# Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions - Missouri River Region

## Abstract

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## Summary

To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the Missouri River Region, is part of a series of twenty (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Code (HUC) Water Resources Regions, across the continental United States, Alaska, Hawaii, and Puerto Rico. Each of these regional reports summarize observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterize climate threats to USACE business lines.

## Keywords

- Missouri River Region
- Water Resources Region 10
- Observed Climate
- Observed Hydrology
- Projected Climate
- Projected Hydrology
- Business Line
- Climate Vulnerability
- Regional Climate Synthesis
RECENT US CLIMATE CHANGE AND HYDROLOGY LITERATURE
APPLICABLE TO US ARMY CORPS OF ENGINEERS MISSIONS

MISSOURI RIVER REGION 10

January 9, 2015

CDM Smith
Contract # W912HQ-10-D-0004, Task Order 147

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Suggested Citation:

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Water Resources Region 10: Missouri River

1. Introduction

US Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty one Water Resources Regions included in this series of reports is shown in Figure 1.1 along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and watershed vulnerability assessment tools.

This report focuses on Water Resources Region 10, the Missouri River, the boundaries for which are shown in Figure 1.2. The Omaha and Kansas City USACE districts each include territory within Water Resources Region 10.
Figure 1.1. 2-digit Hydrologic Unit Code Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico
Figure 1.2. Water Resources Region 10: Missouri River Region Boundary
1.1 A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science-based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local-to-regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post-processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit HUC (Water Resources Region), and that confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Region scale both to introduce relevant climate change literature and to support the vulnerability assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 11, both the 2-digit and 4-digit HUC boundaries are shown in Figure 1.2.

2. Observed Climate Trends

Observed climate trends within Water Resources Region 10 are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014), this section in not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The
interrelationships of Earth’s climate systems are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings. When additional detail is needed, the reader is referred to the specific references cited, including the third National Climate Assessment (NCA) which includes not only regional assessments but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer-reviewed literature on the subject of observed climate. To the extent possible, studies specific to Water Resources Region 10 or its sub-watersheds were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow

In addition to primary variables, peer-reviewed literature addressing climate change within the geographic region of the Water Resources Region or inclusive of the Water Resources Region (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), drought indices, and soil moisture.

The general consensus in the recent literature points toward mild increases in average temperature and streamflow in the Missouri River Region over the past century. In some studies, and some locations, statistically significant trends have been quantified. In other studies and locales within the region, apparent trends are merely observed graphically but not statistically quantified. There is a clear consensus that the growing season in the Missouri River Region is lengthening; however, there is little evidence of increased extreme temperature in the region. Spatial variability was observed in the literature review for observed precipitation and precipitation extremes. The upper portion of the Missouri River Region generally showed decreasing trends while the lower portion of the region generally showed increasing trends for both observed precipitation and precipitation extremes. There has also been some evidence presented of increased frequency in the occurrence of extreme storm events in the lower portion of the region (Wang and Zhang, 2008).

2.1. Temperature

A number of national and regional studies on observed temperature were identified in this review. Results of these national studies relevant to the Missouri River Region are discussed below.

A 2009 study by Wang et al. examined historical climate trends across the continental United States. Gridded (0.5 degrees x 0.5 degrees) mean monthly climate data for the period 1950 – 2000 were used. The focus of this work was on the link between observed seasonality and regionality of trends and sea surface temperature variability. The authors identified positive statistically significant trends in recent observed mean air temperature for most of the U.S. (Figure 2.1). For the Missouri River Region, a positive trend was detected as well, specifically in the winter (December – February) and spring (March – May). During the summer months (June – August) a mild positive linear trend was observed in the upper portion of the Missouri
River Region (Montana, Wyoming, North Dakota, and South Dakota) while the lower portion of the region showed a decreasing linear trend for the same season. This study also observed a region-wide decreasing linear trend during the fall (September – November). A later study by Westby et al. (2013) conflicts with the above findings for the winter months. Specifically, the lower portion of the Missouri River Region identified a decreasing trend in seasonal-mean temperature using data from the period 1949 – 2011. However, these results lacked statistical significance at the 95% confidence level.

