Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

UPPER COLORADO REGION 14

FINAL

June 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
26-06-2015	Civil Works Technical Series	2014 - 2015

4. TITLE AND SUBTITLE
Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions - Upper Colorado Region

5a. CONTRACT NUMBER W912HQ-10-D-0004

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

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- Support from CDM Smith

5d. PROJECT NUMBER

5e. TASK NUMBER 147

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Directorate of Civil Works
US Army Corps of Engineers
Washington, DC

8. PERFORMING ORGANIZATION REPORT NUMBER
CWTS-2015-14

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Institute for Water Resources
7701 Telegraph Road (Casey Building)
Alexandria, Virginia 22315

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Available through National Technical Information Service, Operations Division
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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 Upper Colorado Region, 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 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.

15. SUBJECT TERMS
Upper Colorado Region
Water Resources Region 14
Observed Climate
Observed Hydrology
Projected Climate
Projected Hydrology
Business Line
Climate Vulnerability
Regional Climate Synthesis

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
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CLIMATE CHANGE AND HYDROLOGY LITERATURE SYNTHESIS FOR THE US ARMY CORPS OF ENGINEERS MISSIONS IN THE UNITED STATES

UPPER COLORADO REGION 14

June 26, 2015

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

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Suggested Citation:

USACE (2015). Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions – Water Resources Region 14, Upper Colorado. Civil Works Technical Report, CWTS-2015-14, USACE, Washington, DC

Table of Contents

Water Resources Region 14: Upper Colorado Region

1. Introduction

U.S. 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 the 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 regional vulnerability assessment tools.

This report focuses on Water Resources Region 14, the Upper Colorado Region, the boundaries for which are shown in **Figure 1.2**. The Upper Colorado Region is within the South Pacific Division, which is illustrated in **Figure 1.1**. The Sacramento and Albuquerque USACE districts each include territory within the Upper Colorado Region.

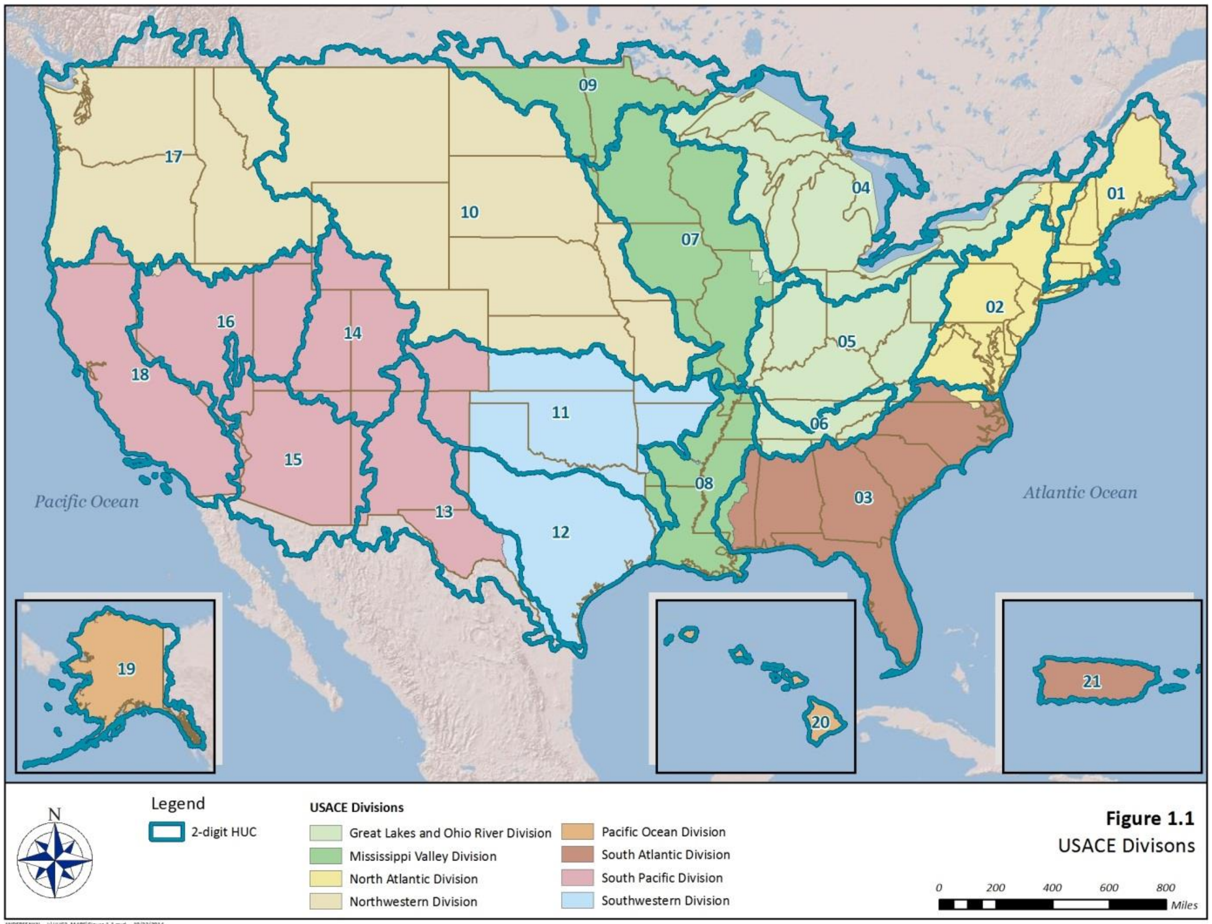


Figure 1.1. 2-digit Water Resources Regional Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.

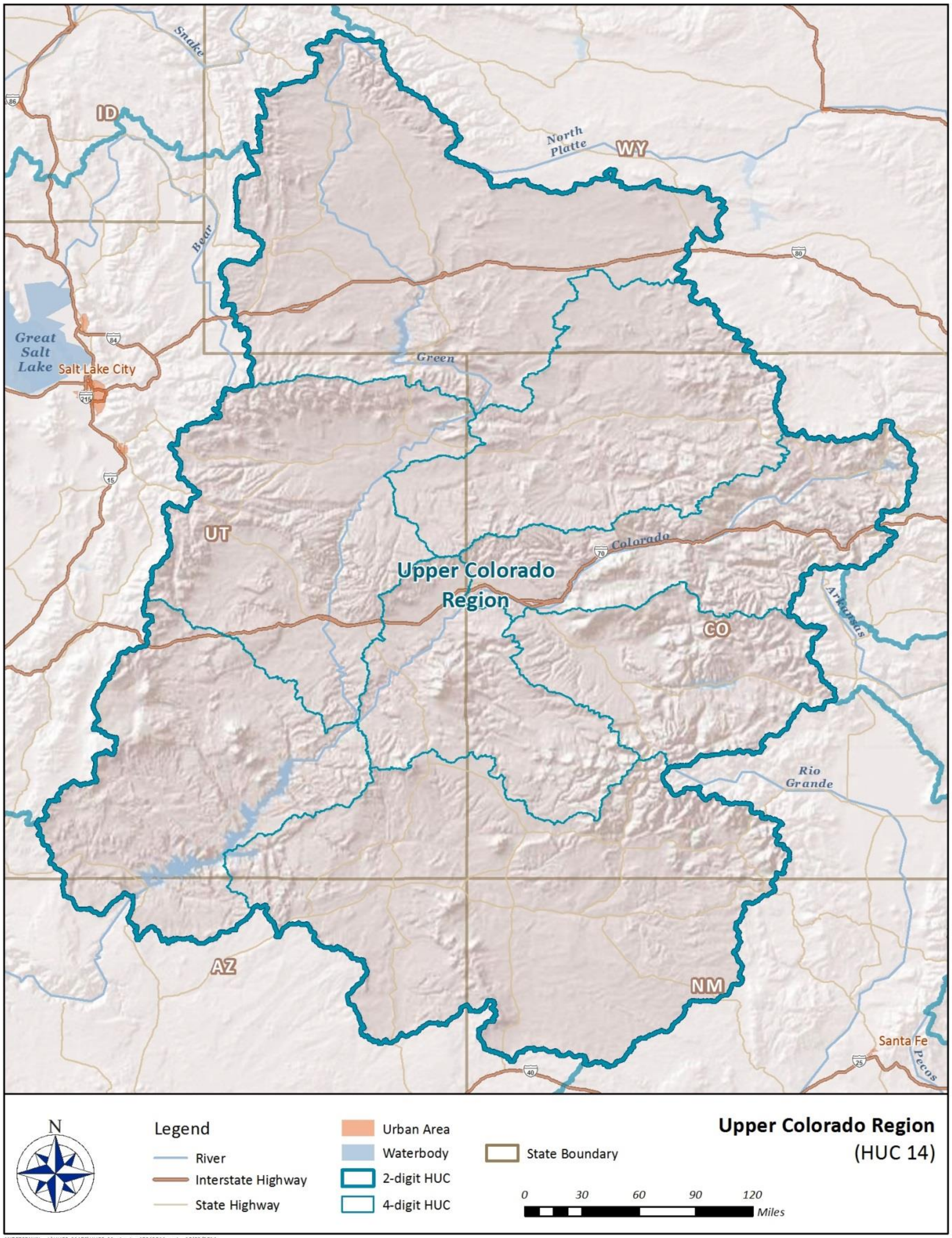


Figure 1.2. Water Resources Region 14: Upper Colorado Region Boundary.

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 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 informational assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 14, both the 2-digit and 4-digit HUC boundaries are shown in **Figure 1.2**.

2. Observed Climate Trends

Observed climate trends within the Upper Colorado Region 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 is 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 the Upper Colorado Region 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 results presented below indicate that moderate upward trending in both mean and extreme temperatures has occurred in the recent historical record for the Upper Colorado Region. There is also a reasonable consensus that streamflow has declined over the course of the previous century. Observed precipitation (mean and extreme) was not found to have an identifiable trend within the Upper Colorado Region.

2.1. Temperature

Many recent regional studies of the Colorado River basin (including the Upper Colorado Region) have focused on identifying trends in observed mean temperature and extreme temperature. In addition, a large number of national studies have also been conducted. This section summarizes the results of a select group of these peer-reviewed studies, all of which have concluded that the observed record generally shows an increase in mean and extreme temperatures for the region.

A study by Wang et al. (2009) 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 Upper Colorado Region, a positive trend was observed by the authors for the spring and summer months (March – August). However, the fall months (September – November) were found to have a moderate negative trend in average air temperature.

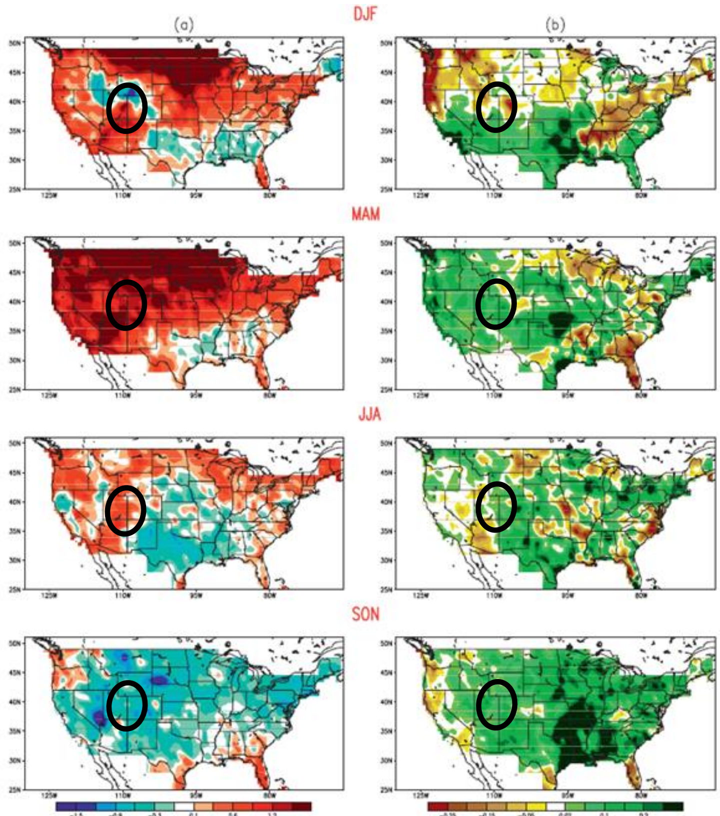


Figure 2.1. Linear trends in (a) surface air temperature and (b) precipitation over the United States, 1950 – 2000. The Upper Colorado Region is within the black oval (Wang et al., 2009).

