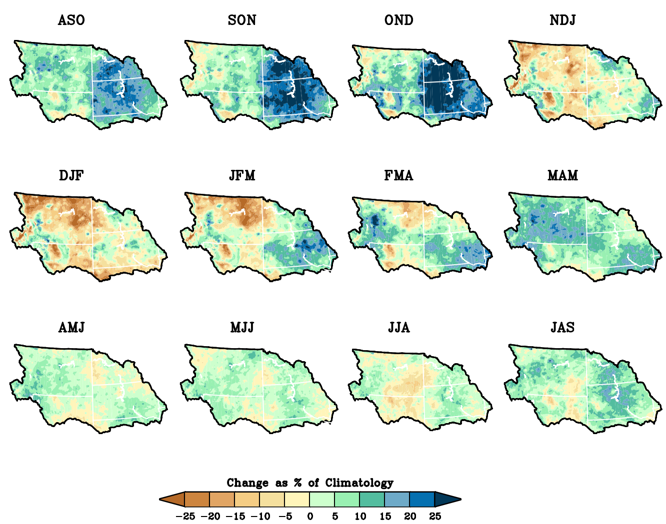
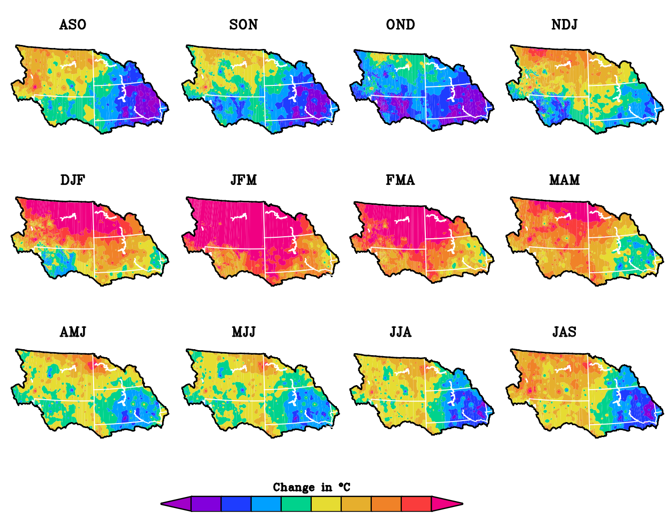


Figure 5. Upper Basin Change in Seasonal Maximum Temperature

The observed change in seasonal TMAX (°C) calculated as the difference (1975-2014) minus (1895-1974). Temperature data source is PRISM.



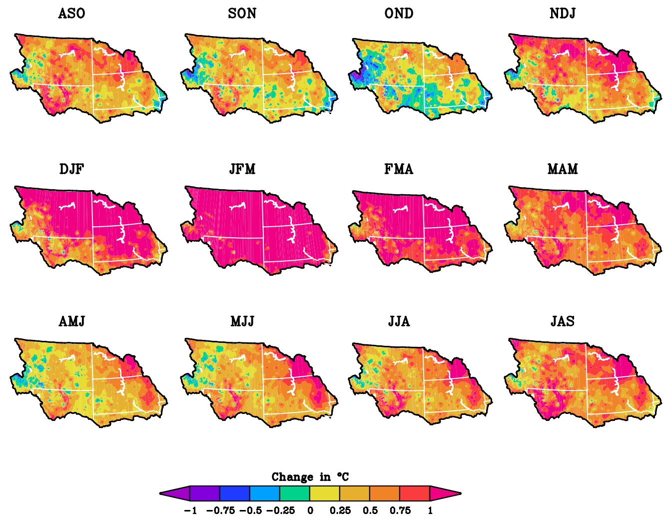


Figure 6. Upper Basin Change in Minimum Temperature

The observed change in seasonal TMIN (°C) calculated as the difference (1975-2014) minus (1895-1974). Temperature data source is PRISM.

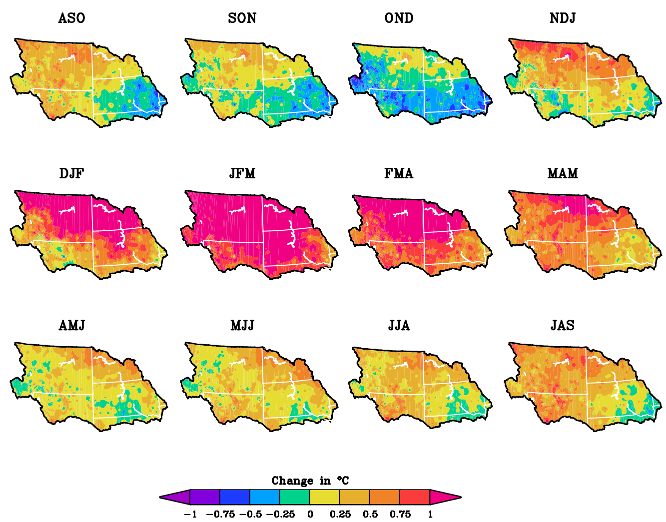


Figure 7. Upper Basin Change in Seasonal Average Temperature

The observed change in seasonal TAVG (°C) calculated as the difference (1975-2014) minus (1895-1974). Temperature data source is PRISM.

Water-year climate over the UMRB has thus become warmer and wetter (Figure 8). Such directionality of the water-year averages has prevailed in most sub-basins of the UMRB as well. The area-averaged annual precipitation over the upper basin has increased +6% for the recent 40-yr mean compared to the prior 80-yr mean, while average temperature has risen about 0.5°C during the recent 40 years. We note that water-year runoff from the upper basin, as measured by the runoff at Sioux City, has increased about 9% over this same period. Given an elasticity of ~2, the water-year precipitation increase alone would have implied a runoff increase of 12%. The smaller observed increase may reflect a reduction in runoff efficiency that could have resulted from increased evaporative demand associated with UMRB warming during this period. A competition between runoff response to wetting versus warming will be discussed in a later section when addressing projected future runoff over the UMRB.

C. PRECIPITATION ANOMALY PATTERNS DURING RECENT HIGH RUNOFF YEARS

Figures 9-11 compare the seasonal cycle of precipitation anomalies for the three highest runoff years during 2011, 1997, and 1978, respectively. There are several common features among these extreme runoff years. All were characterized by unusually wet late summer, fall, and winter conditions at the onset of each water year. In all 3 cases, wet conditions in the fall were focused on the eastern prairies of the upper basin, generally encompassing the Dakotas. The location of winter wet conditions exhibits greater spatial variability among these cases, with western portions being wettest in 1978, but eastern portions being wettest in 1997 and 2011.

The spring and summer rainfall patterns are notably different among these three high runoff years. Spring was not particularly wet in the upper basin in 1997, in marked contrast to both 2011 and 1978 which experienced very wet spring and early summer seasons. In the latter cases, wetness was centered over Montana and northern Wyoming which corresponded to those sub-basin's climatological wet seasons. In 1997, summer was wet only over the far western portions of the upper basin where the total precipitation is a climatological minimum and thus not a major contributor to UMRB runoff. In 2011, late summer conditions were not particularly wet, whereas 1978 witnessed continued very heavy late summer rains over Montana.

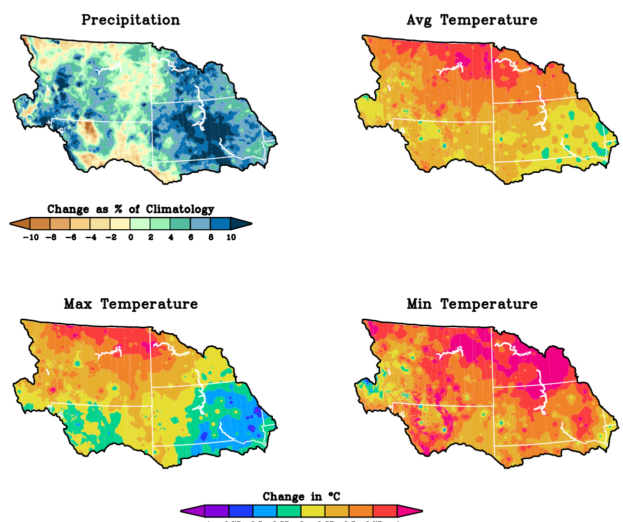


Figure 8. Upper Basin Water Year Precipitation Change

The observed change in annual (water-year) precipitation (% of climatology, top left), TAVG (°C, top right), TMAX (°C, bottom left), and TMIN (°C, bottom right). Changes calculated as the difference (1975-2014) minus (1895-1974). Data source is PRISM.

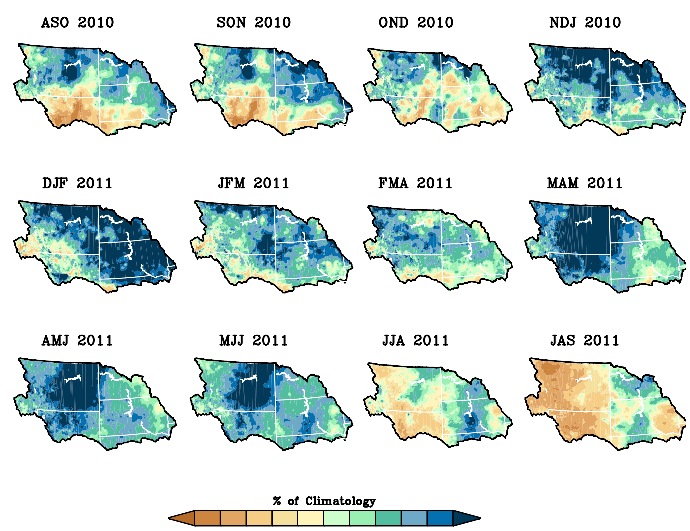


Figure 9. Upper Basin Seasonal Precipitation Anomalies (2010-11)

The observed seasonal precipitation anomalies (% of climatology) during the record high flow year 2010-11. Precipitation data source is PRISM.

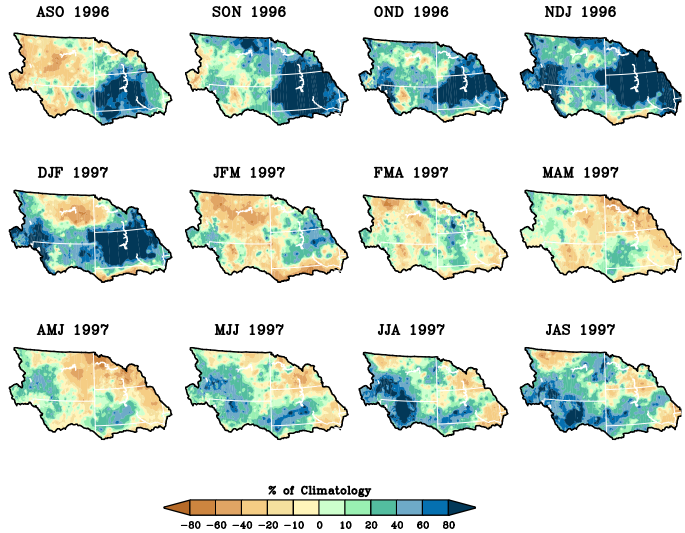


Figure 10. Upper Basin Seasonal Precipitation Anomalies (1996-97)

The observed seasonal precipitation anomalies (% of climatology) during the second highest flow year 1996-97. Precipitation data source is PRISM.

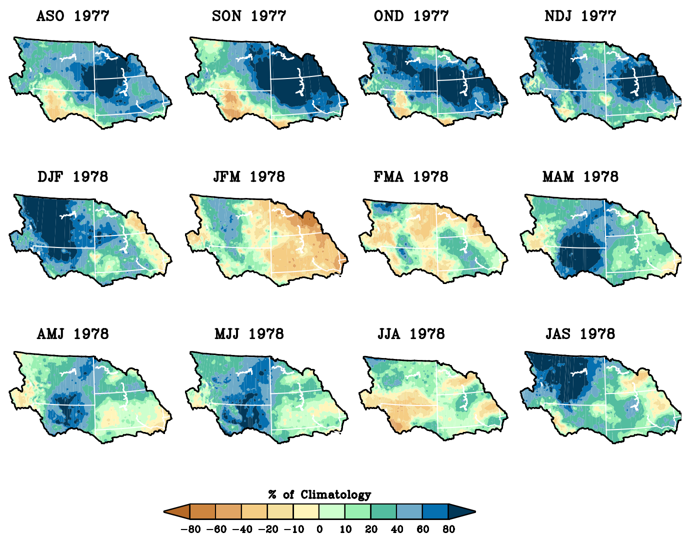


Figure 11. Upper Basin Seasonal Precipitation Anomalies (1977-78)

The observed seasonal precipitation anomalies (% of climatology) during the third highest flow year 1977-78. Precipitation data source is PRISM.

