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

LOWER COLORADO REGION 15

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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 Lower 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

Lower Colorado Region	Observed Hydrology	Business Line
Water Resources Region 15	Projected Climate	Climate Vulnerability
Observed Climate	Projected Hydrology	Regional Climate Synthesis

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CLIMATE CHANGE AND HYDROLOGY LITERATURE SYNTHESIS FOR THE US ARMY CORPS OF ENGINEERS MISSIONS IN THE UNITED STATES

LOWER COLORADO REGION 15

May 18, 2015

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Water Resources Region 15: Lower Colorado

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 15, the Lower Colorado Region, the boundaries for which are shown in **Figure 1.2**. The Lower Colorado Region is within the South Pacific Division, which is illustrated in **Figure 1.1**. The majority of the Lower Colorado Region is within the USACE Los Angeles district territory, but also extends into the USACE Albuquerque district.

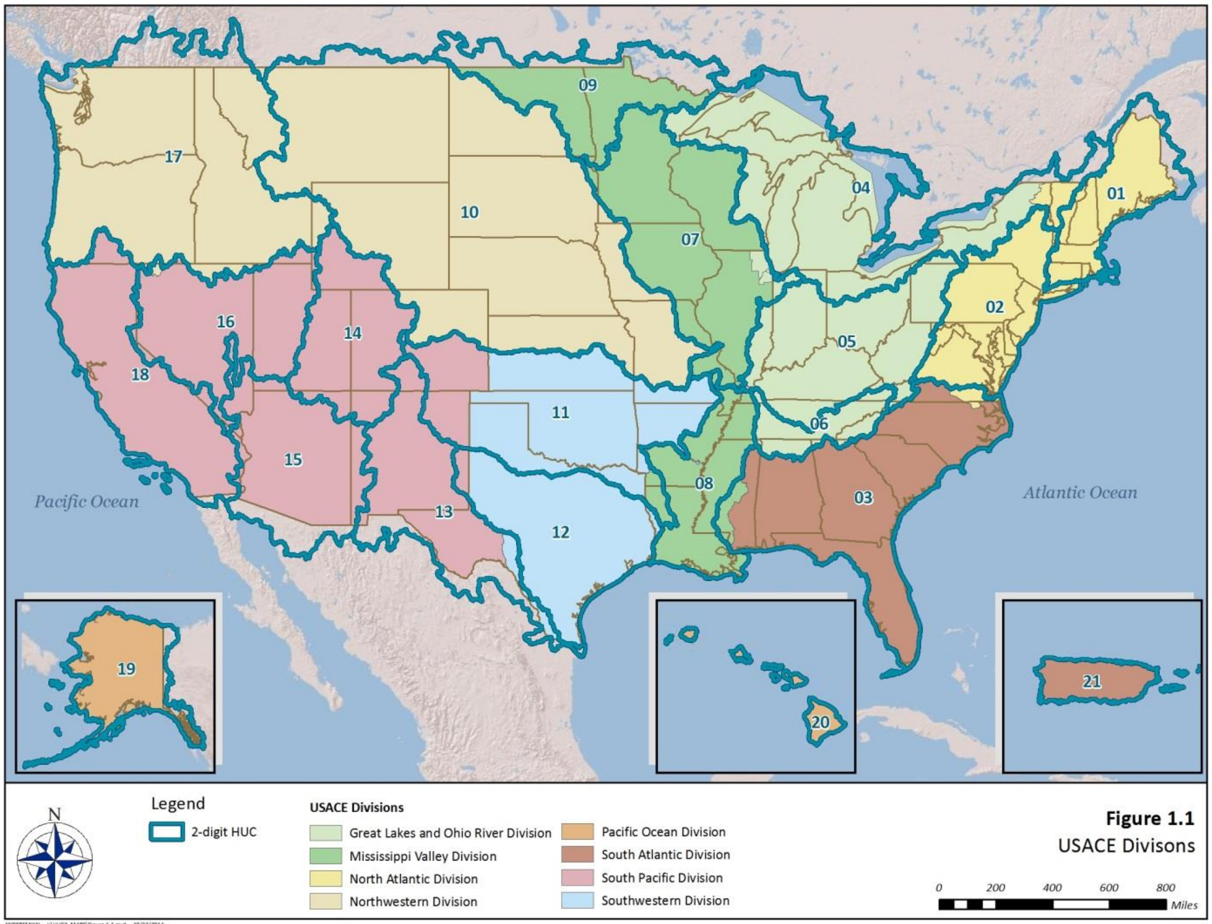


Figure 1.1. 2-digit Water Resources Region Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.

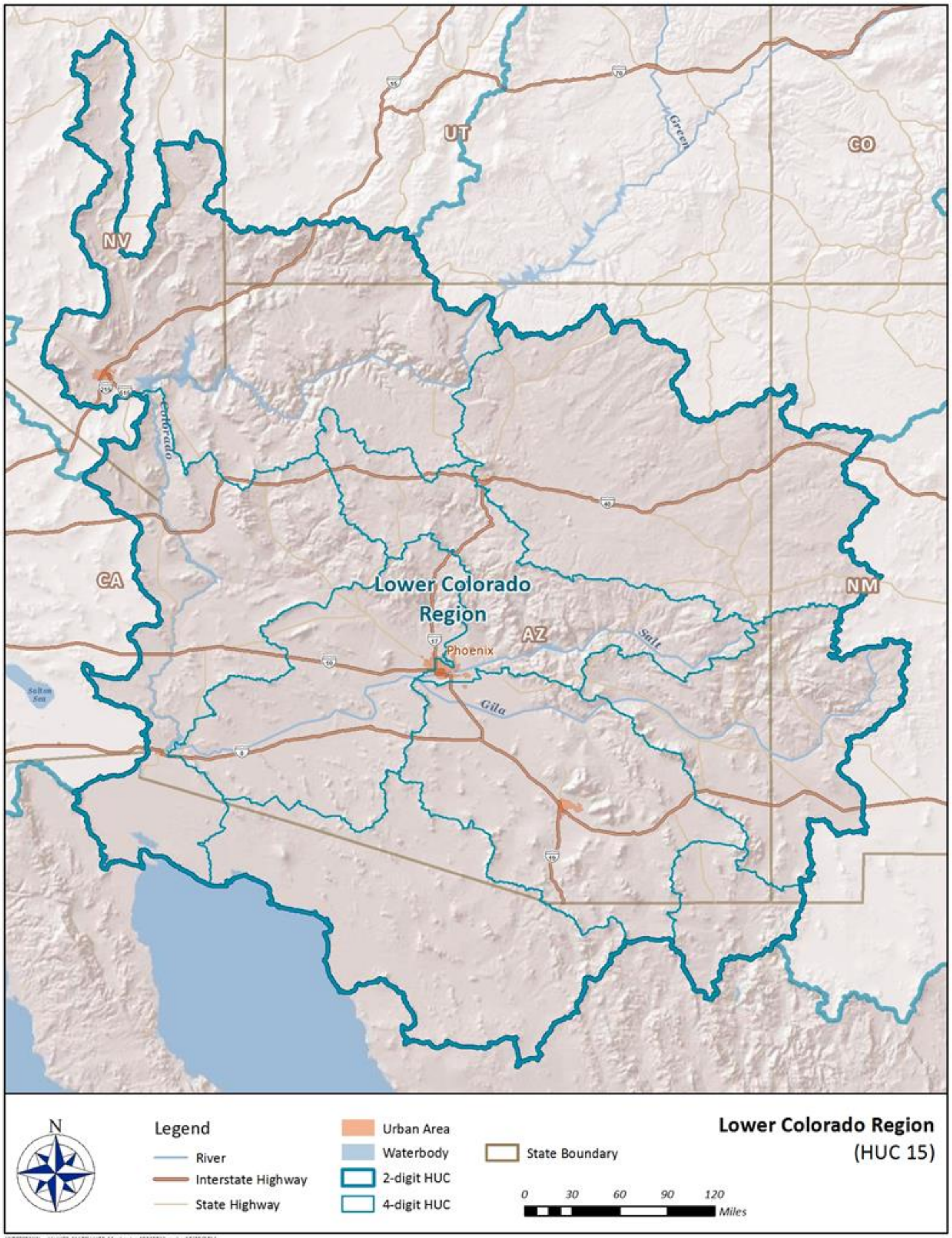


Figure 1.2. Water Resources Region 15: Lower Colorado Region Boundary.

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 vulnerability assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 15, 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 15 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 Lower 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 15 (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), evapotranspiration (ET), and soil moisture.

The results presented below indicate increasing trends in temperature for parts of the Lower Colorado Region. However, clear consensus does not exist for precipitation trends. Studies of regional streamflow reviewed here present no evidence of significant trends in flow over the past 50 to 60 years.

2.1. Temperature

A number of studies focusing on observed trends in historical temperatures were reviewed for this report. These include both national-scale studies inclusive of results relevant to the Lower Colorado Region and regional studies focused more specifically and exclusively on the Lower Colorado Region. Results from both types of studies, relevant to the Lower Colorado Region, are discussed below.

At a national scale, 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 seasonal mean surface air temperature for most of the U.S. (**Figure 2.1**). For the Lower Colorado Region, seasonal differences were identified in the historic mean air temperatures. A positive historic warming trend was identified for the Lower Colorado Region in the winter (December – February) and spring (March – May), and a historic cooling trend was shown for the fall (September – November). Spatial variability in historic temperature trends throughout the Lower Colorado Region is shown in summer (June – August) with some areas showing increasing temperature trends and others showing decreasing temperature trends. The authors do not provide information on statistical significance of the presented observed trends.

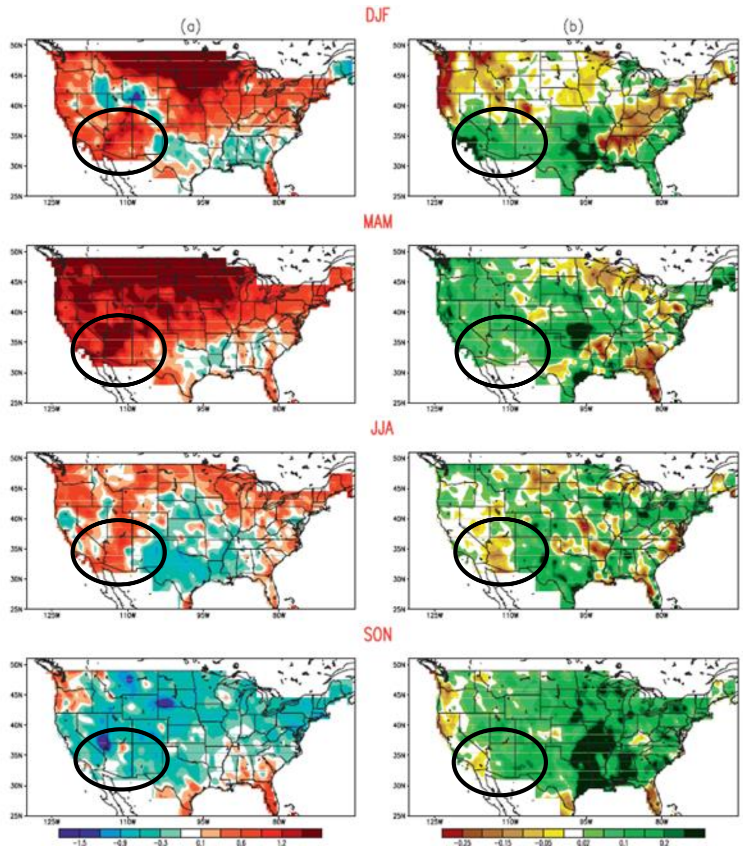


Figure 2.1. Linear trends in (a) surface air temperature in degrees Kelvin (b) and precipitation in mm/day over the United States, 1950 – 2000. The Lower Colorado Region is within the black oval (Wang et al., 2009).

A later study by Westby et al. (2013), using data from the period 1949 – 2011, presents spatial variation in winter temperature trends for the Lower Colorado Region for this time period (**Figure 2.2**). Areas illustrating historic cooling in the northwestern reaches of the region are conflicting with those results presented by Wang et al. (2009). The temperature variability presented by Westby et al. (2013), was not statistically significant at a 95% confidence interval (C.I.).

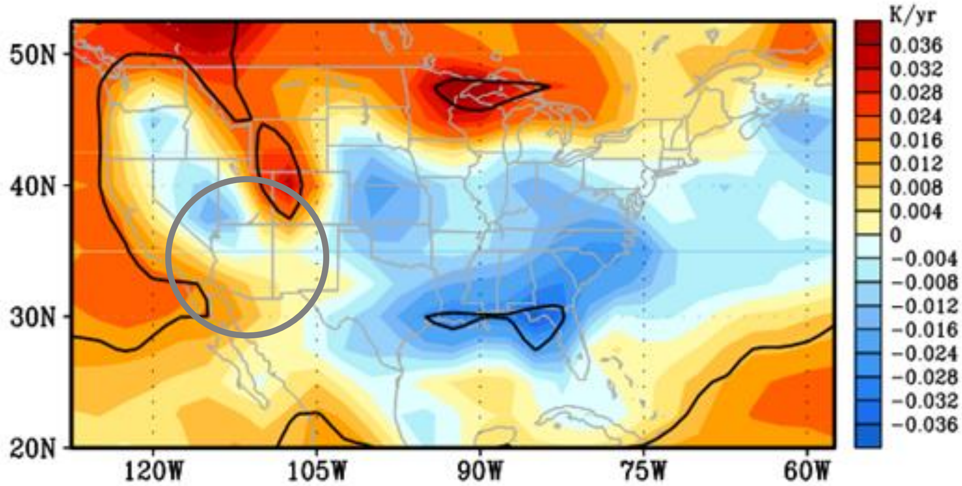


Figure 2.2. Mean winter (December through February) temperature trends from 1949 – 2011 (K/year). Black contours indicate statistical significance at the 95% confidence level. The Lower Colorado Region is within the gray oval (Westby et al., 2013).