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 Colorado Region, the authors found a slight statistically significant increasing trend in the number of one day extreme maximum temperature days per decade; however, no statistically significant trend was identified for the number of one day extreme minimum temperatures. This examination of extreme temperatures is in agreement with the findings of Wang et al. (2009) which evaluated seasonal mean temperatures and presented observed warming trends for the region during the summer months (July through August).

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 Upper Colorado Region, spring onset is generally 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**). Though, a select number of locations are showing a later spring onset of a few days. In other words, an apparent small shift in seasons has been identified for the Upper Colorado Region, with spring warming generally occurring earlier than in the past for most locations.

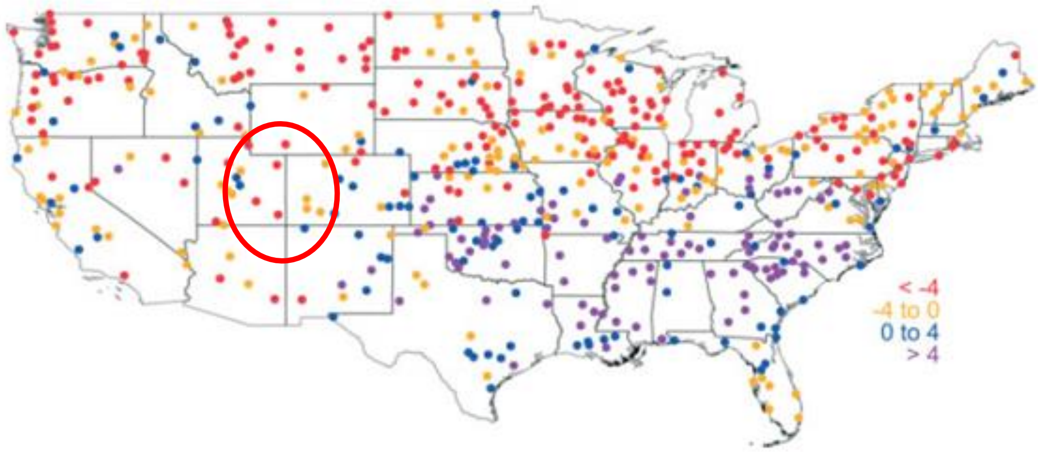


Figure 2.2. Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The Upper Colorado Region is within the red oval (Schwartz et al., 2013).

In support of the recently released third NCA (Kunkel et al., 2013) evaluated historic temperature trends in the southwestern U.S. which includes the Upper Colorado Region states of Arizona, Colorado, New Mexico, and Utah (non- Upper Colorado Region states California and Nevada are also included). Comparing annual historic temperatures to the average temperature of 1901 – 1960, the authors identified upward and statistically significant trends, to the 95% confidence interval (C.I.), for seasonal and annual temperatures from 1895-2011. **Table 2.1** provides the annual and seasonal temperature trends. The authors further identify a steady historic increasing trend in annual minimum and maximum temperatures (**Figure. 2.3**).

Table 2.1 Decadal trends in temperature and precipitation compared to average of 1901 – 1960. Only values significant (> 95% C.I.) are reported (Kunkel et al., 2013).

Season	Temperature (°F/decade)	Precipitation (inches/decade)
Winter	+0.21	—
Spring	+0.16	—
Summer	+0.17	—
Fall	+0.16	—
Annual	+0.17	—

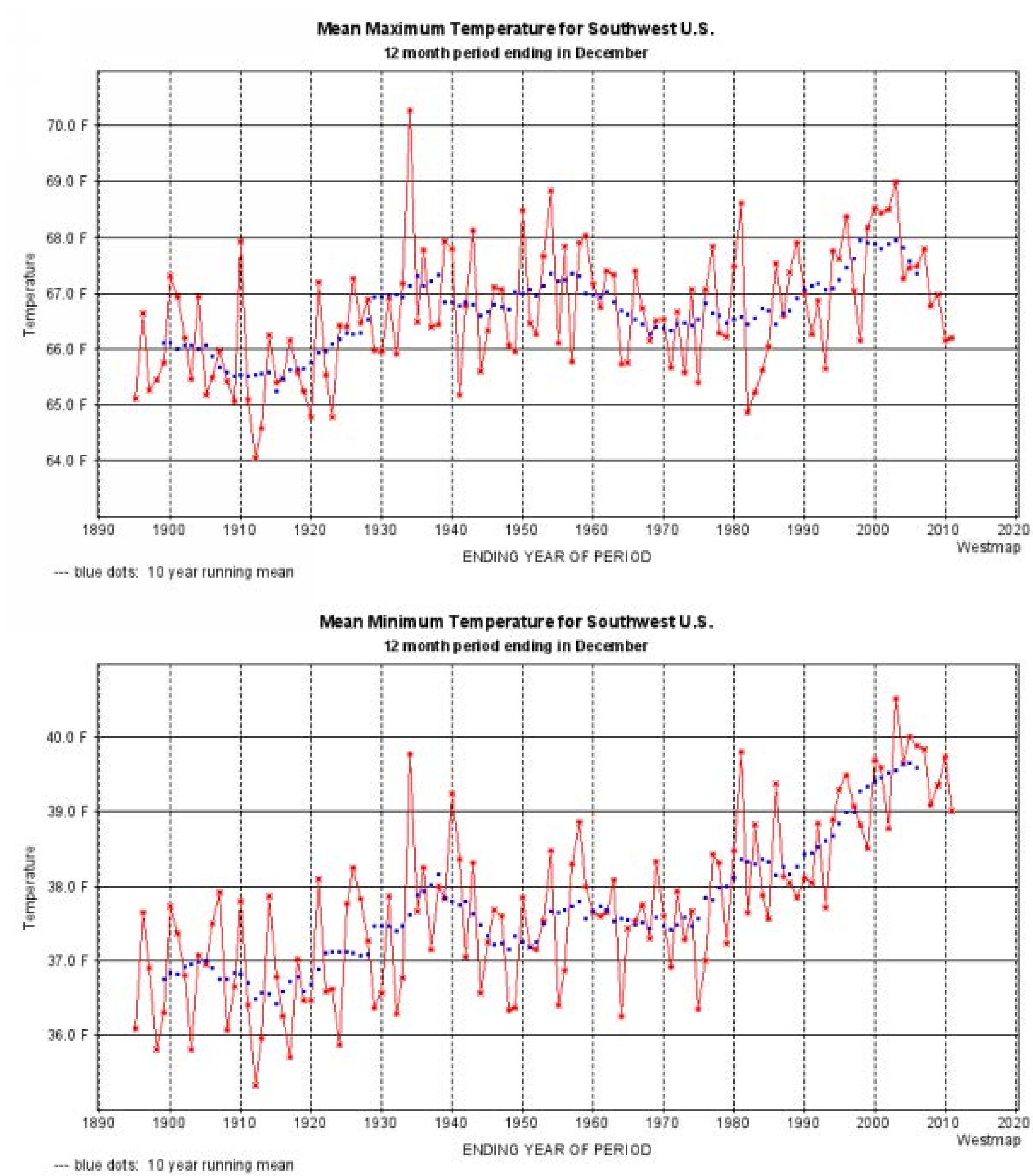


Figure 2.3. Annual mean maximum temperature of the southwestern U.S., 1895 – 2011 (top). Annual mean minimum temperature for the six states, 1895 – 2011 (bottom). Annual values are shown in red, while the 10-year running means are in blue (Kunkel et al., 2013).

Similarly, Hoerling et al. (2013) assessed weather and climate variability and trends in the Southwest using observed climate for the last 100 years. The authors quantified trends in annually averaged daily temperature and daily maximum temperature as estimated from station data for which there were at least 90 years of available data during the period between 1901 and 2010. In the Upper Colorado Region, a statistically significant (95% C.I.) increase of average annual daily temperature was identified within a range of 0.5 to 3.0 °C (0.9 to 5.4 °F). In addition, the authors found increasing trends in both the daily minimum and daily maximum temperature ranging between 0 to 2.5 °C (0 to 4.5 °F) and -1.5 to 3.0 °C (-2.7 to 5.4 °F), respectively.

Specific to Colorado, the recently released *Climate Change in Colorado* report (Lukas et al, 2014) found that annual average temperatures have increased by 2.0 °F (1.1 °C) over the past 30 years. In addition, Lukas et al (2014) found an increase in the daily minimum temperature across Colorado over the same time period.

Key point: A large consensus of reviewed studies found moderate increasing trend in observed mean air temperature in the Upper Colorado Region. In addition, extreme temperatures were found to be trending upwards.

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 study region that includes the Upper Colorado, statistically significant (C.I. = 95%) decreases in total storm precipitation (mm) and storm duration were identified for the winter and fall season. Additionally, statistically significant increases in summer storm intensity (mm per hour) and 15-minute maximum intensity were observed.

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 significant trends in annual precipitation for most of the U.S. For the Upper Colorado Region, the authors identified a moderate increasing trend in precipitation during the spring, summer, and fall. The exception to this was during the summer in the southwestern portion of the Upper Colorado (i.e., Arizona) where a slight decreasing trend was observed. For the winter months, the northern portion of the Upper Colorado Region was observed to have a slight to significant decreasing trend in precipitation while the southern portion was observed to have a slight to moderate increasing trend (**Figure 2.1**).

A study by McRoberts and Nielsen-Gammon (2011) used a new continuous and homogenous data set to perform precipitation trend analyses for subbasins 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 western portion of the Upper Colorado Region (**Figure 2.4**). For this region (i.e., Utah and Wyoming), the trend in annual precipitation indicates an increase on the order of 2 – 10% per century. Statistical significance of this trend is not provided by the authors.