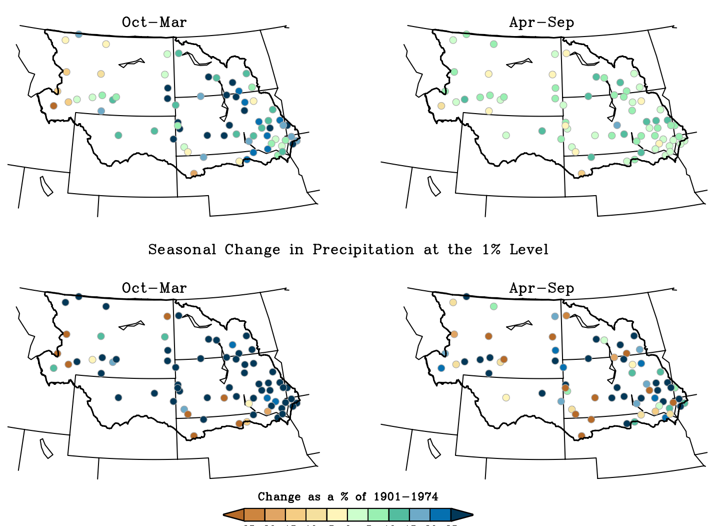


Figure 12. Seasonal Changes in Precipitation

Changes in seasonal mean precipitation (top) and in precipitation falling in extreme daily events(bottom). Cold season (left) and warm season (right). Changes based on differences between 1975-2014 versus 1901-1974, expressed as a percentage relative to 1901-74. Circles denote station location.

It is not surprising that the ranked highest three runoff years each experienced above normal precipitation in the UMRB. However, these flood cases were not the three highest ranked with respect to moisture delivery. For example, the record 2011 runoff year didn't even rank among the top 5 wettest years in the data set used herein (see Figure 1, bottom). This fact indicates that the manner in which precipitation is delivered throughout the seasonal cycle, and the geographical pattern of the precipitation anomalies, are important factors for the hydrologic response. It may be especially important for heightened flood probabilities to receive high precipitation during the cold season, owing to the higher runoff efficiency, as contrasted with the warm season when potential evapotranspiration exceeds precipitation. Further, it also suggests that antecedent soil moisture conditions could be an additional factor for materially affecting the volume of runoff that can be realized for a particular precipitation pattern. A suite of land surface model sensitivity experiments is subsequently diagnosed in order to clarify the relative role of land surface initial conditions versus meteorological forcing for runoff production in the upper basin.

D. EXTREME DAILY PRECIPITATION CHANGES

Runoff generation during rainy days is sensitive to the magnitude of precipitation intensity relative to infiltration rate. More intense rain events are likely to produce greater runoff, to the extent that heavier rains exceed the infiltration capacity of a land surface. This can be viewed as a threshold process. Here we examine the observed change in characteristics of very heavy daily rainfall over the UMRB. The diagnosis is performed at meteorological stations for sites having nearly serially complete records of daily precipitation spanning 1901-2014. For the Missouri Basin as a whole, there are approximately 200 qualifying stations. Further, we aggregate data for a 6-month cold season (October – March) and a 6-month warm season (April – September), corresponding to climatologically dry and wet seasons of the basin, respectively.

Figure 12 (top, left) shows the overall change in cold season precipitation, plotted at each station location. The results are consistent with the prior diagnosis of change using gridded PRISM data (see Figure 4), and reveal a cold season wetting that is most pronounced over the eastern sections of the upper basin with select stations indicating 20-25% increases. Changes in warm season precipitation (Figure 12, top right) are also mostly toward wetter conditions, though with fractional increases that are weaker and mostly less than 10%.

The lower panels show the change in seasonal precipitation falling in very heavy daily events. These are defined at each station according to the magnitude of daily precipitation and are characterized as "very heavy" when their daily totals exceed the 99th percentile of all daily rainfall events. The 99th percentile threshold value was calculated for the 1901-1974 period and Figure 12 shows the change in precipitation amount falling in very heavy events in the recent decades compared to the amount falling during 1901-74. Similar results are found when using a 95th percentile threshold value (not shown) that is used later in the hydrologic analysis. Not surprisingly, the change for rainfall occurring in very heavy storms mimics the overall seasonal precipitation change pattern. It is also apparent, however, that a greater percentage change in the extreme daily totals occurs compared to the percentage change in overall seasonal totals. Indicated hereby is that very heavy storms are contributing more to the seasonal precipitation in recent decades. This is generally true for both cold and warm seasons, though the spatial extent of this signature over the upper basin is greater during the cold season. We will subsequently examine the hydrologic consequences of such observed changes in the character of daily rainfall using the land surface model. Other characteristics of daily precipitation were not assessed in this report, such as changes in sequencing of rainy days and consecutive dry days.

5. LAND SURFACE MODEL SIMULATIONS FORCED WITH OBSERVED HISTORICAL METEOROLOGY: 1950-2013

The Variable Infiltration Capacity (VIC) model (Liang et al.,1994) was selected for this analysis. It is a fully-distributed physically-based hydrologic land surface model that solves the water and energy balances. It has been successfully applied to a range of continental-scale analysis and was selected to simulate UMRB hydrology at a daily time-step and a 1/16-degree horizontal resolution. The model accounts for sub-grid variability of land cover (e.g. vegetation), soil properties, and snow variability. VIC was run in offline mode, such that that atmospheric conditions are specified; in this simulation, the observed meteorological dataset of Livneh et al. (2015) was used, which is at commensurate spatial and temporal resolution as the model. Model outputs are aggregated to a monthly interval for comparison with USACE naturalized-runoff that facilitate model calibration as described in the next section.

A. SIMULATED HYDROLOGY OVER THE UPPER MISSOURI RIVER BASIN

Accurate representation of the UMRB (Figure 13) required parameter estimation for the VIC model, i.e. calibration, in which soil depths, infiltration, base flow velocity and snow roughness were examined. A set of calibration experiments were conducted in which parameter values were modified within a realistic range, with a total of 66 simulations conducted. The UMRB domain is resolved by 24,369 grid cells.

The VIC historical simulations, driven by the observed meteorological drivers, yield statistics of UMRB runoff that has strong agreement with naturalized runoff. The 64-year monthly hydrograph shown in (Figure 14) compares naturalized runoff above Sioux City, IA to that produced by the calibrated VIC model. The model demonstrates excellent performance overall, capturing seasonal timing of peak runoff although with

Figure 13. Upper Basin Mainstem System Reservoir Reaches

Upper Missouri River Basin modeling domain used in VIC, with each sub-basin highlighted.

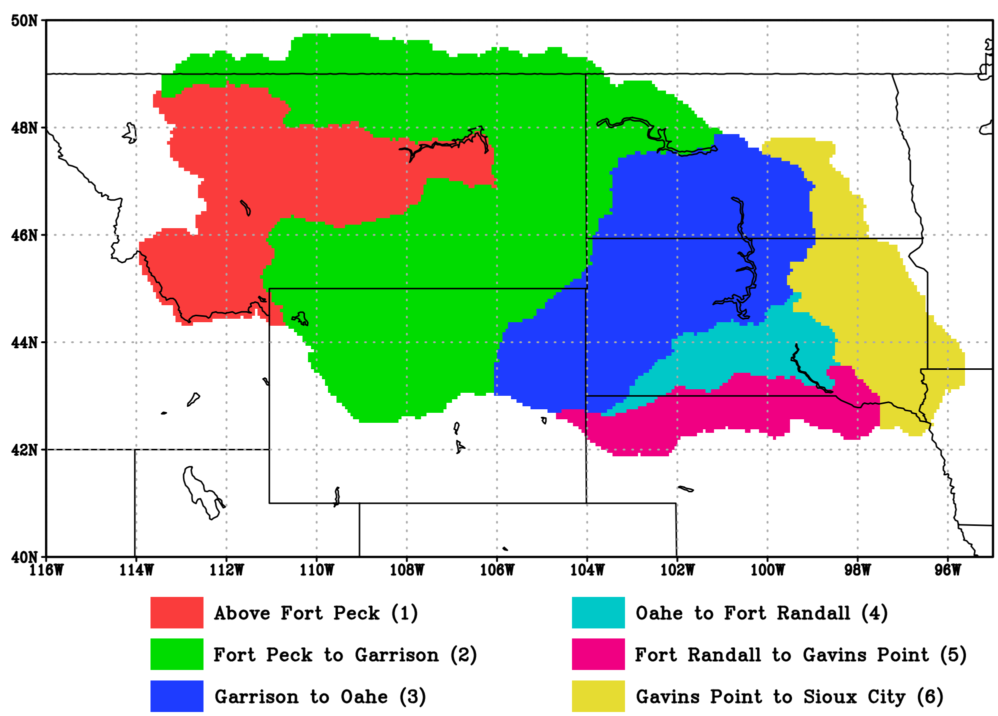


Figure 14. Hydrograph Observations and VIC Simulations (1950-2013)

64-year monthly hydrograph from 1950-2013 for the observations (black) and VIC (red), units of flow are maf.

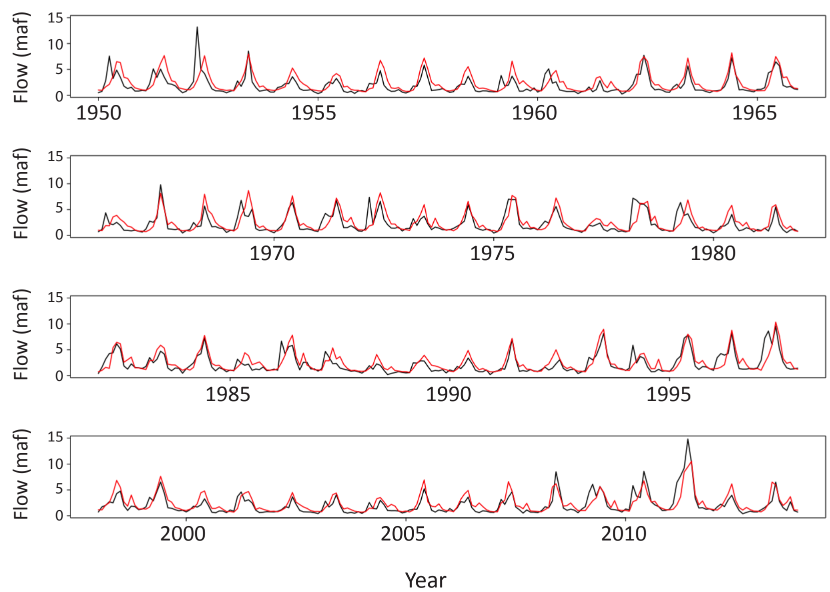
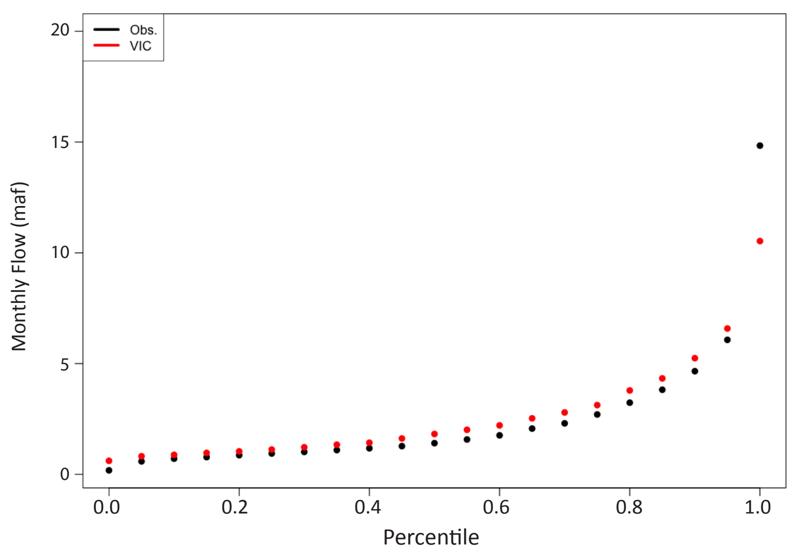


Figure 15. Monthly Flow Observations

Dots denote monthly flow distribution for every 5th percentile for observations (black) and VIC (red), units are maf.

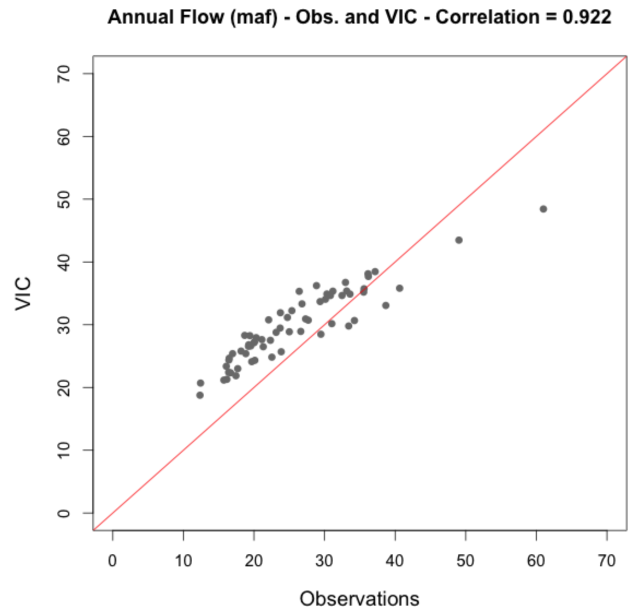


magnitudes of large events slightly underestimated. Numerous hydrologic modeling challenges have been well-documented over this region suggesting that the model performance obtained here is to be considered consistent with a class of comparable models. The monthly naturalized runoff is compared with VIC in Figure 15, wherein VIC tracks the naturalized runoff very closely up to the 95th percentile, beyond which VIC underestimates the intensity of runoff for the upper 5th percentile. For annual runoff totals, averaged over the upper basin (top-panel (Figure 16) VIC simulates runoff volumes realistically, though tending to over predict low runoff years and under predict high runoff years. The interannual variability of simulated runoffs is quite realistic as demonstrated by a 0.9 correlation between naturalized annual total runoff and VIC annual total runoff. However, the underestimation of peak runoff volume for both large years, 1997 and 2011, is important to note, suggesting VIC has a bias towards underestimating the magnitude of large events.