Grundstein and Dowd (2011) investigated trends in one-day extreme maximum and minimum temperatures across the continental U.S. based on daily temperature data compiled by the National Climatic Data Center (NCDC) for 187 stations across the country for the period 1949 - 2010. For the upper portions of the Missouri River region, they found a statistically significant (95 percent confidence interval) increasing trend in the number of one-day extreme minimum temperatures but no significant trend for the number of one-day extreme maximum temperatures. The authors defined the extreme temperatures as those exceeding the 85th percentile for that specific location on a given day (daily minimum and maximum).

Schwartz et al. (2013) investigated changes in spring onset for the continental U.S. Their particular focus was on changes in the seasonality of plant growth as dictated by changing temperature regimes. The authors used historical data from over 22,000 stations across the United States, obtained from the NCDC with periods of record extending through 2010. Their
findings indicate that for the Missouri River Region, spring onset is occurring at least a few days earlier for the current period (2001 – 2010) compared to an earlier baseline reference decade (1951 – 1960) (Figure 2.2). In other words, an apparent small shift in seasons has been identified for the region, with spring warming occurring earlier than in the past.

**Figure 2.2.** Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The Missouri River Region is within the red oval (Schwartz et al., 2013).

These results confirm two earlier regional studies by Badh and Akyuz (2009) and Hu et al. (2005). The first set of authors found that all locations in the study area trended towards a later fall frost date and an earlier last day of frost in the spring, resulting in a longer growing season. This study compared data at six locations in North Dakota from 1879 to 2008. For locations within the Missouri River Region specifically, the length of the growing season was found to increase by 0.23 to 0.45 days per decade. The second group of authors evaluated winter wheat heading dates and minimum temperatures from 1948 to 2004 in the Great Plains region. This study found an increasing trend for winter wheat heading dates and minimum spring temperatures. The phenological trend observed by Hu et al. (2005) provides confidence in the increasing temperature trend observed in data collected via instrumentation which can be subject to error.

In support of the recently released third NCA, Kunkel et al. (2013) summarized historical climate trends for the Great Plains region which is nearly inclusive of the Missouri River Region in its northern extent. For this region of the country, historical data shows that annual temperatures over the past 20 years have been above average when compared to a baseline period of 1901 – 1960. North Dakota, a portion of which is found in the Missouri River Region, was found to have the fastest increase in annual average temperature compared to all other states nationwide over the past 130 years. The authors note that these trends were statistically significant (95 percent confidence interval) for all seasons in the region. This study also noted an increasing trend in the freeze-free season length, noting that there has been an average increase of 6 days in the freeze-free season when comparing 1991 – 2010 to a baseline of 1961 – 1990. This is in agreement with the recent finding by Schwartz et al. (2013) described above.

*Key point: An increasing trend in observed mean and daily minimum air temperature in the study region was observed; however, a trend in daily maximum air temperature is lacking.*
2.2. Precipitation

Palecki et al. (2005) examined historical precipitation data from across the continental United States. They quantified trends in precipitation for the period 1972 to 2002 using NCDC 15-minute rainfall data. For the portion of the study area inclusive of the upper Missouri River Region, statistically significant (90 percent confidence interval) decreases in fall and winter storm totals (mm) and storm duration were identified. Additionally, statistically significant increases in summer storm intensity and 15-minute maximum intensity were identified for the upper portion of the Missouri River Region. The portion of the study area inclusive of the lower portion of the region was observed to have a statistically significant increasing trend in storm totals for the winter months.

Multiple authors have identified increasing trends in total annual precipitation in recent historical records for the lower Missouri River Region and decreasing trends for the upper portion of the region. Grundstein (2009) identified statistically significant (95 percent confidence interval) positive linear trends for the period of 1895 – 2006 in both annual precipitation and the soil moisture index for multiple sites within South Dakota. However, slightly decreasing trends were observed in the upper portion of the Missouri River Region, including Montana and Wyoming (Figure 2.3). Soil moisture is a function of both supply (precipitation) and demand (evapotranspiration [ET]), and therefore is an effective proxy for both precipitation and ET. The upper portion of the region was found to have a slightly decreasing trend in ET while the lower portion was observed to have a slightly increasing trend.