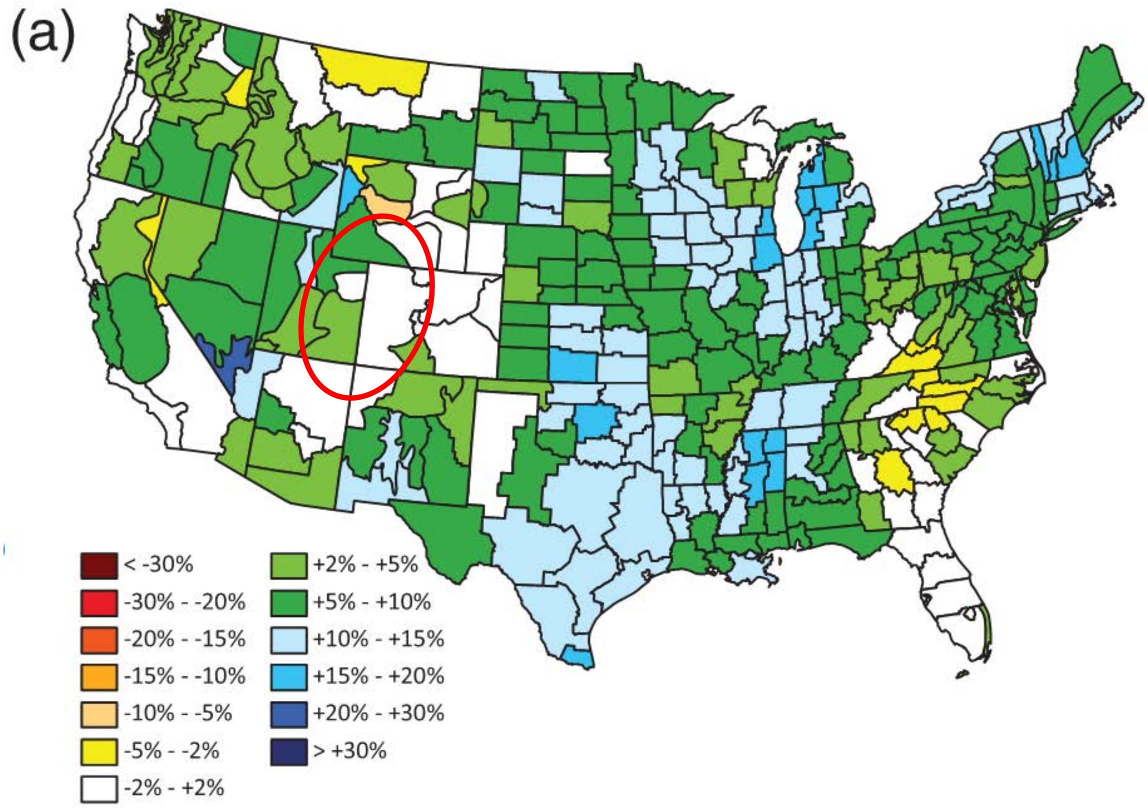


Figure 2.4. Linear trends in annual precipitation, 1895 – 2009, represented as a percent change per century. The Upper Colorado Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

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 western and central U.S., in both the recent historical data and the long term future projections (described below in Section 3). For the Upper Colorado Region, significant changes in the recurrence of this storm were identified for the period 1977 to 1999 compared to the period 1949 to 1976. An increase in frequency of approximately 0 – 33% was quantified for the northern portion of the Upper Colorado Region while the increase in frequency for the southern portion of the region was quantified as 50 – 100%.

Pryor et al. (2009) performed statistical analyses on 20th century rainfall data to investigate for trends across a range of precipitation metrics. They used data from 643 stations scattered across the continental U.S. For the Upper Colorado Region, the analysis showed varied, yet statistically significant, trends in total annual precipitation across the region. In addition, the authors found significant decreasing trends for precipitation intensity as well as the frequency of extreme events in the northwestern portion of the Upper Colorado Region (e.g., 90th percentile precipitation days). This is shown in **Figure 2.5** and is in contrast to other recent studies described above. 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. These trends were determined to be significant at the 90% confidence interval.

a)annual precipitation

b) 90^{th} percentile daily precipitation

c) precipitation intensity (annual total / number of precipitation days)

d) number of precipitation days per year

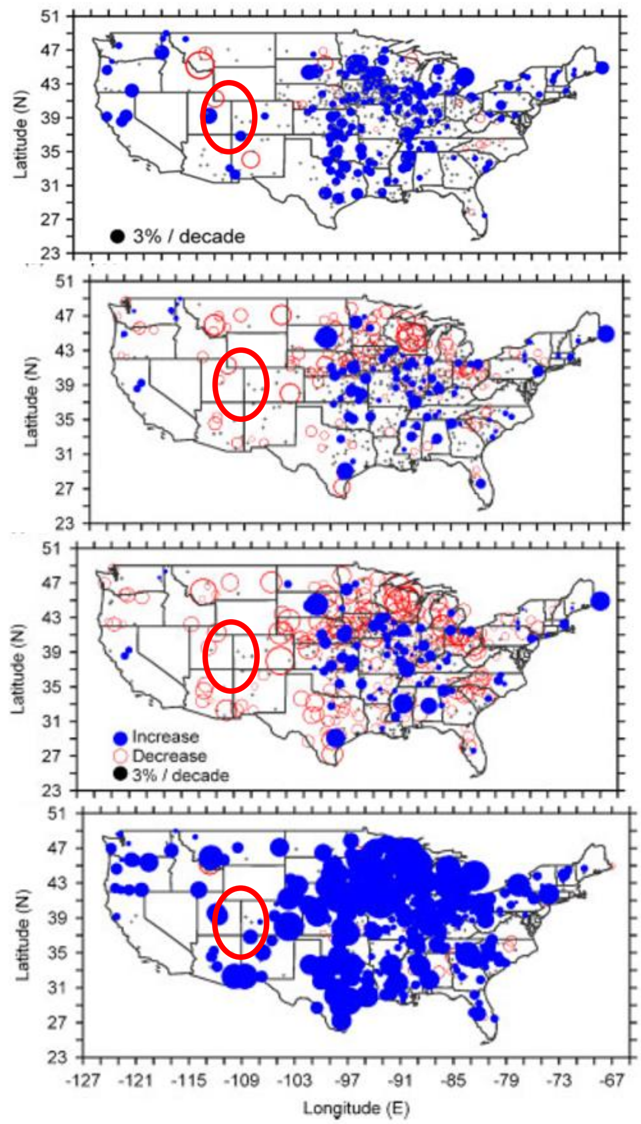


Figure 2.5. Historical precipitation trends in the 20^{th} century. a) annual totals, b) 90^{th} percentile daily, c) precipitation intensity (annual total/number of precipitation days), and d) number of precipitation days per year. Note that blue dots indicate positive trend, non-bolded red circles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

Kunkel et al. (2013), described above, found the Southwest to show no long term trends in annual precipitation totals. However, these authors found an increase in annual precipitation variability over the last 30 years of the study period (1895 – 2011). The authors did not find any statistically significant trends with respect to extreme precipitation events.

As mentioned above, Hoerling et al. (2013) used observed climate records to analyze the last 100 years of climate variability in the southwestern U.S. The authors compared the basin-mean precipitation of 2001 – 2010 to 1941 – 2000 and determined that the Upper Colorado Region was 4% less in the later time period.

Key point: A slight upward trend in precipitation over the past century in the study region has been identified by multiple authors; however, other studies observed no trend or even a decreasing trend in the observed precipitation record. Precipitation extremes were also observed to highly variable across the literature.

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 Upper Colorado Region. The Upper Colorado Region's hydrology is largely influenced by snowpack. Hydrologic trends can be closely tied to the impact of precipitation and temperature on snowpack, particularly with respect to timing. There appears to be general consensus among these studies that trends show a general decrease in river flow in the Upper Colorado Region, as described below.

Hydrological trends were evaluated by (Das et al., 2009) for the mountainous Western United States. The authors analyzed many variables including April 1 snow water equivalent (SWE) and October through March precipitation totals over a historical time period of 1950 – 1999. In addition, the ratio of these variables was evaluated in order to obtain a snow-based climate index that is more directly sensitive to temperature changes. Consistent with the studies described above, these authors found an increasing trend in temperature in the Upper Colorado Region for the study period. Furthermore, for the Upper Colorado, Das et al. (2009) found a decreasing trend in the ratio of April 1 SWE to October – March precipitation total. The results of this study suggest that this decreasing trend in spring snowpack is related to winter and spring time warming.

Matter et al (2010) applied a methodology for evaluating streamflow in the Upper Colorado Region based on characterizing climate regimes type by temperature and precipitation patterns (e.g., cool/wet and warm/dry). Their study focused on two sites on tributaries to the Upper Colorado River: the Yampa River at Steamboat Springs and Gunnison River near Gunnison, CO. The study's primary purpose was to characterize streamflow according to climate regime type in order to shed new light on the Upper Colorado Region's hydroclimatic variability. The authors found that the median annual basin yield decreased during the 20th century at both sites (1911 – 2011). Specifically, the decreasing trend was most pronounced when moving from periods of cool/wet to warm/dry characterizations.

Xu et al. (2013) evaluated hydrologic trends across the continental United States using the Model Parameter Estimation Experiment (MOPEX) data set for the period 1950 to 2000. Additional information on the MOPEX can be found in Duan et al. (2006). For the Upper Colorado Region, the authors found no statistically significant trends in either annual streamflow or baseflow within the Upper Colorado Region. In general agreement with Xu et al. (2013), Kalra et al. (2008) found no trend in streamflow for unimpaired gages located throughout the Upper

Colorado Region for the period 1951 to 2002. These authors looked at both annual total flows and seasonal flows (spring/summer vs. fall/winter).

Hoerling et al. (2013) utilized observed climate records to analyze the last 100 years of climate variability in the southwestern U.S. The authors compared the basin-mean streamflow of 2001 – 2010 to 1941 – 2000 and determined that the Upper Colorado Region was 16% less in the later time period. In addition, these authors evaluated the timing of streamflow by comparing the date at which half of the annual streamflow had been discharged. For the Upper Colorado Region it was observed that streamflow timing is occurring earlier by up to 10 days (**Figure. 2.6**).

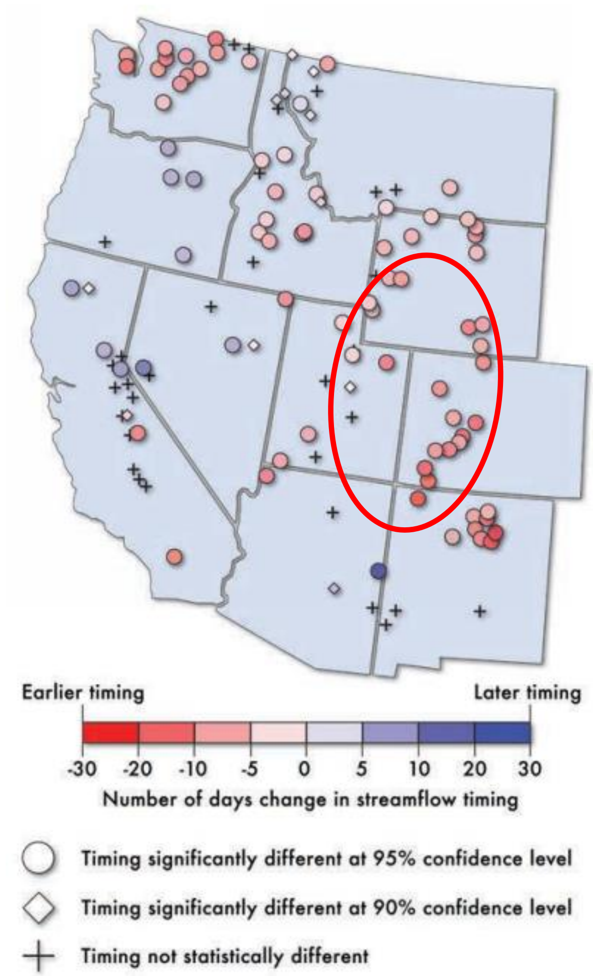


Figure 2.6. Changing streamflow timing 2001 – 2010 compared to 1950 – 2000. Differences between 2001 – 2010 and 1950 – 2000 average date when half of the annual streamflow has been discharged for snowmelt-dominated streams. The Upper Colorado Region is within the red oval (Hoerling et al., 2013).

In 2012, the United State Bureau of Reclamation published the *Colorado River Basin Water Supply and Demand Study*. As part of this body of work, an assessment of historical climate and hydrology was conducted and documented in Technical Report B. This study evaluated natural streamflow at 20 locations within the Upper Colorado Region for a time period of 1906 – 2007.

Results of this study indicated a downward trend in natural streamflow, especially for the periods spanning 1930 – 1970 and 1985 – present (Reclamation, 2012).

Key point: The trends over the observed period and over the recent climatological regime suggest declining streamflow, increases in variability, and seasonal shifts in streamflow for the Upper Colorado Region.