An article by MacDonald (2010) evaluated average annual temperatures over 2001 – 2009 compared to 1951 – 1960. In the Lower Colorado Region annual temperatures were up to 3 standard deviations above the 20th century average (**Figure 2.3**). Details on statistical significance were not provided in the study.

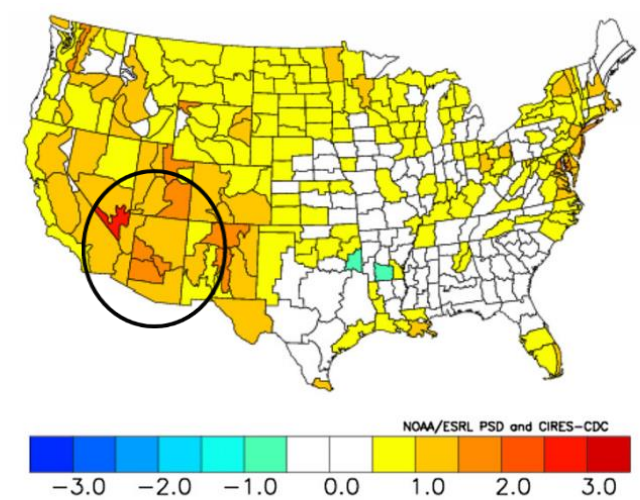


Figure 2.3. Composite standardized temperature anomalies for 2001 – 2009 relative to 1895 – 2000. The Lower Colorado Region is within the black oval (MacDonald, 2010).

A national study by Tebaldi (2012) evaluated average annual historic decadal changes in temperature. Based on data from 1912 – 2011, temperatures within the state of Arizona (which the Lower Colorado Region is primarily within), increased in temperatures at a rate of 0.27 °F (0.15 °C) per decade respectively with a 95% confidence interval. Similarly, Hoerling et al. (2013) assessed annually averaged daily temperature trends in the Southwest using observed climate and paleoclimate records, comparing temperatures of the last 100 years to the last 1,000 years. In the Lower Colorado Region, a statistically significant (95% C.I.) increase in average annual daily temperature of 1.8 to 3.6 °F (1 to 2 °C) was identified.

The third NCA report (Garfin et al., 2014) presents trends in historical annual average temperatures for the southwest region. For the southwest region, including the Lower Colorado Region, historical data shows a general warming of average annual temperatures in the early part of the 21st century. Details on statistical significance are not provided. When comparing a recent 22-year span (1991 – 2012) to a historic average (1901 – 1960), temperatures have increased throughout the Lower Colorado Region up to 2 °F (1.11 °C), as illustrated by **Figure 2.4**. (Walsh et al., 2014) This is consistent with an increasing trend in annual average temperatures within the Lower Colorado Region reported by MacDonald (2010), Tebaldi (2012), and Hoerling et al. (2013).

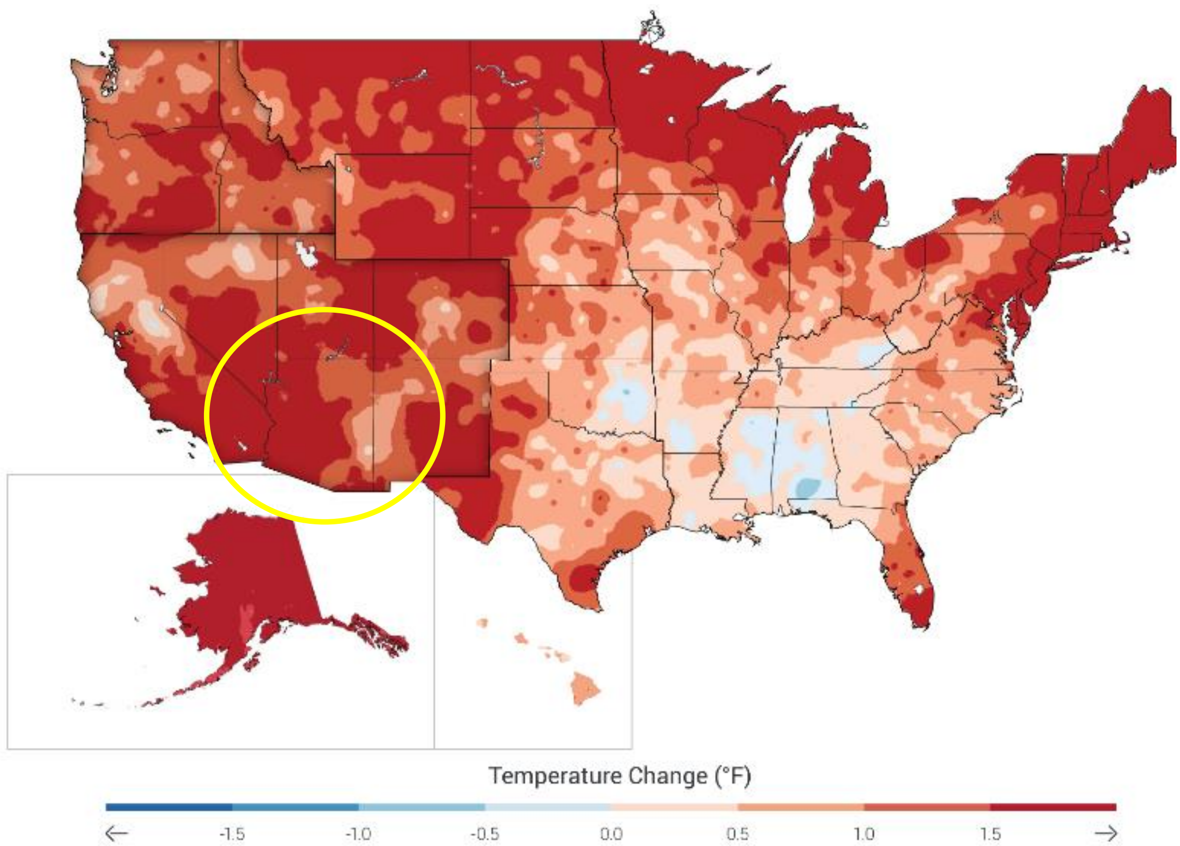


Figure 2.4. Changes in average temperatures for 1991 – 2012 compared to 1901 – 1960 (Walsh et al., 2014). The Lower Colorado Region is within the yellow oval.

In a regional study of the southwestern U.S., Kunkel et al. (2013) evaluated historic temperature trends. Comparing annual historic temperatures to the average temperature of 1901 – 1960, the authors identified upward and statistically significant, to the 95% confidence level, trends 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 night temperatures, while daytime temperatures exhibit less of a trend.

Table 2.1 Decadal trends in temperature and precipitation for 1895 – 2011 compared to average of 1901– 1960 for the southwestern U.S. Only significant values (> 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	—

Mote et al. (2005) evaluated historic temperature and precipitation trends as they relate to mountain snowpack in western North America from the Continental Divide to the Pacific coast. Climate data from November through March was obtained from the U.S. Historical Climate Network (USHCN) for the study. As illustrated in **Figure 2.5**, winter temperatures have dominantly increased in the Lower Colorado Region, up to 4°C (7.2°F) from 1930 to 1997.

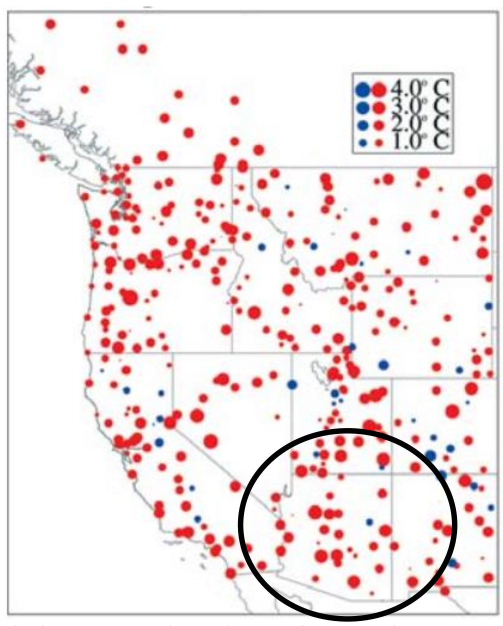


Figure 2.5. Linear trends in November through March temperature from 1930 to 1997. Positive trends are indicated by the red circles and negative trends are indicated by blue circles. The Lower Colorado region is generally within the black circle. (Mote et al., 2005)

Extreme temperatures were studied by Grundstein and Dowd (2011), Hoerling et al. (2013), and Kunkel (2013). Grundstein and Dowd (2011) investigated trends in one-day extreme maximum and minimum apparent temperatures across the continental U.S. The study was based on daily temperature data compiled by the National Climatic Data Center (NCDC) for 187 stations across the country for the period 1949 – 2010. Extreme minimum and maximum temperatures were defined as the number of days per month that exceeded the local 85th percentile for the one-day maximum and minimum temperatures. For the Lower Colorado Region, they found a statistically significant (95% C.I.) increasing trend in the number of one-day extreme minimum and maximum temperatures for three stations in the region. Hoerling et al. (2013) compared seasonal and annual maximum and minimum temperatures averaged across the southwest, inclusive of the

Lower Colorado Region, from 2001 – 2010, to the southwest average for the 20th century. An increase in seasonal and annual minimum and maximum temperatures over the 2001 – 2010 period compared to the 1901 – 2000 period was reported. Minimum and maximum annually averaged daily temperature trends from 1901 – 2010 were also evaluated by Hoerling et al. (2013). Generally positive statistically significant (95% C.I.) changes in maximum and minimum temperature were reported for the southwest region, inclusive of the Lower Colorado Region, of up to 3°C (5.4°F) (**Figure 2.6**).

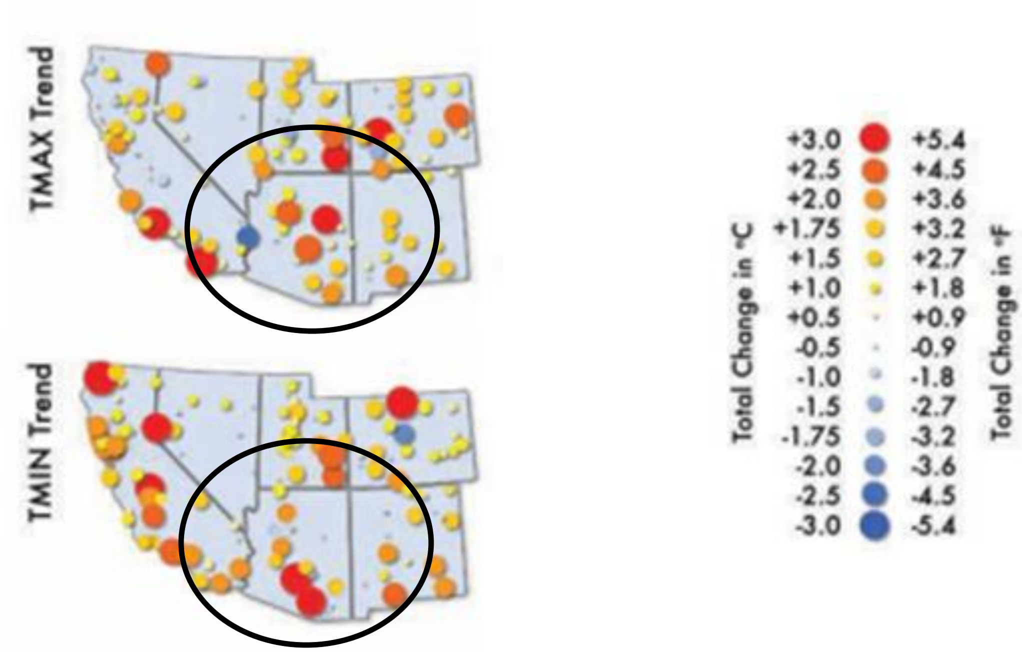


Figure 2.6. Minimum and maximum annually averaged daily temperature trends (95% C.I.) from 1901 – 2010 (Hoerling et al., 2013). The Lower Colorado Region is within the black oval.

Similarly, in a study of the Sonoran Desert, located throughout the southwestern corner of Arizona, into southeastern California, and parts of Mexico and the Baja Peninsula, Weiss et al. (2005) reported increasing trends in extreme monthly minimum temperatures from 1960 – 2000 in the Lower Colorado Region. These trends were statistically significant at a 95% C.I. based on data collected from the NCDC (**Figure 2.7**). These statistically significant increasing minimum temperature trends from 1960 – 2000 within the Lower Colorado Region occurred primarily between January and June. Hoerling et al. (2013) also reported, with high confidence, an increase in the occurrence of heat waves in the southwest U.S. during 2001 – 2010 compared to occurrences during the 20th century. In addition, Kunkel et al. (2013) identified a statistically significant increasing trend in the frequency of extreme heat waves in the southwest region, defined as four-day periods with temperatures exceeding a threshold of a one in five-year recurrence interval, and a statistically significant decreasing trend in extreme cold periods within the southwest region, inclusive of the Lower Colorado Region. In general, there appears to be an increasing trend in both minimum and maximum historic temperatures in the Lower Colorado Region with relatively strong consensus in the literature.

