# CLIMATE ASSESSMENT REPORT

## Understanding and Explaining Climate Extremes in the Missouri River Basin Associated with the 2011 Flooding

Prepared for the US Army Corps of Engineers by the
National Oceanic and Atmospheric Administration

27 December 2013

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This assessment of the climate conditions relevant to the 2011 flooding in the Missouri River Basin is a NOAA response to a request for an expert scientific evaluation of meteorological causes for the flood by the Missouri River Basin Water Management, Northwestern Division, U.S. Army Corps of Engineers.

The effort includes climate experts from NOAA's Earth System Research Laboratory's Physical Sciences Division (Climate Analysis Branch) and its Cooperative Institute (CIRES) located at the University of Colorado. The team has assessed current knowledge of the variability of climate in the Missouri River Basin based on published literature, analysis of the historic observational record, and climate simulations conducted to determine the role of factors causing the extreme meteorological conditions during 2011 that led to flooding. This report also assesses current understanding of anthropogenic climate change impacts in the region of the Missouri River Basin based on recent publications of the Intergovernmental Panels on Climate Change, the U.S. Global Change Research Program, and additional climate simulations. The report presents new analyses of Missouri River Basin weather and climate data, and contrasts the conditions resulting in the 2011 flooding with the drought conditions across the basin in 2012.

June 2011 – Heavy clouds hang over raging water released from Oahe Dam, Pierre, SD, contributing to a flood in progress along the Missouri River. Photo by Jeannie Mooney, FEMA.

# EXECUTIVE SUMMARY

This assessment provides a predictive understanding of the meteorological conditions leading to the 2011 flooding in the Missouri River Basin. The factors immediately responsible for flooding were a sequence of events that individually could have created some flooding, but collectively resulted in historic flooding. Antecedent wet conditions, characterized by the four prior years of above-normal annual precipitation, predisposed the upper basin toward increased runoff efficiency. A particularly cold and wet 2010-2011 winter led to unusually high snow pack, and also minimized the prospects for evaporative loss of moisture within the upper basin from fall through early spring. Record setting heavy rains in late spring were the final, and perhaps most critical, of the meteorological events that eclipsed the capacity of the upper basin land surface to withstand a sudden and massive runoff.

Missouri Basin land surface dynamics integrate past meteorological conditions spanning multi-annual time scales, resulting in modest predictability of annual runoff simply from autocorrelation of the runoff time series itself. The 1-year lag correlation of the 1898-2012 annual runoff time series above Sioux City, Iowa is 0.33. As such, antecedent wet conditions alone provided a modicum of predictability that 2011 would more likely be a high rather than a low runoff year in the upper basin. Such a prediction is not synonymous with forecasting a flood event, however, and its limited predictive power was apparent in 2012 when the same antecedent information would have again predicted high flow owing to basin memory alone, yet low flow occurred.

The year-to-year variability in annual runoff in the upper Missouri Basin is sensitive to contemporaneous meteorological conditions, and these form the backbone for explaining the occurrences of high and low runoff years above and beyond the long term basin memory alone. Empirical analysis of hydro-climate data for 1898-2012 reveals that the most effective seasonal patterns of climate variability for annual flooding are high precipitation delivered to the upper basin in late fall/early winter and again in late spring. Temperature is also a contributor, with late fall and late spring cold conditions being most effective for high annual runoff production. These were the particular patterns of climate conditions to which the upper basin was subjected leading into the 2011 snowmelt season, and thus were likely optimal for maximizing runoff sensitivity and production.

The year-to-year variability in annual runoff in the upper Missouri Basin is also sensitive to global ocean conditions through effects on atmospheric circulation that organize meteorological conditions within the upper basin. For the period 1898-2012, high runoff is found to be correlated with a Pacific-wide pattern of sea surface temperature (SST) anomalies resembling a horseshoe having cold equatorial east Pacific waters (a La Niña signature) encircled by warm tropical west Pacific and warm extratropical North Pacific waters. Such was the prevailing condition of the Pacific Ocean during 2010-11. NOAA issued a "La Niña Advisory" on 5 August 2010, and two months later predicted that La Niña was likely to last at least into spring 2011.

Modeling methods using large ensemble simulations of a high-resolution global climate model are used in this assessment to characterize the nature of the sea surface temperature (SST) and greenhouse gas impacts on the upper Missouri Basin during 2011. Even with perfect foresight of the subsequent SST evolution in the wake of NOAA's La Niña declaration, the model simulations reveal only a modest (10%) increase in winter (December-February) precipitation. The modeled response to SST forcing also produced a decrease in winter and spring surface temperature across the upper part of the basin which likely increased runoff efficiency, and likely also deferred snowmelt until late spring.

Regarding the heavy and record-setting springtime rains, however, the model results indicate that ocean conditions were not an appreciable contributing factor. It is shown that similar probabilities existed for spring 2011 rains to have been extremely high *and* extremely low, though either outcome would have been a very low probability event. No shift in the odds for heavy spring rains over the upper basin was found for La Niña conditions compared to climatological odds. The extreme spring rains were thus a highly unlikely occurrence of intense random atmospheric variation. This immediately caused strong atmospheric low pressure over the Pacific Northwest but had no further causal chain. Long-lead predictability (6 to 9 months) of the spring conditions that ultimately propelled a record runoff in the upper basin was therefore limited, if not absent.

Long-term climate change forcing since the late 19th century has most probably acted to *reduce runoff* in the upper Missouri Basin, and was thus unlikely a contributor to the 2011 flooding event. Long-term human induced climate change information thus would not have provided useful prognostic information for anticipating the 2011 flood event. Various lines of evidence including new climate change simulations performed as part of this assessment and other modeling activities of the Coupled Model Intercomparison Project (CMIP5) suggest that the recent period would, on average, have been one of reduced annual runoff and less annual mean flow in the Missouri River due to climate change alone. The plausible interpretation of observed *upward trends* in annual flow in the upper Missouri Basin above Sioux City over the last century is that it is more likely than not a symptom of natural variability. No explanation is yet available for an observed doubling in year-to-year variability in the annual runoff of the Missouri River above Sioux City during the last 20-year period compared to earlier decades of the historical record. The increased volatility in annual flows has mainly resulted from the fact that 9 of the 10 highest historical flows (since 1898) have occurred in the last 40 years, while extreme low flow regimes have also continued to occur.

# 1. BACKGROUND

The Missouri River drains one-sixth of the United States and stretches about 2341 miles (Missouri River Natural Resources Committee 1998) from the Rocky Mountain headwaters of Montana and Wyoming to its confluence with the Mississippi River near St. Louis (Figure 1). The annual runoff in 2011 was 61 million acre-feet (maf) for the upper basin (above Sioux City, Iowa), a historic total that virtually equaled the storage capacity of the entire Missouri River Mainstem Reservoir System (Figure 2).

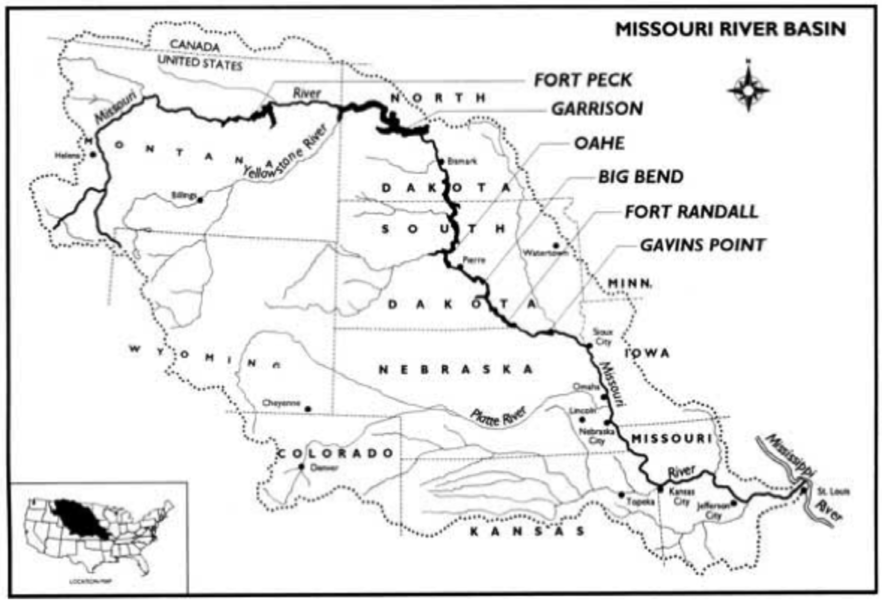


Figure 1. The Missouri River Basin, the Missouri River, and the main U.S. Army Corps of Engineers reservoirs. The Upper (Lower) Basin is the region generally located in a west-east line above (below) Gavins Point near Sioux City Iowa. (Image from the Missouri Department of Natural Resources).

The flow in the river is regulated, with the nation's largest reservoir system (located mostly in the Upper Basin) having a storage capacity of about 73.1 maf as of 2011. Built to store and conserve water and to mitigate the effects of flooding, the Missouri River Mainstem Reservoir System is critical for water supply, electricity generation, and for maintaining river flows below Sioux City. These flows support navigation, commerce, recreation and ecosystems that sustain native river fishes. The principal concern in 2011 was mitigation of flooding.

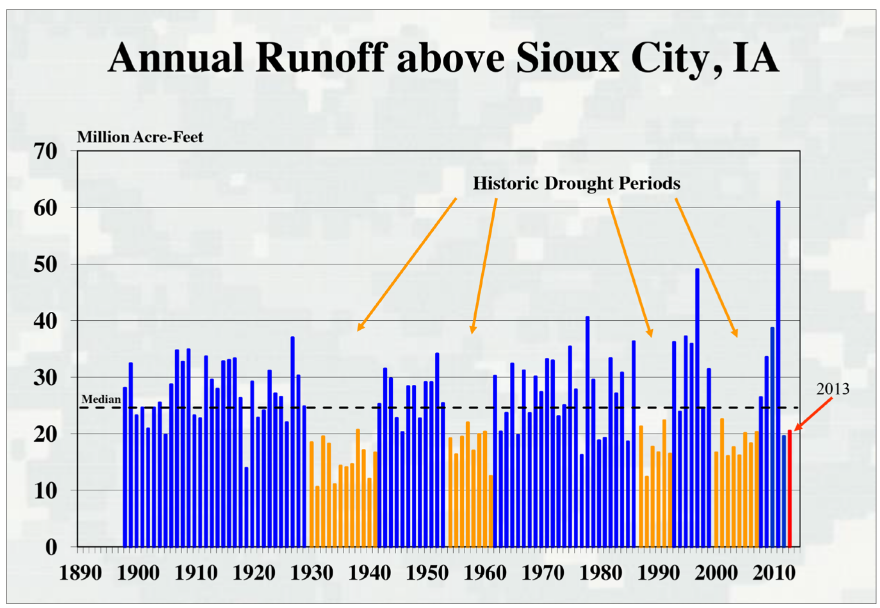


Figure 2. Time series of the annual Missouri River runoff (million acre-feet) above Sioux City, Iowa for 1898-2012. The 2013 value (red bar) denotes a preliminary estimate. Regimes of persistent low flows, denoted by orange bars, denote hydrologic droughts within the basin. Horizontal line shows the historical median value. Data source is USACE.

Record runoff over the Missouri Basin in 2011 occurred in concert with record precipitation delivered to the basin. The period January-May 2011 ranked as the historical wettest (since 1895) for the Missouri River Basin region (Figure 3, bottom). The wet pattern took the form of heavy winter/spring snows in the catchments above Fort Peck (Montana Rockies) and Garrison Dam (Wyoming Rockies), heavy winter snows in the high plains, and record late spring rains that fell mostly above Sioux City. Each could individually induce high runoff. Their combination caused exceptional runoff.

Their combined impacts were further magnified by cumulative effects of prior wet years. In particular, 2010 ranking as the 5th wettest year on record (Figure 3, top), thus creating wetter-than-normal land surface conditions that were conducive for high runoff even before 2011 dawned. A more comprehensive assessment of 2010-11 hydro-climate conditions appears in a recent National Weather Service report (NWS 2012).

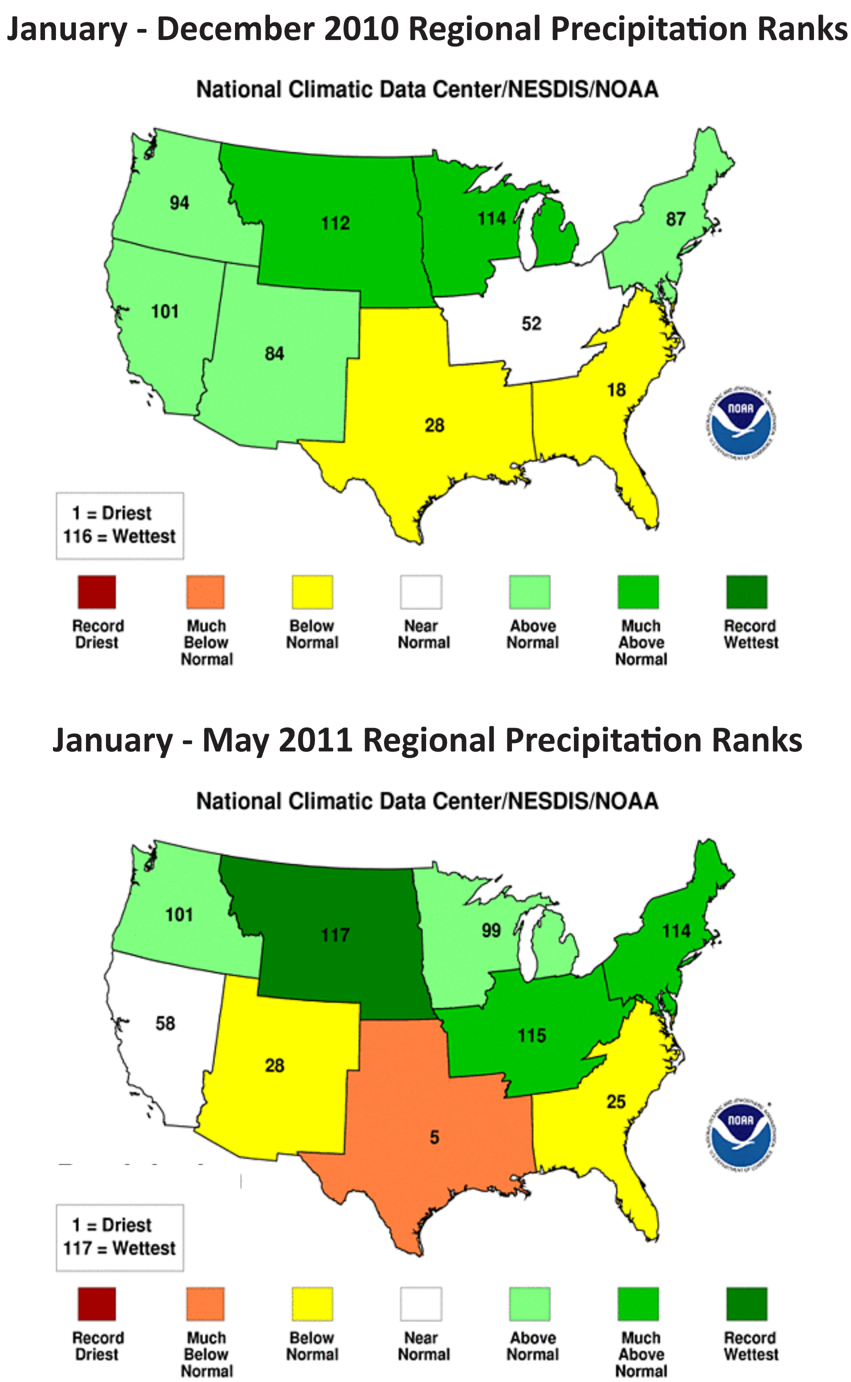


**Figure 3.** The historical ranking of regional precipitation for annual 2010 conditions (top), and for the subsequent January-May 2011 conditions (bottom). Over the Missouri River Basin region, 2010 ranked 5th wettest since 1895, whereas the subsequent 5-month period January-May 2011 ranked as the historical wettest since 1895. Note the dramatic contrast between conditions in the Missouri Basin versus those immediately south. Data source is NOAA.