2.4. Summary of Observed Climate Findings

A large consensus within the peer-reviewed literature found an increasing trend in observed average temperature within the Upper Colorado Region. A similarly strong consensus exists with respect to increasing trends in observed temperature extremes (minimum and maximum). For observed precipitation and precipitation extremes, little consensus was found related to direction of the trend (increasing or decreasing) or the magnitude. Lastly, there is moderate agreement across reviewed studies that historical streamflows have been declining in the region, most notably between 1930 and 1970.

3. Projected Climate Trends

While historical data is essential to 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., 2005). Consequently, the scientific and engineering communities are actively using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed 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 Upper Colorado Region 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 Upper Colorado Region. There is much less consensus on the future trending, or lack thereof, of total precipitation, although many studies agree that storm intensity and extended drought conditions will both likely trend upward in the future. There is also a reasonable consensus in the hydrologic projections for the region that streamflows will generally decrease in the future, due largely to increased evapotranspiration as a function of rising temperatures.

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 Upper Colorado Region typically fall in line with both of these generalizations. Spears et al. (2013) states that for the Upper Colorado Region; confidence in future temperature projections is much higher than that associated with precipitation projections.

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 Upper Colorado Region, show a projected increase in seasonal maximum air temperature of 1.5 to 4 ºC (2.7 to 7.2 ºF) 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 Upper Colorado Region.

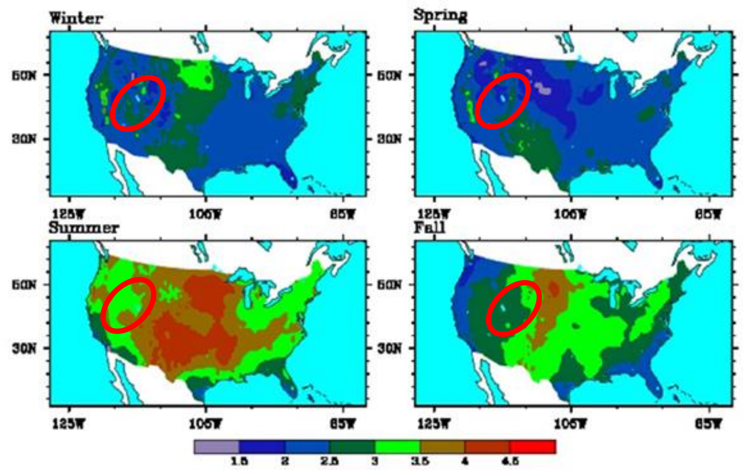


Figure 3.1. Projected changes in seasonal maximum air temperature, ºC, 2041 – 2070 vs. 1971 – 2000. The Upper Colorado Region is within the red oval (Liu et al., 2013).

Similar results are presented by Ashfaq et al. (2010) and Scherer and Diffenbaugh (2014). The first set of authors apply a single regional climate model to project future climate change across the continental U.S. In comparing future projections (2071 – 2100) to historical climate (1961 – 1990), they quantify changes in summer daily maximum temperature of 4 to 5 ºK (7.2 to 9 ºF) for the Upper Colorado Region. Projected changes in winter daily maximum temperatures for the region range from 3.5 to 4.5 ºK (6.3 to 8.1 ºF). The second set of authors apply a multi-member ensemble GCM, assuming an A1B (middle of the road) emissions scenario, to the continental U.S. For the Southwest, including the Upper Colorado 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 4.0 ºC (7.2 ºF) in the summer average daily maximum temperature and 3.4 ºC (6.1 ºF) in the winter average daily minimum temperature, compared to a 1980 – 2009 baseline period. These results agree well with those described previously for Liu et al. (2013).

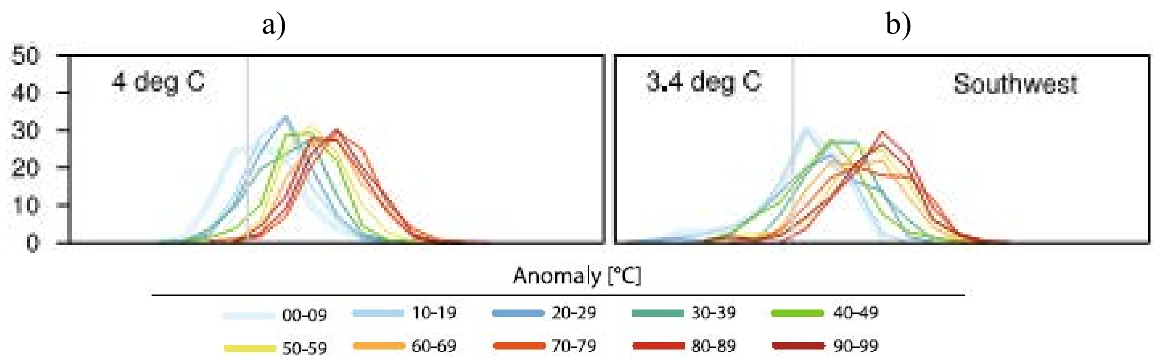


Figure 3.2. Probability distributions of GCM Projections of daily maximum temperatures for Years 2000 – 2100 by decade, Southwest Region a) summer months: June – August, average daily maximum temperatures, b) winter months: December – February, average daily minimum temperatures (Scherer and Diffenbaugh, 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 western Colorado, results show a shift from mostly cold moist and cool semiarid climate types to a larger cool semiarid region and also a cold dry climate type in the latter decades of the 20th century 2041 – 2070 (**Figure 3.3**). In eastern Utah, results show a transition from cool semiarid and cool arid climate types to a more prominent cool arid climate type in and also warm arid in the southeastern Utah.

a) historical observed (1971 – 2000)

b) GCM projections (2041 – 2070)

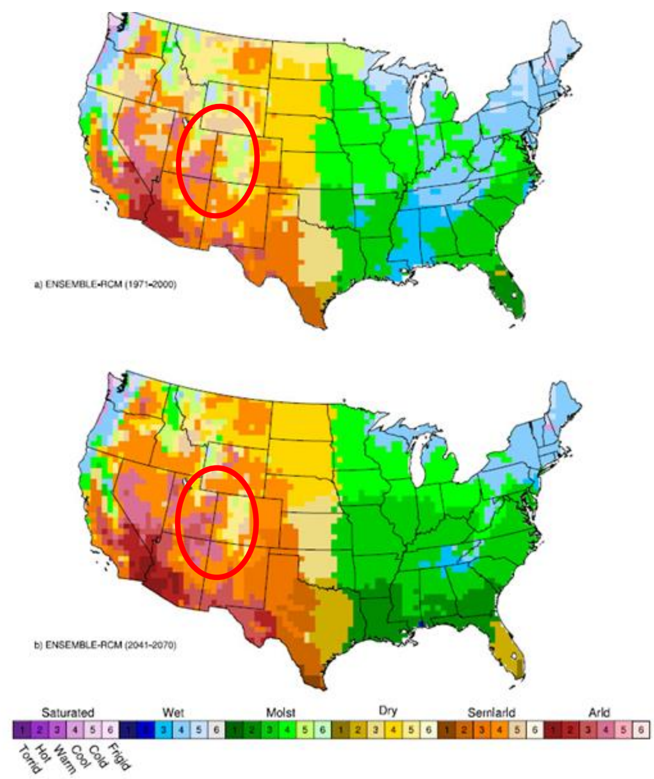


Figure 3.3. Revised Thornthwaite climate types projected by regional climate models. The Upper Colorado Region is indicated by the red oval (Elguindi and Grundstein, 2013).

A study by Tebaldi (2006) applied nine GCMs at a global scale focused on extreme precipitation and temperature projections. Model projections of climate at the end of the century (2080 – 2099) were compared to historical data for the period 1980 – 1999. For the Upper Colorado Region, the authors identified small decreases in the projected extreme temperature range (annual high minus annual low temperature), a moderate increase in a heat wave duration index (increase of 3 to 4 days per year that temperatures continuously exceeds the historical norm by at least 5 ºC [9 ºF]), and a moderate increase in the number of warm nights (c. 6 to 7% increase), compared to the baseline period.

Similar results are presented by Kunkel et al. (2010). In this study, two different downscaled GCMs were 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 Upper Colorado Region, projections indicate a 4 to 6.5 ºC (7.2 to 11.7 ºF) increase in three-day heat wave temperatures and a 60 to 80 day increase in the annual number of heat wave days for a 2090 planning horizon compared to a recent historical baseline.

Gutzler and Robbins (2010) applied an ensemble of 18 GCMs, forced by a middle of the road (A1B) emissions scenario, to project temperature, precipitation, and drought changes for the western U.S. through 2100. Results for the Upper Colorado (**Figure 3.4**) indicate a projected change in annual average temperature of approximately 3.0 to 3.5 ºC (5.4 to 6.3 ºF) for the last quarter of the 21st century compared to the last quarter of the 20th century.

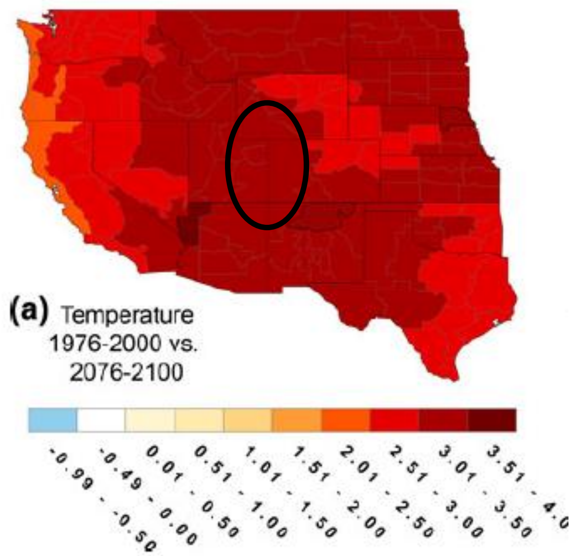


Figure 3.4. GCM projections of annual average temperature change, western United States. The Upper Colorado Region is within the black oval (Gutzler and Robbins, 2010).

The third NCA (Garfin et al., 2014) supports the projections made by Gutzler and Robbins (2010). The NCA summarized climate model projections forced by an A2 (higher emissions) and B2 (lower emissions) scenario. The results, as shown in **Figure 3.5**, show an increase of 4.5 ºF to 8.5 ºF (2.5 to 4.7 ºC) when comparing the time period 2071-2099 to a baseline of 1971-1999. The emission scenarios summarized in the third NCA "book end" the middle of the road (A1B) emissions scenario utilized by Gutzler and Robbins (2010); however, the resulting projected change in annual average temperature are both higher.