VIC runoff statistics are in excellent agreement with naturalized flow for monthly variations. The ratio of model-to-observed monthly standard deviation is 0.99. The temporal correlation between monthly naturalized total runoff and monthly VIC total runoff is 0.81. Additionally, when analyzing VIC's capability to capture the naturalized extreme high runoff annual events (years 1975, 1978, 1986, 1993, 1995, 1996, 1997, 2010 and 2011), seven of the nine extreme naturalized runoff years were represented in VIC as an extreme runoff year, meaning they too were ranked in VIC's top nine runoff years.

B. SIMULATED HYDROLOGY FOR UPPER MISSOURI SUB-BASINS

To further test the realism of the VIC representation of UMRB hydrology, and as a prelude to using the model for diagnostic runoff sensitivity experiments, we examine the spatial variability of runoff production among the six major sub-basins (Figure 17). Disaggregating runoff among these sub-basins reveals that the two largest contributions to total upper basin runoff are from the reach above Fort Peck (28.8% annual contribution to total upper basin runoff) and from between Fort Peck to Garrison (39.2%). The former is located in the headwaters regions of the Missouri River whose runoff is primarily driven by high mountain snowmelt. The latter is the largest sub-basin by area and thus contributes the majority of runoff, while also draining the montane region of the Wyoming Rockies. VIC generates realistic seasonal cycles of runoff in these two sub-basins, both in terms of runoff magnitude and timing of the hydrograph peak. The four remaining sub-basins, Gavins Point to Sioux City (10.7%), Oahe to Fort Randall (3.9%), Fort Randall to Gavins Point (7.9%), and Garrison to Oahe (9.5%), all contribute lesser runoff volume (note the differing vertical axes among the panels) and all achieve monthly peak earlier in the seasonal cycle. This latter feature of the hydrographs over the plains driven is likely a consequence of early spring melt of continental snowpacks, which are generally less-well modeled by VIC (see Table 1).



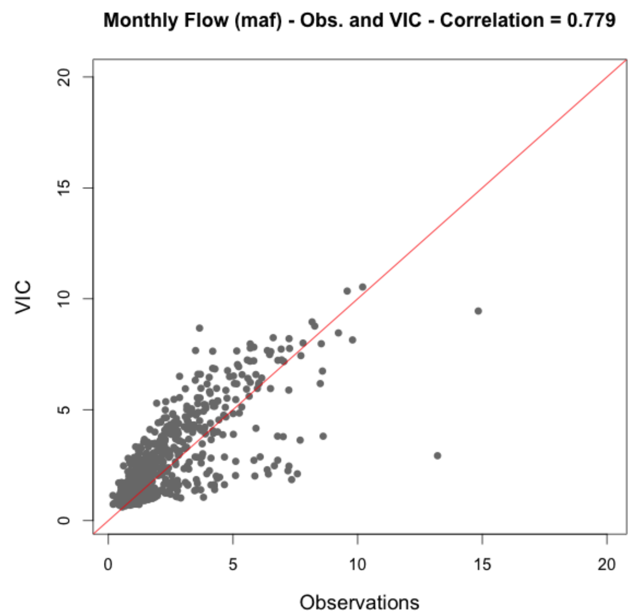


Figure 16. Annual and Monthly Flow Totals

Observed vs. VIC annual flow totals (top) and monthly flow totals (bottom), units are maf. Red-line denotes a perfect match.

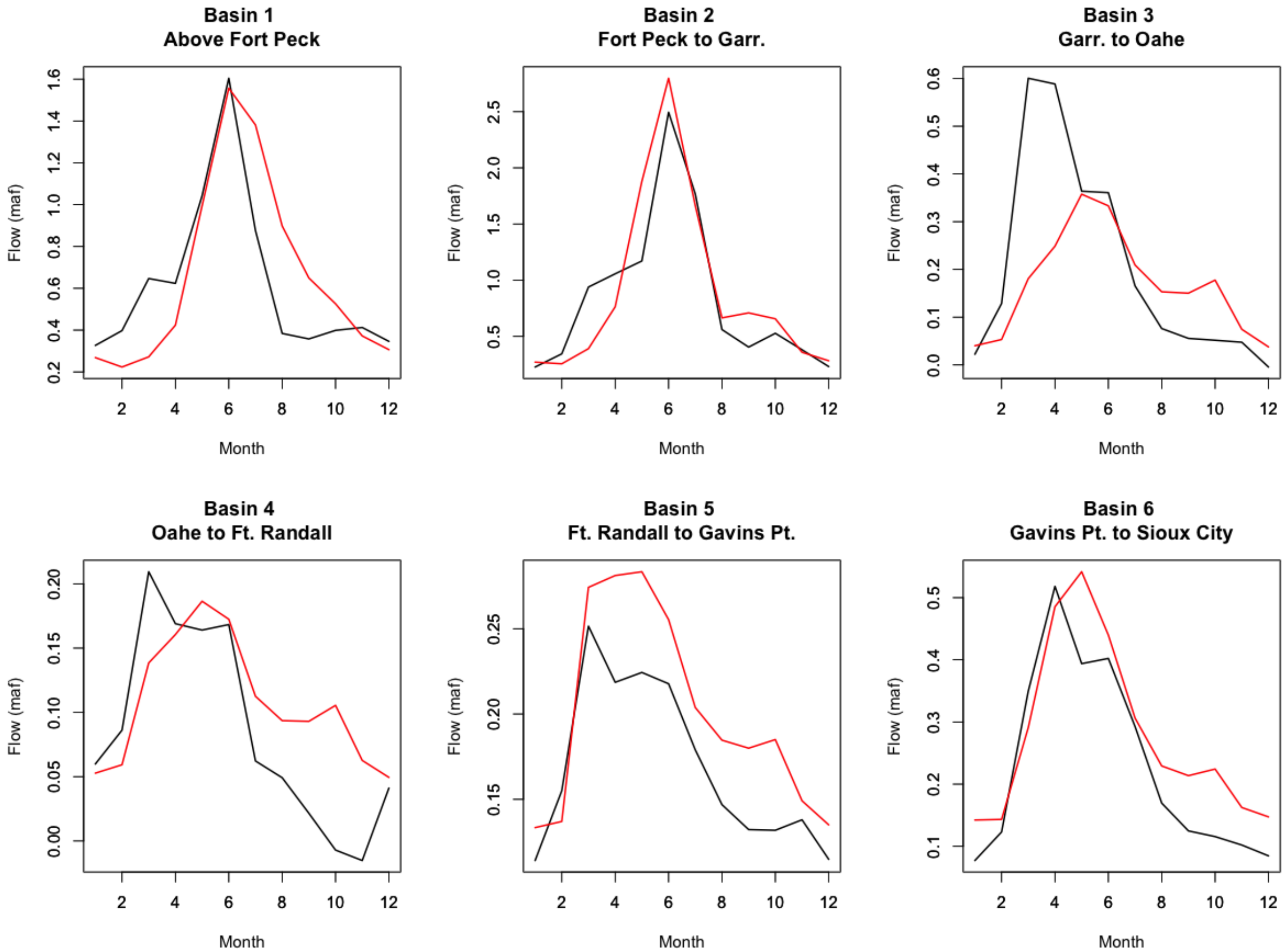


Figure 17. Annual Flow Cycle

Observed (black) and VIC (red) annual cycle of flow for each sub-basin, units are maf.

Table 1: Correlation Between Naturalized Runoff and VIC for Each Sub-Basin

Reach	Correlation
Above Fort Peck	0.71
Fort Peck to Garrison	0.81
Gavins Point to Sioux City	0.84
Oahe to Fort Randall	0.62
Fort Randall to Gavins Point	0.69
Garrison to Oahe	0.52

6. FACTORS DRIVING EXTREME ANNUAL RUNOFF IN THE UPPER MISSOURI RIVER BASIN

In the prior assessment of UMRB flooding during 2011 (Hoerling et al. 2013), an empirical framework was used in order to statistically link meteorological conditions and runoff production in the upper basin. Here we use VIC simulations to quantify runoff sensitivity in a *physical framework*. Guided by the evidence of common meteorological features among extreme annual runoff years of recent decades that included above normal precipitation over the upper basin (see section 4c), we hypothesize (and test) that the increased frequency in annual hydrologic extremes is a direct consequence of high annual precipitation. We test whether the increased frequency in annual hydrologic extremes is a direct consequence of improved runoff efficiency due to wetter initial land surfaces. The latter wetter land surface states have likely prevailed more often post-1975 due to the observed positive precipitation trend over the upper basin (see Figures 4 and 8). To explore the relative importance of these two factors, a suite of ensemble VIC model sensitivity experiments are diagnosed. These are again subjected to realistic observed meteorological driving, but in which the precise temporal sequence of historical land surface and historical meteorological conditions are altered. These experiments are conducted as "counter-factuals" that alter either initial soil moisture or subsequent water-year meteorological forcing for the 2010-11 record runoff year, a case which we treat as archetypical of the proliferation in extreme annual runoff events during recent decades.

In one ensemble of perturbation experiments, water-year meteorological forcing of October 2010-September 2011 is specified, as in the historical (control) run, and 64 parallel VIC simulations are conducted each begun from a different initial soil moisture states. These states are derived from the 1 October soil moisture of each year of the 1950-2013 control experiment. These will be referred to as "antecedent soil moisture (ASM) sensitivity" runs. All are counter-factual in the sense that the true 1 October 2010 initial soil moisture conditions is replaced by each of the other initial conditions from all possible 63 years. In the second ensemble of perturbation experiments, initial 1 October 2010 soil moisture is specified, as derived from the control run, and 64 parallel VIC simulations are conducted each subjected to different specifications of the meteorological forcing from October-September. These meteorological states are derived from the individual observed years, and are identical to those specified in the historical run. Again, all are counter-factual in the sense that the true 2010-11 monthly evolving meteorological forcing is replaced by each of the other water-year evolving forcings from all possible 63 years. These will be referred to as "meteorological forcing (MF) sensitivity" runs. For each ensemble member, we analyze the monthly evolving VIC runoff for each month of the water-year, spatially integrated over the UMRB.

The goal of these experiments is to understand the degree to which an extreme runoff year is determined by the particular initial soils or by the particular evolving meteorology. In other words, was 2011 as extreme as it could be, or were there plausible combinations of other historical land surface-climate conditions that could have generated even greater runoff? Were all the components of runoff - antecedent soil conditions, mountain snow, plains snow, precipitation, temperature all at their respective maximums? Subsequent analysis, to be presented in section 7, will help to further relate these sensitivities to hydrologic consequences of observed historical trends in key meteorological quantities (e.g., temperature changes, warm versus cold-season rainfall changes, and changes in the intensity of extreme daily rainfall events). As a by-product, these experiments also give clues of whether the likelihood of an extreme runoff event could be anticipated at the start of the water year (October 1) based solely on the initial conditions (e.g. antecedent soil moisture), versus how much of the extreme runoff state is dictated by subsequent meteorology (the predictability of which is undoubtedly more limited). To further address the predictability issue, the above suite of experiments was repeated, but for initial states on March 1 (5-months into the water - year), and the monthly evolving VIC runoff for each month of the March 1 to February 28 year is analyzed, and spatially integrated over the UMRB. March 1 is near the start of the major runoff increase during the seasonal cycle, such that these additional ensembles address potential predictability of extreme runoff events had the initial soil conditions on March 1 alone been known, versus had the post-March 1 sequence of meteorological forcing been exactly predicted.

The method by which these experiments was conducted is analogous for both October 1 and March 1 starts. VIC is run using the calibrated model parameters driven by the Livneh et al. (2015) forcing data with model moisture states (i.e. soil and snowpack water storage conditions) saved for the last day of September (initialization for October 1) and the last day of February (initialization for March 1). In this sense, the experiments again utilize realistic observed forcings, and we merely explore the sensitivity to various permutations of observed initial land states and meteorological states that occurred during 1950-2013.

A. RUNOFF SENSITIVITY TO ANTECEDENT SOIL MOISTURE CONDITIONS

Figure 18 presents results of the ASM sensitivity runs. The simulated hydrographs for each of the 64 scenarios are shown on the left, while the cumulative runoff of each is shown on the right. The inset list of years are the 3 highest annual runoff years for the post-1975 period, and plotted with different colors to help identify them within the 64-member plume. Noteworthy in the sensitivity results is that the 2010-11 peak runoff could have been ~10-20% more extreme had the initial soil moisture been higher. We find that nine other initial land surface conditions (1 October of 1951, 1952, 1966, 1973, 1983, 1987, 1994, 1996 and 1998) yielded greater water year runoff in the UMRB runoff than that resulting from the actual 1 October 2010 initial state (the bold green curve in Figure 18). This suggests that flood conditions in 2011 could have conceivably been worse, had the antecedent moisture been higher. For the March 1 initialization (Figure 19), three other initial conditions (1969, 1972 and 1997) provide greater peak runoff than was observed in 2011. It is interesting to note the much greater range of peak runoff magnitudes arising from sensitivity to different 1 March soil states, than from different 1 October soil states. Indeed, as will be shown shortly, knowledge of 1 March soil conditions appears to be of comparable importance to knowledge of the subsequent (post-1 March) meteorological conditions for anticipating the magnitude of peak late spring runoff. By contrast, knowledge of 1 October soil conditions is of much less importance than knowledge of the subsequent (post-1 October) meteorological conditions for anticipating the magnitude of peak late spring runoff.