# 2. PURPOSE OF ASSESSMENT REPORT

Extreme climate conditions are a natural occurrence—albeit rare—of a complex geophysical system that arises from atmospheric winds interacting with oceans and land. They may occur as a result of a single factor having extreme magnitude. More often, they result from a combination and a sequence of factors, which individually need not be extreme, but collectively do achieve an extreme impact. They often arise with little forewarning except perhaps at very short lead times. The questions probed in this report concern the extent to which any foresight may have been rendered, either in the location, the magnitude, or the probability of the particular climate conditions enumerated above.

Establishing causes and providing physical explanations for observed climate conditions and phenomena are a scientific process, sometimes referred to as **climate attribution**. A key purpose in such science, and a primary goal of this report, is to understand the extent to which the conditions may have been anticipated from an in-depth analysis of cause–effect linkages. The goal is thus to provide a better predictive understanding of the 2011 Missouri Basin flood.

This report provides an objective, science-based assessment of the causes for, and long-lead (seasonal and longer) predictability of the conditions leading to the 2011 flooding in the Missouri River Basin. The role of specific factors is examined including, i) the local sensitivity of Missouri River annual runoff to precipitation throughout the seasonal cycle, ii) the local sensitivity of Missouri River annual runoff to surface temperature throughout the seasonal cycle, iii) the remote conditioning of runoff and climate in the Missouri River Basin by global ocean states (e.g., ENSO [El Niño Southern Oscillation], PDO [Pacific Decadal Oscillation]), and iv) the sensitivity of mean climate and the statistics of extreme events to long term change over the Missouri Basin.

The analysis in this report is intended to provide information that can be used by policy, planning and decision makers in their determinations of how to prepare for and manage the risk of future flooding in the basin. The analysis itself is retrospective. It applies methods and diagnoses, some of which reveal prospects for early warning, but which may not have been available or actionable in real time in 2011. In this sense, the current study is not to be confused with predictions themselves, but rather should be understood as an assessment of *potential predictability*. A separate assessment of the prediction of the meteorological conditions related to the runoff event using tools and understanding available in 2011 appears in a companion study.

# 3. METHODOLOGY

Two complementary methods are used to identify causes for the record Missouri Basin runoff of 2011. One employs standard empirical techniques applied to historical observations that span the record of Missouri Basin annual runoff and climate. For the period 1898-2012, the statistical relationships between annual runoff with precipitation, temperature, and global atmospheric circulation and ocean conditions are explored. These historical relationships are compared to the 2011 conditions themselves.

A second method employs simulations of a state-of-the-art global general circulation model. This method tests the extent to which various correlative relationships identified by empirical methods may represent causality, and especially causality having predictive power. Retrospective climate simulations are diagnosed in which the variations of ocean conditions (sea surface temperatures and sea ice) and atmospheric trace gas composition ($CO_2$, $CH_4$, $NO_2$, $O_3$, CFCs) during 1979-2012 have been specified (see Appendix for model details and an assessment of model climatology). The purpose is to assess whether perfect foresight of these forcing factors could have rendered early warning for the aforementioned sequence of meteorological events that led to Missouri Basin flooding. Ensemble methods are used in which the period has been simulated repeatedly (40 times) — each experiment was subjected to identical time evolving ocean and trace gas evolutions but was begun from slightly different initial conditions in 1979. Averaging the runs identifies the recurring pattern of climate effects resulting from the evolution of ocean and trace gas conditions.

The statistical distribution of the 40 experiments is also diagnosed. Interpretation of the single observed condition (e.g., its likelihood of occurrence) is facilitated by comparing it to the probability distribution function (PDF) of all the model realizations. The *mode* of that PDF identifies the maximum likelihood for the expected change in climate conditions during 2011 (relative to a climatological reference) due to the effect of forcing. Also of interest are the statistics for extreme conditions, the so-called "tail behavior". Standard box-whisker analysis is used to examine the range of physically plausible meteorological outcomes over the Missouri Basin in 2011, and how the probabilities of particular threshold exceedances (e.g. record precipitation) in 2011 differed from other years, including the subsequent year (2012) when drought plagued the Missouri River basin.

Finally, an additional set of simulations (using the same model) is conducted to address plausible long-term changes in meteorological conditions over the Missouri Basin. One set of experiments forces the model with ocean conditions and trace gas concentrations of the 30-year average during 1881-1910, and a parallel set with average conditions of 1981-2010. In this method of time slice integrations, 300-year simulations for each period are conducted thereby permitting robust statistical evaluation of long-term change.

The method of atmospheric modeling used herein has certain advantages over methods using coupled ocean–atmosphere modeling. In the latter approach, which often involves diagnosing simulations of the Coupled Model Intercomparison Project (CMIP5, Taylor et al. 2012), only changes in the external radiative forcings are specified, and the ocean response is simulated. The ocean response in these coupled simulations, however, can and for many models does, deviate substantially from the observed ocean changes. These biases lead to appreciable errors in regional climate impacts (e.g. Hoerling et al. 2010; Shin and Sardeshmukh 2011). An attribute of the method used in this report is that the atmospheric model is subjected to the actual observed long-term changes in the global sea surface temperatures and sea ice. One disadvantage of the current approach is that it fails to explain the cause for the observed ocean change itself. It is quite likely that some component of observed change over the last century is unrelated to human influences on global climate, and instead is due to random variability. While clarifying the latter issue is of considerable scientific interest, it is of secondary interest to the purposes of this report, and the atmospheric modeling approach is applied so as to capture the best estimate of the impact of observed changes in boundary and external forcings. This report presents results from a single widely studied atmospheric model, and thus the results may be sensitive to the particular model employed.

# 4. ANNUAL CLIMATE AND ITS VARIABILITY IN THE MISSOURI RIVER BASIN

## A. THE ANNUAL CYCLE

The principal features of the seasonal cycle of Missouri River flow, and the seasonal cycle of climate are well known and require little enumeration. Briefly, the climatological conditions for the Missouri River consist of low water/slow channel flows during winter when precipitation is low and stored in frozen form across the upper basin. High water/fast channel flows occur during late spring/early summer as a result of melting mountain snowpack and melting Great Plains snow, and the emergence of the rainy season on the plains.

The seasonal cycle of river flow is thereby strongly controlled by the annual cycle of precipitation. An Empirical

Orthogonal Function (EOF) analysis illustrates that the normal delivery of moisture into the Missouri Basin is characterized by a basin wide May-June maximum that falls as rain (Figure 4; left side, top and bottom). A secondary, but critical pattern of the seasonal cycle keys on high elevations of the far western basin having a winter/early spring maximum that falls as snow (Figure 4; right side, top and bottom). This latter feature creates a substantial natural water reservoir that accumulates over a 6-month period. Seasonal melting mostly accounts for the initial normal springtime rise in Missouri River Basin hydrographs especially above Rulo, Nebraska (the lower portion of the basin remains rain-driven).

## B. MISSOURI BASIN ANNUAL RUNOFF VARIABILITY

Were clues available in advance that 2011 could be at elevated risk for flooding, based solely upon considerations of the historical behavior in Missouri River flow itself? A quantitative analysis of the time series of annual Missouri River flow above Sioux City (Figure 5, top) provides some answers to this question. The 1898-2012 historical runoff time series has two well-know attributes. The first is system memory and the role of antecedent conditions in hydrologic regimes. These are apparent to visual inspection, and the study of any reasonable segment of the 115-year time series reveals such regimes. The second is an increasing frequency for high annual flows in recent decades. Regarding the first, prolonged low flow occurred during the 1930s Dust Bowl era, the 1950s, early 1990s, and most recently during the first decade of the 21st Century. These low flow regimes have tended to persist 5-10 years, as have the intervening periods of abundant flows. Indeed, the two recent extreme flood years (1997 and 2011) each occurred in the wake of a sequence of high flow years presumably reflective of high moisture content prevalent and stored within the land system of the basin. As a measure of persistence, the 1-year lag correlation of Missouri River annual runoff is 0.33, and the 2-year lag correlation is 0.30. Thus, approximately 10% of the variability in annual runoff above Sioux City is accountable merely by knowing the monitored state of the prior year's annual runoff. Given the hydrologic memory of the system, slightly more of the variance in annual runoff can be explained by the combined influence of the two previous years, approximately 14%.

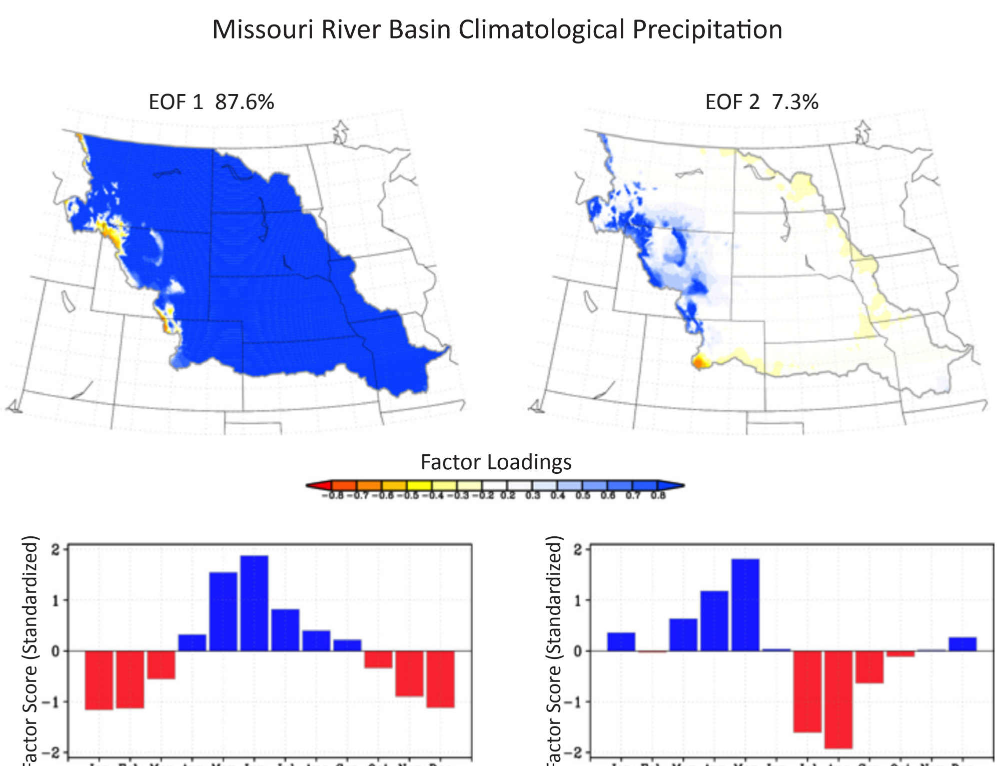


**Figure 4.** The statistical pattern of observed monthly climatological precipitation using the method of Empirical Orthogonal Function (EOF) analysis. The spatial plot shows the leading pattern (88% of variance of the seasonal cycle; left) and second dominant pattern (7% variance of the seasonal cycle; right) of the seasonal cycle of Missouri River Basin precipitation. The first pattern is shown because it illustrates the strong coherence in climatological delivery of moisture across the basin, while the second pattern highlights the different behavior of the headwaters region from the plains region. The time series of these empirical patterns are shown in the lower panels. These reveal the monthly dependency in the climatological delivery of moisture to the Missouri River Basin, being strongest during May-June over most of the basin, but having a winter/spring peak in the headwaters region. Data available from the PRISM Climate Group, Oregon State University, [http://prism.oregonstate.edu](http://prism.oregonstate.edu)

Regarding the second feature, nine of the ten highest annual runoffs in the Missouri Basin have occurred after 1970. Overall, the year-to-year variability of annual runoff has increased dramatically in recent decades, principally due to an increase in high flow events. Figure 5 shows the standard deviation of annual runoff for moving 20-year periods (red curve), from which a substantial increase in variability is seen. A relatively stable annual flow regime in the 1960s has evolved to a more volatile regime during the last 20 years. The year-to-year variability has risen about 70% over the last half-century, and has roughly doubled when including the 2011 flood year in the most recent 20-year window.

This diagnosis of the history of Missouri River Basin runoff mainly affirms the existence of strong memory, which itself renders prediction of future behavior. It also identifies a recent trend toward increased year-to-year variability, which would in principal offset some of the predictive skill that a simple persistence forecast might afford. Thus, regarding the posited question at this section's beginning; the statistics of Missouri Basin flow alone suggest modest predictability (~10% of explained variance by lag relationships) at best. The fact that 2009 and 2010 witnessed above normal annual runoff implied that 2011 would have more likely experienced above normal runoff also, rather than below normal, given basin memory. Expecting above average flow is hardly synonymous with expecting a historic flood, of course. And, the same statistical inference would have led one to expect 2012 runoff to be high also, when instead, low flow prevailed. Herein lie the indications for increased variability. Thus, alternative explanatory factors of the year-to-year variability, and better potential predictors, of Missouri Basin runoff must be considered.

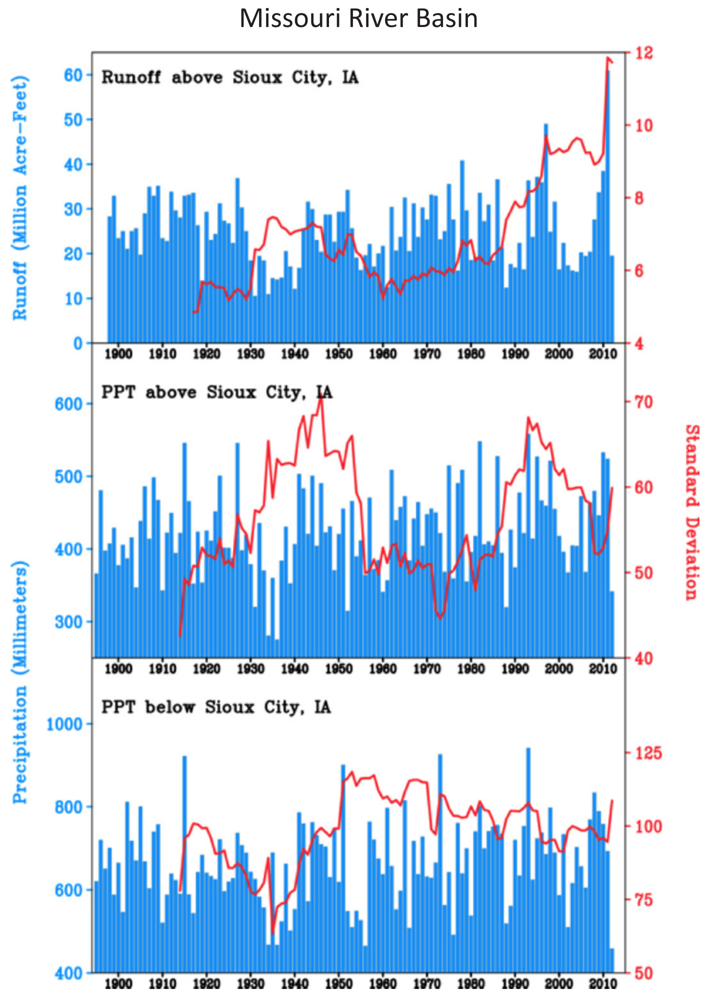


**Figure 5.** Time series of the (top) annual Missouri River runoff (million acre-feet) above Sioux City, Iowa, (middle) annual precipitation (mm) for the Missouri River Basin above Sioux City, and (bottom) annual precipitation for the Missouri River Basin below Sioux City. The runoff time series is 1898-2012 (identical to that in Figure 2), while the precipitation time series is 1895-2012. The standard deviation of annual runoff and precipitation of moving 20-year windows is shown by red curves. The value is plotted at the last year of the moving window; thus the end point for the red curves is plotted for 2012 and denotes the 1993-2012 period. Runoff data source is USACE. Precipitation data source is PRISM.