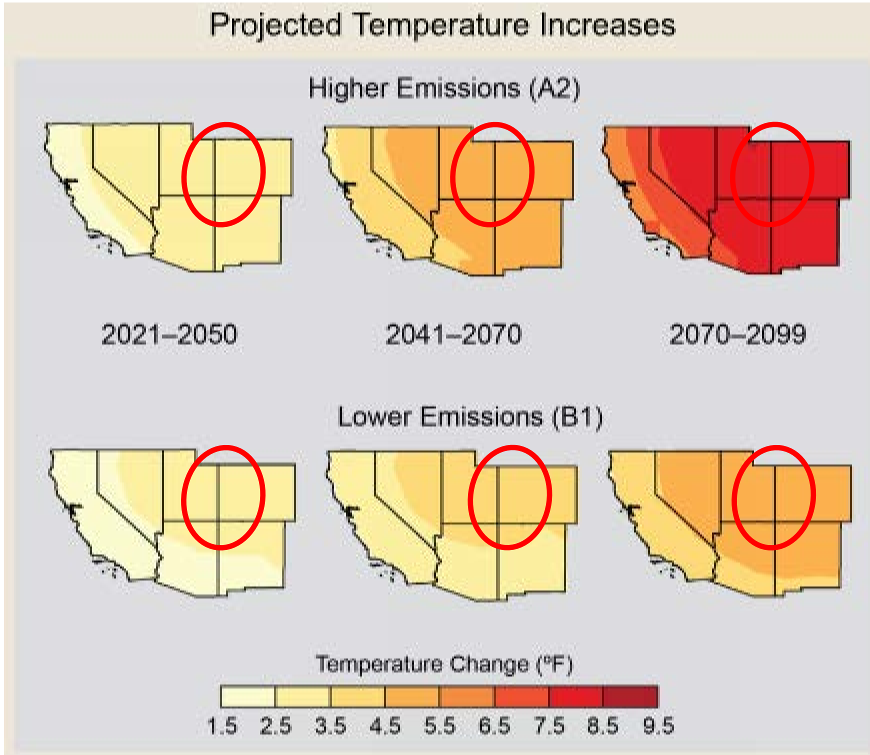


Figure 3.5. Projections of annual average temperature change, as compared to 1971 – 1999, for the western United States. The Upper Colorado Region is within the red oval (Garfin et al., 2014).

Lukas et al (2014) utilized an ensemble of CMIP5 model projections to evaluate projected climate trends in Colorado. The authors focused on the RCP 4.5 (medium-low emissions) and RCP 8.5 (high emissions) scenarios because these two pathways combined cover a large majority of the range of all RCPs utilized in the CMIP5 model projections. Under RCP 4.5, the authors found an annual average increase in temperature of 4 ºF (2.6 ºC) when compared to an observed record of 1971 – 2000. Similar results were also observed for each of the four seasons, with summer being the showing the highest increase (**Figure 3.6**).

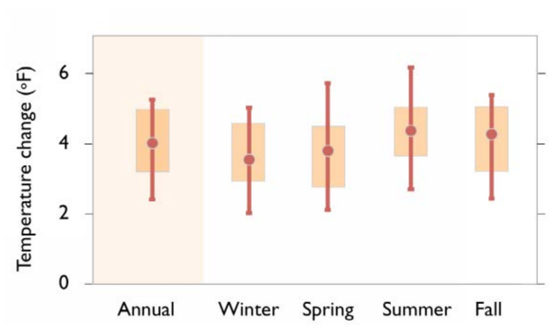


Figure 3.6. Projected Colorado annual and seasonal temperature change under RCP 4.5 for 2035-2064 (Lukas et al, 2014).

Key point: Strong consensus exists in the literature that projected temperatures in the study region show a large increasing trend 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 Upper Colorado Region are variable and generally lacking in consensus among studies or across models. The Liu et al. (2013) study, described above, quantified moderate increases in fall and winter precipitation associated with a 2055 planning horizon, relative to a recent historical baseline (1971 – 2000, centered around 1985) , for the Upper Colorado Region (**Figure 3.7**). Smaller precipitation increases are found for the northern portion of the region in the spring while the southern portion of the region show a slight decrease in spring over the same time period. The entire Upper Colorado Region shows a slight decrease in precipitation during the summer. The authors also project increases in the severity of future droughts for the region for all seasons except spring where some sub-regions of the Upper Colorado show lessening drought severity (results not shown), as projected temperature and ET impacts outweigh the increases in precipitation.

The middle of the road (A1B) ensemble of projections applied by Gutzler and Robbins (2010) show virtually no change in annual average precipitation for the Upper Colorado (**Figure 3.8**) for the last quarter of the 21st century compared to the last quarter of the 20th century. The area of the region within Wyoming is the exception which shows a slight increase (< 2.0 mm/year) in precipitation compared to baseline. Like the Liu et al. (2013) study, the authors also project an increase in future drought indices for the region, as a function of changing climate, that indicate reduced soil moisture and more drought-prone conditions.

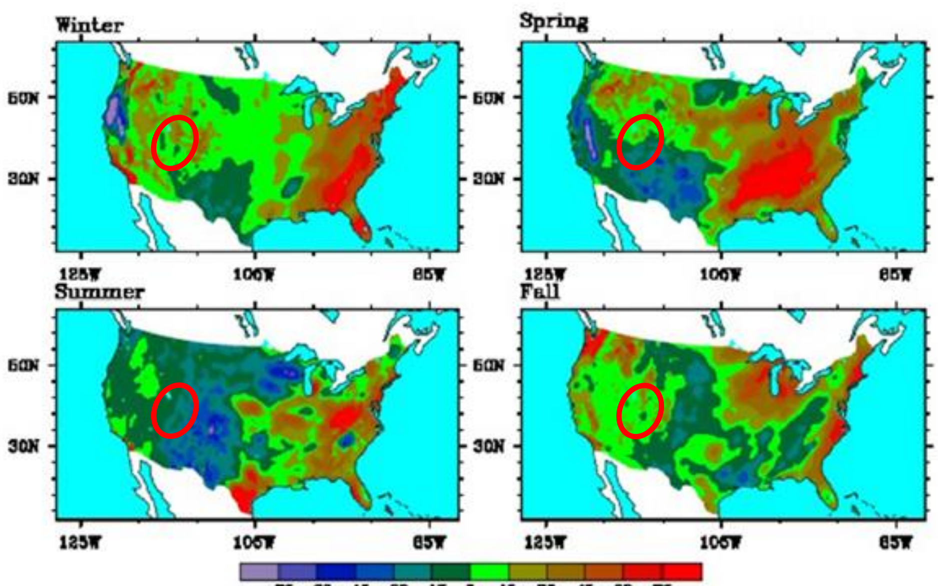


Figure 3.7. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The Upper Colorado Region is within the red oval (Liu et al., 2013).

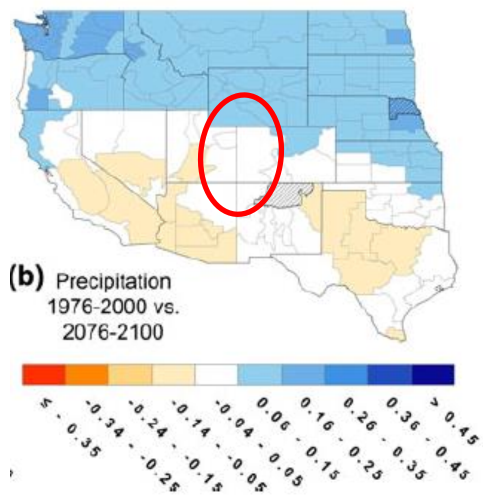


Figure 3.8. GCM projections of annual average precipitation change (mm month^{-1}), western United States. The Upper Colorado Region is within the red oval (Gutzler and Robbins, 2010).

Future projections of storm events are the subject of studies by Tebaldi (2006) and Wang and Zhang (2008). The first authors compared an ensemble of GCM projections for the Upper Colorado Region with a 2090 planning horizon to a historical baseline data (1980 to 1999). They report small increase in the number of high (> 10 mm) precipitation days for the region as well as in the magnitude of the 95th percentile storm events and the daily precipitation intensity index (annual total precipitation divided by number of wet days). In other words, the projections forecast small increases in the intensity of storm events by the end of the 21st century for the general study region. It is unclear whether these projected changes are statistically significant for the Upper Colorado Region. 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) in the general Upper Colorado Region. The projected increases in storm frequency presented by Wang and Zhang (2008) and by Tebaldi (2006) are in agreement with global modeling results, as described in Spears et al. (2013) which consistently suggest a trend toward more intense and extreme precipitation for the globe as a whole.

In support of the third NCA Cayan et al. (2013) prepared a report that summarizes the most recent understanding of climate change in the southwestern portion of the United States. The summary report prepared by these authors varies slightly with the projections of changes in annual average precipitation found by Gutzler and Robbins (2010) described above. These authors calculated the median of sixteen downscaled simulations for three future time horizons: 2021-2050, 2041-2070, and 2070-2099. For the Upper Colorado Region, Cayan et al. (2013) found that under a high-emissions scenarios annual average precipitation is projected to be 90-95% of the historical average. The results are summarized in **Figure 3.9**.

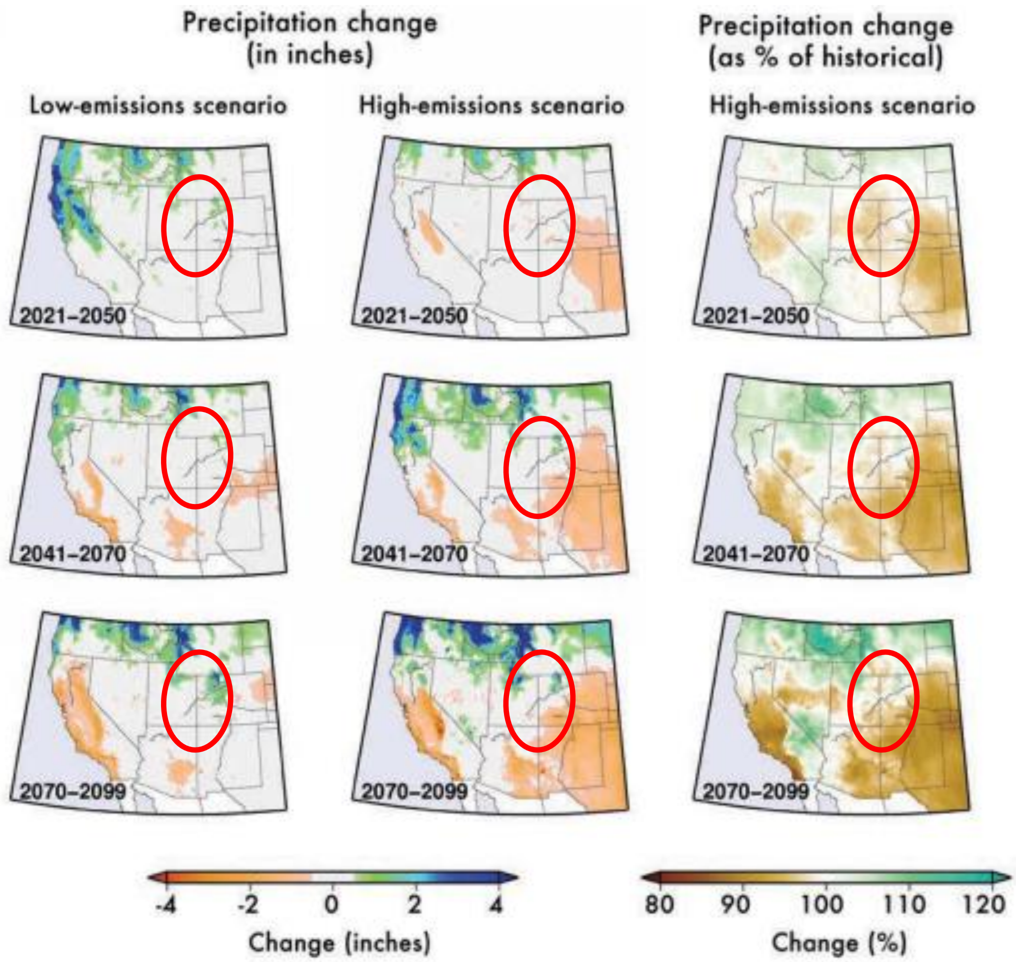


Figure 3.9. Ensemble projections of future precipitation (mid-21st century vs. historical baseline). The Upper Colorado Region is within the red oval (Cayan et al, 2013).

Lukas et al (2014), described above, utilized an ensemble of CMIP5 model projections to evaluate projected climate trends in Colorado. Under RCP 4.5, the authors found a slight increase in annual average precipitation when compared to an observed record of 1971 – 2000 with winter and spring the showing the relative highest increase (**Figure 3.10**).