It is also important to recognize in Figure 18 that each hydrograph, resulting from 2010-11 meteorological forcing, but begun from all possible initial land surface conditions, yields a peak late spring/early summer runoff whose magnitude is at least 30% greater than VIC's climatological runoff averaged over all 64 years (see Figure 24). In other words, the particularly wet meteorological conditions were critical in the generation of very high runoff, regardless of the initial land surface states. There is nonetheless a strong correlation between the initial soil moisture and both the peak runoff and the cumulative annual runoff, as illustrated by the scatter plots of Figures 20 and 21. This confirms that initial soil moisture indeed helps drive the runoff for the following year, as a greater portion of precipitation falling on an anomalously wet soil column becomes runoff and can more readily contribute to large runoff events as demonstrated in these experiments. Overall, these experiments 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.

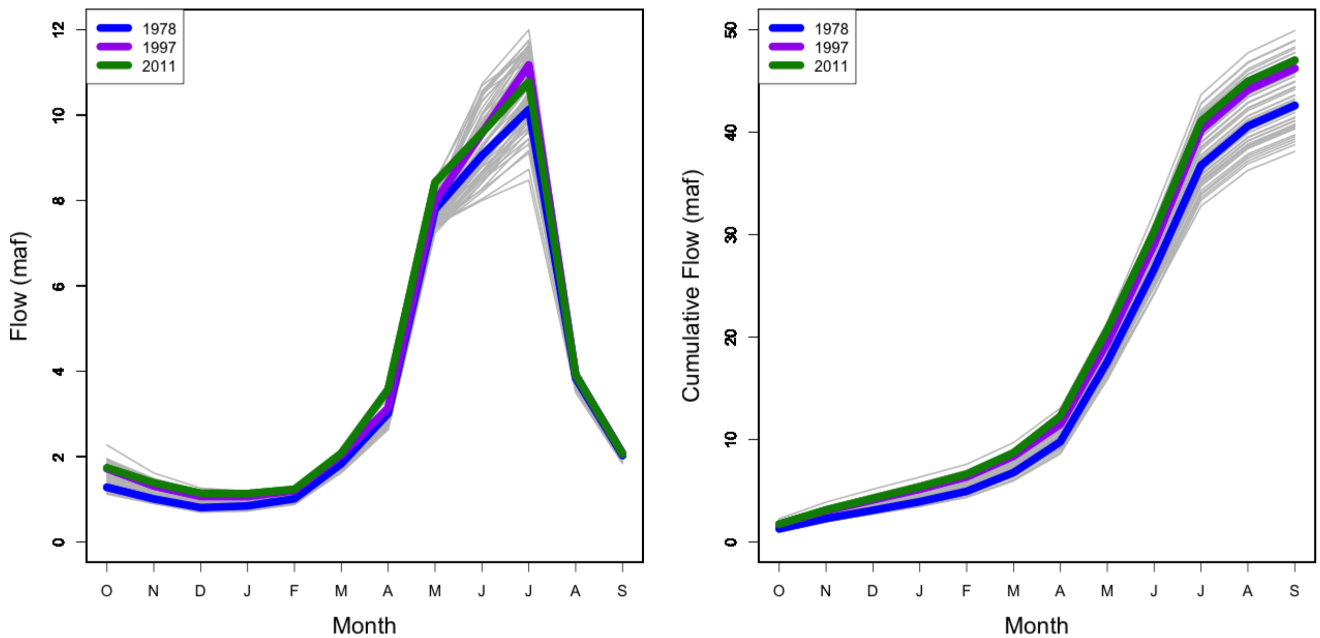


Figure 18. Total Basin Annual Cycle of Flow with 2011 Forcing for all ICs

Annual cycle (left) and cumulative flow totals (right) for ASM experiment starting on October 1, units are maf. Bold and colored lines represent the three highest flow years on record; 1978 (blue), 1997 (purple) and 2011 (green).

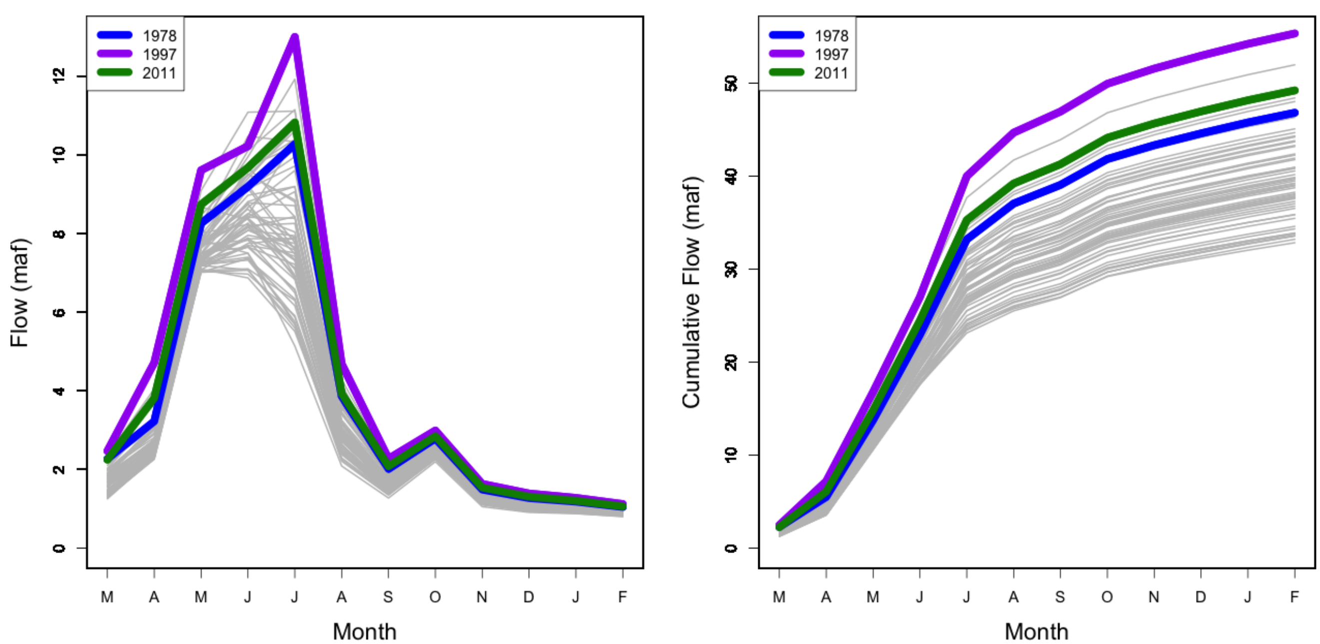


Figure 19. Total Basin Annual Cycle of Flow with 2011 Forcing for all ICs

Annual cycle (left) and cumulative flow totals (right) for ASM experiment starting on March 1, units are maf. Bold and colored lines represent the three highest flow years on record; 1978 (blue), 1997 (purple) and 2011 (green).

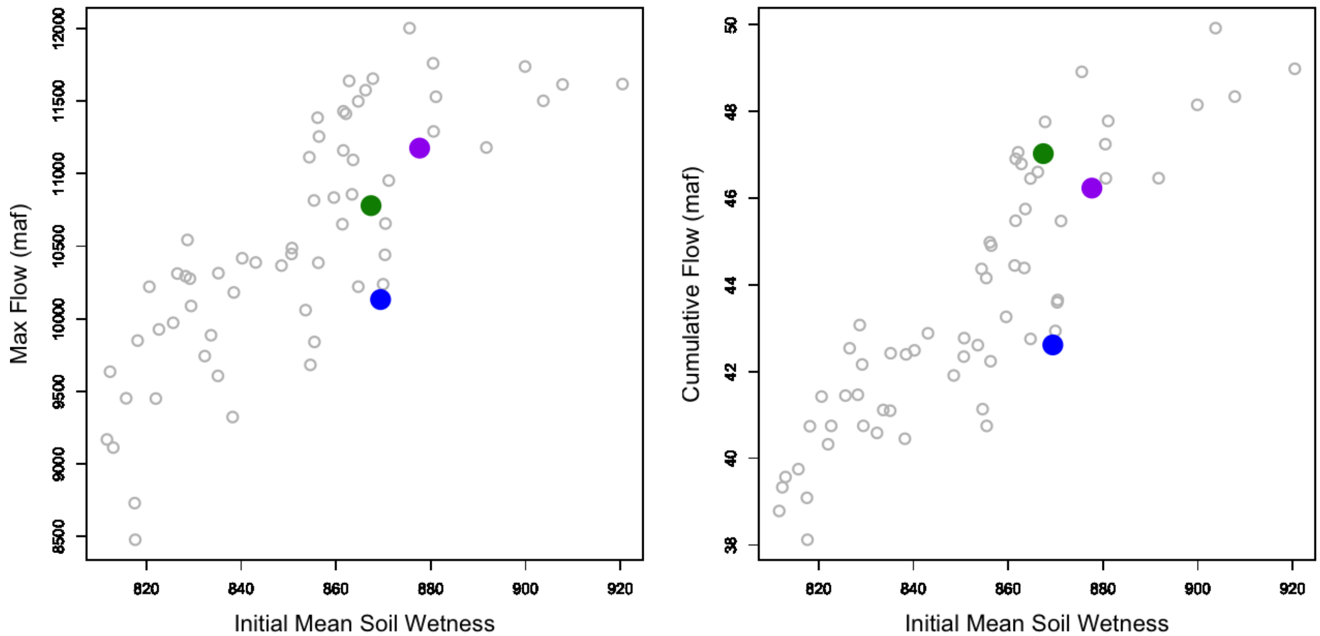


Figure 20. Total Basin Maximum Flow for Each IC

Scatter plots of initial soil wetness vs max flow (left) and cumulative flow (right) for October 1 initialization of ASM experiments. Filled and colored circles represent the three highest flow years on record; 1978 (blue), 1997 (purple) and 2011 (green).

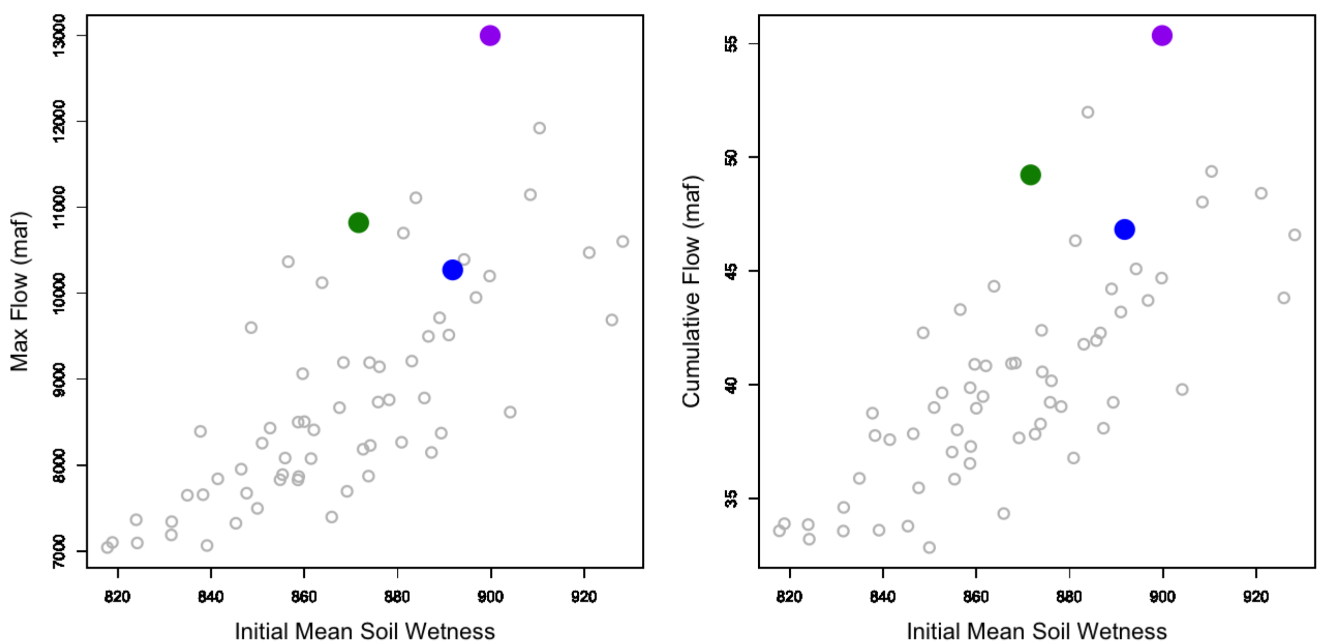


Figure 21. Total Basin Maximum Flow for Each IC

Scatter plots of initial soil wetness vs max flow (left) and cumulative flow (right) for March 1 initialization of ASM experiments. Filled and colored circles represent the three highest flow years on record; 1978 (blue), 1997 (purple) and 2011 (green).