## C. MISSOURI BASIN ANNUAL CLIMATE VARIABILITY

How much does climate variability determine the statistics of high and low flow occurrences in the Missouri River Basin? A substantial effect can be surmised given the strong link between the seasonal cycle of river flow, and the seasonal cycle of precipitation and temperature. The facts that will be dealt with, based on 115 years of co-variability in runoff and climate, are familiar. If there is any novelty in the analysis to be presented, it rests in the quantification of the separate roles of temperature and precipitation, and the efficacy of each in explaining Missouri River runoff on annual and decadal time scales.

The year-to-year variability in annual flow in the Missouri River above Sioux City is highly sensitive to the prevailing climate conditions over the basin. Foremost, a significant sensitivity exists to year-to-year variability in precipitation delivery to the upper basin (Figure 5, middle). The runoff and upper basin precipitation time series correlate at 0.57 for the 1898-2012 period, indicating that about 30% of the variability in annual flow is explained by variability in annual precipitation (Figure 6, top). Not surprisingly, the correlation of annual runoff is only weakly correlated (0.27) with the annual precipitation falling *below* Sioux City (Figure 5, bottom). In this sense, while floods can have adverse effects throughout the Missouri Basin, there may be little indication for the cause of the flood from the perspective of lower basin inhabitants who are principally aware of their local climate conditions. The source for Missouri Basin runoff above Sioux City is mainly from the precipitation falling in the upper basin. Such was especially the situation in 2011, when lower basin precipitation was not unusual, yet a record flood occurred owing to extreme meteorological conditions over the upper basin.

That the interannual relationship of runoff above Sioux City with precipitation above Sioux City is not stronger, indicates the importance of slower time scales for yearly runoff production. The aforementioned lag-1 correlation of annual runoff (0.33) is an expression of such memory. This memory is not due to a comparable memory in precipitation; the lag-1 correlation of annual precipitation for the upper Missouri Basin is near zero. The Missouri Basin instead acts as a low pass filter such that moisture fluctuations from month to month or season to season may not be as important at the cumulative impact over a year or two. A resulting slow time scale for the hydrologic cycle, owing to the basin's land surface dynamics that integrate moisture delivery over several years, implies that year-to-year surface runoff variability is not solely driven by year-to-year precipitation variability.

Temperature is also a significant factor in the Missouri Basin runoff variability. The runoff and upper basin temperature correlate at -0.45 for the 1898-2012 period (see Figure 6, bottom). About 20% of the variability in annual flow is explained by variability in annual temperature, with cool (warm) years associated with higher (lower) annual discharge. The temperature variability is partly driven by precipitation variability. However, the interannual correlation is only -0.27 in the upper Missouri Basin.

Figure 6 provides a summary of the spatial patterns of correlation between the time series of Missouri Basin runoff and time series of annual precipitation (top) and annual temperature (bottom) throughout basin. Variability

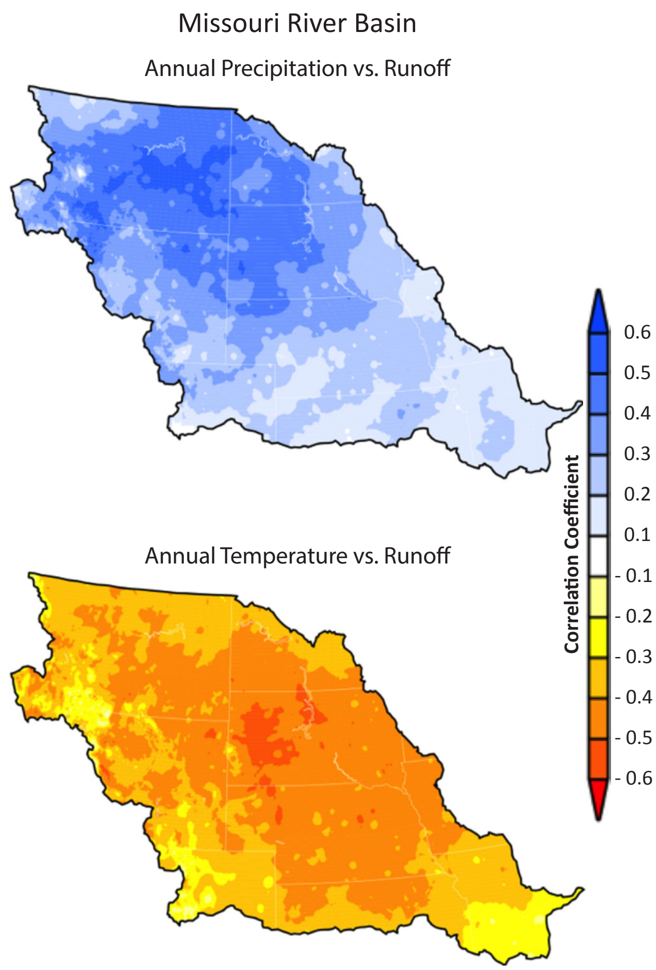


**Figure 6.** The correlation of the 1898-2012 time series of annual Missouri Basin runoff above Sioux City with the time series of annual precipitation (top) and annual surface temperature (bottom). Runoff data source is USACE. Precipitation and temperature data sources are PRISM, available at 4km resolution.

in precipitation delivered over northwest portions of the basin including the elevated terrain of southwest Montana and the plains of eastern Montana exhibit the highest correlation with runoff variability. Little correlation exists between runoff and annual precipitation in the southeast basin. By contrast, the pattern of temperature correlation, besides being of opposite sign, has a different structure with a maximum inverse correlation occurring over the central basin.

As an alternate visualization of the runoff–climate relationship, Figure 7 displays the departure time series of Missouri River runoff (top), precipitation (middle), and surface temperature (bottom), all for conditions above Sioux City. Departures of annual means are computed with respect to the long historical record of each data set. The extreme magnitude of the runoff departure in 2011 is evident, exceeding by over 10 maf the prior record runoff that occurred 1997. By contrast, the annual 2011 precipitation departure in 2011, though not of record proportion, ranked in the top ten wettest years and followed 2010 that also ranked in the top ten wettest years. An examination of runoff relationship with seasonal precipitation, provided in the next section, will further clarify the link between the hydrologic and meteorological extremes of 2011.

Did the 2011 extreme flood occur within a climate regime over the upper Missouri River Basin that was conducive for high flow? The low frequency variations in each time series are highlighted by black curves in Figure 7, which are effectively decadal filter versions of the annual departures. A strong connection between hydrologic and precipitation regimes is evident. Their decadal variations correlate at 0.77 during 1898-2012, appreciably higher than the relationship found on interannual time scales.

The low frequency Missouri Basin runoff is not driven by precipitation alone, however, and the former is also correlated at -0.50 with decadal temperature regimes. This thermal control appears not to be a simple proxy for precipitation in so far as a correlation of the low frequency precipitation and temperature time series is only -0.10. The analysis suggests that runoff efficiency in the upper Missouri Basin is appreciably reduced (enhanced) during warm (cold) epochs. Since the temperature regimes themselves are only weakly linked to precipitation regimes, they can operate somewhat independently as a climate driver of runoff.

Regarding the question posed about whether 2011 occurred within a favorable climate regime for flooding, the above diagnosis for 1898-2012 affirms that regime behavior in runoff is strongly climate controlled. Concerning precipitation, the last several decades have been wet overall, and thus one might have anticipated an increased risk for high flows in 2011. Eight of the ten wettest years in the long historical record have occurred over the upper Missouri Basin in just the last three decades or so. Furthermore, the mean precipitation averaged over this recent epoch has been high compared to the 1930-1960 period. Concerning temperature, this has been a warm epoch, which alone would have led to an expectation for reduced runoff. Eight of the ten warmest years have occurred in roughly the last three decades.

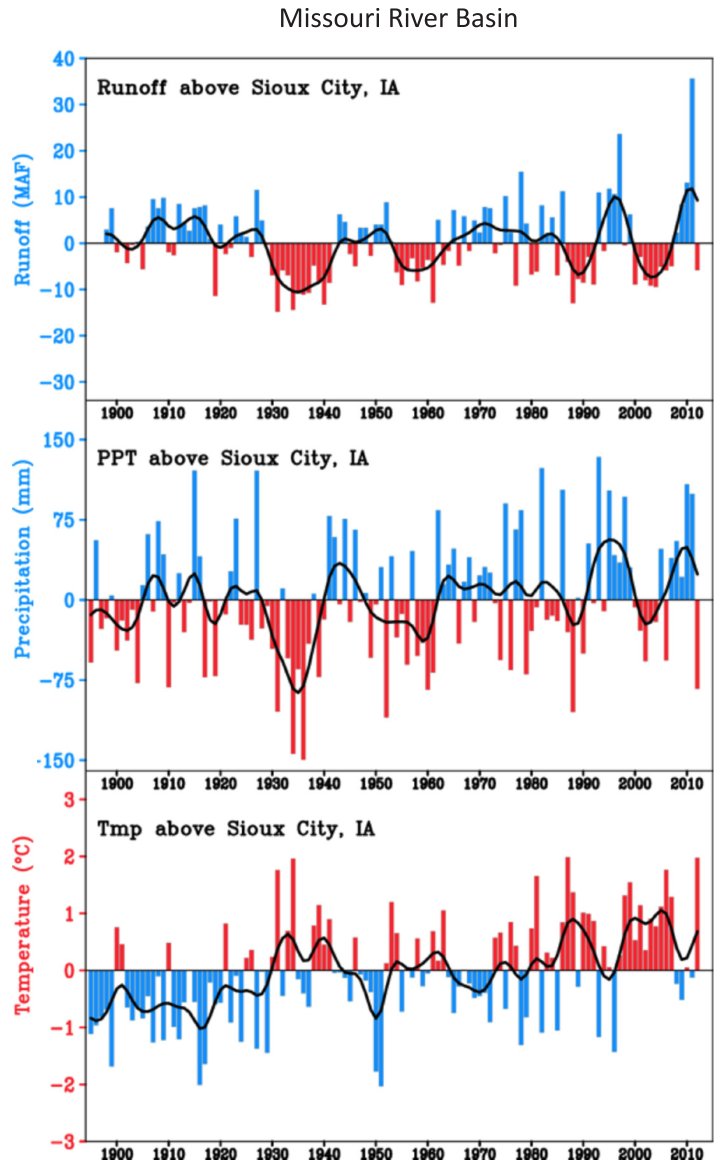


**Figure 7.** Historical time series of departures in annual Missouri River Basin conditions above Sioux City for (top) runoff (maf), (middle) precipitation (mm), and (bottom) surface temperature (°C). Runoff time series spans 1898-2012 and climate time series span 1895-2012. Departures are calculated for the period of record. Black curve shows the 9-point Gaussian filtered low frequency time series.

It is within this multi-decadal climate regime of warm and wet that many of the highest annual flows of the Missouri Basin have occurred. It is also during this warm-wet period in which the year-to-year variability of Missouri Basin flow has greatly increased. A subsequent analysis in Section 8 examines to what extent these prevailing climate conditions of the last 30-years may be symptoms of human-induced climate change.

# 5. SEASONAL CLIMATE VARIABILITY RELATED TO MISSOURI RIVER BASIN RUNOFF

Whereas several factors contributed to the 2011 record runoff in the Missouri Basin, the occurrence of record rains in spring were certainly the last, and perhaps most important, in the sequence of unfortunate climate events. As a prelude to assessing the cause for these record spring rains in the Upper Missouri Basin, Figure 8 presents an analysis of the historical (1898-2012) relationship between annual Missouri River basin flow above Sioux City and seasonal precipitation variability. The diagnosis considers a 12-month period spanning the antecedent late summer and fall seasons, in addition to the subsequent seasons during the calendar year for which the annual runoff was recorded.

Not surprisingly, a positive correlation of seasonal precipitation with annual runoff above Sioux City exists in all seasons (see Figure 6), being strongest for precipitation falling in the upper basin. Perhaps more novel is the result that annual runoff is most sensitive to precipitation occurring from late fall into early winter, but rather insensitive to precipitation falling in late winter. The results stress the importance of the seasonal snow cover buildup. The late fall maximum includes the high elevations of the northwestern basin where total precipitation can be high, but also a high correlation in the plains region where precipitation tends to be seasonally low. Both are likely precursor indicators for subsequent annual runoff that is fed by snowmelt. By comparison, there is much weaker correlation between February–April precipitation with annual runoff, excepting the Wyoming Rockies. A dramatic increase in correlation occurs for the next immediate season of March–May, indicating that May rainfall in the upper Missouri Basin is a key contributor to annual Missouri flow variability. The overall maximum relationship is with May–July rainfall, which of course is also the peak in the annual cycle of total rainfall (see Figure. 4).

The correlation analysis for temperature reveals that colder temperatures in all seasons are associated with high annual runoff (Figure 9). There is once again seasonality to this relationship; temperature variability in late fall and late spring being most strongly correlated with annual runoff. While the analysis reveals temperature variability to be at least as important as precipitation variability in those seasons in a correlative sense, it is likely that the magnitude of annual runoff variability is more strongly determined by precipitation, though the quantitative relationships require further analysis.

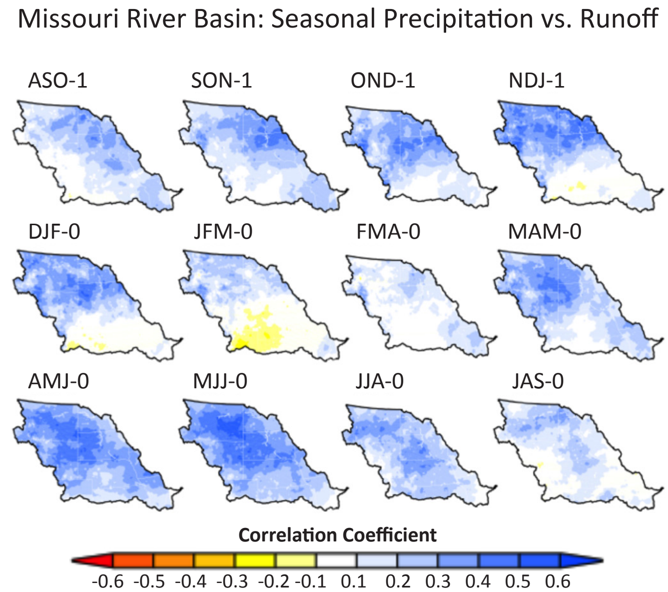


**Figure 8.** The correlation of seasonal precipitation in the Missouri River Basin with the time series of Missouri Basin annual runoff above Sioux City. Top left panel is for August-October of the summer preceding annual runoff (ASO-1), while bottom right panel is for July-September of the coincident summer of annual runoff (JAS-0). High precipitation/high flow relationship (positive correlation) is indicated by blue shades. Missouri Basin annual runoff time series is from USACE (see Figure 5). Precipitation data source is PRISM.

Overall, results of Figures 8 and 9 are consistent with simple physical considerations of how Missouri River annual runoff is expected to respond to climate variability. There is some novelty to the finding of a lack of importance for mid-late winter temperature and precipitation variability, especially relative to a much greater importance of late fall and late spring climate conditions. Also somewhat unexpected is the stronger correlation of annual runoff with temperature than with precipitation in several seasons. It is worth noting that temperature and precipitation over the upper Missouri Basin are not well correlated during the fall and winter, whereas they are strongly correlated in late spring and summer (not shown). As such, fall temperature information likely constitutes a driver (and potential predictor) of basin runoff, that is mostly independent of precipitation. These results suggest that climate outlooks for late fall precipitation (especially over the western basin) and late fall temperature (over the upper basin as a whole) may be especially valuable in operational decision making related to Missouri Basin water resource management. Of course, as the analysis also confirms, foreknowledge of late spring rains in the upper basin would be of particular importance. Such a prediction would need to be generated at long leads (9-months in advance) in order to maximize its value for many reservoir management decisions.