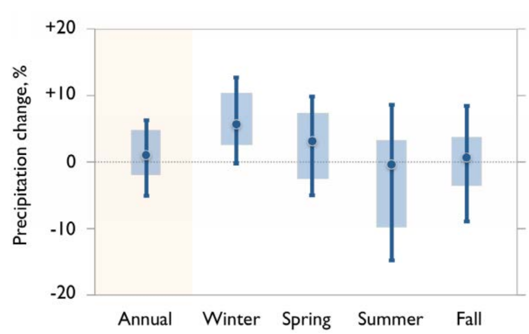


Figure 3.10. Projected Colorado annual and seasonal precipitation change under RCP 4.5 for 2035 – 2064 (Lukas et al., 2014).

Key points: Little consensus exists in the literature with respect to projected trends in future total annual precipitation in the Upper Colorado Region. However, there is moderate consensus that the risk of drought and the intensity of storm events in the region will increase in the future.

3.3. Hydrology

A number of regional and national scale studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro-scale hydrologic models. These studies include projections of potential hydrologic changes in the Upper Colorado 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 3.11**) and for individual Water Resource Regions. For the Upper Colorado Region, 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 increases in water yield.

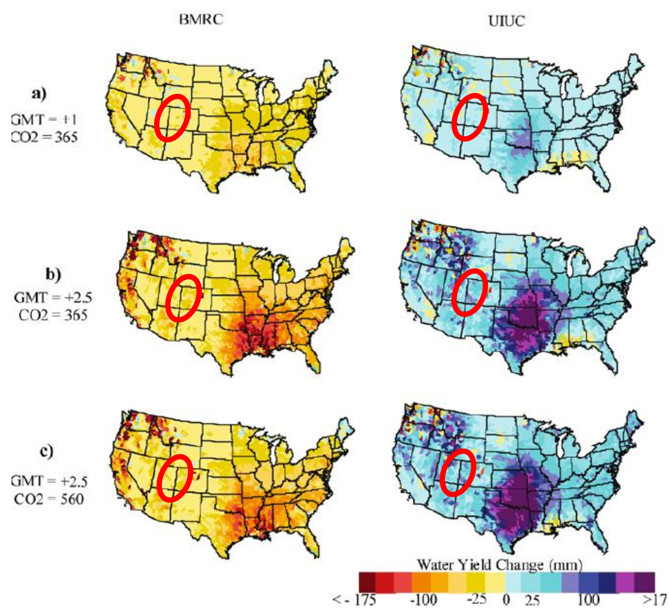


Figure 3.11. Projected change in water yield (from historical baseline), under various climate change scenarios based on two GCM projections. The Upper Colorado Region is within the red oval (Thomson et al., 2005).

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 study by Hagemann et al. (2013). 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 as, or greater than, that associated with the selection of climate models.

More recently, regional studies have been conducted for the Upper Colorado 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 (**Figure 3.12**) specific to the Upper Colorado Region show primarily decreases in 21st century projected flows compared to the historical baseline (1990s). Projection ensemble median changes are all < 20% for both the 2050s and 2070s.

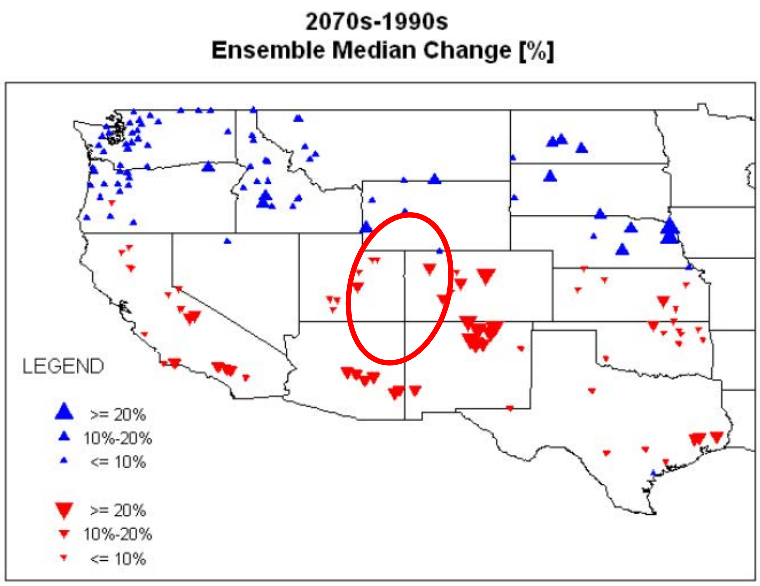


Figure 3.12. Ensemble median runoff projections, changes in annual runoff. The Upper Colorado Region is within the red oval (Brekke, 2011).

Reclamation (2012), described previously, also evaluated projected trends in streamflow through 2095 utilizing downscaled GCM climate information that was then input into a hydrologic model. Downscaled projections were based on the 112 future climate projections from the World Climate Research Programs' CMIP3 database resulting from an ensemble of 16 GCMs under three emissions scenarios (A2-high, A1B-medium, and B1-low). **Table 3.1** summarizes the change in projected streamflow at Lees Ferry, Arizona relative to a baseline mean of 1950-1999 for three future time periods: 2011 – 2040, 2041 – 2070, 2066 – 2095, and 2011 – 2060. Under each emissions scenario, and for each time period, reductions in streamflow are projected, especially in the later part of the 21st century when an average of all 112 projections showed in decrease of over 10 percent.

Table 3.1 Percentage Change in Mean Flow with Respect to Historical Mean (1950 – 1999) at the Colorado River at Lees Ferry, Arizona (Reclamation, 2012).

	2011–2040	2041–2070	2066–2095	2011–2060
All Projections	-5.6	-9.1	-10.5	-6.8
SRESB1	-5.2	-7.9	-8.0	-6.0
SRESA1B	-6.7	-9.1	-10.5	-7.7
SRESA2	-4.9	-10.3	-13.2	-6.5

The same authors also utilized the same set of downscaled projections at Lees Ferry to evaluate the impact climate change on season shifts in streamflow. Compared to a historical period of 1950 – 1999, the authors observed a projected shift of negative one month in streamflow by 2099 when results were averaged across all 112 projections (**Figure 3.13**). In other words, peak flow is projected to occur in May at the end of this century versus the historical period peak flow month of June.

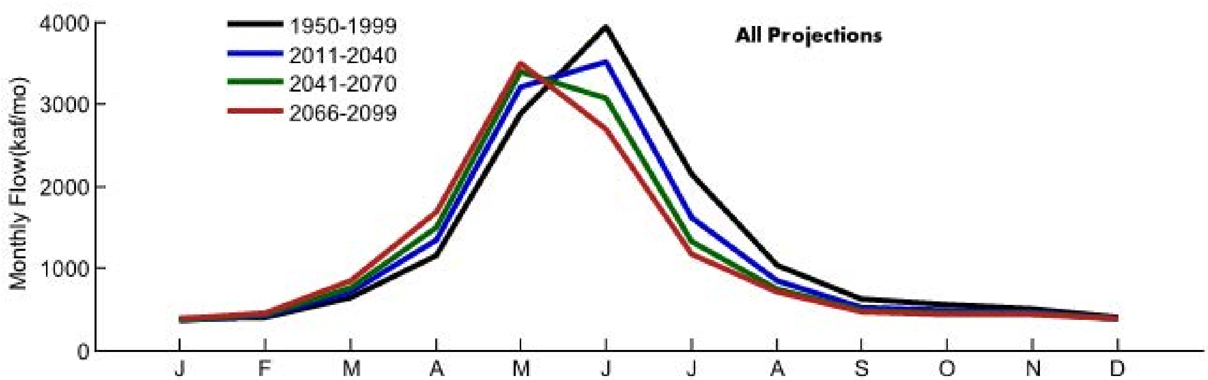


Figure 3.13. Comparison of observed and future simulated mean monthly flows at Colorado River at Lees Ferry, Arizona (Reclamation, 2012).

In support of the third NCA (Garfin et al., 2014) prepared a report that summarizes the most recent understanding of climate change in the Southwest. These authors calculated the median annual runoff of sixteen downscaled simulations for a future time horizon of 2041 – 2070. For the Upper Colorado Region, the authors found that under a high-emissions scenarios annual average runoff is projected to decrease by up to 40% in southwestern Colorado compared to the historical average (1971-2000); however, the majority of the region was found to have relatively little change. These results are summarized in **Figure 3.14**.

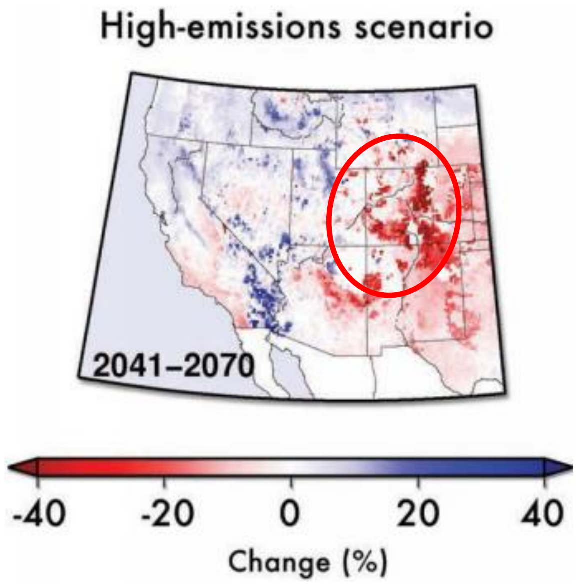


Figure 3.14. Percent change in annual runoff between 2041 – 2070 and the historical period (1971 – 2000) under a high emissions scenario. The Upper Colorado Region is within the red oval (Garfin et al., 2014).

The third NCA's Chapter 20: Southwest (Garfin et al., 2014) presents a projected decrease in snowpack for the southwestern United States, including the Upper Colorado Region. Decreased snowpack, as measured by snow water equivalent (SWE), and a change in type of precipitation (i.e., snow to rain) is strongly related to the amount and timing of runoff within the Upper Colorado (Garfin et al., 2014). A 65 to 75% reduction in SWE is projected for the Upper Colorado Region, compared to a baseline historical period (1971 – 2000), under a high emissions scenarios (A2). The projected decreases in SWE for all states in the southwestern United States are summarized below (**Figure 3.15**). Each bar chart's size is proportional to amount of snowfall experienced by each state.

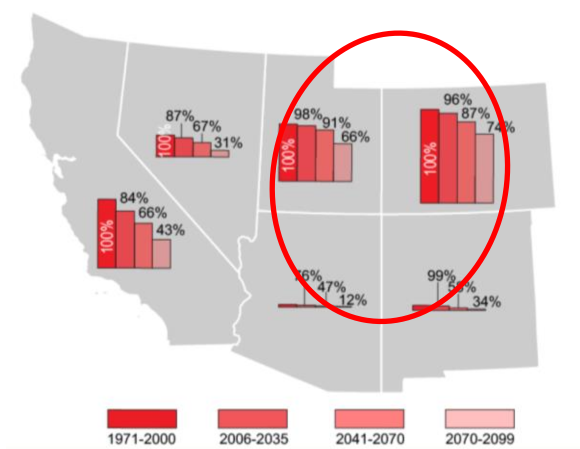


Figure 3.15. Projected snow water equivalent in the southwestern United States. The Upper Colorado Region is within the red oval (Garfin et al., 2014).

Lucas et al (2014), described above, utilized an ensemble of CMIP5 model projections to evaluate projected climate trends in Colorado. Under RCP 4.5, the authors found no clear trend with respect to changes in streamflow in Colorado. This is in contrast to recent studies utilizing CMIP3-based streamflow projections. However, as shown in **Figure 3.16**, the CMIP5-based projections for streamflow are within the envelope of projected streamflow from other studies that relied on CMIP3 and showed a decreasing trend.