B. RUNOFF SENSITIVITY TO WATER-YEAR METEOROLOGICAL FORCING

Figure 22 presents results of the MF sensitivity runs. The simulated hydrographs for each of the 64 scenarios are shown on the left, while the cumulative runoff of each is shown on the right with the inset again listing the 3 highest annual runoff years for the post-1975 period. It is immediately evident that the particular post-1 October meteorological forcing of 2010-11 yields the most extreme UMRB runoff, both in terms of peak and cumulative values. This occurs despite the fact that the water-year precipitation observed in 2011 was not the highest historical total since 1898 (see Figure 1b). Suggested hereby is that a fortuitous combination of moist initial soil conditions, subsequent wet meteorology, and its spatial-temporal distributions were all likely important for generating these extremes. Also, as will be subsequently established, the spatial pattern of the 2010-11 precipitation anomaly played a critical role in maximizing runoff production because the greatest precipitation departures occurred over the eastern portion of the upper basin have a heightened runoff sensitivity, according to the VIC results. In the context of explaining the proliferation of high runoff years since the 1970s, each of these three attributes describe the overall climate trend patterns over the UMRB.

There is a robust signal that the high precipitation years lead to more extreme peak runoffs and the greatest annual runoff in this set of experiments for both 1 October (Figure 22) and 1 March (Figure 23) initialization dates. This strong relationship is revealed by examining the scatter between the water-year observed precipitation (averaged over the upper basin) versus VIC simulated cumulative and maximum runoff, shown in Figure 24. A very telling difference from the scatter plots relating runoff to initial soil moisture alone, is that the RF experiments show that the high historical runoff water-years are all among the wettest precipitation years. By contrast, the initial soil states alone failed to isolate the high historical runoff years. These results collectively emphasize the leading role of meteorological forcing.

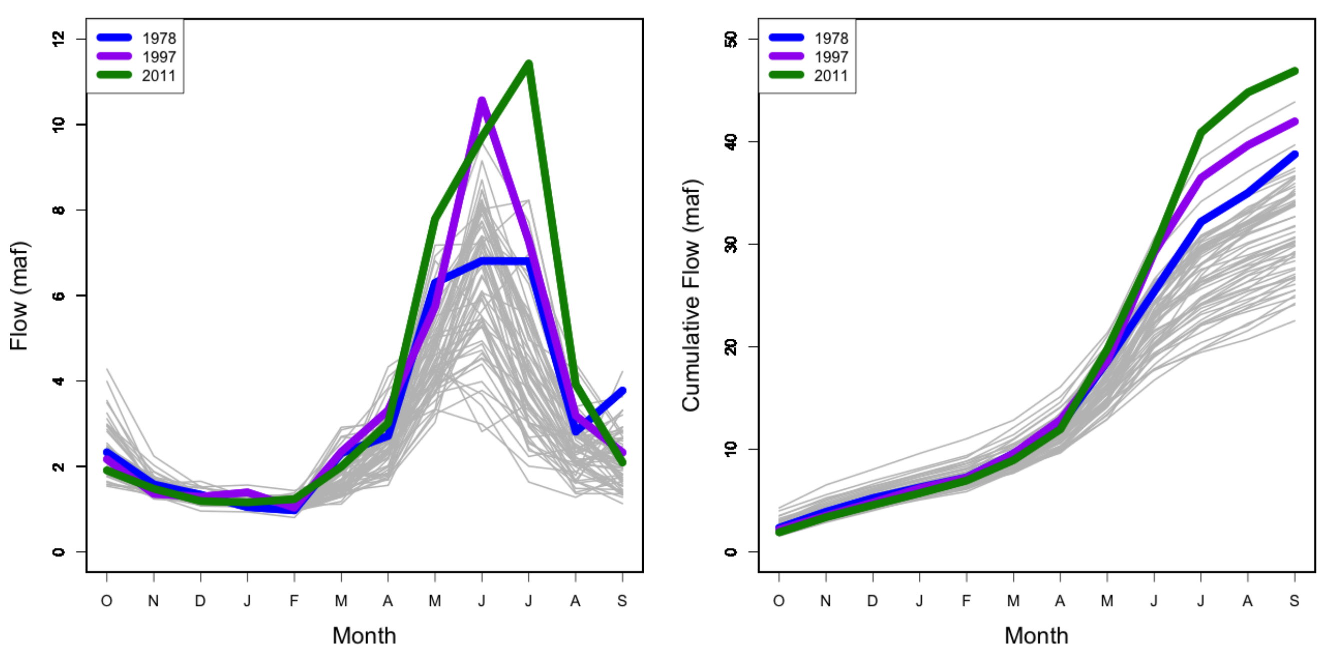


Figure 22. Total Basin Annual Cycle of Flow for All Forcings with 2011 IC

Annual cycle (left) and cumulative flow totals (right) for MF experiment starting on October 1, units are maf. Bold and colored lines represent the three highest flow years on record; 1978 (blue), 1997 (purple) and 2011 (green).

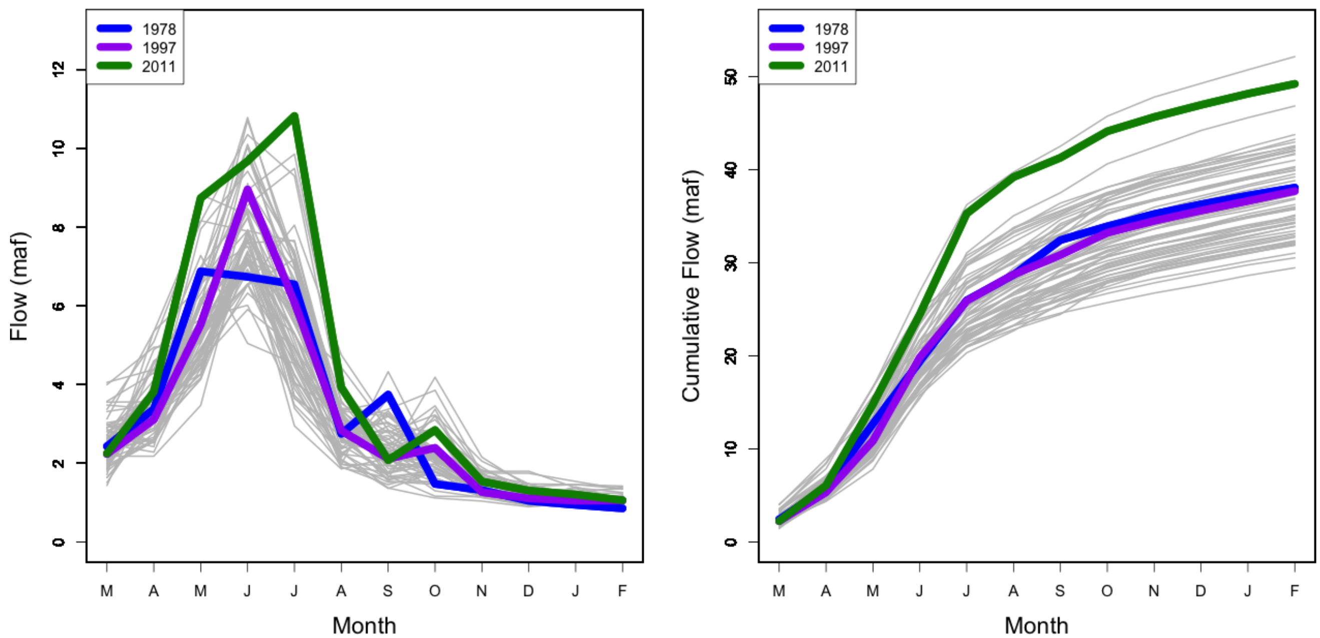


Figure 23. Total Basin Annual Cycle of Flow for All Forcings with 2011 IC

Annual cycle (left) and cumulative flow totals (right) for MF experiment starting on March 1, units are maf. Bold and colored lines represent the three highest flow years on record; 1978 (blue), 1997 (purple) and 2011 (green).

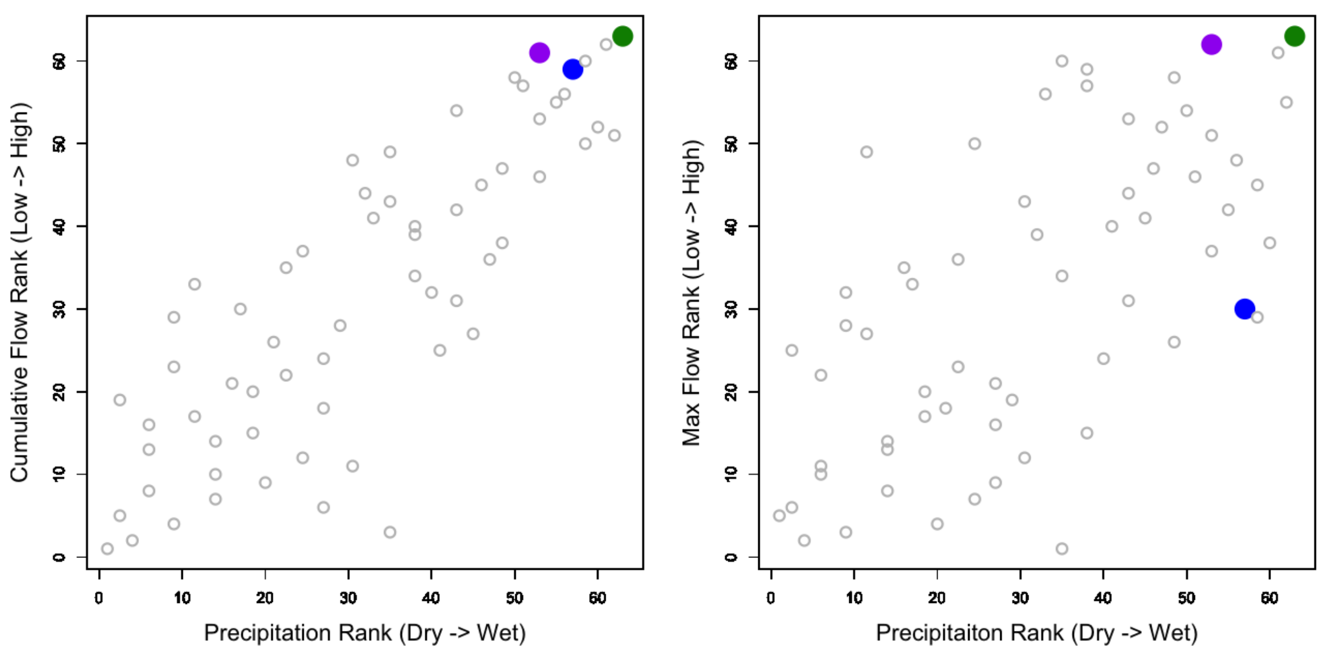


Figure 24. Total Basin Cumulative Flow Rand vs Precipitation Rank

Scatter plots of initial soil wetness vs max flow (left) and cumulative flow (right) for October 1 initialization of MF experiments. Filled and colored circles represent the three highest flow years on record; 1978 (blue), 1997 (purple) and 2011 (green).

C. THE MAKING OF AN EXTREME RUNOFF YEAR IN THE UPPER MISSOURI RIVER BASIN: A CASE STUDY OF 2011

The prior results of the section 6a and 6b reveal that an extreme runoff year cannot be looked at as simply having the wettest initial land conditions conditions or having the most water year precipitation, but usually involves a combination of both, which when convolved, produces an extreme runoff event. Using the record-setting 2011 UMRB flood event as an example, we explored the conditions that led to the 2011 event outlining the conditions necessary to drive an extreme event.

To illustrate the importance of these factors, we binned the observations into four regimes based on observed precipitation and VIC-simulated initial soil wetness: above (below) average precipitation and above (below) average initial soil wetness. The contingency diagram (Figure 25) demonstrates a clear and distinct separation of runoff behavior among these regimes. Using basin-scale areal means, the above average precipitation years produce greater runoff than below average precipitation years, and initial soil wetness tends to play only a muted role. However, it is very important to note that this expression of initial moisture does not include snowpack, which can represent an appreciable source of predictability as subsequent meltwater becomes runoff. It follows that all nine extreme runoff events since 1975 in question had above average precipitation. By contrast, only five had above average soil wetness (2011 had above average initial soil wetness).

This discrimination of runoff production as a function of the two factors is generally shared for each of the sub-basins comprising the Upper Missouri, with the notable exception of the Gavins Point to Sioux City sub-basin (Figure 26). The Gavins Point to Sioux City sub-basin exhibits far greater sensitivity to initial soil moisture conditions than the rest. The result indicates an almost 50% increase in runoff during above-aver-

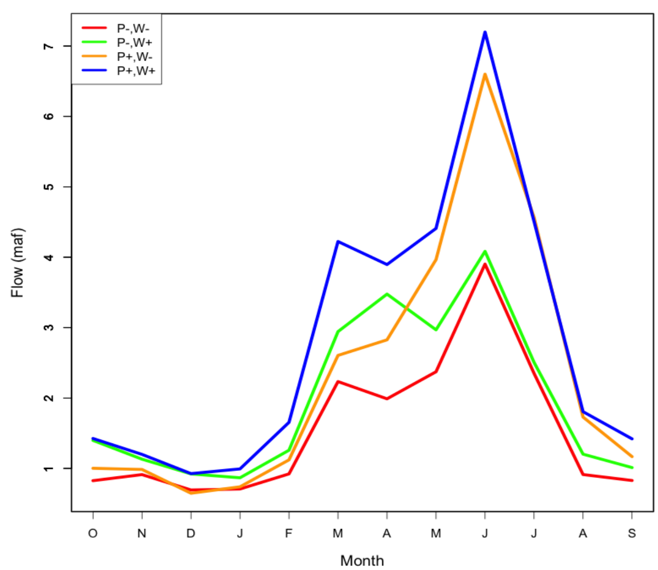


Figure 25. Total Basin Annual Cycle of Precipitation–Wetness Regimes Using Observations

Annual cycle for the four precipitation-soil wetness regimes for total basin flow; below average precipitation and below average soil wetness (red), below average precipitation and above average soil wetness (green), above average precipitation and below average soil wetness (orange), and above average precipitation and above average soil wetness (blue). Units of flow are maf.