Long-lead seasonal predictability of Missouri Basin annual runoff, if its exists, will most likely emerge from a regional sensitivity to slow variations in global sea surface temperature (SST). Is the annual flow in the Missouri River strongly constrained by ocean conditions? To assess the probable strength of ocean effects over the last 115-year period in general, Figure 10 presents the correlation of the 1898-2012 Missouri Basin annual runoff time series with seasonal SSTs. The dominant feature is one in which cold states of the tropical Pacific, sometimes referred to as La Niña, relate to high annual flow years in the Missouri. Analysis of model simulations affirms that this La Niña relation is one of causality (see section 7). The Pacific-wide pattern of SSTs associated with high flow resembles a horseshoe with cold equatorial east Pacific encircled by warm tropical west Pacific and warm extratropical North Pacific waters, and then also with stronger cold waters along the coast of North America. This overall structure describes the so-called Pacific decadal (PDO) mode of variation (Mantua et al. 1997) for which empirical evidence suggests a Pacific and North American impact (e.g., Biondi et al. 2001; McCabe et al. 2004). Although modeling evidence cautions that the PDO itself may have more diagnostic rather than prognostic power (e.g. Kumar et al. 2013). In addition to a Pacific relationship, Figure 10 also reveals that cold states of the North Atlantic are correlated with high flow. The consistency of this relationship across all seasons suggests a relation to multi-decadal Atlantic SST variability. In spite of these relationships with both Pacific and Atlantic SSTs, it must be concluded that the annual flow in the Missouri River above

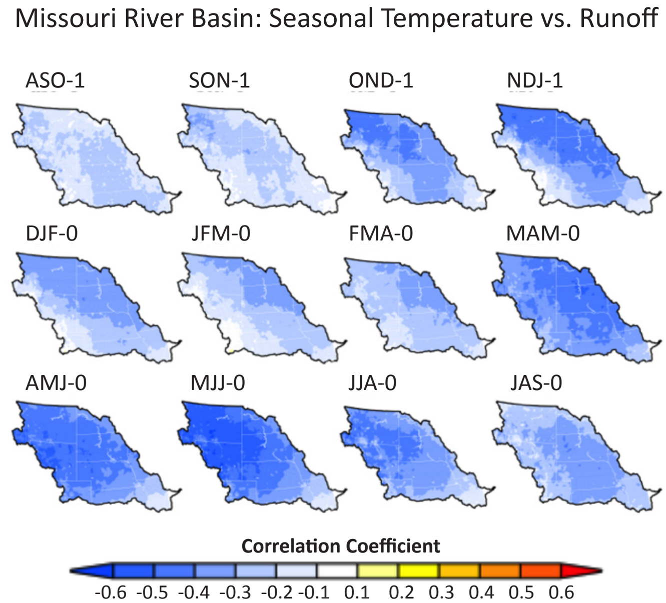


**Figure 9.** Same as Figure 8 except for the correlation of seasonal temperature in the Missouri River Basin with the time series of Missouri Basin annual runoff above Sioux City. Note the reversal of the scale, such that a cold temperature/high flow relationship (negative correlation) is indicated by blue shades.

Sioux City is not strongly constrained by ocean conditions and have little overall explanatory power as suggested by weak overall correlations of only -0.2.

The physical process by which remote SSTs can affect annual Missouri River flow is via atmospheric teleconnections that act to redirect the storm tracks, especially in winter. Figure 11 shows the seasonal 500 mb (steering level for storms) circulation patterns most strongly linked with hydrologic variability over the upper Missouri Basin. The patterns are quite familiar, having low pressure near and just west of the basin, which would imply a favorable trajectory for cyclones to deliver moisture into the region. In winter, this pattern has connections to the tropical Pacific, a feature of the planetary waves that occur in concert with La Niña/El Niño events. There is also indication for a link to circulation over the North Atlantic during late fall, with the north-south dipole pattern in the heights suggestive of the North Atlantic Oscillation (NAO). It is unclear from this diagnosis alone whether the NAO is an independent atmospheric mechanism driving annual Missouri River Basin flow, or is merely a symptom of a planetary scale wave pattern that ultimately links to Pacific Ocean variability.

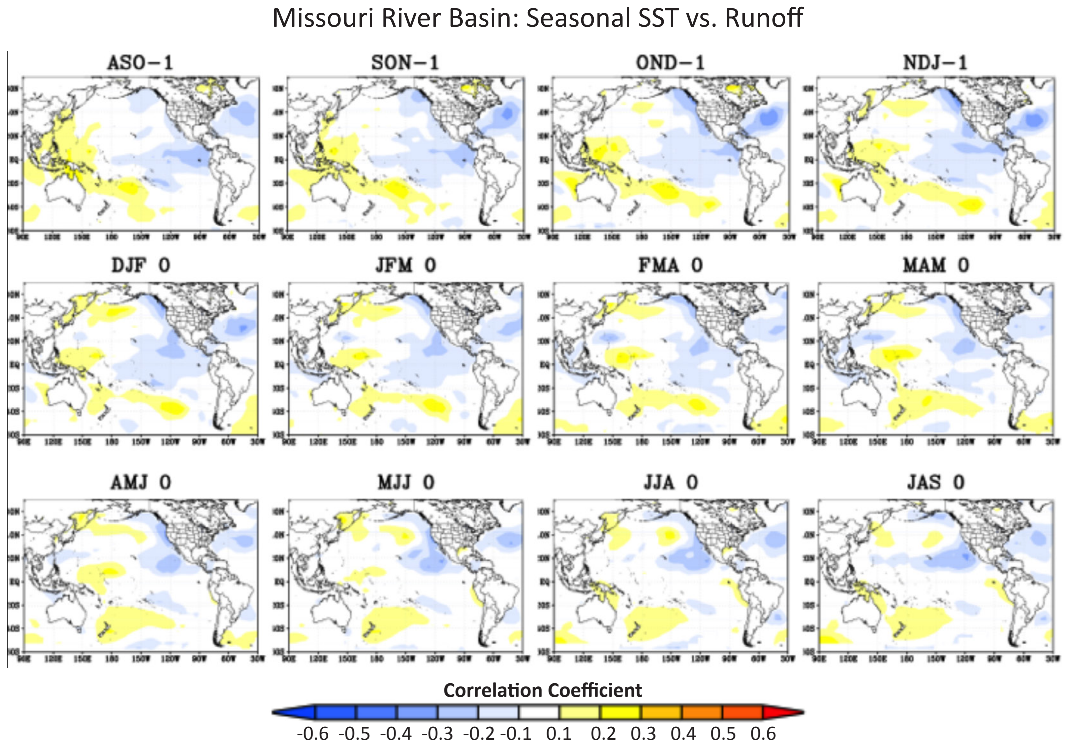


**Figure 10.** Correlation of seasonal sea surface temperature with the time series of Missouri Basin annual runoff above Sioux City. Cold sea surface temperature/high flow relationship (negative correlation) is indicated by blue shades. Period of analysis is 1898-2012. Sea surface temperature data is based on NOAA MLOST data set.

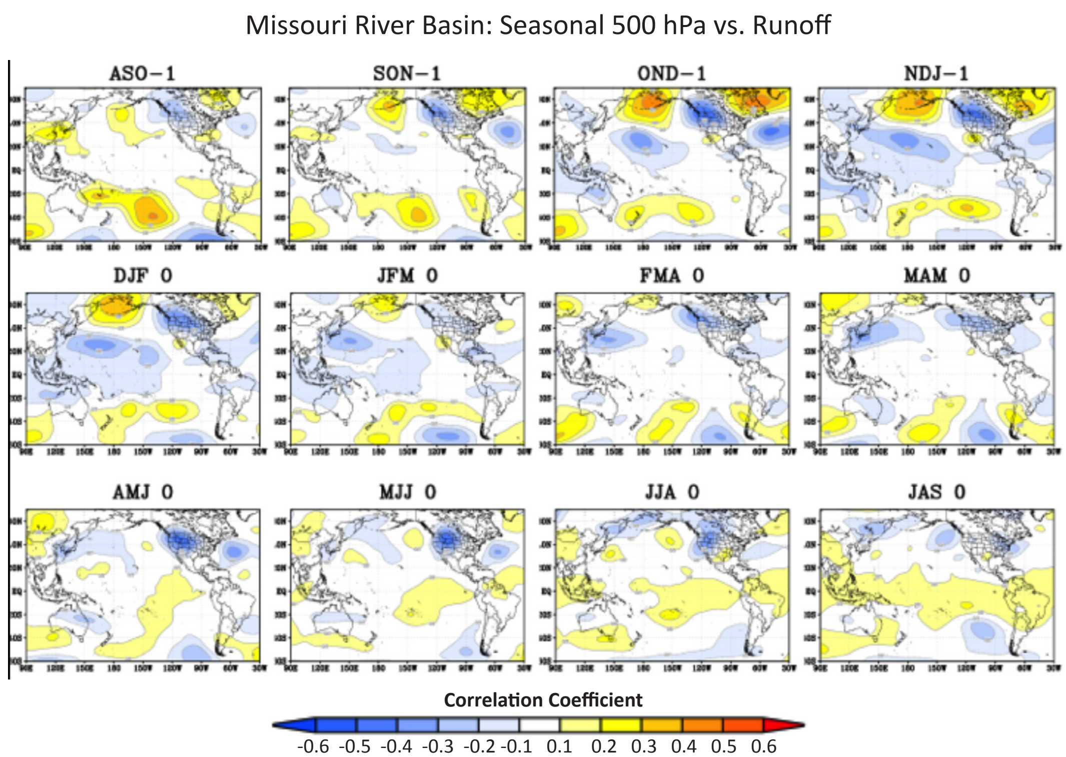


**Figure 11.** Same as Figure 10 except for the correlation of seasonal 500 mb heights with the time series of Missouri Basin annual runoff above Sioux City. Low pressure/high flow relationship (negative correlation) is indicated by blue shades. Period of analysis is 1948-2012. The 500 mb height data is based on NCEP/NCAR reanalysis.

# 6. OBSERVED 2010–2011 CLIMATE CONDITIONS

The prevailing wet and cold environment in which the 2011 flooding emerged had been extensively documented in prior assessments. The results herein add to that body of knowledge by demonstrating that the detailed temporal and spatial patterns of the climate conditions projected on the most sensitive structures for runoff production above Sioux City. Each and every season from summer 2010 until summer 2011 had above normal precipitation in the upper basin (Figure 12). Especially noteworthy were departures more than double their climatological normal over portions of the upper basin during late fall/early winter and again during spring. These are the specific seasons and the particular regions for which precipitation delivery to the Missouri Basin induces the largest response in annual runoff above Sioux City (Figure 8).

Sandwiched between the warm summer seasons of 2010 and 2011, the fall through spring temperatures were markedly colder than normal over the plains region of upper basin (Figure 13). These late fall cold conditions over the high plains were co-located with the area of maximum annual runoff correlation with temperature (see Figure 9). Likewise, the cold upper basin spring conditions during 2011 are a feature strongly correlated with high annual runoff historically, though recognizing that the cold in spring is itself a classic symptom of above-normal precipitation. The cool and wet conditions across the upper Missouri Basin in 2010-11 were those expected from the upper tropospheric circulation patterns observed during the period (Figure 14). The anomalies in all seasons consisted of low pressure anchored over the Pacific Northwest. This is the particular atmospheric flow configuration that is correlated with high Missouri River Basin runoff above Sioux City in the historical record (see Figure 11). The persistence and strength of this pattern was central to the organization of surface meteorological conditions across the Missouri Basin from which the record flood emerged.

Atmospheric circulation generally exhibits little memory from one season to another without an external constraint, for instance involving persistent ocean forcing. While an unusual situation of random atmospheric noise alone

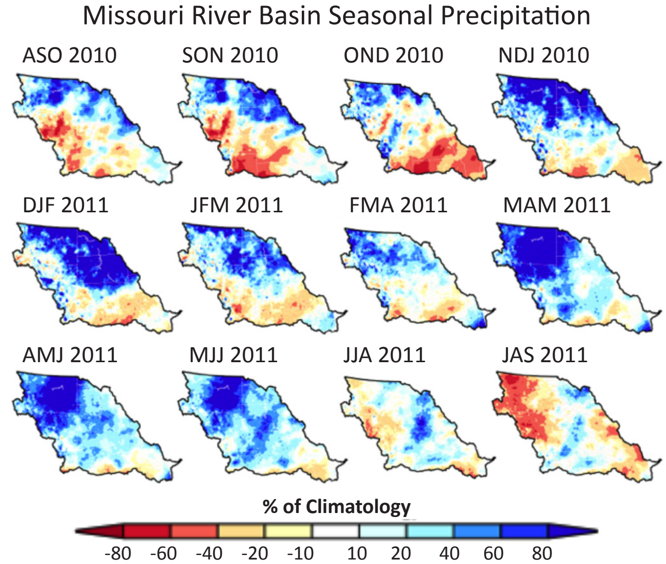


**Figure 12.** Observed Missouri Basin seasonal precipitation departures (% above or below climatology) from August-October 2010 (top left) through July-September 2011 (lower right). Anomalously wet (dry) areas denoted in blue (red) shades. Climatological reference is period of record 1895-2012. Precipitation data source is PRISM.

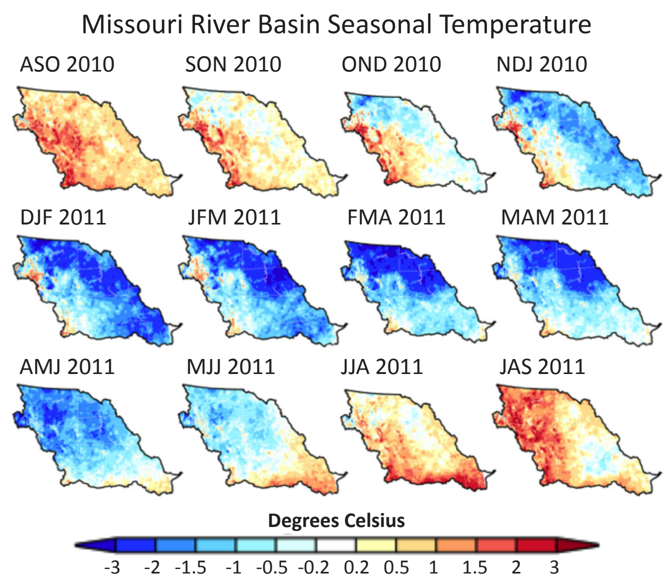


**Figure 13.** Same as Figure 12 except observed seasonal temperature departures (°C). Anomalously cold (warm) areas denoted in blue (red) shades.

cannot be ruled out as a factor for the enduring circulation regime of 2010-11, it is noteworthy that the state of the world oceans in 2010-11 was itself quite anomalous and persistent. Cause-effect relationships, and the implied

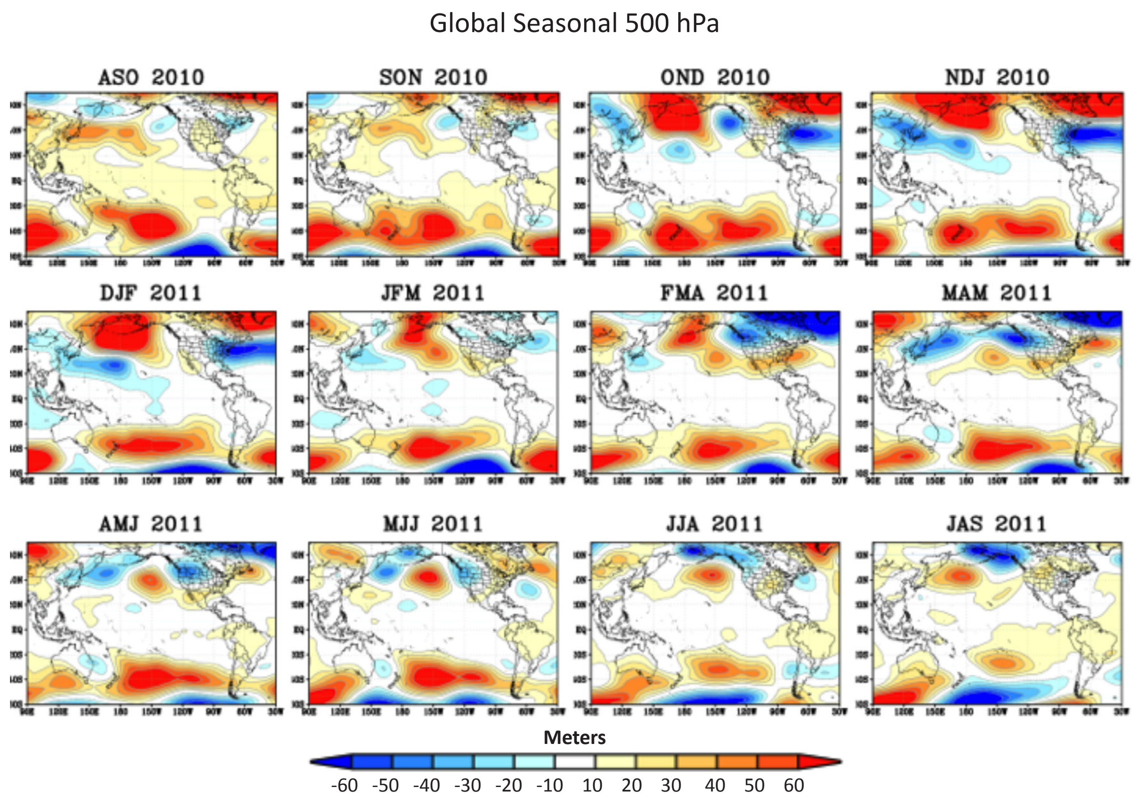


**Figure 14.** Observed seasonal 500 mb height anomalies (m) for August-October 2010 (top left) through July-September 2011 (lower right). Anomalously low (high) pressure areas denoted in blue (red) shades. Departures are relative to period of record 1948-2012. The 500 mb height data is based on NCEP/NCAR reanalysis.