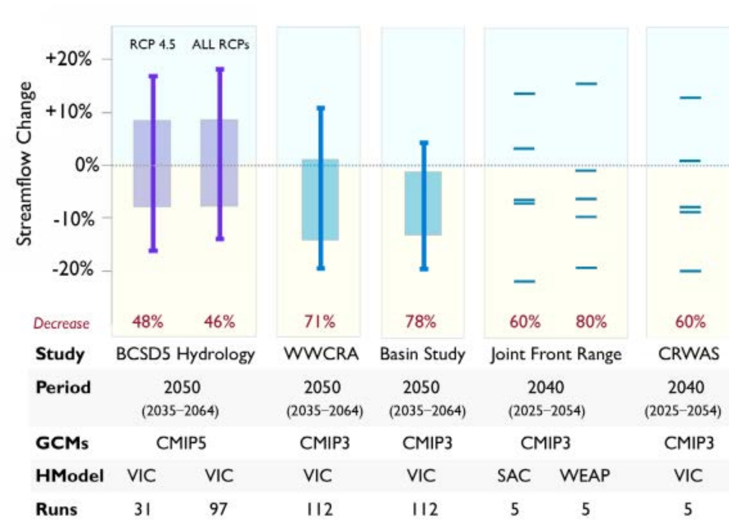


Figure 3.16. Projected changes in Colorado River headwaters (Cameo Gage) streamflow by the mid-21st century from five recent studies. (Lukas et al., 2014).

Key point: There is consistent agreement across the reviewed literature that hydrologic parameters such as runoff and snow water equivalent (SWE) will decrease over the next century.

3.4. Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the Upper Colorado 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 4.5 to 8.5 ºF (2.5 to 4.7 ºC) by the latter half of the 21st century for the Upper Colorado Region. Reasonable consensus 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 region are less certain than those associated with air temperature. On the whole, the region appears to sit on a divide between a generally projected wetter north and a projected dryer south. There is reasonable consensus in the literature, however, that the frequency and intensity of large storm events in the region will increase in the future. Multiple studies reviewed here also indicate increasing frequency and severity of future droughts in the region.

Despite the lack of clarity in precipitation projections, the majority of studies reviewed here generally predict a small to moderate decrease in future streamflows and water availability. These projections were generated by coupling GCMs with macro-scale hydrologic models, which introduce additional uncertainty. Based on the temperature and precipitation projections described above, it appears that future water availability will be limited more so by changes in temperature and ET than by precipitation changes.

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 3.17**).

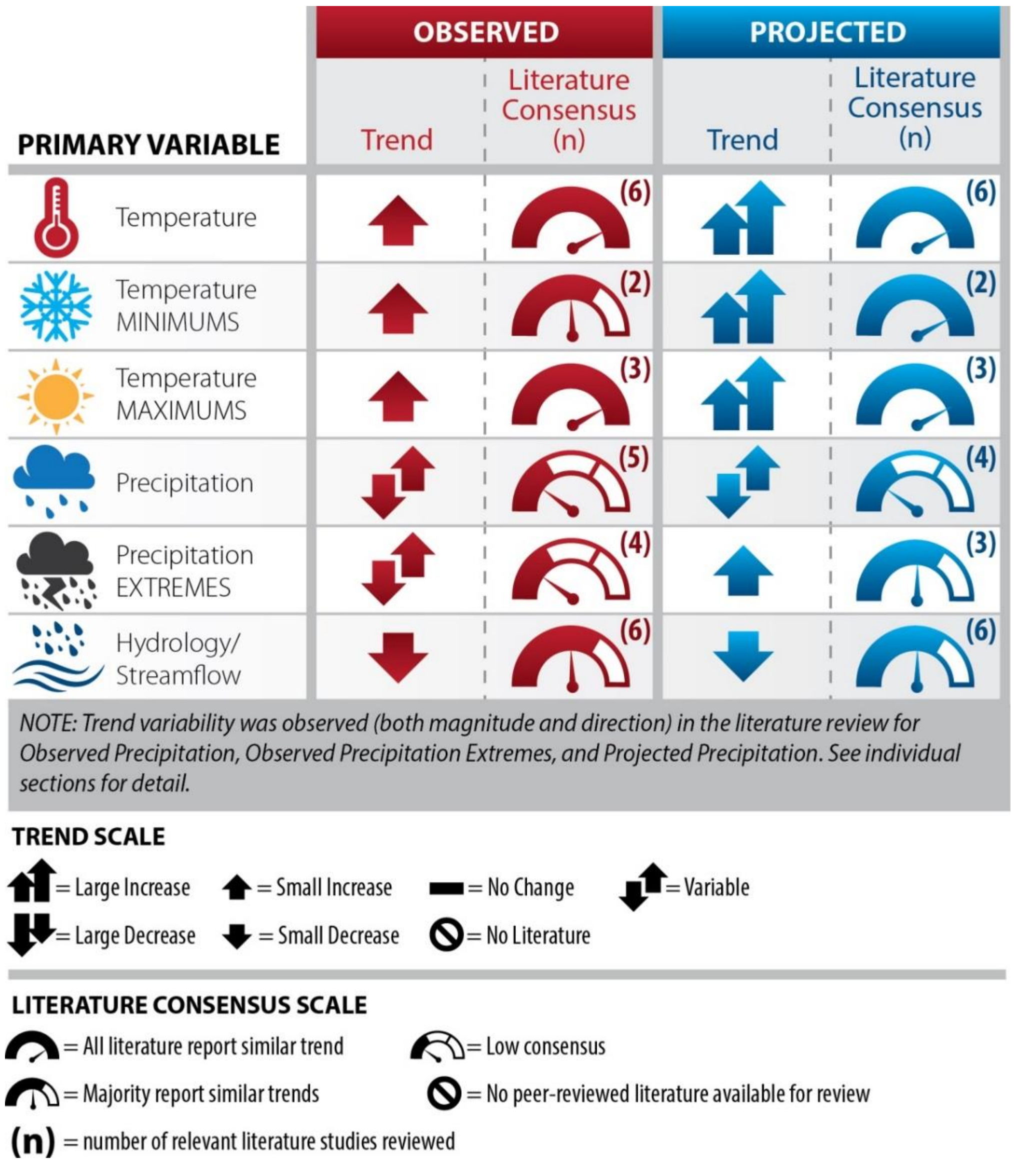


Figure 3.17. Summary matrix of observed and projected climate trends and literary consensus.

4. Business Line Vulnerabilities

The Upper Colorado Region encompasses southwestern Wyoming, the eastern half of Colorado, the western half of Utah, and the Four Corners. 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:

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

USACE implements flood risk management projects in the region including structural projects to maintain the flows. Increased precipitation event frequency and intensity are predicted for the region. This may increase runoff and may cause flash floods. Flood risk management projects may be very important for reducing the residual flooding impacts due to extreme storm events, which are predicted to be more frequent and intense.

USACE also maintains and operates several fresh water supplies to maintain water quality in the region. Snowpack which provides water sources in the region is expected to decrease. This along with the contrast between increasing mean air temperatures along with increased frequency and magnitude of heat waves will make managing competing water needs a challenge, especially when water demand is high and water supply is low.

USACE implements several ecosystem restoration projects in the Upper Colorado Region to restore, protect, and manage the native habitats in the region. Increased air temperatures and increased frequencies of drought, will 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. Increased storm intensities coupled with prolonged periods of drought conditions in the Upper Colorado Region, may pose complications to planning for ecosystem needs and lead to decrease in flows.

Recreational facilities in the Upper Colorado Region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature along extended heat waves in the summer months and the increased frequency and intensity of extreme storm events 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. An increase in extreme storm events may make recreational activity difficult, dangerous, or impossible.

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. Extreme storm events are capable of creating emergency situations in which USACE would be needed to provide assistance in the Upper Colorado Region. These types of storms are capable of intense precipitation and winds. Since these may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

USACE's regulatory mission has a serious commitment to protecting aquatic resources while allowing for 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 regulations or an increase in 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 including 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	VULNERABILITY
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 a change to a more semiarid and cool/dry ecosystem, 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. **BUSINESS LINES IMPACTED:**
Increased Maximum Temperatures	Air temperatures are expected to increase 4.5-8.5˚C by the end of the 21st century. The number and intensity of heat waves is also likely to increase. 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. **BUSINESS LINES IMPACTED:**
Increased Storm Intensity and Frequency	Extreme storm events may become more intense and frequent over the coming century which are expected to influence the following vulnerabilities on business lines in the region: • Increased flows and runoff at the time of the event, 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. • Change in engineering design standards to accommodate new extreme storms magnitudes. • Increased flash flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:**
Streamflow Variability	Streamflow is likely to decrease, mostly due to increasing temperatures and decreased snowpack which is expected to influence the following vulnerabilities on business lines in the region: • Decrease in streamflows has implications for maintain water levels in the rivers. • A decrease in water availability in the region for competing sources may present some significant, additional challenges to an already complex water resource system. • Ecosystem damage, such as loss of vegetation and habitat for aquatic species. **BUSINESS LINES IMPACTED:**

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

= Navigation = Flood Risk Management = Ecosystem Restoration = Hydropower = Recreation = Water Supply = Emergency Management

Figure 4.1. Summary of projected climate trends and impacts on USACE business lines.

Appendix A: References Climate/Hydrology Summary Table

	Observed										Projected									
References	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Ashfaq M, Bowling LC, Cherkauer K, Pal JS, Diffenbaugh NS (2010)											X	X	X							
Brekke L (2011)																X				
Cayan (2013)														X						
CDMSmith (2012)																X				
Das T, Hidalgo HG, Pierce DW, Barnett TP, Dettinger MD, Cayan DR, Bonfils C, Bala G, Mirin A (2009)						X														
Duan Q, Schaake J, Andreassian V, Franks S, Goteti G, …, Oudin L, Sorooshian S, Wagener T, Wood EF (2006)						X														
Elguindi N, Grundstein A (2013)											X			X						X
Garfin G, Franco G, Blanco A, Comrie A, Gonzalez P, Piechota T, Smyth R, Waskom R (2014)											X			X		X				
Grundstein A, Dowd J (2011)	X	X	X																	
Gutzler DS, Robbins TO (2010)											X			X						
Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, …, Ludwig F, Voss F, Wiltshire AJ (2013)																				
Hoerling MP, Dettinger M, Wolter K, Lukas J, Eischeid J, Nemani R, Liebmann B, Kunkel KE (2013)																X				
Kalra A, Piechota T, Davies R, Tootle G (2008)																X				
Kunkel KE, Liang X-Z, Zhu J (2010)																				
Kunkel KE, Stevens LE, Stevens SE, Sun L, Janssen E, Wuebbles D, Redmond KT, Dobson JG (2013)	X	X	X	X							X		X							
Liu Y, Goodrick SL, Stanturf JA (2013)											X		X	X			X	X		
Lukas et al. (2014)	X	X									X	X	X	X	X	X				
Matter MA, Garcia LA, Fontane DG, Bledsoe B (2010)						X														
McRoberts DB, Nielsen-Gammon JW (2011)														X						
Milly PC, Betancourt JL, Falkenmark M, Hirsch R, Kundzewicz Z, Lettenmaier D, Stouffer R (2008											X									
Palecki MA, Angel JR, Hollinger SE (2005)				X																
Pryor SC, Howe JA, Kunkel KE (2009)														X	X					
Reclamation (2012)						X										X				
Scherer M, Diffenbaugh N (2014)											X	X	X							
Schwartz MD, Ault TR, Betancourt JL (2013)	X								X											
Spears M, Harrison A, Sankovich V, Gangopadhyay S (2013)											X			X						
Tebaldi C (2006)											X	X	X	X	X					
Thomson AM, Brown RA, Rosenberg NJ, Srinivasan R, Izaurralde RC (2005)																X				
Walsh J, Wuebble D, Hayhoe K, Kossin J, Kunkel K, Stephens G, Thorne P, …, Kennedy J, Somerville R (2014)	X																			
Wang H, Schubert S, Suarez M, Chen J, Hoerling M, Kumar A, Pegion P (2009)	X		X	X																
Wang J, Zhang X (2008)				X	X									X	X					
Xu X, Scanlon BR, Schilling K, Sun A (2013)						X														

Appendix B: Reference List

Ashfaq M, Bowling LC, Cherkauer K, Pal JS, Diffenbaugh NS (2010) Influence of climate model biases and daily-scale temperature and precipitation events on hydrological impacts assessment: A case study of the United States. Journal of Geophysical Research 115.