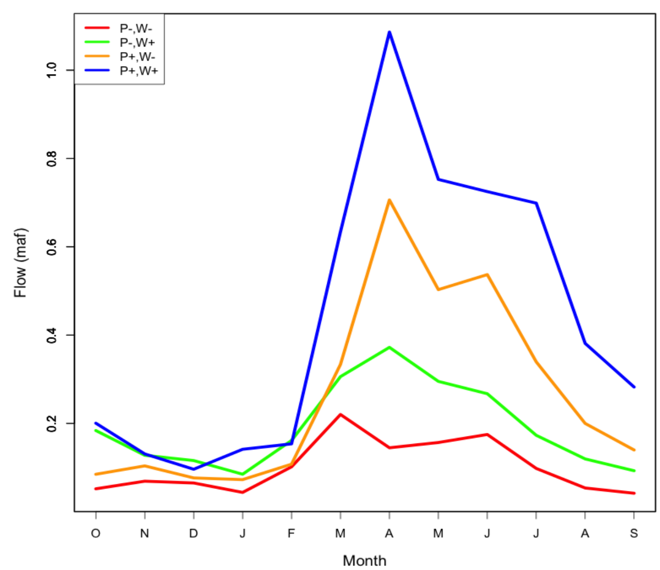


Figure 26. Sub-Basin 6 Annual Cycle of Precipitation–Wetness Regimes Using Observations

Annual cycle for the four precipitation-soil wetness regimes for sub-basin 6 (Gavins Point to Sioux City); below average precipitation and below average soil wetness (red), below average precipitation and above average soil wetness (green), above average precipitation and below average soil wetness (orange), and above average precipitation and above average soil wetness (blue). Units of flow are maf.

age-precipitation plus above -average-initial-soil wetness regimes compared to the above-average-precipitation and below-average-initial-soil-wetness regimes, by far the largest difference of any sub-basin.

Given the importance of initial wetness in this case, we further explore how anomalous the initial soil wetness was for the 2011 water-year (starting October 1, 2010) relative to the 1950-2013 mean. We find a large coherent region of significantly wet soils was present in the Gavins Point to Sioux City sub-basin (Figure 27). We emphasize this interesting coincidence, i.e. that the region with runoff most sensitive to initial soil wetness, in fact had the most anomalously wet conditions in 2011, potentially contributing to high runoff production that year. We also note that this same portion of the UMRB has experienced the largest percentage increase in precipitation during recent decades (see Figure 3), and thus may have led to an amplification of runoff response on this multi-decadal time scale. Indeed, as will be shown in section 7, the reach from Gavins to Sioux City contributed more than twice as much to the total upper basin annual runoff post-1975 compared to pre-1975.

As a percentage, the majority of upward trend in annual precipitation has occurred in the cold season, and subsequent sensitivity experiments and other physical considerations of runoff efficiency will argue for a heightened runoff response to cold versus warm season precipitation anomalies. Suffice it to point out here, in the context of the 2011 extreme year, that a significant attribute of that year was the cold season wet precipitation anomalies, Figure 28 shows the mean annual cycle of precipitation (blue line) with $\pm$ 1 standard deviation and the mean annual cycle of modified mean daily precipitation (red line). The 2011 precipitation (black-dashed line) exhibited a remarkable 36.7% increase in cold season precipitation relative to the climatology and was above average for most of the 2011 water year. The extent to which the UMRB experienced anomalous cold-season precipitation from October 1, 2010 to March 31, 2011 (Figure 29), shows that 18.7% of the domain had statistically significant high cold season precipitation that year. Furthermore, 49.5% of the domain had precipitation that was greater than 1 standard deviation above the mean and 89.7% of the domain experiencing above average precipitation.

From the various sensitivity experiments carried out in sections 7a and 7b, and also giving consideration to empirical evidence such as the common features of the observed spatial patterns of upper basin precipitation in each three ranked highest runoff years (see Section 4c), some conclusions about UMRB runoff extremes can be drawn. Using 2011 as an example, the culmination of two notable sensitivities—anomalously high initial soil wetness in the Gavins Point to Sioux City sub-basin, as well as anomalously high cold-season precipitation—appear to have driven the hydrology to an extreme condition. There are also some indications for predictability, though these are more speculative and require further study including evaluation of actual prediction systems and their hindcasts. Nonetheless, the enhanced sensitivity of runoff to water year precipitation relative to initial conditions demonstrated in the MF and ASM experiments suggests that the 2011 event and others like it could not have been well anticipated based on knowledge of the initial moisture in the system at the start of the water year alone. Further, even knowledge of the soil wetness at the start of the spring runoff, i.e. ~1 March, would also not have contributed to appreciable forecast skill of this event. However, monitoring and modeling of antecedent moisture conditions could provide some contribution to skill, particularly in the sub-basin 3 reach that is consequently minimally regulated, and thus may be of interest for future efforts. It is fair to say that there are many indicators of the likely trajectory for future runoff. Soil moisture is one of these indicators, but knowledge of soil moisture alone is likely insufficient to provide appreciable skill for the upper basin runoff as a whole. However, our results on sub-basin sensitivity suggests that soil moisture could be a more useful predictor for example in the Gavins to Sioux City reach.

Figure 27. Normalized Difference for 2011 Initial Soil Moisture vs Mean

Soil moisture conditions on for the start of the 2011 water-year on October 1, 2010; difference from the mean is normalized by the standard deviation, cross-hatched area indicates significant at the 95% level.

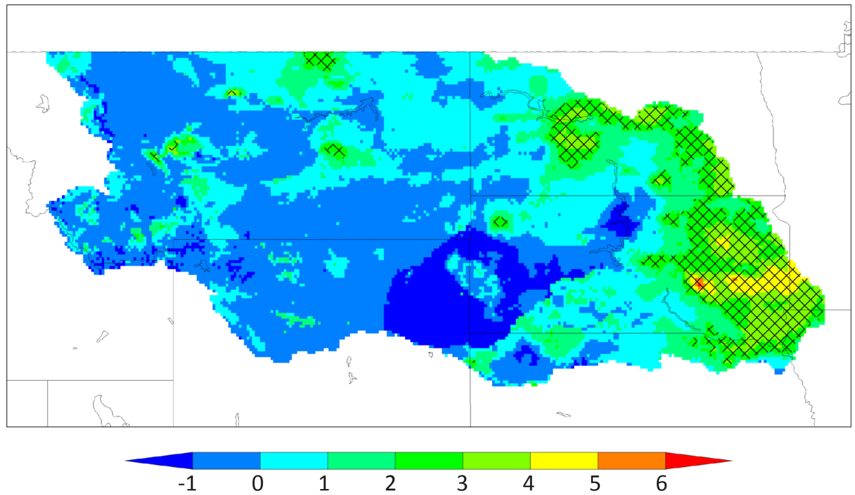


Figure 28. Annual Cycle of Mean Precipitation and 2011 Precipitation

Annual cycle of mean precipitation for the total basin (blue) with error bars indicating one standard-deviation. Red line indicates the modified precipitation used in modified mean precipitation experiment and black-dashed indicates the 2011 water-year precipitation.

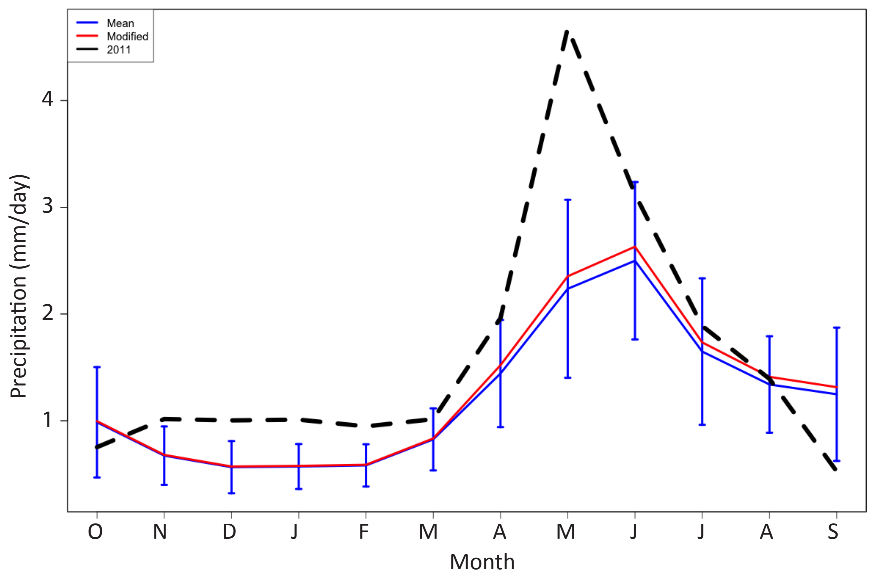
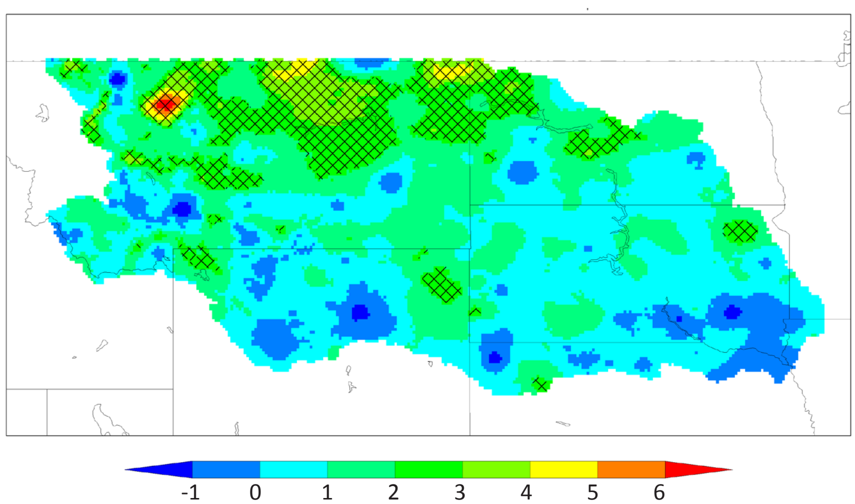


Figure 29. Normalized Difference for 2011 Cold-Season Precipitation vs Mean

Cold-season precipitation for the 2011 water-year on October 1, 2010 - March 31, 2011; difference from the mean is normalized by the standard deviation, cross-hatched area indicates significant at the 95% level.



7. IDEALIZED FORCING SENSITIVITY EXPERIMENTS OF UPPER MISSOURI RIVER BASIN RUNOFF

In this section, diagnosis of three sets of additional VIC experiments is presented. In each of these, idealizations of the long-term change in meteorological conditions are specified as forcings. Different from the VIC simulations of Sections 5 and 6 which all employed actual observed meteorological forcing, here we apply certain features of the observed trends in conditions that distinguish the period 1975-2014 from prior decades: a) trends in seasonal temperature, b) trends in daily extreme precipitation, and c) trends in seasonal precipitation.

A. EFFECTS OF TEMPERATURE CHANGE

The role of climate warming was explored through modifications to seasonal temperatures (see Figure 12) over the cold-season, warm-season and annually. These changes were carried out by adding the observed 6-month averaged seasonal mean changes in temperature to both the minimum and maximum daily temperatures used to force VIC. This approach increases the daily mean temperature without altering the diurnal temperature range.

Figure 30 reveals that such specified changes in mean temperature alone have little effect on the annual runoff (or the shape of the hydrograph). Some slight sensitivities can be discerned, for example, modifying cold-season temperature leads to a marginal increase in cold-season runoff, while modifying the warm-season temperature causes increased runoff in the rising limb of the annual cycle but a decrease in peak annual runoff. Combining these two responses for the annual temperature change roughly superposes the effects on the hydrograph. However, these changes are collectively small, and on the order of 1-3%. A more careful evaluation that isolates temperature effect more realistically would be warranted. For instance, the observations reveal that minimum temperature have risen more than maximum temperatures, but effects of such reductions in daily temperature range are not treated in these idealized runs. That temperature effects deserve more careful assessment is also indicated by the projections of future climate. These indicate that the UMRB is at the cusp of a strong warming trend that will accelerate in coming decades (see Section 8). It is currently unclear what the consequences of such future large warming alone would be on runoff efficiency, seasonality, and annual runoff from the UMRB.

B. EFFECTS OF DAILY EXTREME PRECIPITATION CHANGE

Extreme daily rainfall events can have devastating hydrologic consequences on short time scales, creating severe urban and riparian flash floods. Here our focus is on the effects of changes in extreme daily rainfall on the annual runoff and the seasonal hydrograph. Idealized modifications to heavy precipitation events were applied for the cold-season, warm-season and annually. For all locations, all events greater than the 95^{th} percentile for the entirety of the simulation were modified by the observed percent change in magnitude, as shown in Figure 12. The total precipitation for each particular grid-box was conserved, meaning the absolute amount of water added (or subtracted) in the modified extreme precipitation, was then removed (or added) equally from (to) precipitation events less than the 95^{th} percentile. A limitation of this approach concerning assessing impacts of the overall changes in very heavy rain events is that important multi-day precipitation events, which may not have any particular day with precipitation greater than the 95^{th} percentile, could be changing and could be relevant to upper basin runoff dynamics but are not treated in this analysis.