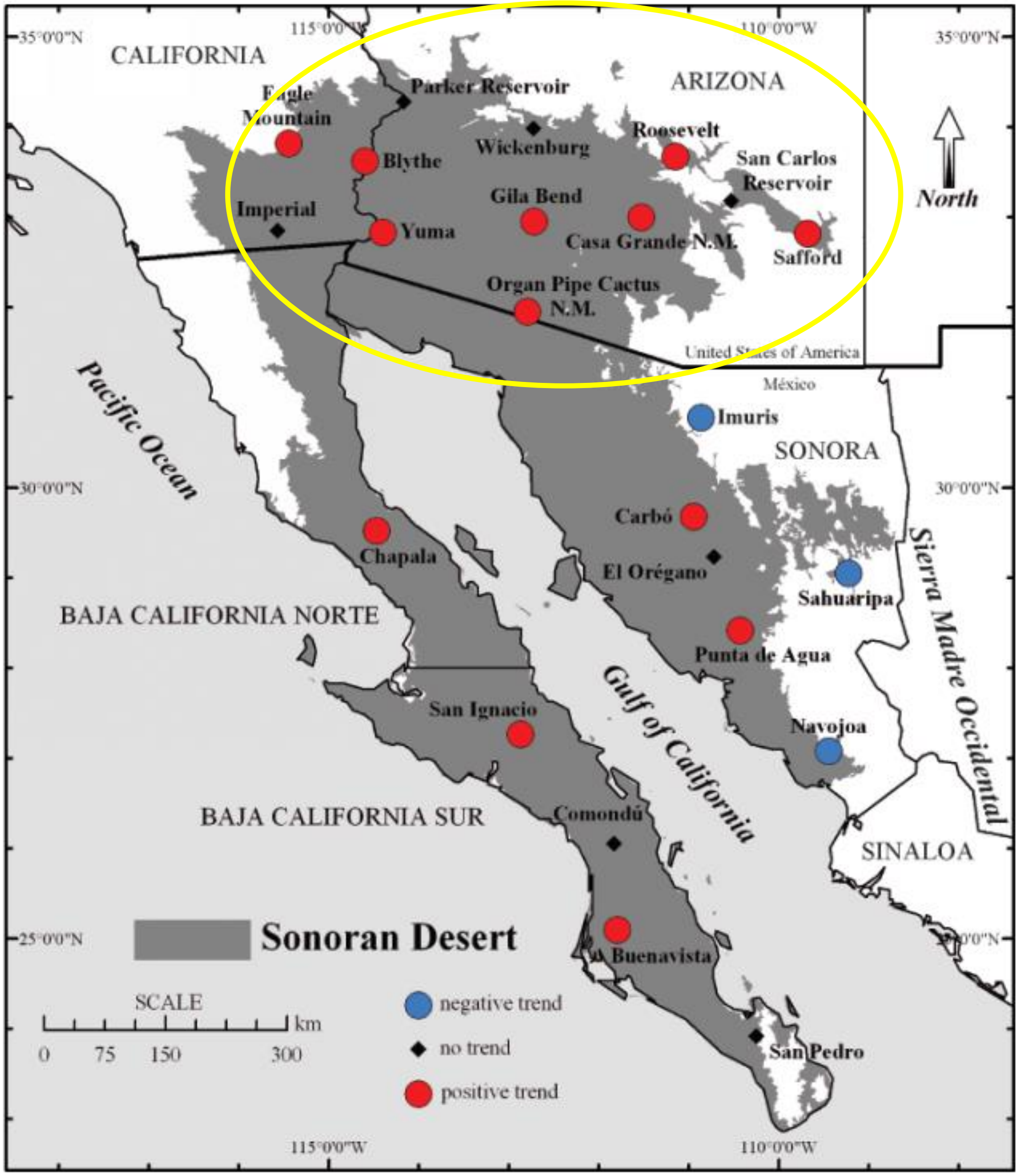


Figure 2.7. Significant linear trends ($p < 0.05$) of deseasonsed monthly extreme minimum temperatures from 1960 – 2000. Red circles indicate a positive trend and blue circles indicate a negative trend. Black diamonds indicate no trend. The portion of the Sonoran Desert within the Lower Colorado Region is illustrated by the yellow circle. (Weiss et al., 2005)

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 most of the Lower Colorado Region, spring onset is occurring primarily a few days earlier compared to the baseline reference decade (2001 – 2010 vs. 1951 – 1960) (**Figure 2.8**). In other words, in most areas within the Lower Colorado Region, spring warming is occurring earlier than in the past.

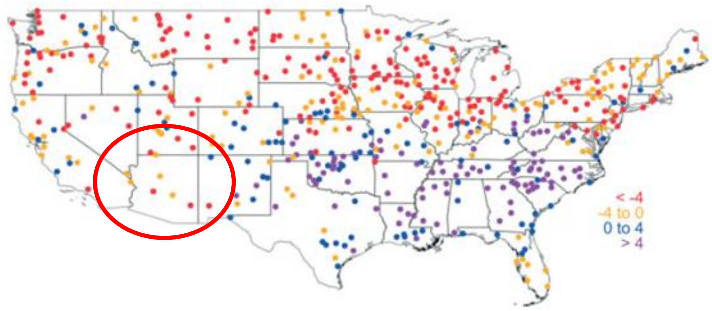


Figure 2.8. Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The Lower Colorado Region is generally within the red oval (Schwartz et al., 2013).

Key point: Increasing trends have been identified in the region's temperature data for the 20th century.

2.2. Precipitation

Multiple authors, evaluating precipitation trends on a national scale, have identified significant increasing trends in total annual precipitation in recent historical records for the study region. Grundstein (2009) found a slight decrease in statistically significant (95% C.I.) trends in soil moisture index, and no trend in annual precipitation in the Lower Colorado Region based on annual data from 1895 to 2006. No significant trend in potential evaporation was found either for this region (**Figure 2.9**). Soil moisture is a function of both supply (precipitation) and demand (ET), and therefore is an effective proxy for both precipitation and ET. Note that there are a total of four climate division stations in the Lower Colorado Region.

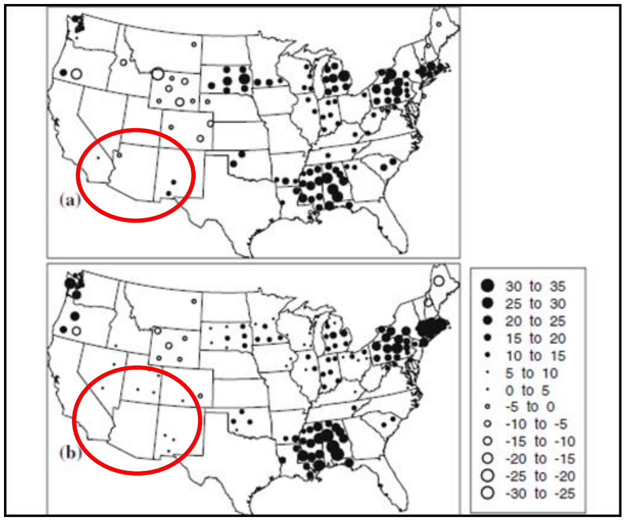


Figure 2.9. Statistically significant linear trends in (a) soil moisture index (unitless) and (b) annual precipitation (cm) for the continental U.S., 1895 – 2006. The Lower Colorado Region is within the red oval (Grundstein, 2009).

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 significant trends in annual precipitation for most of the U.S. For the Lower Colorado Region, in general, an increasing trend in precipitation was found. During summer, the Lower Colorado Region showed spatial variability with primarily decreasing trends in precipitation (**Figure 2.1, above**). The authors do not provide information on statistical significance of the presented observed trends.

A 2011 study by McRoberts and Nielsen-Gammon used a new continuous and homogenous data set to perform precipitation trend analyses for areas 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. (**Figure 2.10**). For the Lower Colorado Region, results indicate spatial variability with primarily an increasing trend in precipitation (-2 to +30% change per century). The authors do not provide information on statistical significance of the presented observed trends.

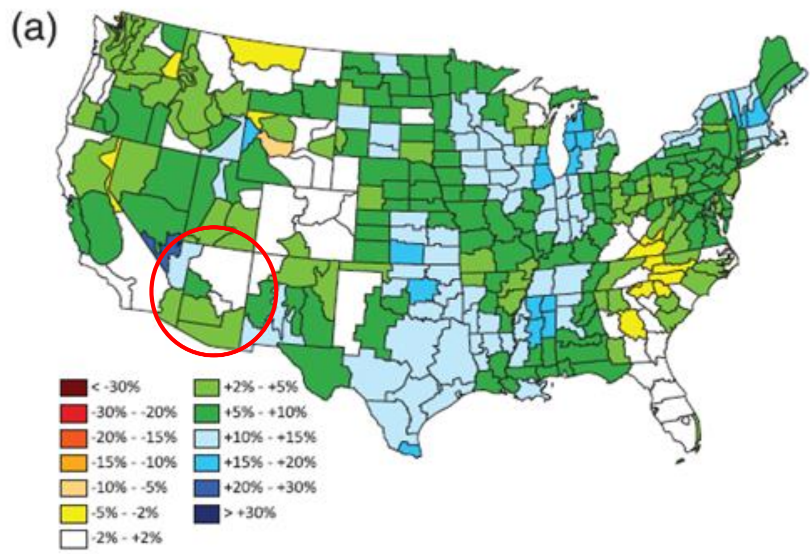


Figure 2.10. Linear trends in annual precipitation, 1895 – 2009, percent change per century. The Lower Colorado Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

Similarly, a study by MacDonald (2010) evaluated national precipitation from 2001 – 2009 standardized relative to data from 1895 – 2000. These results show a decrease in precipitation within the Lower Colorado Region (**Figure 2.11**).

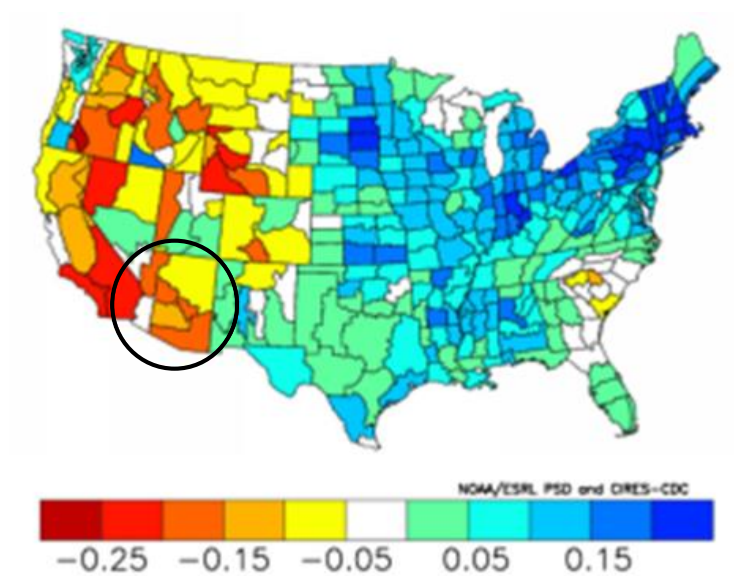


Figure 2.11. Standardized precipitation anomalies for 2001 – 2009 relative to 1895 – 2000. The Lower Colorado Region is within the black oval (MacDonald, 2010).

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. A predominant statistically significant decrease (95% C.I.) in winter and fall storm precipitation and duration were identified for the Lower Colorado Region, with some areas of decrease with no statistical significance. However, for the majority of the region, a statistically significant increase (90% C.I.) in fall storm intensity was identified. In summer, a statistically significant increase (95% C.I.) in mean storm intensity (total precipitation divided by storm duration) and 15-minute maximum intensity were identified in the region which contains the Lower Colorado Region.

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 Lower Colorado Region, the analysis showed no general trend in total annual precipitation, with one area on the eastern edge of the region with an increasing trend. A decreasing trend in extreme high precipitation events (90th percentile daily) and precipitation intensity, and an increasing trend in the number of precipitation days per year (**Figure 2.12 a, b, c, and d**) were found in the Lower Colorado Region. These trends were determined to be significant at the 90% C.I. 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.

a) Annual precipitation

b) 90th percentile daily precipitation

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

d) Number of precipitation days per year

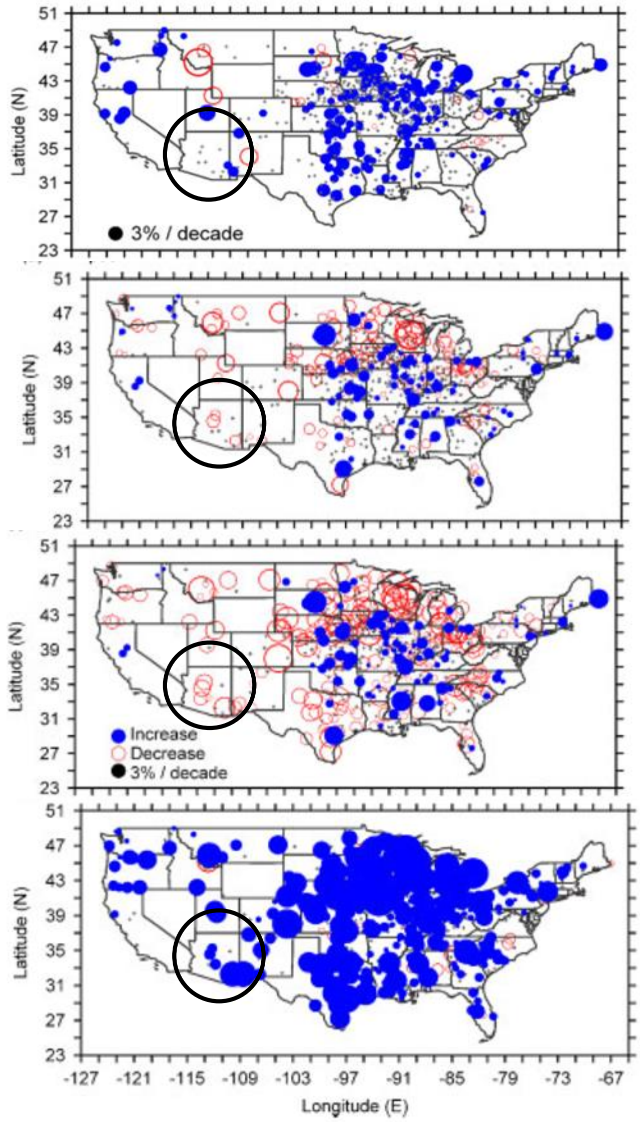


Figure 2.12. Historical precipitation trends (20th century). a) annual totals, b) 90th percentile daily, c) precipitation intensity (annual total/number of precipitation days), and d) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The Lower Colorado Region is within the black circle (Pryor et al., 2009).