![Figure 2.3](image.png)

**Figure 2.3.** Statistically significant linear trends in (a) soil moisture index (unitless) and (b) annual precipitation (cm) for the continental U.S., 1895 – 2006. The Missouri River Region is within the red oval (Grundstein, 2009).

As described in Section 2.1, a similar study by Wang et al. (2009) also focused on historical climate trends across the continental U.S. using gridded climate data and a shorter period of record (1950 – 2000). The authors identified generally positive trends in annual precipitation for most of the U.S. For the Missouri River Region, the authors identified a moderate increasing trend in precipitation during the spring and fall. A mild decreasing trend for the winter was
identified for the entire Missouri River Region and in the summer for the upper portion of the region.

A 2011 study by McRoberts and Nielsen-Gammon used a new continuous and homogenous data set to perform precipitation trend analyses for sub-basins across the United States. The extended data period used for the analysis was 1895 – 2009. Linear positive trends in annual precipitation were identified for most of the U.S, including the Missouri River Region (Figure 2.4) with the exception of Montana which showed a slight decreasing trend. The trend in annual precipitation indicates a change on the order of -5 to 15% per century depending upon location.

![Figure 2.4](image)

**Figure 2.4.** Linear trends in annual precipitation, 1895 – 2009, percent change per century. The Missouri River Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

Changes in extreme precipitation events observed in recent historical data have been the focus of a number of studies. Studies of extreme events have focused on intensity, frequency, and/or duration of such events. Wang and Zhang (2008) used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. Statistically significant increases in the frequency of the 20-year storm event were quantified across the lower portion of the Missouri River Region for the period 1977 to 1999 compared to the period 1949 to 1976. An increase in frequency of approximately 33 – 50% was quantified for this area. For the upper portion of the Missouri River Region a decreasing frequency of the 20-year storm event was identified on the order of -33%.

Pryor et al. (2009) performed statistical analyses on 20th century rainfall data to investigate trends across a range of precipitation metrics. They used data from 643 stations scattered across the continental U.S. For the Missouri River Region, the analysis showed generally increasing, and statistically significant, trends in total annual precipitation for the lower portion of the region. A decreasing trend for both the 90th percentile daily and precipitation intensity (annual total/number of precipitation days) was observed in the upper portion of the Missouri River.
Region and spatially blended trends (increasing and decreasing) were identified for the lower portion of the region. An increasing trend in the number of precipitation days per year was identified across the entire region (Figure 2.5). The authors note that the trends identified are not necessarily linear, with an apparent increase in the rate of change in the latter part of the century for most of the trends.

![Figure 2.5](image)

Figure 2.5. Historical precipitation trends in the 20th century. a.) annual totals, b.) 90th percentile daily, c.) precipitation intensity (annual total/number of precipitation days), and d.) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The Missouri River Region is within the red oval (Pryor et al., 2009).

These results are generally supported by the findings of Villarini et al. (2013). These authors identified statistically significant (p < 0.05) increasing trends in the frequency of occurrence of heavy rainfall in the lower portion of the Missouri River Region (Missouri and Iowa) for multiple climate stations with at least 50 years of historical record. While significant trends were
identified for a number of stations in the region, an approximate equal number of stations in the region exhibited no significant trends.

Trends in the frequency and severity of droughts in the U.S. were the subject of a study by Cook et al. (2014). This study used tree ring data to assess the frequency and severity of droughts over the past millennium (1000 – 2005), across the U.S. For the Central Plains (CP) region, which includes the Missouri River Region, the authors identified a statistically significant decline in drought frequency (droughts per century) over the past 1,000 years and a general increase in soil moisture, as defined by the Palmer Drought Severity Index (PDSI), over the same period (Figure 2.6).

Figure 2.6. Drought frequency and severity for central plains USA (light green), based on Palmer Drought Severity Index (PDSI). 1000s – 1900s. (Cook et al., 2014).

Key point: A mild upward trend in annual and extreme precipitation in the lower portion of the Missouri River Region has been identified by multiple authors while the upper portion has been identified to have a decreasing trend for annual and extreme precipitation.