Figure 30. Annual Cycle for Mean Temperature Increases

Annual cycle of flow for mean temperature modification experiment; control (grey), total year modification (green), warm season modification (orange) and cold season modification (blue). Units of flow are maf.

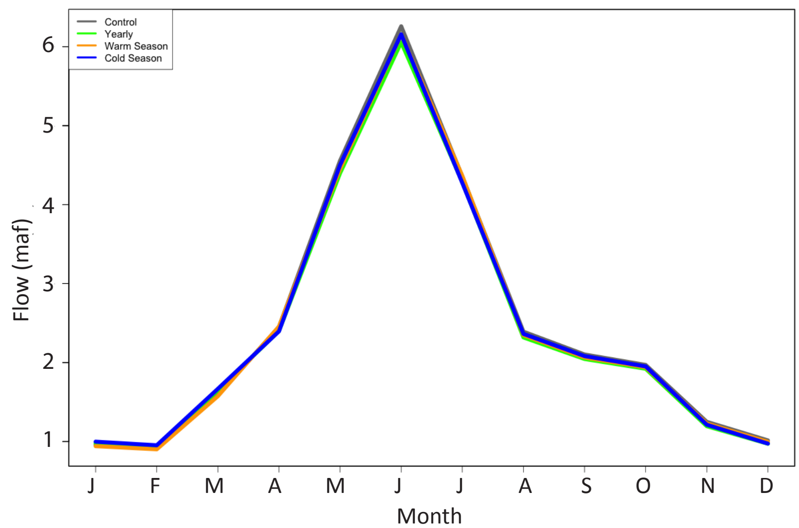


Figure 31. Annual Cycle for Upper-Tail Precipitation Increase

Annual cycle of flow for mean extreme precipitation modification experiment; control (grey), total year modification (green), warm season modification (orange) and cold season modification (blue). Units of flow are maf.

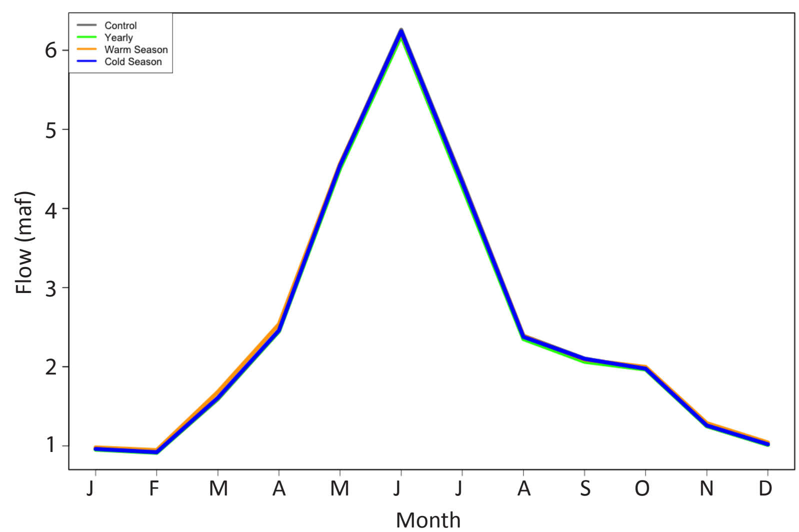


Figure 32. Annual Cycle for Mean Precipitation Increase

Annual cycle of flow for mean precipitation modification experiment; control (grey), total year modification (green), warm season modification (orange) and cold season modification (blue). Units of flow are maf.

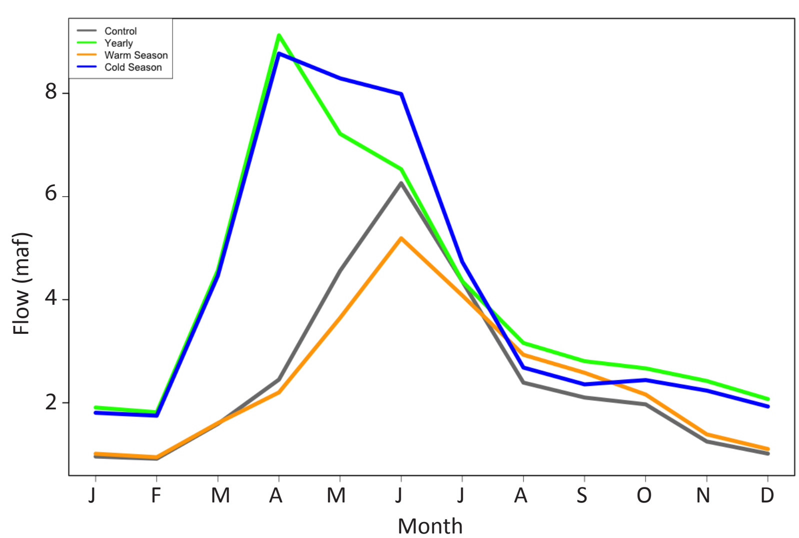


Figure 31 reveals that such specified changes in extreme rainfall statistics alone have little effect on the annual runoff (or the shape of the hydrograph). We interpret this to mean that changes in extreme daily precipitation (above 95th percentile) has not played a significant role in altering the changes in the occurrence of recent hydrologic extremes. One possibility, as noted before, is that extreme multi-day precipitation events may indeed be important for the extreme changes in question, although these were not captured by the present methodology. However, given there was such little change, it seems unlikely that multi-day precipitation extremes would contribute greatly. Overall, this finding suggests that the system is generally resilient to extreme daily events as have occurred over the last century.

C. EFFECTS OF SEASONAL PRECIPITATION CHANGE

Hydrologic sensitivities to mean changes in cold-season (October to March), warm-season (April to September) and annual precipitation are considered separately. The magnitude of observed changes is derived using historical station data from 1901 to 2014 (see Figure 12). These incremental historical changes are then applied to the station based dataset of Livneh et al. (2015), and the resulting meteorology is used to drive VIC. We note that for each 6-month season, the experiments assume that there are no monthly differences in the trends meaning that month-to-month differences in the trend changes are not considered. As such, the forcing used on these experiments should be viewed as idealization of the true observed changes in meteorological forcing which exhibit appreciable month-to-month differences. For the upper basin as a whole, the cold-season precipitation change is 21.1*mm/mon* corresponding to an 11.9% (2.52*mm/mon; 1"/mon*) increase for the modifications. The warm-season precipitation change is 52.6*mm/mon* and a 5.2% (2.75*mm/mo*n; 0.1"/mon) increase for the modifications. The modified atmospheric forcing was calculated by adjusting all daily precipitation values greater than 1*mm* (0.04") within the chosen season by the spatial patterns shown in Figure 12. This was done once for the cold-season months, once for the warm-season months, and once annually whereby both warm and cold season changes were applied.

As shown in Figure 32, the seasonal hydrograph is quite sensitive to these trend patterns in mean precipitation, exhibiting much greater sensitivity than was found to either changes in extreme daily rainfall totals or to changes in temperature alone. Further, the simulations indicate an acute sensitivity to changes in the cold season versus the warm season precipitation. Most striking is the shift in timing of the peak runoff to early spring, as compared to late spring in the control experiment and an overall increase in annual runoff over 40% for annual totals.

Physical considerations of upper basin runoff production support the result of small changes in UMRB runoff in response to increases in warm-season rainfall. The plausibility of this VIC result rests on the known low runoff efficiency in summer, when potential evapotranspiration (PET) is greater than precipitation. Since atmospheric demand is generally greater than precipitation in this season, the system is water limited, such that increases in precipitation will generally have limited impact on runoff, as they would largely be returned to the atmosphere as evapotranspiration. As such, it is plausible that the small (~5%) rise in summer rains is largely consumed by atmospheric demand or infiltration, with little runoff yield.

The dramatic changes in VIC response to cold-seasonal precipitation change can be at least be "qualitatively interpreted" based on the known physical aspects of UMRB runoff dynamics learned from our report's empirical analyses and the historical VIC simulations using realistic forcing. In contrast to summer, the cold-season generally has small evaporative demand (PET) relative to precipitation, such that additional precipitation can have a large impact on runoff. Although the annual average runoff efficiency is 8% it is generally larger in the cold-season and smaller in the warm season. We also found the UMRB annually-estimated elasticity to be ~2, i.e. the unit change in runoff relative to a unit change in precipitation. As such, a cold season precipitation increase of about 15% as applied in these runs for the upper basin as a whole might reasonably be assumed to yield at least a 30% increase in the runoff generated.

Nonetheless, this dramatic increase in runoff in the idealized cold season precipitation forcing run is clearly an exaggeration of the change in the UMRB hydrograph post-1975 produced, since we saw that the realistically forced VIC historical simulations showed an annual increase in runoff of approximately 9%. This exaggeration is due partly to the simplifications applied to the precipitation change in the idealized runs. The idealized runs assumed each precipitating day during 1-October - 31 March experienced identical incremental change in precipitation, based on the mean cold-season mean. In fact, the observed monthly precipitation trend analyses reveal a more nuanced pattern -- most of the cold season (Oct-March) wet trend occurred in the flank months (October and March), not the core winter months (see Figure 4). These differences affect the runoff efficiency and also the snowpack sensitivity discussed further below.

To get a more realistic quantitative estimate of potential cold-season sensitivities would require explicit treatment of the forcing change using the individual monthly varying trends rather than the entire season as was done in Figure 32. A more realistic treatment would be expected to reduce the magnitude of this dramatic cold-season sensitivity. Such runs are likely to more closely align quantitatively with the changes in the historical runs. Another caveat with the cold-season sensitivity concerns limitations in the VIC model itself. Preliminary indications are that land surface feedback occurs in VIC when the model is subjected to this idealized cold-season precipitation change that leads to unrealistically large snow water equivalent (SWE) increases in the UMRB especially over the prairie region. This dramatically increases the spring runoff and shifts the hydrograph to an earlier peak. While the directionality of cold-season wetting is likely to be correct, the magnitude of this SWE increase is unrealistically large in these runs, even though the SWE in the historical runs is more realistic.

8. SUMMARY AND EPILOGUE

A. SUMMARY

This report demonstrates that the increased frequency of high runoff years in the UMRB in recent decades has been due to an increase in precipitation falling over the upper basin. While both warm and cold seasons have become wetter, results from empirical analysis, from physical considerations of runoff dynamics, and from results of land surface models indicate increases in cold season precipitation were more important for elevating annual runoff. Also, an overall wetter climate has likely increased soil moisture in the UMRB, with the implication that more water-years in recent decades were initiated from moist antecedent land states. Land surface model sensitivity experiments establish that such a situation alone enhances annual runoff efficiency and increases high runoff liklihoods in the UMRB. Nonetheless, each of the 9 highest annual runoff years since 1975 were abnormally wet years, but only five began from abnormally high initial soil moisture conditions. *Both empirical and model simulations thus establish the dominant effect of the observed increase in overall precipitation delivery to the upper basin for the higher runoff production and the proliferation in extreme runoff years since the 1970s.*

A trend toward increasing intensity of daily rainfall has also been observed, and a greater fraction of annual total rainfall is now falling in extreme daily events. Yet, land surface models were mostly insensitive to such recent changes in heavy daily rainfall alone, though not all characteristics of daily rainfall (e.g. consecutive wet days) were considered in this report. Specifically, the focus was on large 1-day events, whereas multi-day heavy rainfall events were not analyzed and may indeed be of importance for extreme runoff. The results nonetheless emphasize that the overall increase in precipitation, accumulated across all categories of daily rainfall intensity, has been the most important driver for increased flooding. Temperature changes have not been important factors in explaining increased high runoff event either.

Surface temperatures have warmed over the upper basin, especially during winter over northern reaches. While empirical analysis shown in the report suggests the observed warming may have reduced runoff efficiency slightly, neither winter or summer warming of the magnitudes observed to date appear to materially affect extreme runoff events. The 40-year period (1975-2014) was only about 0.5°C warmer than the prior 80-year 1895-1974 period when averaged annually and spatially over the UMRB. Much greater warming of the upper basin is projected over future decades, and temperature may increasingly become a factor influencing the statistics of high and low annual runoff in the upper basin. We also note that the Great Plains Climate Assessment Report (Ojima et al. 2012) highlights that significant further increases in extreme daily precipitation events are likely in the 21st century as a result of global warming, which could also become an increasingly important factor for high runoff event probabilities.

B. EPILOGUE

This report assessed underlying causes for the proliferation in high runoff events in the UMRB during recent decades. It demonstrated the physical connection of these high annual runoffs to increased annual precipitation, using both observationally informed empirical analysis and meteorologically-forced hydrologic model simulations. An open question is the cause for these meteorological changes.