As part of the third NCA, Walsh et al. (2014) reported annual precipitation changes from 1991 – 2012 compared to the 1901 – 1960 average. For the Lower Colorado Region, precipitation primarily decreased, up to 15%, with some spatial variability throughout the region (**Figure 2.13**). Statistical significance of trends was not provided in the report.

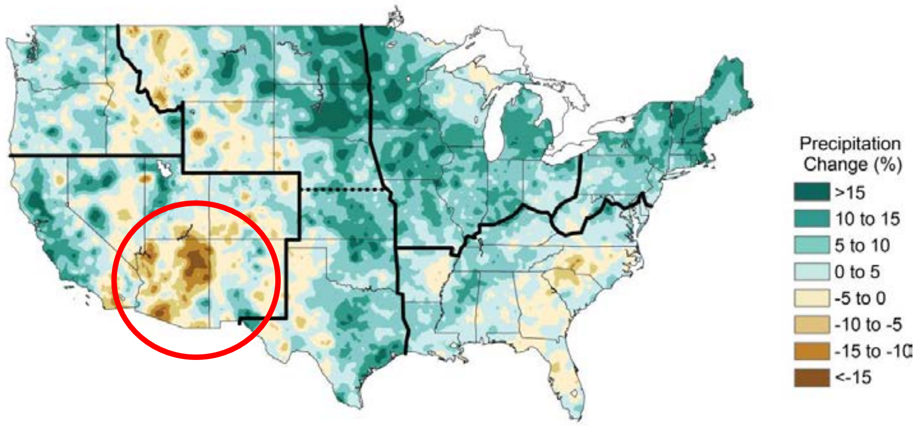


Figure 2.13. Annual total precipitation changes for 1991 – 2012 compared to the 1901 – 1960 average. The Lower Colorado Region is approximately within the red circle (Walsh et al., 2014).

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. Increases in the frequency of the 20-year storm event were quantified in the southwestern U.S. in both the recent historical data and the long-term future projections (described below). For the Lower Colorado Region, an increase in the recurrence of the 20-year daily maximum precipitation event for the period 1977 – 1999 was computed to be one to two times greater than the recurrence of the same storm during the period of 1949 – 1976.

A number of recent studies have focused more specifically on the southwest region of the U.S., including the Lower Colorado Region. Kunkel et al. (2013) found no statistically significant trends in historic annual, seasonal, or extreme precipitation from 1895 – 2011 for the southwest region. No trends in the frequency of extreme precipitation events were found either. In the Lower Colorado Region specifically, Hoerling et al. (2013) reported a statistically significant (95% C.I.) spatial variability (+20% to -50%) in precipitation between 1901 and 2010 (**Figure 2.14**). Mote et al. (2005) found increasing precipitation trends for the majority of the Lower Colorado Region, based on winter precipitation data from 1930 to 1997 as illustrated in **Figure 2.15**. Statistical significance of the trends was not provided.

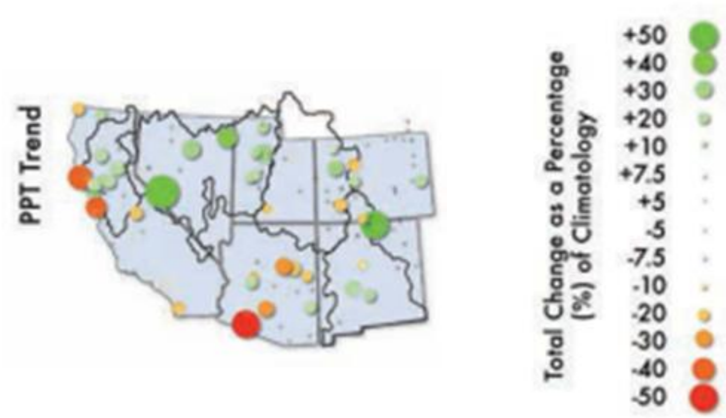


Figure 2.14. Precipitation trends (95% C.I.) from 1901 – 2010. Crosses shown in graphic indicate precipitation changes of less than 5%. (Hoerling et al., 2013)

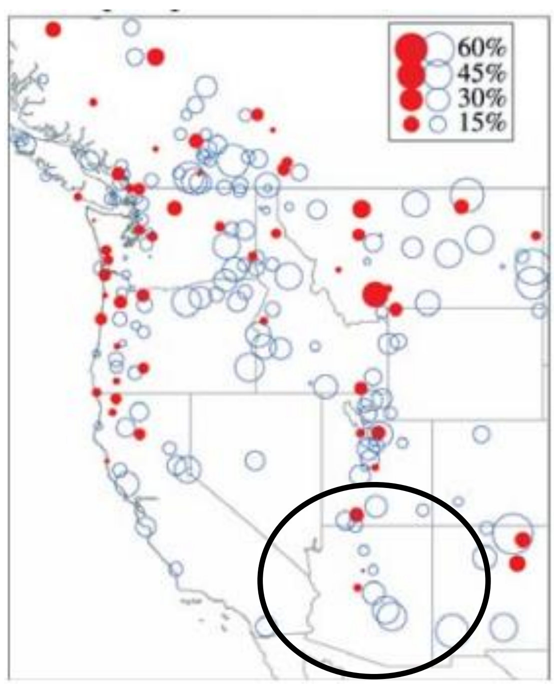


Figure 2.15. Linear trends in November through March temperature from 1930 to 1997. Positive trends are indicated by the blue circles and negative trends are indicated by red circles. The Lower Colorado region is generally within the black circle. (Mote et al., 2005)

A study by Cook et al. (2014) studied tree ring data to assess the frequency and severity of droughts over the past millennium (1000 – 2005) across the U.S. For the southwest region, which includes the Lower Colorado Region, the authors identified a decline in the number of droughts per century, although the finding is not considered statistically significant ($p = 0.11$). The authors also found a marginally significant increase in the balance between moisture supply (precipitation) and demand (evapotranspiration as a function of temperature) as defined by the Palmer drought severity index (PDSI) over the same period (**Figure 2.16**).

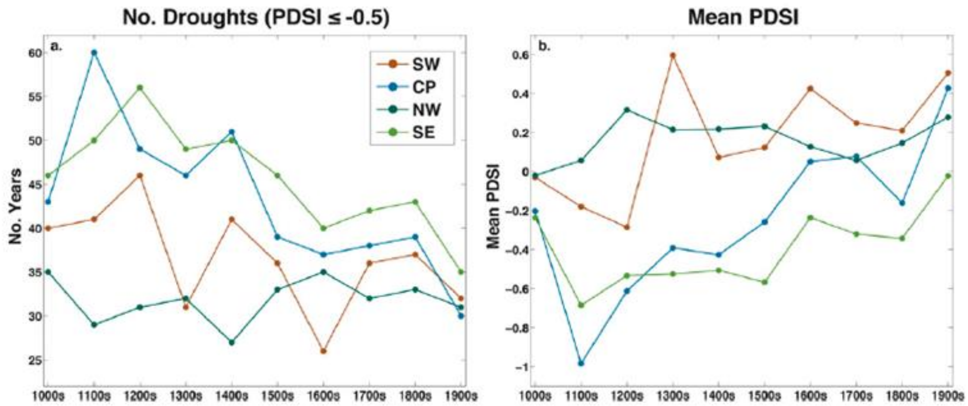


Figure 2.16. Trends in number of drought years per century (left) and mean PDSI across all years of each century. The Lower Colorado Region is within the Southwest (SW) (Cook et al., 2014).

Key point: No consistent trend has been identified in the region's historic precipitation data, with little consensus 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., which are inclusive of the Lower Colorado Region. In 2013, Xu et al. investigated trends in streamflow for three stations in the Lower Colorado Region. This study used the Model Parameter Estimation Experiment (MOPEX) data set for the period 1950 – 2000. One hydrology station exists within the Lower Colorado Region, which reported an increasing significant (at 95% C.I.) trend in streamflow.

A study by Sangarika et al. (2014) evaluated data from 240 unimpaired streamflow stations throughout the U.S. from 1951 – 2010. Similar to Xu et al., an increasing statistically significant (90% C.I.) trend was found for the one station within the Lower Colorado Region.

Kalra et al. (2008) performed a study using recorded streamflow data from 639 unimpaired stations to assess trends and step changes in streamflow between 1951 and 2002. Kalra et al. reported no significant (95% C.I.) trend in streamflow within the Lower Colorado Region.

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. These authors found no trend in winter temperature, ratio of April 1 SWE compared to October through March precipitation totals, or runoff fractions in the Lower Colorado Region for the study period.

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 Colorado River Region had 16% less mean flow from 2001 – 2010 compared to the 1941 – 2000 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 Lower Colorado Region, spatial variability of streamflow adjustments in timing was observed, with some areas with streamflow timing occurring earlier by up to 10 days, and some areas with streamflow timing occurring later by about 30 days. Streamflow timing observations were reported with 90 to 95% confidence. (**Figure. 2.17**).

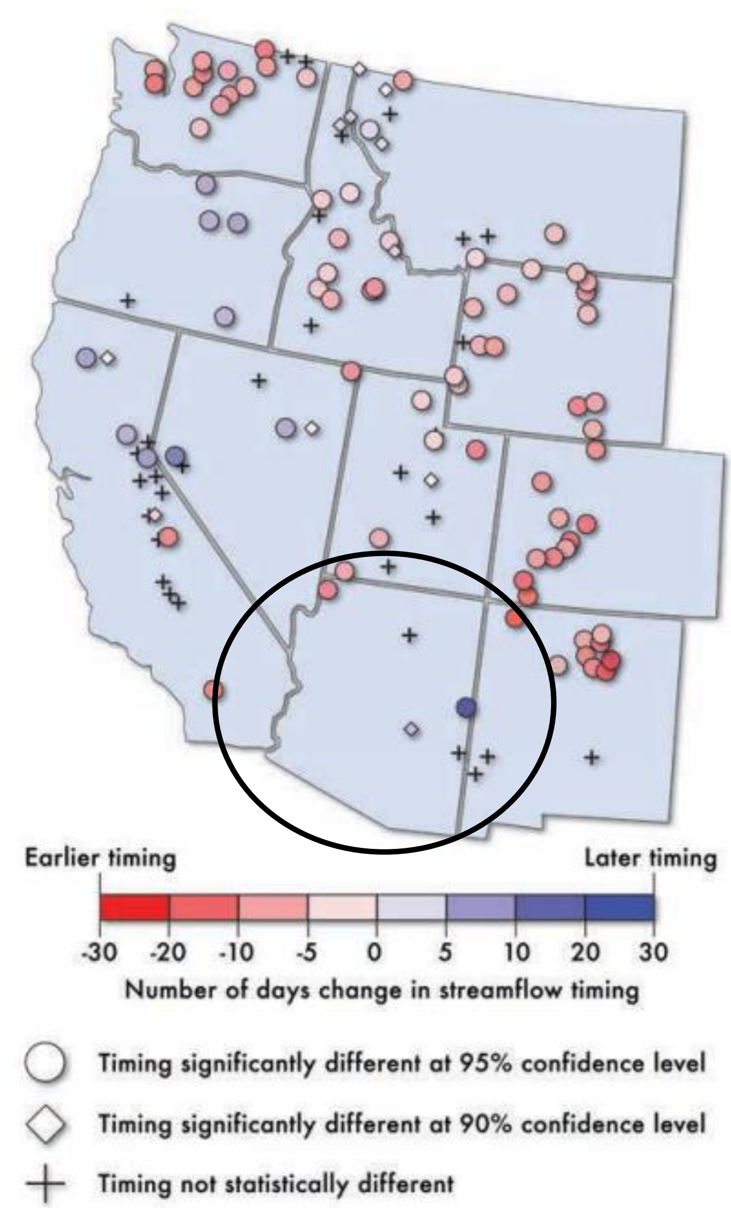


Figure 2.17. Changing streamflow timing 2001 – 2010 compared to 1950 – 2000. Differences between 2001 – 2010 and 1950 – 2000 average date when half of the annual streamflow has been discharged for snowmelt-dominated streams. The Lower Colorado Region is generally with the black circle (Hoerling et al., 2013).