2.3. Hydrology

Studies of trends and nonstationarity in streamflow data collected over the past century have been performed throughout the continental U.S., some of which include the Missouri River Region. There appears to be reasonable consensus among these studies that trends show a general increase in river flow in the region.

Mauget (2004) analyzed 42 daily streamflow gages throughout the U.S., 11 of which are located within the Missouri River Region. They identified an increasing trend (1939 – 1998) in river flow in the region as a whole. They quantified a significant increase in “surplus” flow days and a decrease in drought incidence for the latter part of the record compared to earlier years. Xu et al. (2013) identified trends for multiple stream gages in a study area inclusive of the region. This study used the Model Parameter Estimation Experiment (MOPEX) data set for the period 1950 – 2000. Additional information on the MOPEX can be found in Duan et al. (2006). A mix of positive trends and no trends in both annual streamflow and baseflow was identified for gages in the lower portion of the basin while the upper portion showed uniformly no trend in the results, except for western Montana, which showed a decreasing trend. These authors attribute the observed trends to a combination of climate change and human landscape impacts.
The following year, Qian et al. (2007) presented a study targeting surface water trends, including runoff, in the entire Mississippi River watershed, which includes the Missouri River Region. In agreement with the previous authors, these authors quantified statistically increasing trends in runoff of up to 100 mm/century in the region for the period 1948 – 2004. They also noted increasing trends in observed precipitation, air temperature and ET in the region for the same time period. Their methods included the use of hydrometeorological observations combined with hydrological model simulations (Community Land Model, Version 3, CLM3).

In agreement with the findings described above, Kalra et al. (2008) found an increasing trend and step change in streamflow for unimpaired gages throughout the Missouri River Region for the period 1951 – 2002. However, no specific quantitative detail is provided for the Missouri River Region. These authors looked at both annual total flows and seasonal flows (spring/summer vs. fall/winter) and found an increasing trend and step change for both.

**Key point:** A mild upward trend in mean streamflow in the Missouri River Region has been identified by multiple authors, but a clear consensus is lacking in the upper portion of the region.

### 2.4. Summary of Observed Climate Findings

The general consensus in the recent literature points toward mild increases in average temperature and streamflow in the Missouri River Region over the past century. In some studies, and some locations, statistically significant trends have been quantified. In other studies and locales within the region, apparent trends are merely observed graphically but not statistically quantified. There is a clear consensus that the growing season in the Missouri River Region is lengthening; however, there is little evidence of increased extreme temperature in the region. Spatial variability was observed in the literature review for observed precipitation and precipitation extremes. The upper portion of the region generally showed decreasing trends while the lower portion of the region generally showed increasing trends for both observed precipitation and precipitation extremes. There has also been some evidence presented of increased frequency in the occurrence of extreme storm events in the lower portion of the region (Wang and Zhang, 2008).

### 3. Projected Climate Trends

While historical data is essential in understanding current and future climate, nonstationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2008). Consequently, the scientific and engineering communities have begun using computer models of the Earth’s atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. While significant uncertainties are inherent in these model projections, the models, termed global climate models (GCMs), are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.
This section summarizes projected climate trends, as projected by GCMs, within the Water Resources Region 10 identified in a review of recent peer-reviewed literature. The information presented should be considered an overview and, similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth’s climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of “climate futures” so each study’s assumed emission scenario(s) are noted. When additional detail is needed, the reader is referred to the specific references cited, including the third NCA, which includes not only regional assessments but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

The USACE vulnerability assessments (https://corpsclimate.us/rccvar.cfm) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey, Climate Central, Scripps Oceanographic Institute and Santa Clara University, and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed or basin-scale water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate a strong consensus in the scientific literature that air temperatures will trend upward over the next century in the Missouri River Region. There is less consensus on the future trending of precipitation in the region. However, most studies reviewed report a general increase of precipitation in the region. Consensus amongst recent literature is lacking regarding the direction of projected trends in streamflow and related variables such as runoff and water yield. The direction of the streamflow trend seems to be dependent on modeling assumptions.