One factor, always prevailing in meteorological time series, is natural decadal variability that can produce protracted wet and dry regimes. In other words, through the lens of a much longer historical perspective, the last 40 years might be viewed as a "wet cycle". These are transient and typically unrelated to secular changes in external forcings (e.g. changing chemistry of the atmosphere) unless those forcings themselves are characterized by decadal variations. Even during periods of strong external forcing associated with

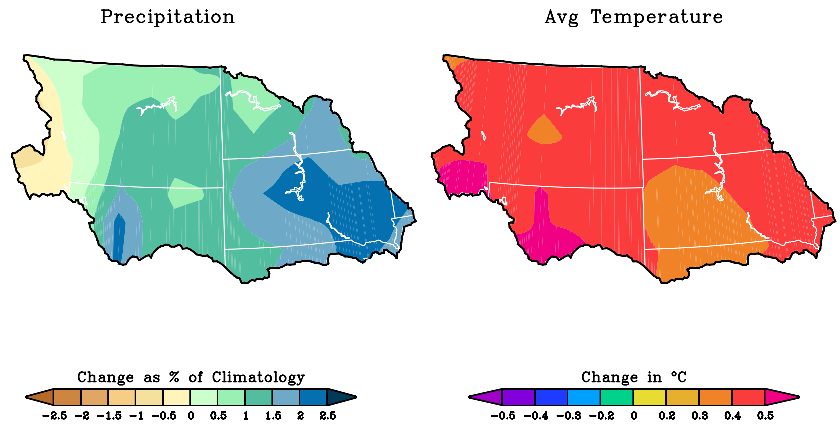


Figure 33. Upper Basin Water Year Annual Precipitation Change

The simulated change in annual (water-year) precipitation (% of climatology, left) and TAVG (°C, right). Changes calculated as the difference (1975-2014) minus (1895-1974). Data source is 40-member ensemble mean of NCAR CESM1 historical simulations.

increasing greenhouse gases, natural decadal swings in precipitation occur owing purely to internal climate dynamics, the effects of which can overwhelm externally forced signals (e.g. Hoerling et al. 2012; Deser et al. 2012). Figure 1 of this report illustrated the profound historical decadal variations in annual precipitation that have occurred over the UMRB, and it is plausible that much of these are naturally occurring cycles of the climate system, albeit a complete assessment would be required to establish the nature of the time variations (see also Mantua et al. 1997; McCabe et al. 2007; Hoerling et al. 2010).

The analysis of historical climate simulations forced by known variations in external radiative forcing (greenhouse gases, anthropogenic aerosols, volcanic and solar variations) are a useful tool to determine underlying causes for the observed changes in climate conditions. Shown in Figure 33 are the (1975-2014) minus (1895-1974) differences in water-year precipitation and temperature simulated by such a transient climate simulation. Here we use the NCAR-CESM1 model which is among those used in the Fourth Assessment Report of the Intergovernmental Panels on Climate Change (IPCC, 2013) having the particular attribute that the simulations were conducted 40 times using identical forcing. The ensemble mean of all model simulations provides an estimate of the externally forced climate change, while the spread among the simulations reveals effects of naturally occurring "climate noise". The ensemble mean results indicate a wetting and warming of the upper basin, qualitatively consistent with the observed changes (cf. Figure 8). The magnitude of the UMRB average rainfall increase is much weaker than the observed increase however: +1% in the model versus +6% observed. Suggested hereby is that natural, internal variations have been the main cause for the observed rainfall increases. By contrast, a upper basin wide warming signal due to external radiative forcing changes of +0.4°C compares closely to the magnitude of the observed warming, suggesting an important effect of anthropogenic influence on temperature changes in the upper basin. Given that both VIC simulations and naturalized runoff indicated little sensitivity to such recent warming, and that the most important factor driving increasing runoff and heightened extreme event likelihood was the precipitation increase, these CESM1[1] results suggest that natural, rather than anthropogenic factors, have been responsible for this change. *Most of the magnitude in observed precipitation increases in the recent 40 year, and hence much of the runoff increases, have likely occurred via natural variations in the region's climate. The warming trend, by contrast, has been consistent with an emergent signal of human-induced climate change.*

When looking to later decades of the 21st century, climate simulations indicate a directionality toward

1 The CESM1 model has an overall wet bias in the UMRB compared to observations (~650mm vs ~450mm), and its annual runoff (~45maf) is commensurately higher than naturalized runoff (~25maf).

wetter and warmer conditions in the UMRB as a symptom of human induced climate change (see also Petterson et al. 2013; Wuebbles et al. 2013). The time evolution of upper basin precipitation and temperature for 1920-2100 based on the suite of CESM1 historical simulations and their future extensions under a scenario of aggressive GHG emissions (RCP8.5; Taylor et al. 2012) indicates further modest increases in precipitation (Figure 34, top), and dramatic increases in temperature (Figure 34, middle). There is considerable spread in the rainfall changes among individual runs, consistent with prior discussions, such that multi-decadal periods could have rainfall regimes much different from this modest ensemble mean wet signal. However, the warm signal quickly becomes much larger than the intrinsic variability of temperature by the early-mid 21^{st} Century.

Increasingly through time, the unprecedented, acute projected warming of the basin appears to become a contributor to the runoff trend. Figure 34 (bottom) shows the time series of model runoff, which declines despite the overall increase in precipitation[1]. We speculate that the runoff declines because of increased evaporative demand overwhelming the increase in precipitation by the latter half of the 21^{st} Century. Surface temperatures by 2050 are projected to be 4°C warmer than current climate. Such conditions have no analogs in the instrumental record, and thus the models become a principal guidepost for the land surface response. More careful evaluation of the land surface physics and sensitivities to such meteorological driving would be needed to affirm the nature of the basin's hydrologic response.

It is interesting that despite the projected overall decline in runoff production in the Upper Missouri Basin in CESM1, the frequency of very high annual runoff events actually increases. Figure 35 compares histograms of the exceedances in annual runoff above the 90^{th} percentile of all runoff years simulated by CESM1. The analysis is shown for three time-slices, one for the early 20^{th} century, one for current climate, and for the end of the 21^{st} century. There are numerous extreme event exceedances in the projected model statistics

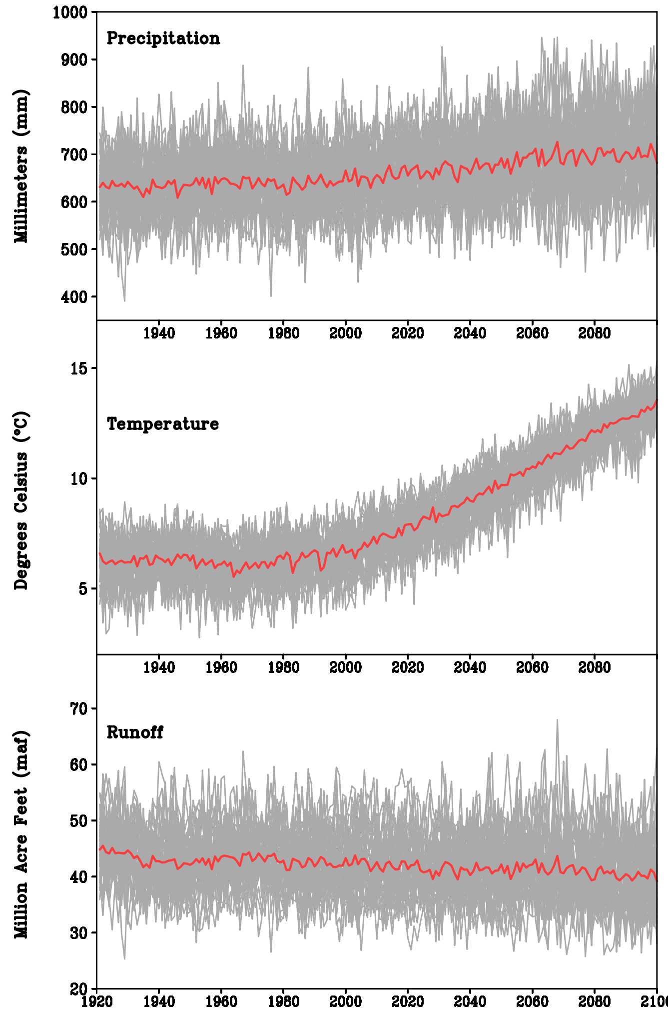


Figure 34. Upper Missouri River Basin Precipitation, Average Surface Temperature, and Runoff

Simulated time series of water-year Upper Missouri River Basin precipitation (mm, top), daily average surface temperature (°C, middle), and runoff (maf, bottom). Red line is the average of the 40 model simulations, and gray lines are the individual runs. Period is 1920-2100. Data source NCAR CESM1.

of runoff at the end of the 21^{st} century for which no analogues exist in either the current or past climate. A similar change in low runoff water-year statistics is also found to occur in CESM1 (not shown) with extreme low runoff years in the late 21^{st} Century occurring that having no historical analogues in the 20th Century model data. *Overall, the projections paint a hydroclimate of the upper basin in which annual runoffs become considerably more volatile owing to human-induced climate change.*

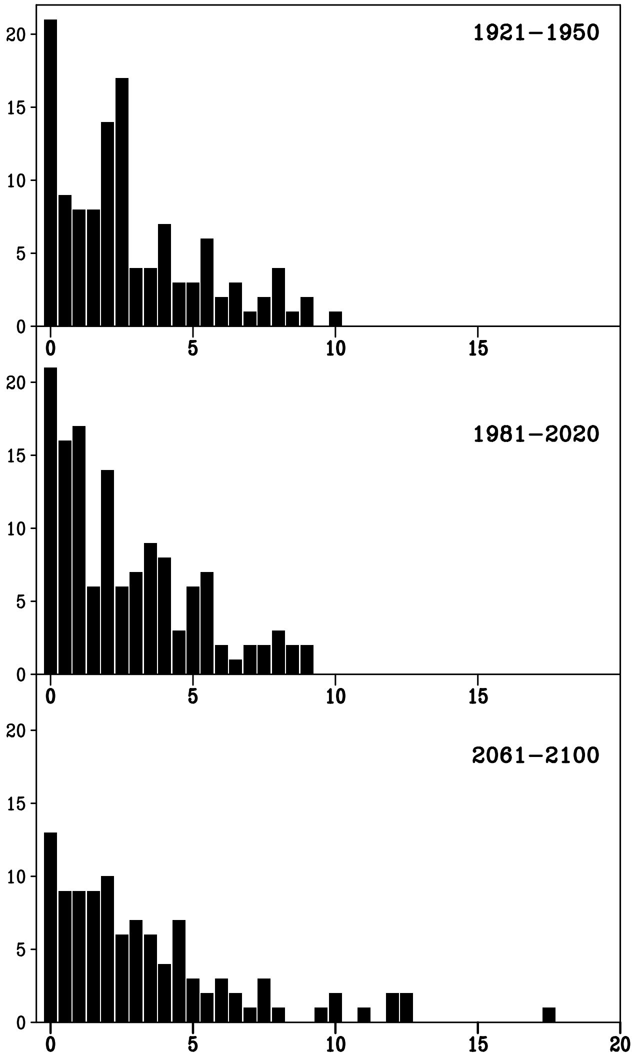


Figure 34. Simulated Upper MRB Extreme Runoff

Histograms of simulated water-year Upper Missouri River Basin runoff exceedances above the 90th percentile (maf) for 1921-1960 (top), 1981-2020 (middle), and 2061-2100. The 90th percentile threshold value is ~50 maf, and was derived from the 1921-60 period. There are about 120-140 exceedance events in each epoch, derived from the 40-member CESM1 historical simulations and projections using the RCP8.5 emissions scenario.

Given the biases in the CESM1 model's ability to simulate the climate of the upper basin (e.g. too wet, too much mean runoff, and too low runoff coefficient), these results must be viewed with considerable caution. It is also important to be careful to not attribute the recently more volatile annual runoff observed in the Upper Missouri Basin as symptomatic of future forcings. Indeed, various lines of evidence presented in this report indicate that natural cycles of climate have been mainly responsible for the changing characteristics of observed annual runoff during recent decades. To be sure, a projected future change in CESM1 annual runoff toward a more volatile hydroclimate in the upper basin, one bearing a resemblance to the recent observed trends, is of interest and would warrant further careful investigation. Indeed, one might reasonably ask if the underlying conditions and factors leading to the observed increase in volatility of Upper Basin runoff since the 1970s could nonetheless be at least partially symptomatic of human-induced climate change. An answer would require careful analysis of other climate models used in the the AR4 activities. It would also require a careful analysis of how the upper basin land surfaces would theoretically respond using designed sensitivity experiments, and would require the land models be calibrated to observed basin hydrology. Such analysis would be warranted if desiring to learn whether the recent increased frequency of extreme runoff has merely been a temporary condition of a naturally varying climate, or whether it is symptomatic of directional change that could define a new normal for the hydro-climate of the basin for the foreseeable future.

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APPENDIX 1: LAND SURFACE MODEL

Distinguishing characteristics of the VIC model include: sub-grid variability in land surface vegetation classes (i.e. a mosaic of land cover); sub-grid variability in the soil moisture storage capacity (statistically represented); non-linear drainage from the lower soil moisture zone (base flow); and the inclusion of elevation bands in topographically complex regions that allows for orographic precipitation gradients and temperature lapse rates to be applied. Evapotranspiration is computed from a dynamically computed Penman-Monteith potential evapotranspiration (PET) from which components of soil, canopy evaporation and transpiration are estimated based on resistance-terms that are a function of soil and plant stress. The University of Maryland land cover classification system was used to assign different vegetation types (and bare soil) to each grid cell, as VIC allows for a mosaic of land cover. A full energy and water balance snow model (Andreadis et al., 2009) that simulates both canopy and sub-canopy snowpack evolution.

In this study, the VIC model was built at a 0.0625º (~6km) spatial resolution. Soil parameters were derived from Livneh et al. (2015). However, additional calibration was required in order to match simulated and observed hydrograph characteristics. The soil parameters listed in Table A.1 were modified. The spatial pattern for these was based on the distributed of observationally based soil bulk density as depicted in Figure A.1.

Table A.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