In 2012, the United States 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 eight locations within the Lower Colorado Region for a time period of 1906 – 2007. Streamflow was only evaluated at two of the eight sites. Results of this study indicated seasonal variability in historic streamflow trends, with downward trend in natural spring streamflow when comparing data from 1906 – 2007 to 1978 – 2007. Little change was noted in mean annual streamflow when comparing data from the same time periods. (Reclamation, 2012)

Lastly, the third NCA report indicates a decreasing trend in streamflows in the Lower Colorado Region. (Garfin et al., 2014) Between 2001 and 2010 streamflows within the Colorado watershed (inclusive of the Upper Colorado Region) were reported to have been 5% to 37% lower than the 20th century average. Statistical significance of this information was not provided.

Key point: No statistically significant trends have been identified in the region's streamflow data for the latter half of the 20th century.

2.4. Summary of Observed Climate Findings

Evidence has been presented in the recent literature of increases in annual temperature in the Lower Colorado Region over the past century. High consensus exists in the literature supporting increasing observed temperature trends. Increasing trends in maximum and minimum temperatures have also been reported with relatively high consensus across the literature.

Trends in annual precipitation totals have been variable within the Lower Colorado Region in the 20th century. Consensus is low. Variability has been observed in streamflow and other hydrologic data for the Lower Colorado Region with relatively low consensus across the literature in results.

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., 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. 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 Lower 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-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 and extreme precipitation events will increase over the next century in the Lower Colorado Region. Strong consensus exists supporting a projected decrease in hydrology for the Lower Colorado Region. There is much less consensus on the future trending, or lack thereof, in precipitation in the region.

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. Results of studies inclusive of the Lower Colorado 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) in a national analysis. The results of their study, specific to the Lower Colorado Region, show a projected increase in winter and spring maximum air temperature of 2 – 3.5 ºC (3.6 ºF – 6.3 ºF) for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (**Figure 3.1**). The results of the study project increases in maximum air temperature from 2.5 to 4 ºC (4.5 ºF – 7.2 ºF) for summer and fall temperatures.

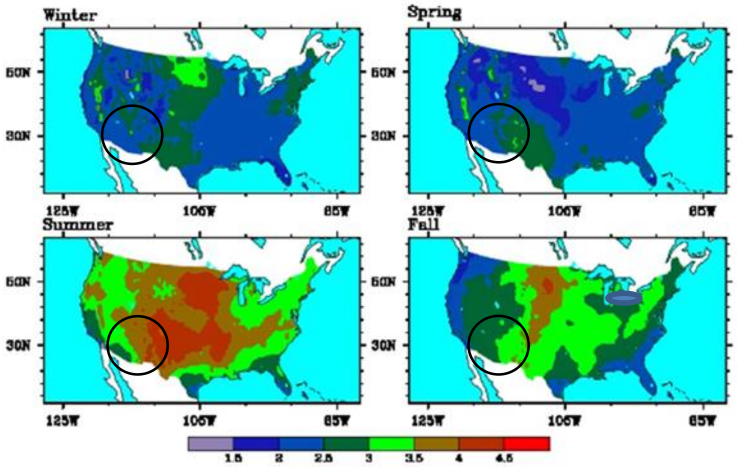


Figure 3.1. Projected changes in seasonal maximum air temperature, ºC, 2055 vs. 1985. The Lower Colorado Region is within the black oval (Liu et al., 2013).

Similar results are presented by Ashfaq et al. (2010) and Scherer and Diffenbaugh (2014). The first set of authors applied 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 and fall daily maximum temperature of approximately 4.5 ºK (8.1 ºF or 4.5 ºC) for the Lower Colorado Region, and fall and winter maximum temperature changes of approximate 3 to 4 ºK (5.4 to 7.2 ºF or 3 to 4 ºC). Daily minimum temperature changes were also projected to increase by approximately 5 ºK (9 ºF or 5 ºC) for the summer and fall, and approximately 3.5 ºK (6.3 ºF or 3.5 ºC) for winter and spring in the Lower Colorado Region.

Scherer and Diffenbaugh applied a multi-member ensemble GCM, assuming an A1B (middle of the road) emissions scenario, to the continental U.S. For the southwest region of the country, including the Lower 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 (7.2ºF) in the summer and 3.4 ºC (6.1ºF) in the winter, compared to a 1980 – 2009 baseline period. These results agree well with those described previously for Liu et al. (2013).

a) b)

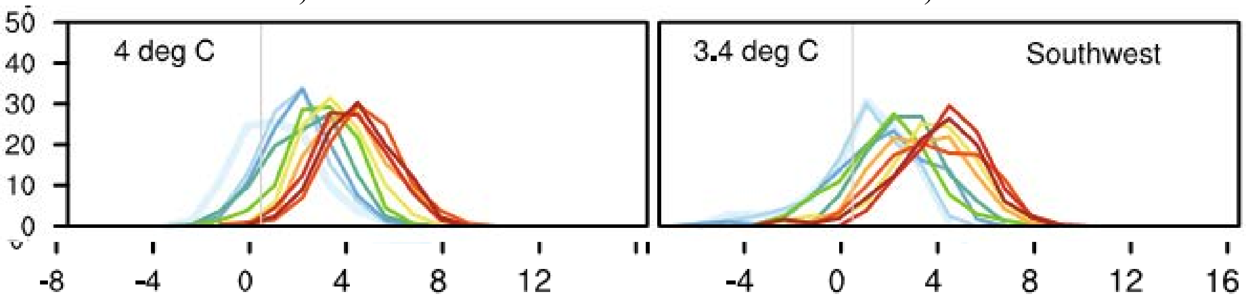
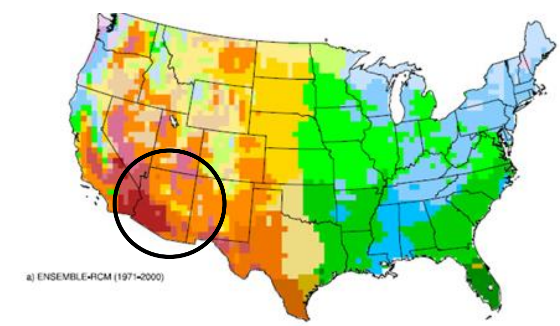


Figure 3.2. Probability distributions of GCM projections of daily maximum temperatures for years 2000 – 2100 by decade, southwest region a) summer months: June – August, b) winter months: December – February. Colors indicate the decade of the 21st century. Probabilities on the vertical axis are in 0.01%. The value in the upper left-hand corner of each box is the expected anomaly during the 2090s (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 Lower Colorado Region, results show a shift to a hotter and more arid climate by the period 2041 – 2070 (**Figure 3.3**).

a) Historical observed (1971 – 2000)



b) GCM projections (2041 – 2070)

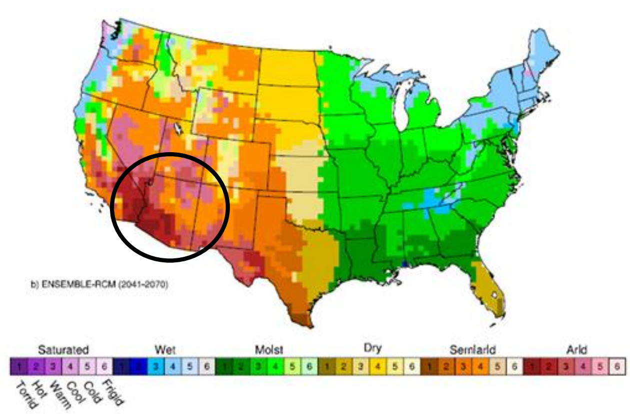


Figure 3.3. Revised Thornthwaite climate types projected by regional climate models. The Lower Colorado Region is within the black oval (Elguindi and Grundstein, 2013).

In a regional study, Cayan et al. (2013) investigated projected temperature trends for the southwest region of the U.S. Several Coupled Model Intercomparison Project (CMIP3) GCMs were used, coupled with dynamically downscaled models and biased correction and spatial downscaling. The A2 (high) and B1 (low) emissions scenarios were evaluated for future projections. An increase in annual average temperature is predicted with high confidence for the southwest U.S. from 2001 to 2100. Seasonal temperatures trends are projected to increase, with the highest increases in summer temperatures (**Figure 3.4**).

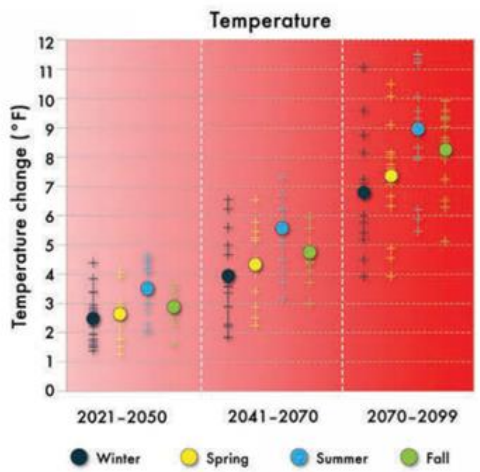


Figure 3.4. Projected trends in seasonal (winter: December – February, spring: March – May, summer: June – August, and fall: September – November) temperatures for the southwest region, based on a fifteen-model average for the high emissions scenario relative to the 1971 – 2000 reference period (Cayan et al., 2013)

Within the Colorado River Basin, including the Lower Colorado Region, historic and projected temperature trends for January and July were evaluated for the A2 (high) and B1 (low) from 1950 – 2100 emissions scenarios. (**Figure 3.5**) Similar to the southwest region as a whole, temperature increases are projected within the Lower Colorado Region in January and July, with the largest potential temperature increases in summer under high emissions scenarios. With the increase in temperatures, the length of the freeze-free season is projected to increase by approximately 24 to 38 days in 2041 – 2070 compared to a baseline period of 1971 – 2000. Specific information on confidence intervals was not provided with the study.

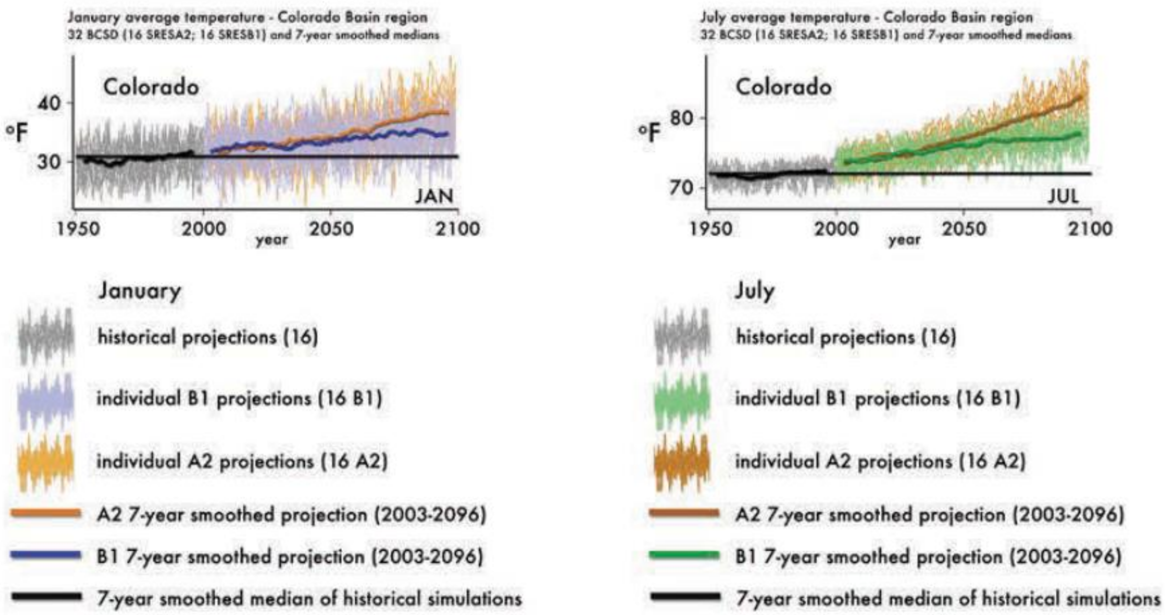


Figure 3.5. Biased corrected and spatially downscaled CMIP3 climate prediction average temperatures. (Cayan et al., 2013)

A regional study by 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 Lower Colorado Region (**Figure 3.6**) 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.

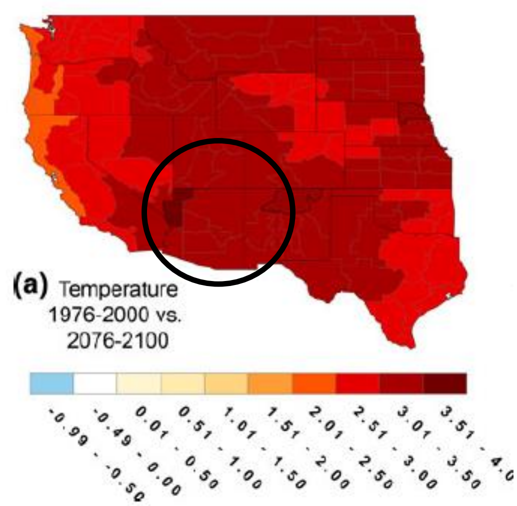


Figure 3.6. GCM projections of annual average temperature change, western United States. The Lower Colorado Region is within the black oval (Gutzler and Robbins, 2010).

The third NCA (Garvin et al., 2014) generally supports the findings presented above. Climate model projections for the southwest region of the U.S., inclusive of the Lower Colorado Region, presented in this report indicate an increase in annual average temperature over the next century (**Figure 3.7**).