### 3.1. Temperature

GCMs have been used extensively to project future climate conditions across the country. At a national scale, model projections generally show a significant warming trend throughout the 21st century, with a high level of consensus across models and modeling assumptions. There is much less consensus on future patterns of precipitation. Results of studies inclusive of the Missouri River region typically fall in line with both of these generalizations.

Maximum air temperature projections were investigated by Liu et al. (2013) using a single GCM and assuming an A2 greenhouse gas emissions scenario (worst case). The results of their study, specific to the Missouri River Region, show a projected increase in seasonal maximum air temperature of 1.5 to 4.5 °C for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (Figure 3.1). They also project an increase in the Keetch Byrum Drought Index (KBDI), a measure of soil moisture deficit, for the Missouri River region.
Figure 3.1. Projected changes in seasonal maximum air temperature, °C, 2041 – 2070 vs. 1971 – 2000. The Missouri River Region is within the red oval (Liu et al., 2013).

Similar results are presented by Scherer and Diffenbaugh (2014). These authors apply a multi-member ensemble GCM, assuming an A1B (middle of the road) emissions scenario, to the continental U.S. For the Great Plains region of the country, including the Missouri River Region, model projections indicate steadily increasing air temperatures throughout the 21st century for both summer and winter seasons (Figure 3.2). By 2090, projections show an increase of approximately 4.0 °C in the summer and 6.0 °C in the winter, compared to a 1980 – 2009 baseline period. These results differ in magnitude but the increasing trend agrees with the trend described previously in Liu et al. (2013).

Figure 3.2. Probability distributions of GCM Projections of daily maximum temperatures for Years 2000 – 2100 by decade, Great Plains region (a. summer months: Jun – Aug, b. winter months: Dec – Feb) (Scherer and Diffenbaugh, 2014).

Elguindi and Grundstein (2013) present results of regional climate modeling of the U.S. focused on the Thornthwaite climate type – a measure of the combination of relative temperature and precipitation projections. For the upper portion of the Missouri River Region, results show a shift from predominantly dry and cold to a semi-arid and warm or dry and cool climate type by the period 2041 – 2070. The lower portion of the region is projected to transition from a predominantly moist and cool climate type to moist and hot (Figure 3.3).
a) Historical observed (1971 – 2000)

b) GCM projections (2041 – 2070)

**Figure 3.3.** Revised Thornthwaite climate types projected by regional climate models. The Missouri River Region is within the red oval (Elguindi and Grundstein, 2013).

Kunkel et al. (2010) presented results of two different downscaled GCMs applied to the continental U.S., assuming high greenhouse gas emissions scenarios (A2 and A1F), with a focus on summer heat wave occurrence and intensity. For the Missouri River Region, projections indicate a 3.5 to 8 °C increase in three-day heat wave temperatures and a 0 to 80 day increase in the annual number of heat wave days for a 2090 planning horizon compared to a recent historical baseline.

The third NCA (Ojima et al., 2014) supports the findings presented above. Climate model projections for the Great Plains region of the U.S. presented in this report indicate an increase in the occurrence of hot days and warm nights on the order of 13 to 28 days and <20 to 40 days, respectively. (Figure 3.4).
Additionally, as part of the third NCA, (Kunkel et al., 2013) summarized projected climate characteristics for the Great Plains region (extent of region shown in Figure 3.4) based on two future paths of greenhouse gas emissions (A2- high and B1 – low) utilizing the Coupled Model Intercomparison Project, 3rd release models (CMIP3, http://gdo-dcp.ucarlnc.gov/downscaled_cmip_projections/). Their work found that average temperature would increase by 2.8 °F by 2035, 4.4 °F by 2055, and 8.0 °F by 2085 under the A2 scenario. Under the low emissions (B1) scenario, projected changes in temperature were similar for 2035 but much less by 2085. Kunkel et al. found early period model projections (<2035) lacking in statistical significance for most models while the later period (>2035) included more statistically significant model projections, all greater than a 95% confidence level (Kunkel et al., 2013).

The above results confirm a regional study of the St. Mary River and Milk River basins conducted under the United State Bureau of Reclamation’s (USBR) WaterSMART Program. This study evaluated future water supplies and demands under all 112 different climate change projections. The USBR study focused on two planning horizons: one centered around 2030 and another centered around 2050. This study found that the simulated annual mean temperature would increase by 3 to 4 °F by 2050 and that year-to-year variability in mean temperature would also increase.