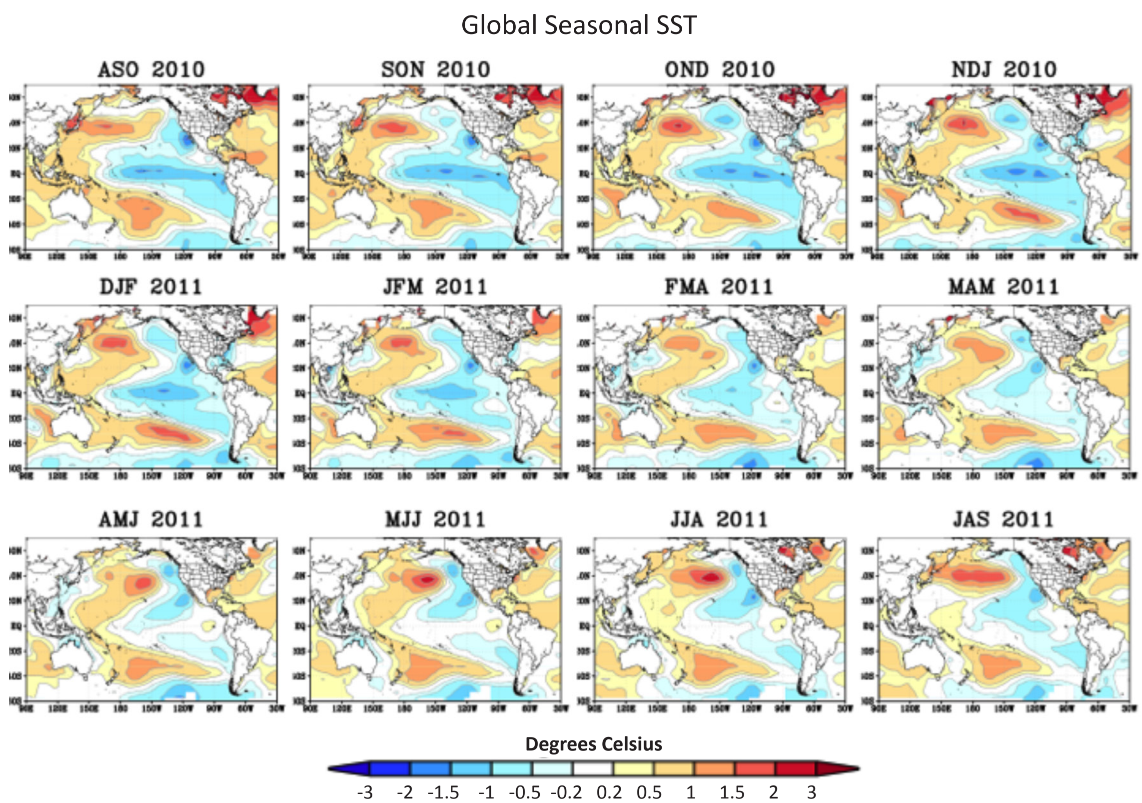


**Figure 15.** Same as Figure 14 except for the seasonal sea surface temperature anomalies (°C) Anomalously cold (warm) areas denoted in blue (red) shades. Departures are relative to a 1971-2000 reference. Sea surface temperature data is based on NOAA MLOST data set.

predictability, are addressed in Section 7. Here it suffices to note, from the empirical evidence alone, that the SST anomalies during 2010-11 were of a type conducive for higher, rather than lower, annual runoff over the upper Missouri (compare Figures 10 and 15). Summer 2010 SSTs already displayed features of the canonical leading Pacific basin pattern of natural variability (the negative phase of the Pacific decadal mode) configured in a classic horseshoe structure of warm SST departures in the west and North Pacific wrapped around a belt of cold departures in the tropical east Pacific. NOAA hoisted a "La Niña Watch" on 8 July 2010, and quickly upgraded that to a "La Niña Advisory" on 5 August (NOAA 2010a,b). In its 7 October 2010 statement, NOAA expected that La Niña was likely to last at least into spring 2011 (NOAA 2010c). Overall, the seasonal timing and the strength of the La Niña were typical of prior events occurring in the historical record.

# 7. SIMULATED 2010–2011 CLIMATE CONDITIONS

## A. THE FORCED COMPONENT

The model simulated, ensemble averaged seasonal precipitation departures over the Missouri Basin during 2010-2011 are shown in Figure 16. These can be compared to the observed precipitation departures (Figure 12), noting that the contour interval for the 40-run average is half that shown for observations. The model's forced component (i.e., the signal due to ocean forcing in particular) is dominated by a dipole having wet upper basin and dry lower basin conditions. Such a dipole signal, especially prominent in winter, mimics the observed anomalies and indicates that the wet conditions above Sioux City were unlikely due to random atmospheric variability alone in winter. As will be shown subsequently, upper Missouri Basin wintertime wet conditions are *qualitatively* consistent with statistical effects of La Niña; however, the extreme intensity of the observed wet conditions in winter and then especially in spring 2011 are not explained by remote ocean forcing alone. Note that the model's winter wet signal over the upper portion of the basin is 10% above climatology, which is an order of magnitude weaker than the observed wetness whose departure was more than double climatology. *In this sense, the intensity of rains over the high plains could not have been readily anticipated even had there been perfect foreknowledge of ocean conditions.*

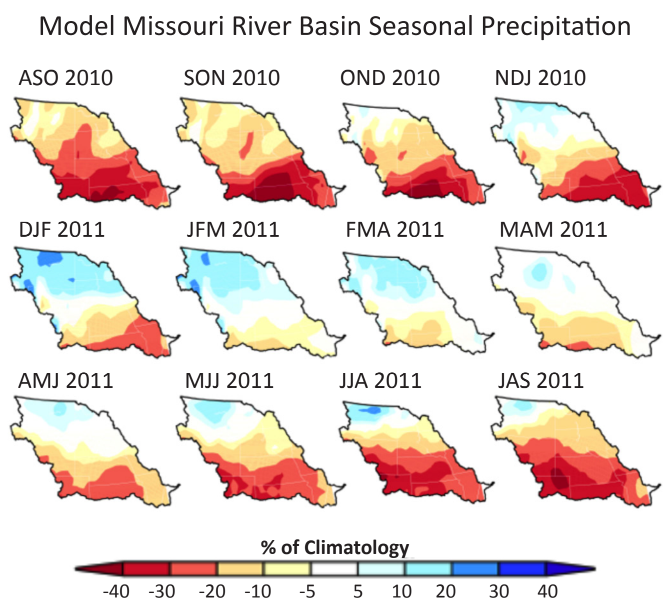


**Figure 16.** Model simulated Missouri Basin seasonal precipitation departures (% above or below climatology) from August-October 2010 (top left) through July-September 2011 (lower right). Anomalously wet (dry) areas denoted in blue (red) shades. Climatological reference is based on the ECHAM5 model simulation period of record 1979-2012. Precipitation data is based on the 40-member ensemble averaged of the ECHAM5 simulations.

The model's forced temperature signal (Figure 17) was warm through early winter 2011, and then became cold in late winter and spring especially over the upper basin. This signal's evolution in time, and its spatial structure over the Missouri Basin agree very well with observations (see Figure 13). Once again, the magnitude of the cold signal was appreciably weaker than observed in the upper basin, being about -1°C compared to the greater than -3°C departures observed in winter and spring.

The forced component of Missouri Basin surface climate conditions were the immediate consequence of a forced teleconnection pattern in upper air circulation that linked tropical latitudes with middle latitudes during the La Niña event. Figure 18 shows this forced component in 500 mb height departures, from which a wave train emanating out of the tropical central Pacific and arching over North America is readily seen in all seasons. A mirror of this pattern can be seen in the southern hemisphere thereby affirming an equatorial Pacific root as the source region, which was primarily the anomalously cold equatorial Pacific Ocean.

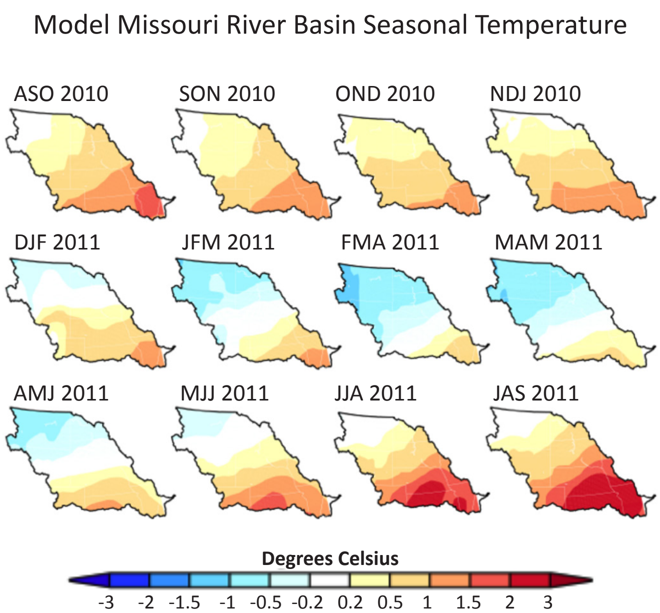


**Figure 17.** Same as Figure 16, except the model simulated Missouri Basin seasonal temperature departures (°C). Anomalously warm (cold) areas denoted in red (blue) shades. Climatological reference is based on the ECHAM5 model simulation period of record 1979-2012. Temperature data is based on the 40-member ensemble averaged of the ECHAM5 simulations.

These describe a well-known canonical sensitivity of global climate to La Niña (e.g. Hoerling and Kumar 2002).
The model thus affirms that the persistence of an atmospheric circulation regime, from late summer 2010 through spring 2011, was at least in part a symptom of persistent forcing, a feature for which there is considerable long lead predictability.

Persistence of atmospheric low pressure created a climate regime favorable for above normal precipitation over the upper Missouri basin especially in winter. Yet that alone would not have created the meteorological conditions for *record flooding*. It is particularly apparent that the observed extreme intensity of springtime low pressure over the Pacific Northwest cannot be reconciled with forcing alone.

## B. PROBABILISTIC COMPONENT AND TAIL RISK

How did remote forcing change the probabilities for seasonal climate conditions over the Missouri Basin in 2011? In particular, was there an increase in so-called "tail risk" for unusually heavy precipitation? Because these are very rare and infrequently (if at all) observed conditions, the tail probabilities are not well known. Even more difficult to know is how tail risk may change under the influence of some constraint, such as the La Niña event that occurred in 2011.

One of the attributes of model-based analyses is the capability to generate ensembles that can permit analysis of the change in probabilities. It is important to recognize that these probabilities cannot be readily verified from the observations, however, and that different models may yield different results especially regarding tail risks. There are nonetheless some diagnoses that help to address model suitability, the simplest being the comparison of observed variations against the statistical spread of ensemble model simulations. The box-whisker display of the full model distributions of 40-simulations for each season during 1979-2012 is shown in Figs. A2 and A3 for seasonal precipitation and temperature, respectively, and green circles are superposed denoting the observed seasonal departures. A rudimentary assessment reveals that the observations almost always reside within the model spread, suggesting the model's overall variability is likely realistic. It is also apparent that extreme climate states are a basic feature of the probability space of the model ensemble in each and every season, and that the extreme observed rainfall anomaly that occurred over the upper Missouri Basin in 2011 has a certain (small) risk of occurring in any year, regardless of SST forcing.

A total of 40 simulations, as is available in this assessment, is still inadequate to fully describe the statistical distribution for any single year, such as 2011. To mitigate the sampling problem, the simulations conducted for other seasons that also experienced similar La Niña forcing are merged in order to form a larger population drawn from analogous samples of boundary forcing. This approach also facilitates an assessment of whether the ocean-forced signal in 2011 was materially different from that expected of a population of Missouri Basin climate statistics drawn from prior, canonical La Niñas.

Figure 19 shows frequency distributions of model simulated upper Missouri Basin December-February precipitation for a collection of six prior historical La Niña conditions (red curve), and six historical ENSO-neutral conditions (green curve). Each PDF thus is comprised of 240 samples. The distribution of the 40-runs for 2011 is plotted separately on the abscissa (black bars). Also plotted on the abscissa are the observed upper Missouri Basin precipitation departures for those same prior six La Niñas (red bar), and the 2011 value (long black bar). The increased wintertime risk of wet conditions during La Niña is evident by the shift in the distribution, with a mean increase +4.4%. The model simulated 2011 mean departure is +5.3%, and is thus consistent with the canonical model La Niña signal. Observed precipitation during the prior six observed La Niñas mostly span the model distribution, ranging from -30% of normal to about +20% of normal, with some slight increased risk of wet as a most probable condition (A larger sample of historical La Niñas, extending to 1900, also exhibits a wintertime mean wet signal over the upper Missouri Basin). However, the observed 2011 extreme wet conditions, having nearly a +60% departure, are clearly unusual relative to recent observed occurrences of La Niña events. The 2011 wetness is also rare relative to the model's historical La Niña distribution.

The overall shift in the model's La Niña distribution toward wetter conditions, even though being an only modest mean increase, leads to a substantial increase in tail probabilities. To illustrate, consider an arbitrary threshold of an event having a magnitude of about a 1.5 standardized departure (roughly +30% above normal), which exceeds the highest observed departure among any of the prior six La Niña winters. A visual comparison of the two model PDFs reveals that the odds of exceeding such a threshold under La Niña forcing increases relative to ENSO-neutral conditions. Thus, it is reasonable to suspect that the odds of heavy winter precipitation in 2011 were elevated. Of course, this evidence for an increase in *relative* probability must be tempered by the fact that the *absolute* probability for such an event remained low.