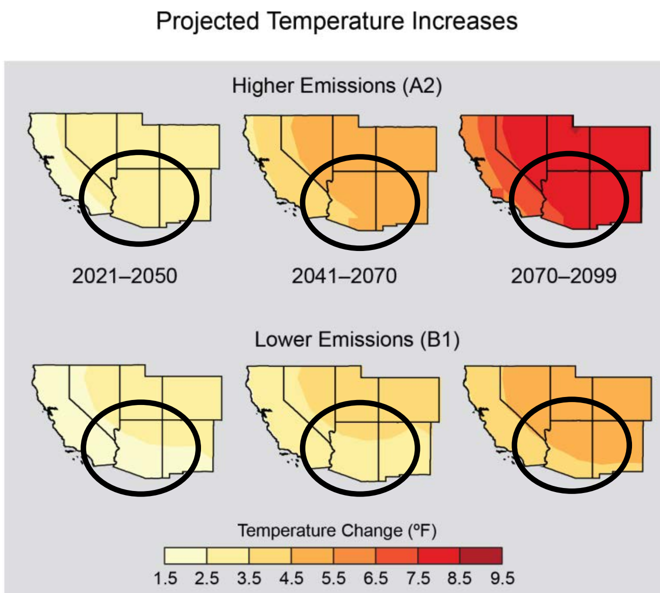


Figure 3.7. GCM projections of temperature change in the southeast USA. The Lower Colorado Region is within the black oval (Garfin et al., 2014).

On a more refined scale, Christensen et al. (2007) evaluated projected climate trends within the entire Colorado River Basin (inclusive of the Lower Colorado Region) as part of a larger effort of evaluating climate change impacts on hydrology and water resources in the study area. The study used downscaled and bias corrected output from 11 GCMs for the A2 (unconstrained growth) and B1 (elimination of global emission increases by 2100) Intergovernmental Panel on Climate Change (IPCC) emissions scenarios. The study compared projections for three future periods (2010 – 2039, 2040 – 2069, and 2070 – 2099) to baseline conditions (1950 – 1999). The climate projections illustrated increasing temperatures for all future scenarios. Spatially averaged results from the 11 GCMs project an increase in future average temperatures under the A2 emissions scenario by 4.4°C (7.9°F) by 2099. Under the B1 emissions scenario, average projections from the 11 GCMs illustrate an increase in temperatures by 2.7°C (4.9°F) by 2099. Timeseries of the projected changes in temperatures from the 11 GCMs for the A2 and B1 emissions scenario are shown in **Figure 3.8**.

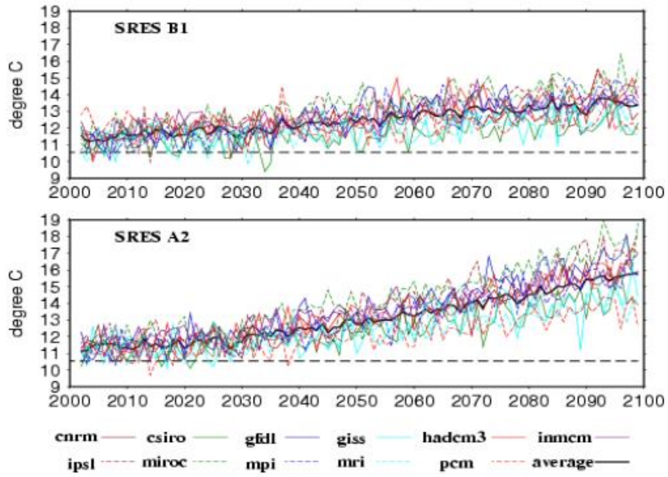


Figure 3.8. Spatially averaged (across the Colorado River Basin) projected temperatures from 11 GCMs for the A2 (top) and B1 (bottom) emissions scenarios. (Christensen et al., 2007)

Figure 3.9 shows the monthly variability in projected temperature change, spatially averaged across the Colorado River Basin (which the Lower Colorado Region is within) and averaged across the 11 GCMs evaluated for the study over two different emissions scenarios. These results illustrate the highest increase in temperatures during summer months under both emissions scenarios and for the three time periods evaluated.

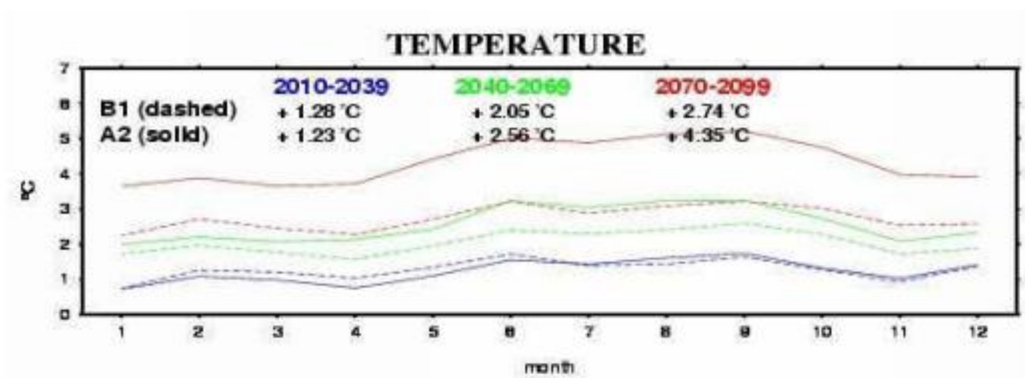


Figure 3.9. Monthly changes in temperature (averaged from 11 GCMs and spatially averaged across the Colorado River Basin) under the B1 (dashed) and A2 (solid) emissions scenarios for three projected time periods compared to the baseline period (1950 – 1999). (Christensen et al., 2007)

Projections of changes in temperature extremes have been the subject of several recent studies. A 2006 study by Tebaldi et al. 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 general Lower Colorado Region, using an A1B climate scenario, spatial variability in extreme temperature range (annual high minus annual low temperature) is illustrated, with some areas of slight increases and some areas of slight decreases shown. A statistically significant increase in a heat wave duration index (increase of 3 to 4.5 days per year that temperatures continuously exceeds the historical norm by at least 5 ºC or 9 ºF), and a statistically significant moderate increase in the number of warm nights (6 to 7.5% increase in the percentage of times in the year when minimum temperature is above the 90th percentile of the climatological distribution for the given calendar year), compared to the baseline period in the Lower Colorado Region. The number of frost days, (defined as the annual number of days with minimum temperatures below 0 ºC or 32 °F) is predicted to decrease, with statistical significance, by 5 days per year in the southwestern region of the U.S., inclusive of the Lower Colorado Region.

In a study by Kunkel et al. (2010), 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 Lower Colorado Region, projections indicate a 3.5 to 5.5 ºC (6.3 to 9.9 ºF) increase in three-day heat wave temperatures and a 50 to 85-day increase in the annual number of heat wave days for a 2086 planning horizon compared to a recent historical baseline of 1976. A later study of the southwest region by Kunkel et al. (2013) showed a statistically significant (with 50% of models showing statistically significant change, and more than 67% of the models agreeing on the sign of the change) decrease in the number of days with a minimum temperature less than 32 °F (0 ºC) for the 2041 – 2070 time period compared to the reference period of 1980 – 2000 based on the output from the eight North American Regional Climate Change Assessment Program (NARCCAP)'s Regional Climate Model simulations of the A2 emissions scenario, as shown in **Figure 3.10**.

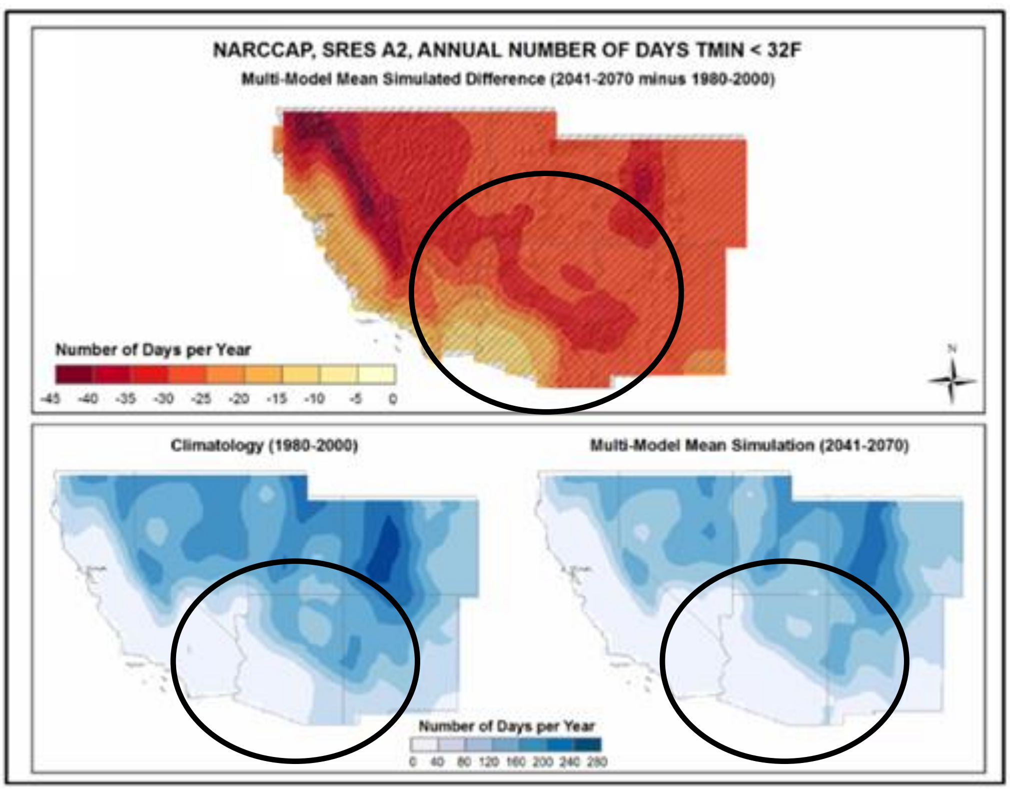


Figure 3.10. Simulated difference in mean annual number of days with a minimum temperature less than 32 °F (0 °C) for the 2041 – 2070 time period compared to a 1980 – 2000 reference period (top). Hatching indicates statistical significance (> 50% of the models show a statistically significant change with 67% agreeing on the sign of the change). Mean annual number of days with minimum temperatures less than 32 °F (0 °C) for the 1980 –

2000 reference period (bottom left) and simulated mean annual number of days with minimum temperatures less than 32 °F (0 °C) for the future time period (2041 – 2070) are shown (bottom right) (Kunkel et al., 2013). The Lower Colorado Region area is generally within the black ovals.

Within the Lower Colorado Region, the number of days with minimum temperatures less than 35 °F (1.7 ºC) is projected to decrease by up to 30 days per year. Similarly, the number of days with maximum temperatures exceeding 95 °F (35 ºC) is projected to increase by up to 40 days per year in 2041 – 2070 compared to the baseline period of 1980 – 2000 as shown in **Figure 3.11**.

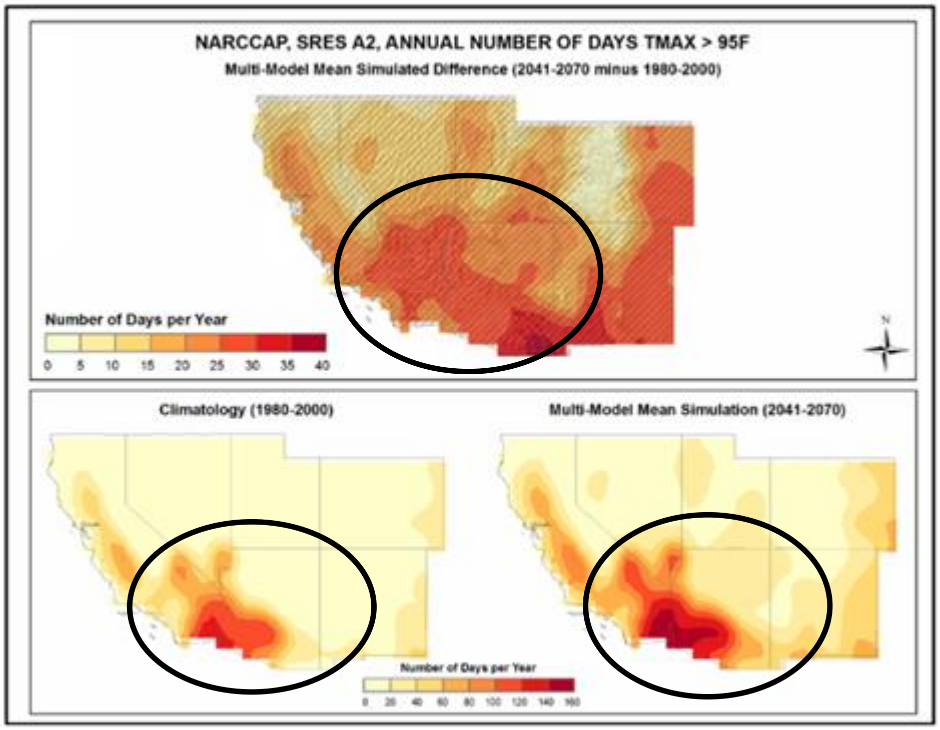


Figure 3.11. Simulated difference in mean annual number of days with a maximum temperature greater than 95 °F (35 °C) for the 2041 – 2070 time period compared to a 1980 – 2000 reference period (top). Hatching indicates statistical significance (> 50% of the models show a statistically significant change with 67% agreeing on the sign of the change). Mean annual number of days with maximum temperatures greater than 95 °F (35 °C) for the 1980 – 2000 reference period (bottom left) and simulated mean annual number of days with maximum temperatures greater than 95 °F (35 °C) for the future time period (2041 – 2070) are shown (bottom right). The Lower Colorado Region is generally within the black ovals. (Kunkel et al., 2013).