*Key point:* Strong consensus exists in the literature that projected temperature trends in the study region show a steady increase over the next century.
3.2. Precipitation

In line with projections for the rest of the country, projections of future changes in precipitation in the Missouri River Region are variable and generally lacking in consensus among studies or across models. The 2013 Liu et al. study, described above, quantified slight to moderate increases in winter and spring precipitation associated with a 2055 planning horizon, relative to a recent historical baseline (1971 – 2000), centered around 1985, for the Missouri River (Figure 3.5). Slight increases to moderate decreases, are projected for the other seasons (summer and fall). However, the authors also project increases in the severity of future droughts for the region, as projected temperature and ET impacts outweigh the increases in precipitation.

![Figure 3.5. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The Missouri River Region is within the red oval (Liu et al., 2013).](image)

As part of the third NCA, (Kunkel et al., 2013) investigated the change in annual precipitation compared to a baseline period of 1971–1999. Future periods included 2021 – 2050, 2041 – 2070, and 2070 – 2099. Results presented showed an increase in annual precipitation for all future time periods and for the majority of the Missouri River Region based on a multi-model mean (CMIP3 global climate simulations) for the A2 (high) and B1 (low) emissions scenarios. The upper portion of the region is projected to see the largest increase, on the order of 6 to 12% relative to the baseline period (Figure 3.6).
Figure 3.6. Simulated difference in annual mean precipitation (%) for the Great Plains region. Color only indicates that less than 50% of the models show a statistically significant change in precipitation. Color with hatching indicates that more than 50% of the models show a statistically significant change in precipitation, and more than 67% agree on the sign of the change. Whited out areas indicate that more than 50% of the models show a statistically significant change in precipitation, but less than 67% agree on the sign of the change. The Missouri River Region is within the red oval (Kunkel et al., 2013).
Future projections of extreme events, including storm events and droughts, are the subject of a study by Wang and Zhang (2008). In addition to the historical data trend analyses by (Wang and Zhang (2008)) described above, these authors also used downscaled GCMs to look at potential future changes in precipitation events across North America. They used an ensemble of GCMs and a single high emissions scenario (A2) to quantify a significant increase (c. 0 to 100%) in the recurrence of the current 20 year 24-hour storm event for their future planning horizon (2075) and the Missouri River Region (Figure 3.7).

(Kunkel et al. (2013)), described above, also evaluated the change in occurrence of mean annual number of days with precipitation greater than one inch for the Great Plains region by comparing the 2041 – 2070 time period to a baseline period of 1980 – 2000. These results, based on multi-model means from eight North American Regional Climate Change Assessment Program (NARCCAP) regional climate simulations for the high (A2) emissions scenario, are shown below in Figure 3.8. The Missouri River Region shows a projected increase of nearly 60% in some areas; however, few areas are statistically significant. Consistent with (Kunkel et al. (2013)) a regional study by USBR on the St. Mary’s River and Milk River basins, described above, found that simulated annual total precipitation would range from drier to wetter; however, most climate change projections in this study showed overall wetter conditions in these two river basins located
in northern Montana. Precipitation, similar to temperature, was also found to increase in variability year to year (USBR, 2012).

**Figure 3.8.** Simulated difference in annual mean annual number of days with precipitation of greater than 1 inch for the Great Plains region. Color only indicates that less than 50% of the models show a statistically significant change in precipitation. Color with hatching indicates that more than 50% of the models show a statistically significant change in precipitation, and more than 67% agree on the sign of the change. Whited out areas indicate that more than 50% of the models show a statistically significant change in precipitation, but less than 67% agree on the sign of the change. The Missouri River Region is within the red oval (Kunkel et al., 2013).

*Key point: A general consensus exists in the literature with respect to an increasing trend in future precipitation in the study region.*
3.3. Hydrology

A number of global and national scale studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro-scale hydrologic models. In addition, a recent regional study of the St. Mary’s and Milk River basins was published as part of the USBR WaterSMART Program. These studies include projections of potential hydrologic changes in the Missouri River Region and are summarized below.