Model Global Seasonal 500 hPa

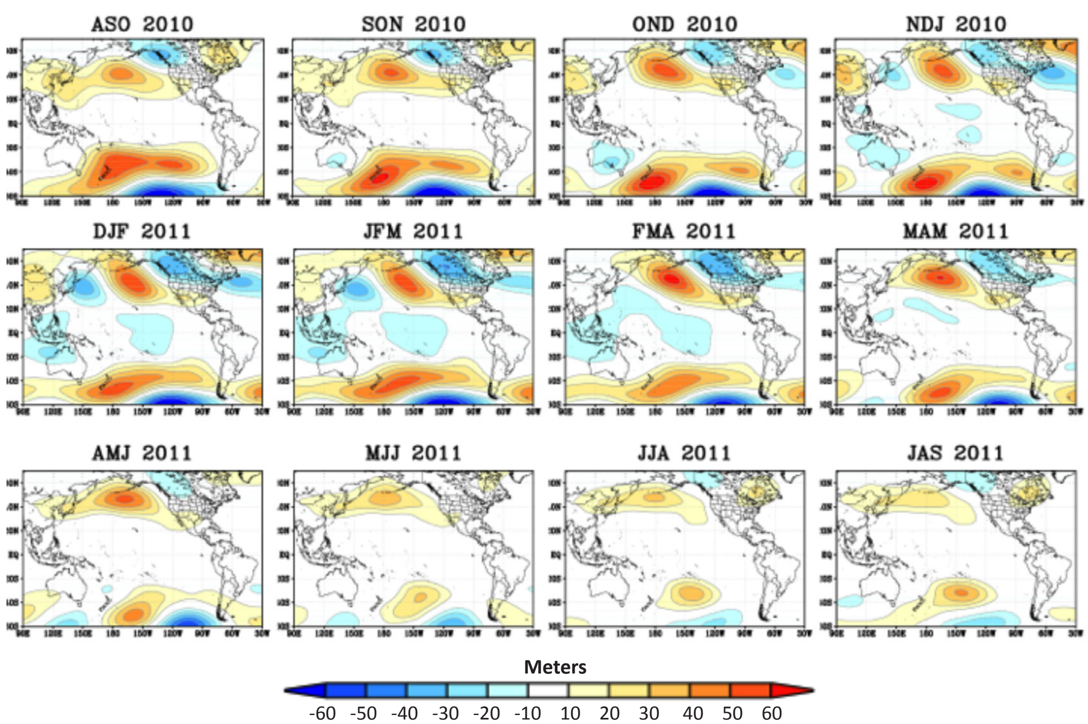


**Figure 18.** Model seasonal 500 mb height anomalies (m) for August-October 2010 (top left) through July-September 2011 (lower right). Anomalously low (high) pressure areas denoted in blue (red) shades. Climatological reference is based on the ECHAM5 model simulation period of record 1979-2012. Temperature data is based on the 40-member ensemble averaged of the ECHAM5 simulations.

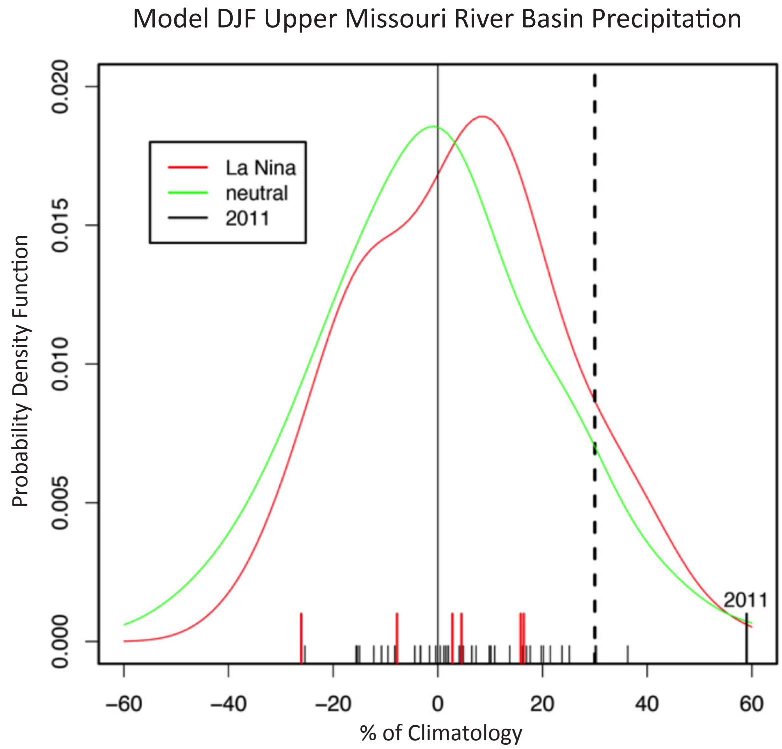


**Figure 19.** The probability distribution functions (PDFs) of upper Missouri River Basin winter (December-February) model simulated precipitation departures (% above or below normal) for ENSO-neutral conditions (green curve) and for La Niña conditions (red curve). The neutral years are 1979/80, 1981/82, 1983/84, 1990/91, 2004/05, and 2008/09. The La Niña years are 1984/85, 1988/89, 1995/96, 1998/99, 1999/00, and 2007/08. The observed wintertime precipitation departures for these 6 La Niñas are shown by the long red bars. The short black bars show the model simulated precipitation departures for 40-members of the 2010/11, and the long black bar is the observed departure for winter 2010/11. Each PDF is comprised of 240 winter samples (40 simulations per case). The curves are non-parametric smoothed fits to the raw frequency distributions. Dashed line denotes +30% above normal.

Whereas these antecedent wet and cold conditions in the upper basin likely saturated the land surface to near its moisture holding capacity, subsequent record setting spring rains over the high plains almost certainly loaded the region far beyond that capacity. Yet, there is little effect of La Niña on spring climate conditions averaged over the upper Missouri Basin, even though a discernible effect does exist for winter. Neither a mean wet signal nor an increased risk for heavy seasonal rains occurs in the spring simulations for the upper basin during La Niña. Figure 20 shows the La Niña and ENSO-neutral PDFs for April-June conditions, from which a slight dryness (median is -6%, mean is -4%) during La Niña is instead apparent. Outwardly consistent with this is the fact that 4 of the prior 6 observed La Niña springs (red bars) were drier than normal in the upper basin. The model distribution of 40-members for the actual 2011 forcing conditions (median -6%, mean is 0%) is not materially different from its historical La Niña distribution. Further comparison of the two model PDFs reveals that the odds of exceeding a 1.5 standardized departure (roughly +30% above normal, and greater than any observed wet departure during the prior 6 La Niñas) is statistically indistinguishable for ENSO-neutral and La Niña conditions.

What then is the interpretation of the cause for the very heavy rains in spring 2011 whose cumulative effects were critical for provoking a runoff surge and flooding of the Missouri River? The rains were almost certainly not a consequence of the anomalous global ocean conditions operating during 2011, and thus they could not have been anticipated at long leads to facilitate early warning. By all indications presented herein, the rains were instead an occurrence of an intense random atmospheric variation, whose immediate cause was strong atmospheric low pressure over the Pacific Northwest but which had no further causal chain. It is not uncommon that extreme meteorological events do not result from extreme forcing per se (e.g. SST, greenhouse gas changes), as has also recently been emphasized in the case of the central Great Plains 2012 drought (Kumar et al. 2013). The model results for spring 2011 indicate that the extreme upper Missouri Basin rains were an event having very low, but non-zero probability of occurrence. La Niña did not materially alter those odds. *In this sense, neither the NOAA La Niña Alert Status (hoisted in late 2010) nor subsequent exact knowledge of the details of the ocean conditions (had that been available) would have forewarned of extreme heavy spring rains.*

How is one to interpret the fact that at least one of the model's 40 members yielded spring rains more extreme than observed; is this not some proof of a more "predictable cause" than has been summarized above? Indeed, two of the ensemble members generated wet conditions close to the observed extreme value (see the abscissa of Figure 20). Yet, this merely affirms the model capacity for simulating such extreme events; comparably strong and equally rare extremes occur in large population samples regardless of the ocean conditions, as was revealed by the 1979-2012 box-whisker analysis (see Figure A2). Such extremes are merely the expected property of chaotic dynamic systems, which support a wide statistical distribution of seasonal rainfall probabilities even in the absence of oceanic forcing. The results of this analysis indicate that extreme wet probabilities for spring 2011 were not greatly different from extreme dry probabilities (see Figure 16, though a slight skewness of the rainfall PDFs to a "fat wet tail" does reveal a natural inclination toward extreme wet relative to extreme dry). *In this sense, spring 2011 could have been very different from what actually happened over the upper Missouri Basin due to the vagaries of random variability alone which substantially determined the 2011 conditions, as opposed to the effects of oceanic (or other) forcings which were weak.*

Is climate becoming more extreme, and if so, why? How

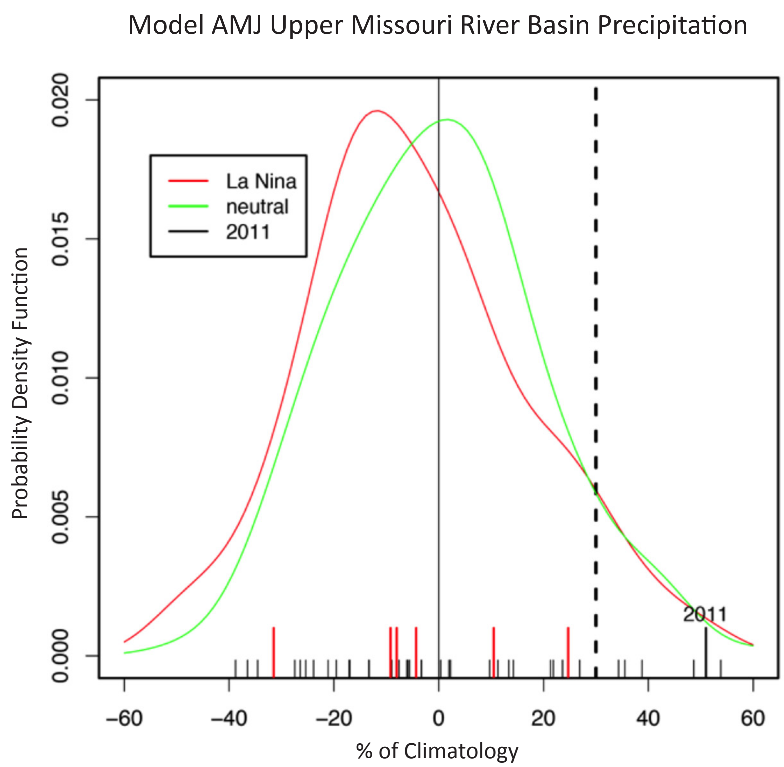


**Figure 20.** Same as Figure 19 except for spring (April-June) precipitation over the upper Missouri River Basin. The neutral years are 1980, 1982, 1984, 1991, 2005, and 2009. The La Niña years are 1985, 1989, 1996, 1999, 2000, and 2008. The spring observed precipitation departures for these 6 La Niñas are shown by the long red bars. The short black bars show the model simulated precipitation departures for the 40-members of spring 2011, and the long black bar is the observed departure for spring 2011. Dashed line denotes +30% above normal.

# 8. A CENTURY OF CLIMATE CHANGE OVER THE MISSOURI RIVER BASIN

has human-induced climate change affected individual extreme events? These are among the physical science questions that were addressed in the recent IPCC assessment report on managing the risks of extreme events (IPCC 2012). The report states, "*many extreme weather and climate events continue to be the result of natural climate variability. Natural climate variability will be an important factor in shaping future extremes in addition to the effects of anthropogenic changes in climate*". Such a view is consistent with this report's assessment that upper Missouri Basin weather and climate conditions during 2010-11 were not strongly constrained by forcing, and that the very heavy spring 2011 rains which fell above Sioux City were principally a consequence of random atmospheric variability. Nonetheless, the question of long-term change continues to be a matter of ongoing research, especially at regional scales. A particular open question, which is beyond the scope of this assessment, is the cause for increased variability in runoff in the upper Missouri Basin, and whether this represents a new normal for hydrology in the basin.

What is the observational evidence for climate change and changes in extremes over the U.S.? Most notably, since 1950, there has been an increase in warm days and warm nights, with an overall decline in the number of cold days and cold nights. At the global scale, the IPCC (2012) assesses that it is likely the human-induced climate change has led to warming and increases in warm extremes, though attribution is less confident at regional scales. Despite the difficulty at present in confidently attributing regional warming, the cold winter/spring conditions over the Missouri Basin in 2011 were certainly contrary to longer-term observed warming trends, and most likely inconsistent with a plausible human-induced warming temperature signal of climate change.

Concerning precipitation, the IPCC expresses medium confidence in the evidence for an observed increase in heavy daily precipitation since 1950 over western North America. The IPCC also expresses medium confidence

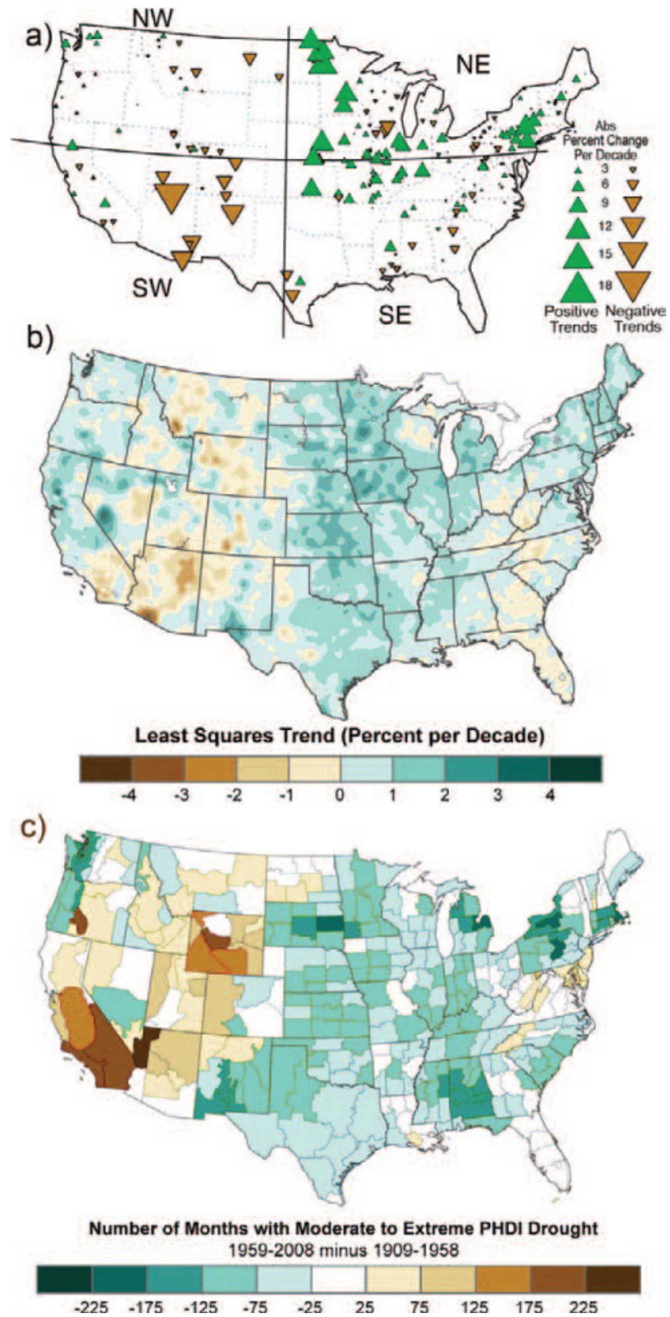


**Figure 21**. The geographic distribution of century-scale changes in (a) flooding, (b) precipitation, and (c) droughts. In (a), the triangles are located at 200 stream gauges, which have record lengths of 85–127 years. The analysis compares observed 50-year averages for the recent 1959-2008 period to the prior 1909-1958 period. From Petersen et al. (2013).

that, at a global scale, anthropogenic influences (primarily related to greenhouse gas increases) have contributed to such intensification of extreme precipitation. The question of land use change effects on precipitation is unresolved and constitutes an area of active research. Quantifying the contribution of human-induced climate change to individual events remains challenging, almost certainly more so for precipitation and related hydrologic events than for temperature events. Part of the issue is that precipitation and hydrologic variations exhibit strong decadal variability (relative to the magnitudes of long-term trends) making even the detection (let alone the attribution) of a statistically significant change difficult.