Brekke L (2011) West-wide climate risk assessments: bias-corrected and spatially downscaled surface water projections. US Department of the Interior, Bureau of Reclamation, Technical Service Center.

Cayan, D., M. Tyree, K. E. Kunkel, C. Castro, A. Gershunov, J. Barsugli, A. J. Ray, J. Overpeck, M. Anderson, J. Russell, B. Rajagopalan, I. Rangwala, and P. Duffy (2013). "Future Climate: Projected Average." In Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment, edited by G. Garfin, A. Jardine, R. Merideth, M. Black, and S. LeRoy, 101–125. A report by the Southwest Climate Alliance. Washington, DC: Island Press

CDMSmith (2012) Incorporating Climate Change into Water Supply Planning and Yield Studies: A Demonstration and Comparison of Practical Methods

Das T, Hidalgo HG, Pierce DW, Barnett TP, Dettinger MD, Cayan DR, Bonfils C, Bala G, Mirin A (2009) Structure and Detectability of Trends in Hydrological Measures over the Western United States. Journal of Hydrometeorology 10:871-892.

Duan Q, Schaake J, Andreassian V, Franks S, Goteti G, Gupta HV, Gusev YM, Habets F, Hall A, Hay L, Hogue T, Huang M, Leavesley G, Liang X, Nasonova ON, Noilhan J, Oudin L, Sorooshian S, Wagener T, Wood EF (2006) Model Parameter Estimation Experiment (MOPEX): An overview of science strategy and major results from the second and third workshops. Journal of Hydrology 320:3-17.

Elguindi N, Grundstein A (2013) An integrated approach to assessing 21st century climate change over the contiguous U.S. using the NARCCAP RCM output. Climatic Change 117:809-827.

Garfin G, Franco G, Blanco A, Comrie A, Gonzalez P, Piechota T, Smyth R, Waskom R (2014) Ch. 20: Southwest. Climate Change Impacts in the United States: The Third National Climate Assessment. Melillo, J.M., Richmond, Terese (T.C.), Yohe, G.W. edn, U.S. Global Change Research Program, pp. 462-486.

Grundstein A, Dowd J (2011) Trends in extreme apparent temperatures over the United States, 1949-2010. Journal of Applied Meteorology and Climatology 50:1650-1653.

Gutzler DS, Robbins TO (2010) Climate variability and projected change in the western United States: regional downscaling and drought statistics. Climate Dynamics 37:835-849.

Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, Hanasaki N, Heinke J, Ludwig F, Voss F, Wiltshire AJ (2013) Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth System Dynamics 4:129-144.

Hoerling MP, Dettinger M, Wolter K, Lukas J, Eischeid J, Nemani R, Liebmann B, Kunkel KE (2013) Chapter 5: Present weather and Climate: evolving Conditions. in Garfin G JA, Merideth R, Black M, LeRoy S (eds.), National Climate Assessment (ed.) Assessment of climate change in southwest United States : a report prepared for the National Climate Assessment. Island Press, Washington, D.C., pp. pp. 74-100.

Kalra A, Piechota T, Davies R, Tootle G (2008) Changes in U.S. Streamflow and Western U.S. Snowpack. Journal of Hydrologic Engineering 13:156-163.

Kunkel KE, Liang X-Z, Zhu J (2010) Regional climate model projections and uncertainties of U.S. summer heat waves. Journal of Climate 23:4447-4458.

Kunkel KE, Stevens LE, Stevens SE, Sun L, Janssen E, Wuebbles D, Redmond KT, Dobson JG (2013) NOAA Technical Report NESDIS 142-5: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 5. Climate of the Southwest U.S. National Oceanic and Atmospheric Administrayion (NOAA), National Environmenatl Satellite,Data, and Information Service (NESDIS), pp. 1-79.

Liu Y, Goodrick SL, Stanturf JA (2013) Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. Forest Ecology and Management 294:120-135.

Lukas JJ, Barsugli J, Doesken N, Rangwala I, Wolter K (2014) Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation. A Report for the Colorado Water Conservation Board. in Western Water Assessment CIfRiES (ed.). University of Colorado Boulder.

Matter MA, Garcia LA, Fontane DG, Bledsoe B (2010) Characterizing hydroclimatic variability in tributaries of the Upper Colorado River Basin—WY1911-2001. Journal of Hydrology 380:260-276.

McRoberts DB, Nielsen-Gammon JW (2011) A new homogenized climate division precipitation dataset for analysis of climate variability and climate change. Journal of Applied Meteorology and Climatology 50:1187-1199.

Milly PC, Betancourt JL, Falkenmark M, Hirsch R, Kundzewicz Z, Lettenmaier D, Stouffer R (2008) Stationarity Is Dead: Whther Water Management. Science 319.

Palecki MA, Angel JR, Hollinger SE (2005) Storm precipitation in the United States. Part I: Meteorological characteristics. Journal of Applied Meteorology 44:933-946.

Pryor SC, Howe JA, Kunkel KE (2009) How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? International Journal of Climatology 29:31-45.

Reclamation Bo (2012) Colorado River Basin Water Supply and Demand Study. U.S. Department of the Interior.

Scherer M, Diffenbaugh N (2014) Transient twenty-first century changes in daily-scale temperature extremes in the United States. Climate Dynamics 42:1383-1404.

Schwartz MD, Ault TR, Betancourt JL (2013) Spring onset variations and trends in the continental United States: Past and regional assessment using temperature-based indices. International Journal of Climatology 33:2917-2922.

Spears M, Harrison A, Sankovich V, Gangopadhyay S (2013) Literature Synthesis on Climate Change Implications for Water and Environmental Resources. Technical Memorandum 86-68210-2013-06. U.S Bureau of Reclamation, pp. 1-352.

Tebaldi C (2006) Going To The Extremes: An Intercomparison of Model-Simulated Historical and Future Changes in Extreme Events. Climate Change 79:185-211.

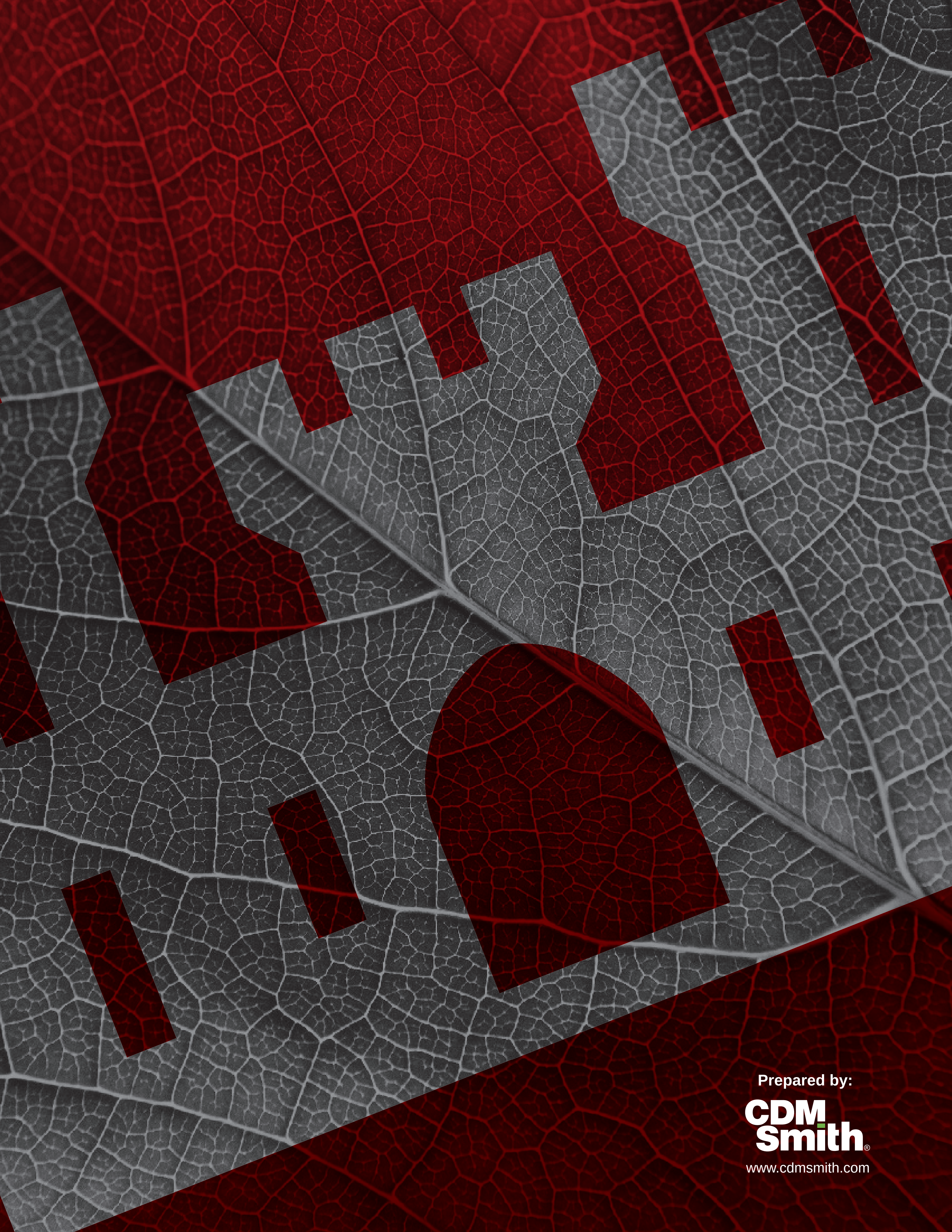
Thomson AM, Brown RA, Rosenberg NJ, Srinivasan R, Izaurralde RC (2005) Climate change impacts for the conterminous USA: An integrated assessment: Part 4: Water resources. Climatic Change 69:67-88.

Walsh J, Wuebble D, Hayhoe K, Kossin J, Kunkel K, Stephens G, Thorne P, Vose R, Wehner M, Willis J, Anderson D, Kharin V, Knutson T, Landerer F, Lenton T, Kennedy J, Somerville R (2014) Ch 2: Our Changing Climate. Climate Change Impacts in the United States: The Third National Climate Assessment Melillo, J.M., Richmond, Terese (T.C.), Yohe, G.W. edn, U.S. Global Change Research Program, pp. 19-67.

Wang H, Schubert S, Suarez M, Chen J, Hoerling M, Kumar A, Pegion P (2009) Attribution of the seasonality and regionality in climate trends over the United States during 1950-2000. Journal of Climate 22:2571-2590.

Wang J, Zhang X (2008) Downscaling and projection of winter extreme daily precipitation over North America. Journal of Climate 21:923-937.

Xu X, Scanlon BR, Schilling K, Sun A (2013) Relative importance of climate and land surface changes on hydrologic changes in the US Midwest since the 1930s: Implications for biofuel production. Journal of Hydrology 497:110-120.



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