(Thomson et al. (2005)) applied two GCMs, across a range of varying input assumptions, in combination with the macro-scale Hydrologic Unit Model to quantify potential changes in water yield across the United States. Results are presented for both continuous spatial profiles across the country (Figure 3.9) and for individual HUCs. For the Missouri River Region (HUC 10), contradictory results are generated by the two GCMs. For the same set of input assumptions, one model predicts slight decreases in water yield, the other projects slight to significant increases in water yield.

Figure 3.9. Projected change in water yield (from historical baseline), under various climate change scenarios based on 2 GCM projections. The Missouri River Region is within the red oval (Thomson et al., 2005).

More recently, regional studies have been conducted for the Missouri River Region. One such study by the U.S. Bureau of Reclamation developed a comprehensive set of hydrologic runoff projections for the western U.S. corresponding to each of the 112 different downscaled CMIP3 GCM projections (Brekke, 2011). Both the climate and runoff projections are available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

The hydrologic projections were generated using a macro-scale generalized hydrologic model, the Variable Infiltration Capacity (VIC) model, seeded with climate forcing variables (temperature and precipitation). The projections are particularly useful for assessing relative
changes in runoff or flow that might be caused by projected changes in climate. Results of this work specific to the Missouri River Region show primarily increases in 21st century projected flows (2070) compared to the historical baseline (1990s). Projection ensemble median changes are between 10% and 20% in the western portion of the region and greater than 20% in the eastern portion of the region.

The results presented by Thomson et al. (2005), described above, highlight the significant uncertainties associated with global climate modeling, particularly with respect to hydrologic parameters. Additional uncertainty is generated when these climate models are combined with hydrologic models that carry their own uncertainty. This comparison and quantification of uncertainty is the subject of a 2013 study by Hagemann et al. In this study, the authors apply three GCMs, across two emission scenarios to seed eight different hydrologic models for projecting precipitation, ET, and runoff on a global scale. Their findings, in agreement with CDMSmith (2012), indicate that the uncertainty associated with macro-scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections for the Missouri River Region show an overall spatial range of future runoff from slightly decreasing to slightly increasing (~40 mm/year to 40 mm/year) for the future planning horizon (2071 – 2100) compared to recent historical baseline (1971 – 2000), assuming an A2 emissions scenario (Figure 3.10). Similarly, with respect to projected trend direction, a regional study by USBR of the St. Mary’s River and Milk River basins, described above, found that the combined change in streamflow in these two basins would range from a decrease of 86,000 acre-feet (AF) to an increase of 225,000 AF relative to a combined historical average of 780,000 acre-feet per year (AFY) (based on 1959 – 2008).

Figure 3.10. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Missouri River Region is within the red oval (Hagemann et al., 2013).

*Key point:* Consensus amongst recent literature is lacking regarding the direction of projected trends in streamflow and related variables such as runoff and water yield. The trend direction seems to be dependent on selection of GCM, emissions scenario, and hydrologic model (if applicable).
3.4. Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the study region, and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of approximately 4 to 8 °C by the latter half of the 21st century for the Missouri River Region; however, the magnitude of projected changes by season vary from study to study. Reasonable consensus, regardless of emissions scenarios, is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long term future compared to the recent past.

Projections of precipitation in the study region are less certain than those associated with air temperature. On the whole, more studies appear to point toward a wetter, rather than dryer, future climate in the Missouri River Region. A majority of the projections reviewed here forecast an increase in annual precipitation and in the frequency of large storm events. However, statistically significant trends in the projection data are lacking.

Similarly, clear consensus is lacking in the hydrologic projection literature. Projections generated by coupling GCMs with macro-scale hydrologic models in some cases indicate a reduction in future streamflows but in other cases indicate a potential increase in streamflows. Of the limited number of studies reviewed here, more results point toward the latter than the former.