Peterson et al. (2013) assessed the state of knowledge on changes in heat waves, cold waves, floods, and droughts in the United States over the century-long time scale. This study significantly extends the period of assessment examined by the IPCC (2012, which was for the post-1950 period only) and also focuses exclusively on the U.S. Figure 21 (reproduced from Figure 3 of Peterson et al.) shows an estimate of century-long change in the peak annual river floods (top) for about 200 stream gauges having about a century of records. Their analysis reveals a positive trend in the peak annual flow on the Missouri near Sioux City, as one might infer visually from inspecting the time series of annual runoff for the Basin (see Figure 2). The increased annual runoff near Sioux City has been consistent with a trend toward greater precipitation especially over the Dakotas, northern Iowa, and western Nebraska (Figure 21, middle) and a commensurate reduction in number of drought months (Figure 21, bottom).

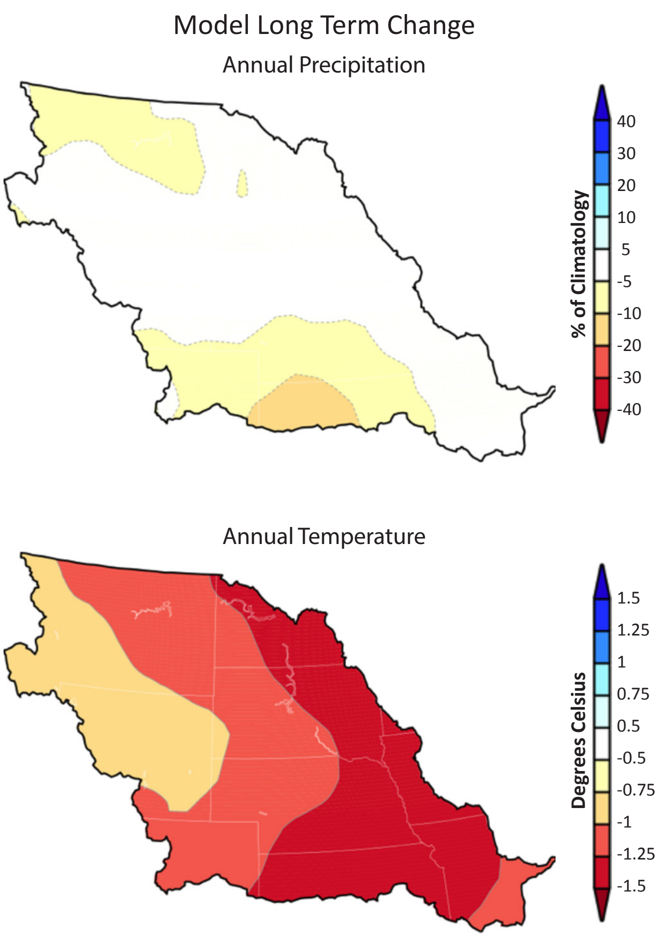


**Figure 22.** The simulated change in annual precipitation (% change relative to 1881-1910 climatology, top) and annual surface temperature (°C, bottom) for the period (1981-2010) relative to the period (1881-1910). Based on time-slice simulations of ECHAM5 forced with the 30-year averaged SSTs, sea ice, and GHG concentrations of each period. Results derived from a 300-year long simulation for each of the two periods.

However, the hydro-climate conditions that led to 2011 flooding was not of the archetype that has produced a century-long increase toward high peak annual flows on the Missouri River near Sioux City. It is apparent based on analysis in this report that the anomalous precipitation pattern in the upper Missouri Basin associated with the 2011 flood event is considerably different from the trend pattern in Peterson et al. Most of the moisture source for the runoff in 2011 was in the high plains of Montana, especially in spring 2011, where the Peterson et al. analysis actually shows a slight decline in annual moisture over the past century. In the same sense, the major tributaries feeding into the mainstem of the Missouri, especially the Yellowstone River, were above flood stage in 2011, but show a slight declining trend over the last century.

A trend is not to be confused with a cause, especially a cause related to long-term change in climate forcing. Peterson et al. caution that confounding the analysis of trends in river flooding is the strong multiyear and multidecadal variability in hydrologic time series, largely related to atmospheric circulation variations. These atmospheric states could be merely symptoms of random noise, and in turn the Missouri river trend itself would be a symptom of noise.

To assess the extent to which the recent period of wetness in the Missouri Basin might be reconciled with a long-term change in forcing, Figure 22 presents results for addi-

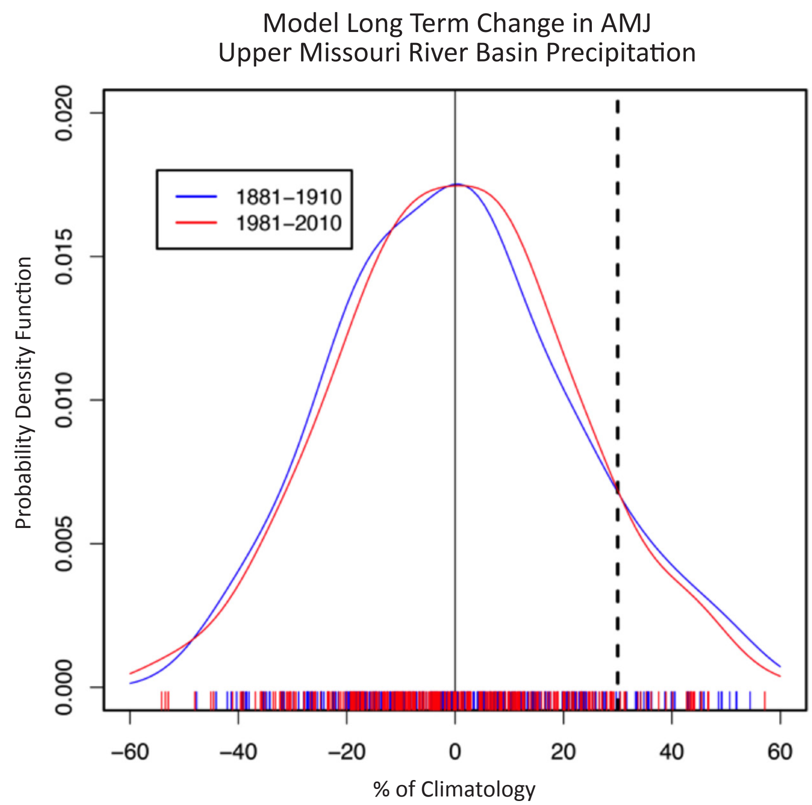


**Figure 23.** The probability distribution functions (PDFs) of upper Missouri River Basin spring (April-June) model simulated precipitation departures (% above or below normal) for 1881-1910 climate forcing (blue curve) and for 1981-2010 climate forcing (red curve). Each PDF is comprised of 300 seasonal mean spring samples based on equilibrium simulations of ECHAM5. The curves are non-parametric smoothed fits to the raw frequency distributions. Dashed lines denote +30% above normal.

tional climate simulations using the same model as was employed for the 2011 analysis. Observational estimates of ocean surface temperatures, sea ice extent, and greenhouse gas concentrations for 1881-1910 were specified in the model and a 300-year equilibrium experiment conducted. The annually average climate over the Missouri Basin experiment is compared to a parallel 300-year simulation using 1981-2010 averages in boundary and external forcings. The change in forcing causes a significantly warmer climate over the Missouri Basin, being 0.75°-1.5°C warmer in the recent epoch (Figure 22, bottom). This model response is quite consistent with the roughly +1°C warming of upper Missouri Basin temperatures that has been observed since 1895 (Figure 7c), and also supports the IPCC assessment that human-induced climate change has been a contributing factor to regional U.S. warming. Annual precipitation across the entire Missouri Basin declines as a response to long term forcing change in the simulations. In the upper basin, the annual averaged drying is about 5% of annual totals. Furthermore, the statistics of spring seasonal precipitation change in these ECHAM5 simulations (Figure 23) indicate a reduced frequency for very wet springs (>30% above normal); a 10-year return period in the earlier period versus a 13-year return period in the recent period. The model results thus do not support a notion that the heavy spring rains over the upper basin in 2011 were linked to a climate change forced increase in mean annual precipitation.

Overall, the implied reduction in land surface water availability inferred from the elevation in annual temperatures and the reduction in annual precipitation appears to be consistent with results of CMIP5 models. These reveal a signal, albeit weak, of reduced soil moisture during this same century-long period over western North American (Wuebbles et al. 2013). Various model simulations thus suggest that the recent period would, on average, have been one of reduced annual runoff and less annual mean flow in the Missouri River due to climate change alone. The plausible interpretation of observed *upward trend* in annual flow is that it is inconsistent with long-term climate change, being opposite in sign to how annual flow would respond to the human-induced warming and drying signals, and thus is most likely a symptom of natural variability.

The above assessment begs a more interesting question regarding a long-term change in characteristics of Missouri River runoff, namely a tendency toward increasing year-to-year variability (see Figure 5). For the 20-year window of 1993-2012, the standard deviation of annual runoff is nearly 12 maf. This compares to only 5 maf during the 1898-1917 period. The 20-year average runoff during those periods is not substantially different, and thus the coefficient of variability (COV) has more than doubled from less than 0.2 to greater than 0.4. The ratio in both epochs is appreciably less than 1 indicating that, despite the rise, the Missouri Basin runoff distribution continues to be one of low variance. The COV is often interpreted as the inverse of the signal-to-noise ratio, and measures the dispersion within the probability distribution. The underlying cause for the recent doubling is unknown, aside from knowing that it is a symptom of increased high flow years. The COV for precipitation or temperature do not exhibit a similar doubling. Determining how natural variability and longer-term climate change may have contributed to this change in variance, and assessing the role of other factors such as changing land use and other management practices would be a fruitful subject for future research.

The year 2011 was historic for the Missouri River Basin, and

# 9. EPILOGUE

the January-May period was the wettest since at least 1895. Annual runoff of 61 maf above Sioux City surpassed the prior record by 12 maf. This exceedance is all the more remarkable when recognizing the historical low volatility in annual flow fluctuations. By measures of the year-to-year variability in the early 20th century, *the prior record was exceeded by 2 standardized departures of the expected variability*.

Given these events and the memory inherent in Missouri Basin hydrology, it was only reasonable to anticipate that the subsequent 2012-year would also be susceptible to flooding. After all, each of the prior 5 years witnessed above average annual precipitation in the upper basin, and the consecutive sequence of annual runoff from 2008-2011 exhibited progressively higher positive departures.

Yet, the observed 2012 annual runoff in the Missouri Basin was below normal. As wet as 2011 was in the upper basin, 2012 was comparably dry. Over the entire Missouri Basin, the period January-June 2012 ranked in the lower decile of driest years since 1895, and July-September 2012 was the historical driest in 118 years of records. The monthly time series of observed rainfall and temperatures reveal that this change in prevailing conditions to dry and warm emerged by late summer 2011 (Figure 24).

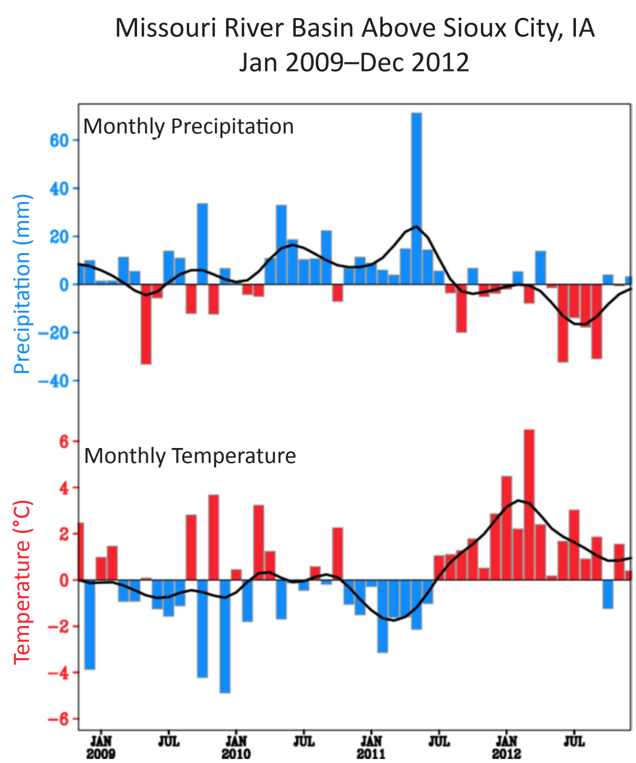


**Figure 24.** The observed monthly precipitation departures (mm) and surface air temperature departures (°C) averaged over the upper Missouri River Basin above Sioux City, Iowa for the period November 2008 through December 2012. Curve is a 9-point Gaussian filter applied to the raw monthly departures. Departures are relative to a 1981-2010 climatology.

What a remarkable difference a year made, both in the meteorology and the attending hydrologic response. The climate forcings themselves had not appreciably changed between these years. Certainly, the concentrations of anthropogenic greenhouse gases were for all practical purposes the same. The global ocean conditions in 2012 were also not materially different from those in 2011, with remnants of La Niña and a Pacific basin horseshoe pattern that resembled the negative phase of the PDO still operative. The monthly time series of ensemble mean simulations show a prevailing condition of warm and dry in 2012, similar to the forced signal in the prior 2 years, though with much weaker magnitudes compared to observations (Figure 25). Only during winter is there a weak signal of wetness in the model simulations, while most other months are dry. The 2012 dry conditions across the basin are of the same sign as the simulated decrease in annual precipitation as a response to long-term climate change (see Figure 22).

The 2012 case is only briefly presented here, after the detailed assessment of 2011, as a way to again emphasize the appreciable randomness of atmospheric variability and its strong controlling effect on Missouri River runoff. The fate of 2012 was apparently not set by the antecedent conditions of 2011, any more than antecedent conditions determined the fate of 2011. Instead, in both years annual runoff depended primarily on prevailing meteorological factors, and these abruptly returned the basin from a climate state conducive to high flow for much of 2011 to a climate state conducive for low flow starting in late 2011. Given the gross similarities in climate states and forcings, the 2012 climate conditions serve as an object lesson on the power of intrinsic atmospheric variability and its control over annual runoff on the large scale of the Missouri River Basin.