Another regional study by Dettinger et al. (2012) evaluated trends in annual minimum temperature and annual mean precipitation (the latter of which is discussed in Section 3.2) for the southwest region using results from National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) coupled ocean atmospheric GCM model and National Center for Atmospheric Research's Parallel Climate Model (PCM1) simulating the A2 (middle-of-the-road) and B1 (low) emissions scenarios over the 21st century. Results from this analysis show an increasing trend in annual average minimum temperature, up to 6 °C (10.8 °F), for all models and associated emissions scenarios (**Figure 3.12**).

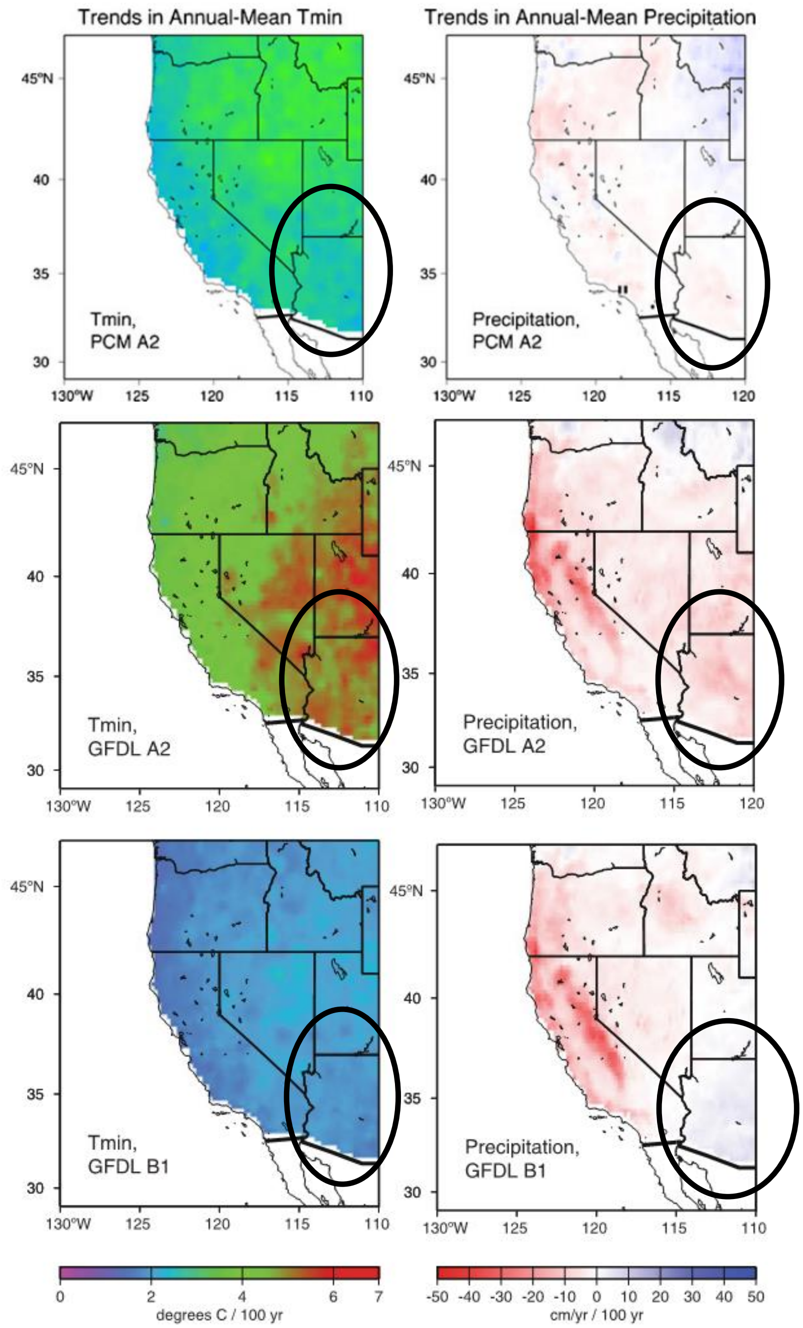


Figure 3.12. Downscaled temperature (left) and precipitation (right) trends for the 21st century under the A2 and B1 emissions scenarios from the GFDL and PCM1 (Dettinger, 2012). Part of the Lower Colorado Region is within the black ovals.

Dominguez et al. (2010) evaluated projected trends in winter temperature and precipitation across Colorado, New Mexico, Utah, and Arizona with the use of two models: the Max Planck Institute's ECHAM5 model, and the UK Met Office HadCM3 model. They evaluated the B1 (low), A1B (middle of the road), and A2 (high) emissions scenarios. Winter temperatures in the area of Arizona and New Mexico within the Lower Colorado Region, were projected to increase with 95% statistical significance for the period of 2000 – 2099.

Key point: Strong consensus exists in the literature that projected mean and extreme temperatures in the study region show an increasing trend over the next century. Average temperatures are projected to increase by 5.4 to 9°F (3 to 5°C) by the end of the 21st century, with largest temperature increases projected in summer months. Increases are projected for both minimum and maximum temperatures within the Lower Colorado Region.

3.2. Precipitation

In line with projections for the rest of the country, projections of future changes in precipitation in the Lower Colorado Region are variable and generally lacking in consensus among studies or across models. From a global analysis using three GCM projections, Hagemann et al. (2013) projects a spatial variability in annual precipitation, with a range from 40 mm per year to -140 mm per year for the Lower Colorado Region (**Figure 3.13**).

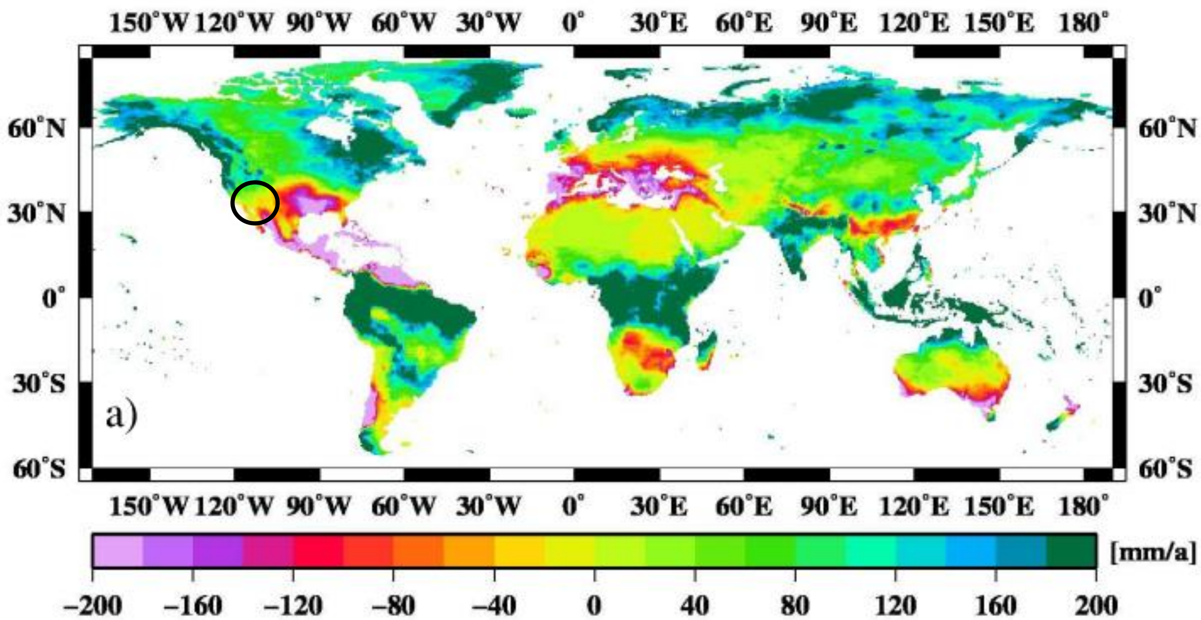


Figure 3.13. Projected (2071 – 2100) changes in annual precipitation compared to baseline, 1971 – 2000, conditions, mm/year. The Lower Colorado Region is within the black oval (Hagemann et al., 2013)

The Liu et al. study (2013) of the U.S., described above, quantified slight increases in winter and fall precipitation associated with a 2041 – 2070 planning horizon, relative to a recent historical baseline (1971 – 2000, centered around 1985) as a dominant trend, for the southwestern U.S., including the Lower Colorado Region (**Figure 3.14**). Much spatial variability exists within the Lower Colorado Region with regard to projected seasonal precipitation trends.

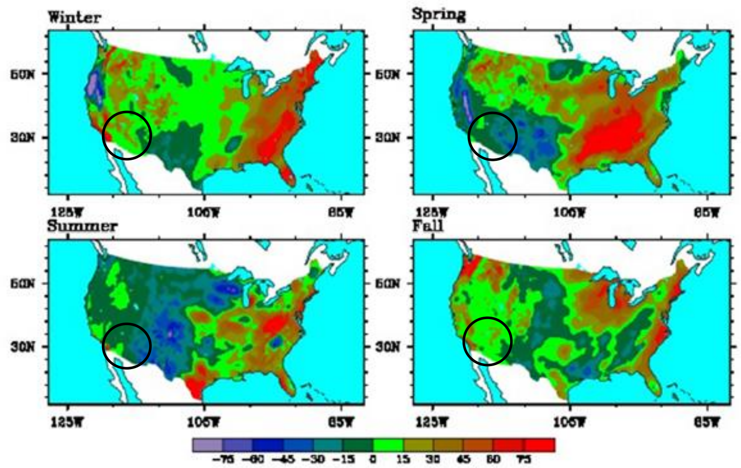


Figure 3.14. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The Lower Colorado Region is generally within the black oval. (Liu et al., 2013).

In a study of the western U.S. by Gutzler and Robbins (2010), the middle of the road (A1B) ensemble of projections show slight decreasing trends or no change in annual average precipitation for the Lower Colorado Region (**Figure 3.15**) for the last quarter of the 21st century compared to the last quarter of the 20th century. 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.

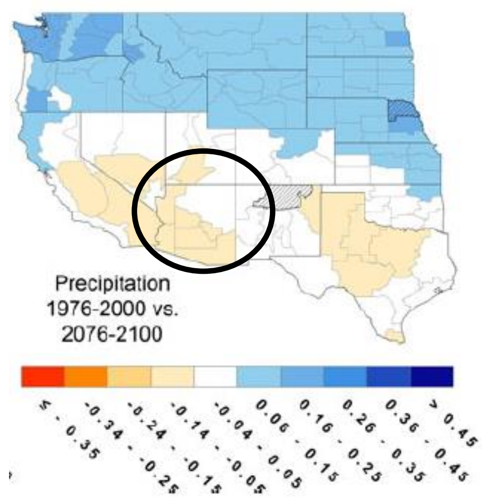


Figure 3.15. GCM projections of annual average precipitation change (mm month-1), western United States. The Lower Colorado Region is within the black oval(Gutzler and Robbins, 2010).

In support of the third NCA, Cayan et al. (2013) prepared a report that summarizes the most recent understanding of projected climates in Southwest United States. These authors calculated the median of sixteen downscaled simulations for three future time horizons: 2021 – 2050, 2041 – 2070, and 2070 – 2099. For the Lower Colorado Region, Cayan et al. (2013) found that under a high-emissions scenario annual average precipitation is projected to be 80 – 110% of the historical average. The results are summarized in **Figure 3.16**.

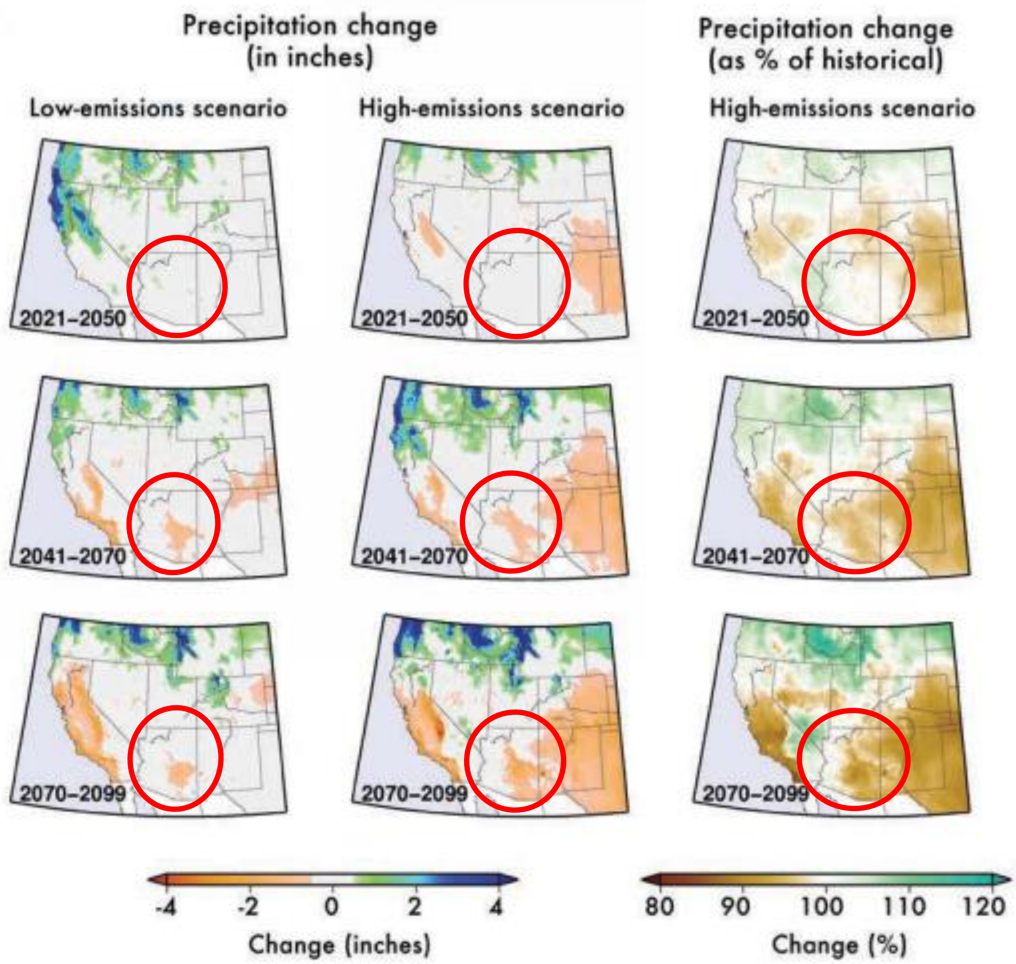


Figure 3.16. Ensemble projections of future precipitation (mid-21st century vs. historical baseline). The Lower Colorado Region is within the red oval (Cayan et al, 2013).