The trends and literary consensus of observed and projected primary variables noted above have been summarized for reference and comparison in the following figure (Figure 3.11).
4. Business Line Vulnerabilities

The Missouri River Region encompasses a vast area in the north-central region of the United States. The projected changes in climate conditions within the entire Missouri River Region may influence future USACE planning, engineering and operational activities, as well as those activities of other users of lands and waters within this river basin. Impacts to this area will be affected by climatic conditions beyond this given region. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the
natural environment. To assess the potential vulnerabilities that climate change may pose on USACE’s missions, a set of primary USACE business lines were identified. They include:

- Navigation
- Flood Risk Management
- Water Supply
- Ecosystem Restoration
- Hydropower
- Recreation
- Emergency Management
- Regulatory
- Military Programs

Navigation is an important mission on the Missouri River Region, operating harbors and inland navigable waterways, which are important for the regional and national economy. The expected increases in air temperatures, especially in the summer, may impede USACE’s ability to maintain the approved navigation depths on these waterways.

USACE implements flood risk management projects in the region to maintain the streamflows in many of the river basins. There is likely to be an increase in annual precipitation, with the upper portion of the region likely to see a larger increase – particularly in the winter and spring. Flood risk management projects may be important to reduce flooding during these seasons.

USACE maintains and operates several fresh water supplies. Managing competing water needs can be a challenge, especially when water demand is high and water supply is low. Water supplies may also be strained due to increased temperatures and heat waves in the summer months. Maintaining necessary flows for competing sources such as hydropower generation, navigation and ecosystem management, may present some significant, additional challenges to an already complex water resource system.

USACE implements several ecosystem restoration projects in the Missouri River Region. Increased air temperatures, particularly in the summer months, may result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures are associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies.

The hydropower facilities in the Missouri River Region may be affected by climate change. Increased annual precipitation may increase in hydropower output; however there may be variability year to year. Conversely, increased air temperatures may cause seasonal drought situations, especially in the summer, and may reduce the amount of power that may be generated by the hydropower plants.

Recreational facilities in the region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature along extended heat waves in the summer months have the potential to decrease the number of visitors to USACE’s recreational facilities. Periods of extreme high heat poses human health concerns and higher water temperatures can result in algal
blooms and other water quality issues which may cause health risks for those involved in aquatic activities.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency managers and assigned staff in each region and subregion that are able to quickly mobilize. In the Missouri River Region, the expected climate impacts may not create more of the types of emergency management situations USACE typically responds to.

USACE’s regulatory mission has a serious commitment to protecting aquatic resources while allowing reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulation or increase the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services include the rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. The interrelationships between business lines must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt. Figure 4.1 summarizes the projected climate trends and impacts on each of the USACE business lines.
### Climate Variable: Increased Ambient Temperatures

Increased ambient air temperatures throughout the century, and over the next century are expected to create the following vulnerabilities on the business lines in the region:

- Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system.
- Decrease in flows may result from periods of drought has implications for maintain water levels in the rivers; however hydrological models show little concurrence on streamflow.
- Risk of wildfires during hot and dry conditions may cause an increased risk of wildfires, especially in heavily forested and dry areas. Flora and fauna that are not drought resistant can also be impacted by longer drought conditions, which may reduce opportunities for recreational wildlife viewing.

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### Climate Variable: Increased Maximum Temperatures

Air temperatures are expected to increase 4-8°C in the latter half of the 21st century, especially in the summer months. This is expected to create the following vulnerabilities on business lines in the region:

- Increased water temperatures leading to water quality concerns, particularly for the dissolved oxygen (DO) levels, growth of nuisance algal blooms and influence wildlife and supporting food supplies.
- Increased evapotranspiration.
- Human health risk increases from extended heat waves, impacting recreational visitors and increasing the need for emergency management.

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### Climate Variable: Increased Annual Precipitation

By the middle of the century, annual precipitation is expected to increase in the region which are expected to influence the following vulnerabilities on business lines in the region:

- Times of increased streamflows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality.
- Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns.
- Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area.

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**Note:** The Regulatory and Military Program business lines may be impacted by all climate variables

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**Figure 4.1.** Summary of projected climate trends and impacts on USACE business lines
### Appendix A: References Climate/Hydrology Summary Table

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Appendix B: Reference List


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National Environmental Satellite, Data, and Information Service, Washington D.C.