To summarize, this report identified key climate conditions, which occurred in the Missouri Basin, and contributed to record flooding in 2011. The report addressed principal causes for these conditions, drew inferences about predictability, and also explored the likelihood of such an event occurring in the future. In 2011, the factors immediately responsible for flooding 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 snow pack, and record setting rains in late spring. The

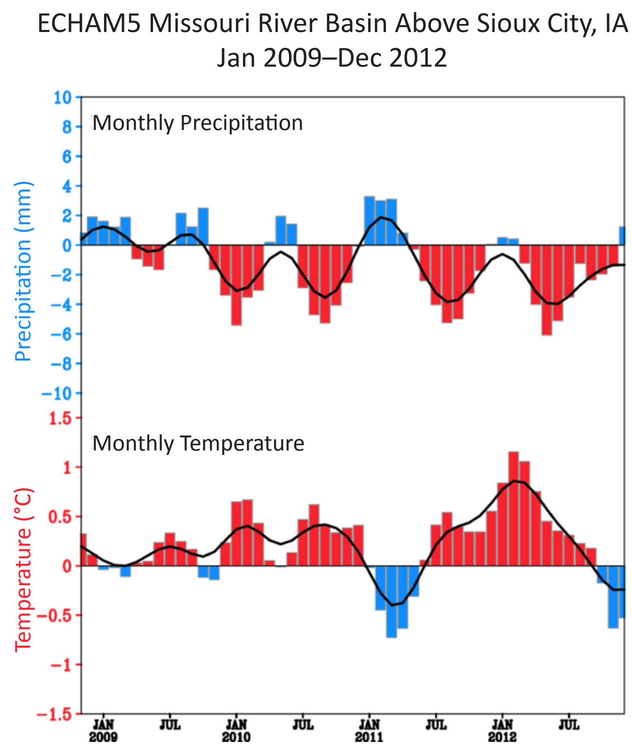


**Figure 25.** Same as Figure 24 except based on the 40-member ensemble averaged simulations of the ECHAM5 climate model. Departures are relative to the model's 1981-2010 climatology.

latter condition was almost certainly the most critical in the meteorological sequence for understanding the historic proportion of Missouri Basin flooding that developed in late Spring 2011. The wintertime cold and wet conditions were shown to be consistent with those occurring in the upper Missouri Basin during La Niña events, and in this sense NOAA's La Niña Advisory issued on 5 August 2010 provided early warning for such prevailing winter conditions, at least qualitatively. However, La Niña in general, and the particular ocean conditions in 2011 specifically, were found not to materially alter the risks for wet spring in the upper Missouri Basin. The report concludes that neither the NOAA La Niña Alert Status nor subsequent exact knowledge of the details of the ocean conditions would have forewarned of extreme heavy spring rains. The analyses in the report indicate that record setting discharge from the upper Missouri Basin by late spring could not have been anticipated appreciably before the heavy spring rains themselves materialized, and could almost certainly not have been anticipated at long seasonal (6-9 month) lead times during which some mitigation might have been feasible.

The report finds that the record Missouri Basin flooding event of 2011 was consistent with the physical response of basin runoff to a sequence of *naturally occurring climate conditions*, the majority of which resulted from random atmospheric variability for which predictability is judged to be low, at least based on the current state of science. Having resulted from an unusual sequence of extreme meteorological events, a flood of the 2011 magnitude was thus a rare occurrence, and this finding suggests a comparable event has low probability for recurring in the immediate future. A caveat to this conclusion is the fact that annual flow in the Upper Missouri Basin was found to be more volatile in recent decades compared to prior decades dating to 1898. Nine of the ten highest annual runoffs in the Missouri Basin historical record were found to have occurred after 1970, and the report demonstrates that year-to-year variability of annual runoff has increased dramatically in recent decades principally due to an increase in high flow events. This report does not address the underlying cause for this recent proliferation of high runoffs events, but recommends that an assessment of plausible factors be conducted as this could have bearing on better informing decision makers on the risks for future severe flooding events in the Missouri River Basin.

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# APPENDIX
# CLIMATE MODEL SIMULATIONS

## A. MODEL AND SIMULATIONS

A global atmospheric model was run over the period 1979-2012. The model is the European Center Hamburg model version 5 (ECHAM5; Roeckner et al 2003), with simulations performed at T159 (~80km) resolution and 31 atmospheric levels. This same model has been widely used in other studies, recently for instance in a diagnosis of the 2012 central U.S. drought (Hoerling et al. 2013).

The only constraining information representing observed conditions in these simulations is the sea surface temperature, sea ice, and external radiative forcing associated with greenhouse gases ($CO_2$, $CH_4$, $O_3$, $NO_2$, and CFCs). These are specified in the model as monthly time evolving boundary conditions from January 1979- December 2012. Climate simulations of this type are referred to as 'AMIP (Atmospheric Model Intercomparison Project)' experiments, and are designed to determine the sensitivity of the atmosphere, and the extent to which its temporal evolution is constrained by known boundary forcings.

Key to this modeling technique for assessing the impact of boundary conditions is an ensemble approach, whereby the period of simulation is repeated a multitude of times. Here simulations have been repeated 40 times (a 40-member ensemble). Four sets of 10-member runs were performed. One employs the full forcing variability, a second set is identical except sea ice is held fixed, a third is identical except that ozone is held fixed, and a fourth is identical except that all greenhouse gases are held fixed. No significant differences exist among the 2011 simulations over the Missouri basin (indicating that neither sea ice nor anthropogenic greenhouse gases were a material factor in the flooding), and thus the experiments are comingled to form a 40-member average. The various simulations principally differ from one another only in their initial atmospheric conditions in January 1979 but each employ identical time evolving observed global sea surface temperatures. The strategy is to average the monthly variability across the 40 members in order to determine the signal resulting from the specified forcings. The process of averaging eliminates the random internal variability of the atmosphere, and facilitates identifying the coherent signal from the forcing. Also, the spread among the individual runs is studied to determine the change, if any, in certain event probabilities.

## A. MODEL CLIMATOLOGY OVER THE MISSOURI RIVER BASIN

Key features of the observed annual cycle in precipitation are realistically simulated in the ECHAM5 model. The leading pattern of the seasonal cycle (Figure A1, top) shows a coherent basin wide pattern in which all, except the high terrain of the western basin, exhibit the same march of seasonal precipitation. The time series of the leading climatological mode exhibits a distinct late spring/early summer wet season, quite consistent in timing with the onset of basin-wide rains seen in observations (see Figure 4). The wet season in the model appears to end sooner than observed.

The model's second pattern of the seasonal cycle focuses maximum variance over the western basin of high terrain in the Wyoming and Montana Rocky Mountains. Undoubtedly, the use of fine spatial resolution is important for resolving this local feature that is key to the climate and hydrology of the Missouri Basin. The temporal peak of this second mode is winter, consistent with observations, with a distinct summertime dry season over the western basin.

## A. MODEL VARIABILITY OVER THE MISSOURI RIVER BASIN

Several assessments have been conducted of the model's variability in seasonal precipitation over the Missouri Basin, each of which provide strong evidence for realism in the model's simulations. One analysis involves EOF methods, analogous to that applied to the climatology, but applied to the interannual variability. This shows a leading pattern of interannual variability in precipitation to be a monopole having maximum loading over the central basin, which is in excellent agreement with observations (not shown). The model also realistically simulates the second pattern of interannual precipitation variability, which consists of an out-of-phase dipole between the upper and lower basin. Such a pattern was particularly prevalent during 2011.

A second assessment is illustrated by the box-whisker analyses for seasonal precipitation (Figure A2) and seasonal temperature (Figure A3). For each season, the "box" in these plots contains the middle half of the data points, in this case the middle half of the simulated anomalies of the 40-member ensemble for each season during 1979-2012. The median value, which divides the 40-members into two halves, is highlighted by the solid black curve. The whiskers plot the upper and lower quartile range of the distribution, and the single most extreme high and low value are denoted by blue and red circles, respectively. A key model attribute to assess in ensemble modeling is that the range of individual realizations for any particular season (i.e., the internal variability, or dispersion in the population) includes the observed value. The latter are plotted as green circles for each season. It is evident that with very few exceptions, the observational variability is consistent with the model's variability. It is plausible that the few cases where the observational values are outside the model's variability range may be a symptom of too small of an ensemble size, rather than any systematic model bias, though a more detailed assessment would be required.

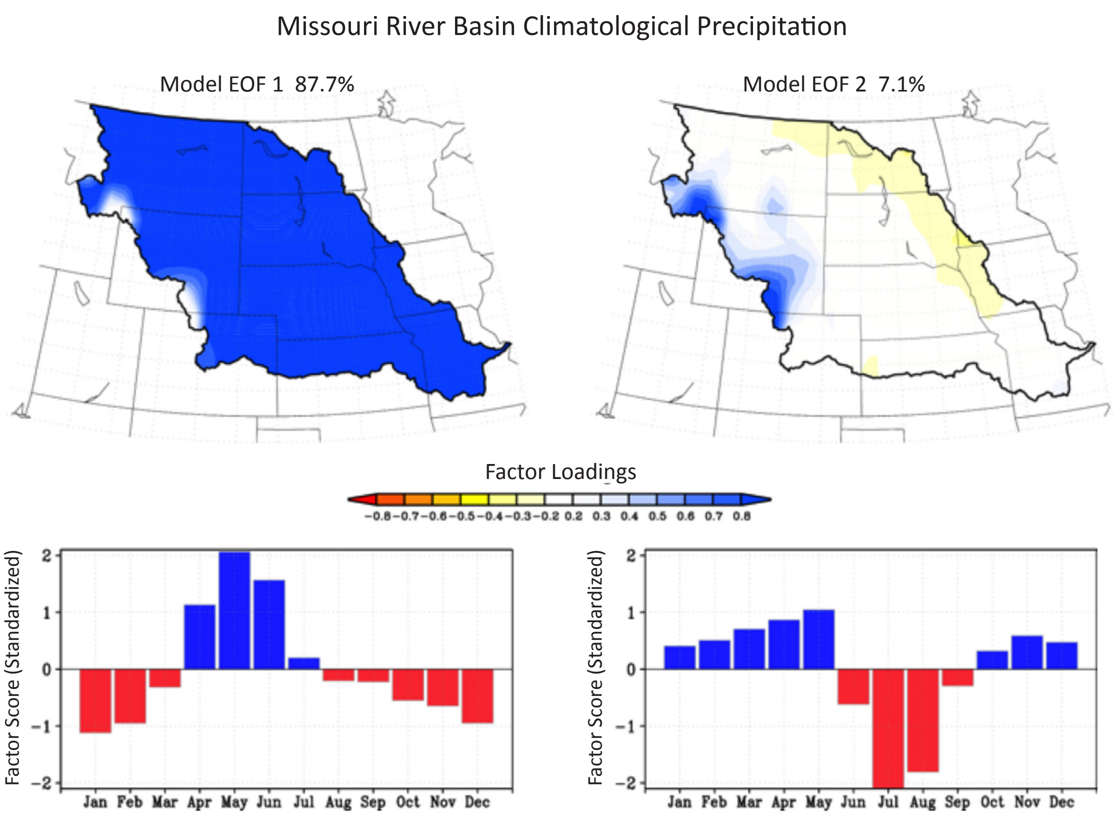


**Figure A1.** Same as Fig. 4 except he statistical pattern of model simulated monthly climatological precipitation using the method of Empirical Orthogonal Function (EOF) analysis. The spatial plot shows the leading pattern (88% of variance of the seasonal cycle; left) and second dominant pattern (7% variance of the seasonal cycle; right) of the model's seasonal cycle of Missouri River basin precipitation. The time series of these empirical patterns are shown in the lower panels. Results based on the ECHAM5 simulations for 1979-2012.

Upper Missouri River Basin Seasonal PPT
1979-2012

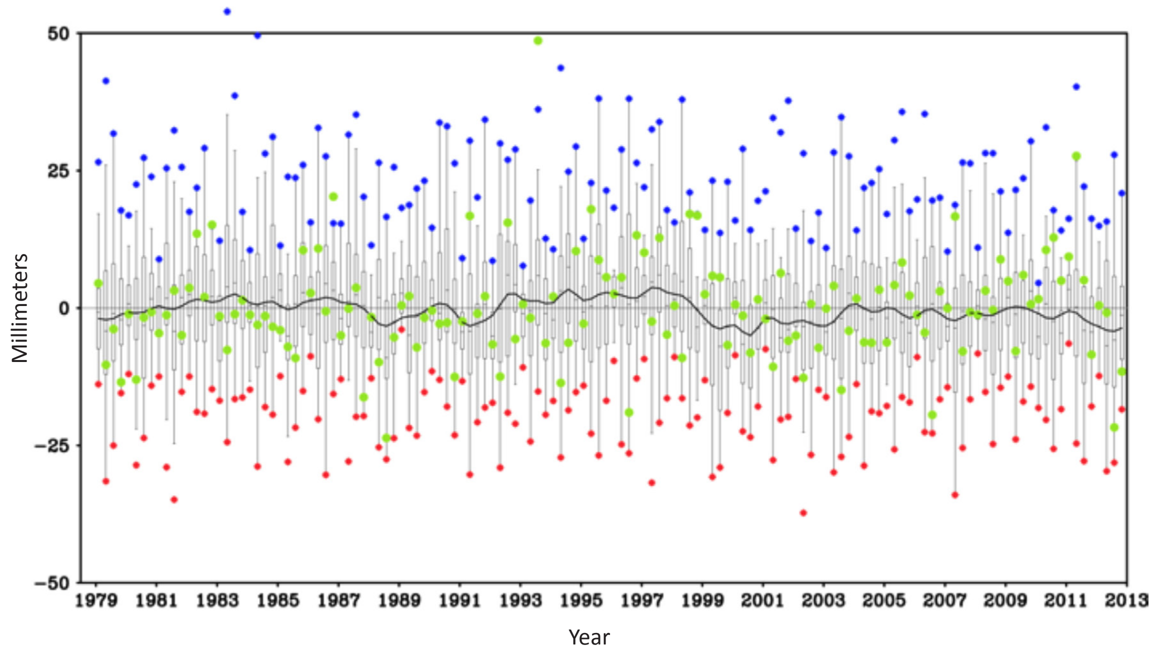


**Fig. A2.** Box-whisker plots of the seasonal simulated upper Missouri Basin precipitation variability (mm) for 1979-2012. The distribution summarizes the statistics of 40 simulations for each season beginning with January-March 1979 and ending with October-December 2012. Red (blue) asterisk denote the extreme dry (wet) ensemble member for each season, and the thin dark line is the time varying median anomaly. Green circles plot the observed values. The region consists of the sub-area of the Missouri Basin above Sioux City, IA. Anomalies are relative to a 1979-2012 reference.

Upper Missouri River Basin Seasonal Tmp
1979-2012

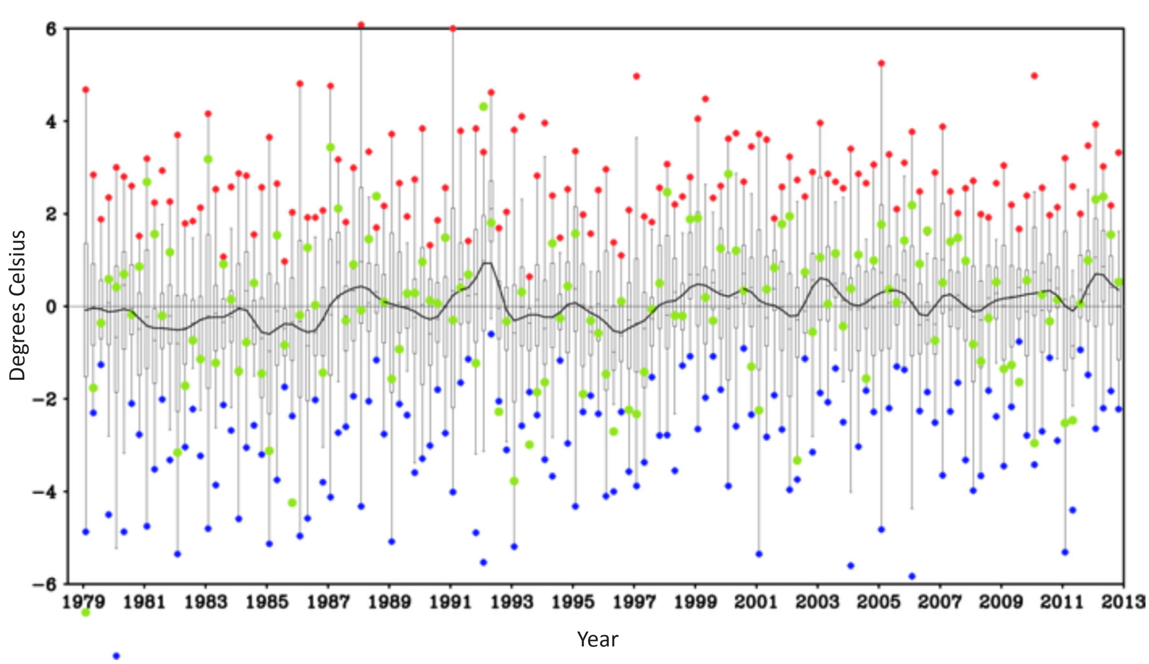


**Figure A3.** Same as Figure A2, except for surface air temperature anomalies (°C).