Several regional studies have been performed on precipitation trends in the southwestern U.S., inclusive of the Lower Colorado Region. A study by Seager and Vecchi (2010) studied climate trends in southwestern North America based on 24 climate models used as part of the IPCC Assessment Report Four (IPCC AR4). Results of the analysis indicate a drop in precipitation in the 21st century, and an increase in winter evaporation. (**Figure 3.17**).

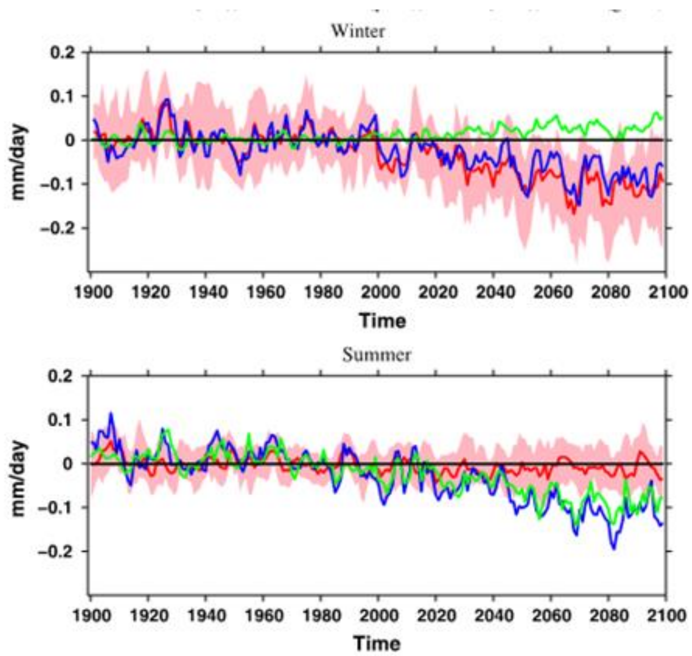


Figure 3.17. Timeseries of 1900 – 2009 of the median of 24 IPCC AR4 model's simulated and projected change in precipitation (blue), evaporation (green) and precipitation–evaporation (red), with the 25th and 75th percentiles of the distribution (shading) for winter (October through March) and summer (April through September) (Seager et al., 2010).

Similar to national projections, a study by Cayan et al. (2013) of the southwestern U.S. noted large spatial and temporal variability in historic and projected precipitation trends. This variability for the Colorado Region (inclusive of the Lower Colorado Region) is illustrated in **Figure 3.18**. This study found, with medium-low confidence, a decrease in precipitation in the southern portion of the southwest region.

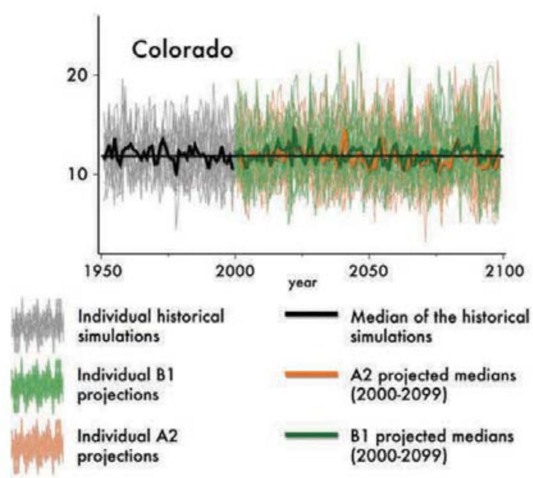


Figure 3.18. Bias corrected and downscaled CMIP3 precipitation model projections (inches) and historical simulations of the A2 and B1 emissions scenarios. (Cayan et al., 2013)

As discussed in Section 3.1, a study by Dettinger (2012) simulated projected trends in annual mean precipitation over the 21st century based on two regionally downscaled model results with two emissions scenarios for the southwest region of the U.S. For the Lower Colorado Region specifically, the emissions scenario and model used produced differing results, with some scenarios projecting increasing precipitation trends, and others projecting decreasing annual mean precipitation trends for the 21st century, as is shown above in **Figure 3.12**.

Dominguez et al. (2010) performed a study, discussed in Section 3.1, which evaluated projected trends in winter precipitation (January through March) over the 21st century. For the southern portion of the Lower Colorado Region, projections primarily indicated no change or a decrease in monthly precipitation of up to 0.5 mm per year. However, in the northern portion of the Lower Colorado Region, variability of +/- 0.5 mm per year in monthly precipitation was projected, with the variability depending on the model and emissions scenario evaluated. None of these results were statistically significant to a 95% confidence interval.

Christensen et al. (2007) evaluated climate change projections in the Colorado River Basin, as discussed in Section 3.1. Projections from the 11 GCMs used in the study illustrated a general drop in precipitation throughout the Colorado Basin, specifically within the Lower Colorado Region, with areas of the Upper Colorado Region showing increasing precipitation trends, as shown in **Figure 3.19**.

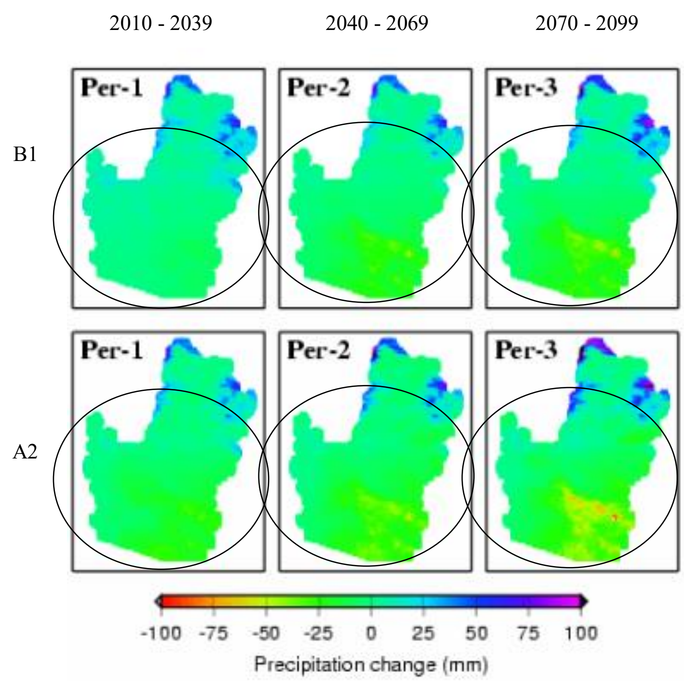


Figure 3.19. Annual average precipitation changes (averaged from 11 GCMs) for 2010 – 2039 (left), 2040 – 2069 (middle), and 2070 – 2099 (right) compared to the baseline period (1950 – 1999) for the B1 (top) and A2 (bottom) emissions scenarios. The Lower Colorado Region is generally within the black circles. (Christensen et al., 2007)

Figure 3.20 shows the monthly variability in projected precipitation change, spatially averaged across the Colorado River Basin (which the Lower Colorado Region is within) and averaged across the 11 GCMs evaluated for the study over two different emissions scenarios. These results illustrate the largest decrease in precipitation during spring months under both emissions scenarios and for the three time periods evaluated. Slight increases in precipitation are projected for summer, winter, and fall months, with the largest increases seen in summer months.

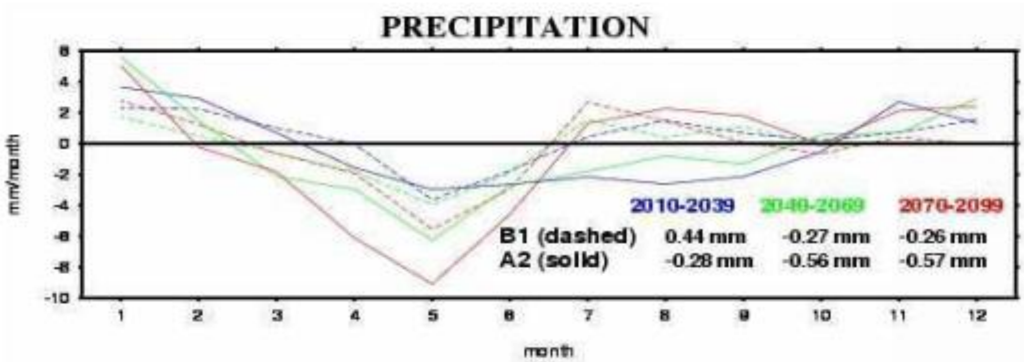


Figure 3.20. Monthly changes in precipitation (averaged from 11 GCMs and spatially averaged across the Colorado River Basin) under the B1 (dashed) and A2 (solid) emissions scenarios for three projected time periods compared to the baseline period (1950 – 1999). (Christensen et al., 2007)

Future projections of extreme events, including storm events and droughts, are the subject of studies by Tebaldi et al. (2006) and Wang and Zhang (2008). The first authors, as part of a global study, compared an ensemble of GCM projections for a 2080 – 2099 planning horizon with historical baseline data (1980 – 1999) with emissions scenario A1B. They report slight decreases or no change in the number of high (> 10 mm) precipitation days for the region, increases in the number of storm events greater than the 95th percentile of the historical record and increases in the daily precipitation intensity index (annual total precipitation divided by number of wet days). In other words, the projections forecast increases in the intensity of storm events by the end of the 21st century for the general study region. Wang and Zhang (2008) also used downscaled GCMs to look at potential future changes in precipitation events across North America. The GCMs were forced with the IPCC high emissions scenario (A2) to quantify a significant increase in the recurrence (1.5 to 2 times) of the current 20-year 24-hour storm event for their future planning horizon (2050 – 2099) in the Lower Colorado Region (**Figure 3.21**).

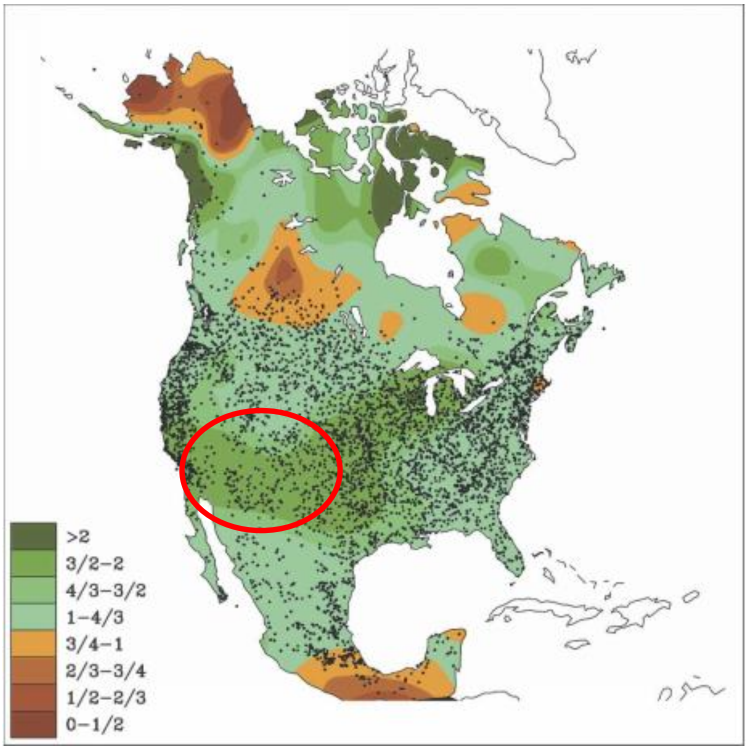


Figure 3.21. Projected risk of current 20-year 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The Lower Colorado Region is within the red oval (Wang and Zhang, 2008).

Key point: The intensity of future storm events is projected to increase. However, low consensus exists with respect to projected changes in total annual precipitation and precipitation extremes for the Lower Colorado 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. These studies include projections of potential hydrologic changes in the southwestern United States. 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 (considered to be a surrogate for streamflow) across the United States. Results are presented for both continuous spatial profiles across the country (**Figure 3.22**). For the Lower Colorado Region, and most of the United States, contradictory results are generated by the two GCMs. For the same set of input assumptions, one model predicts significant decreases in water yield, the other projects significant increases in water yield.

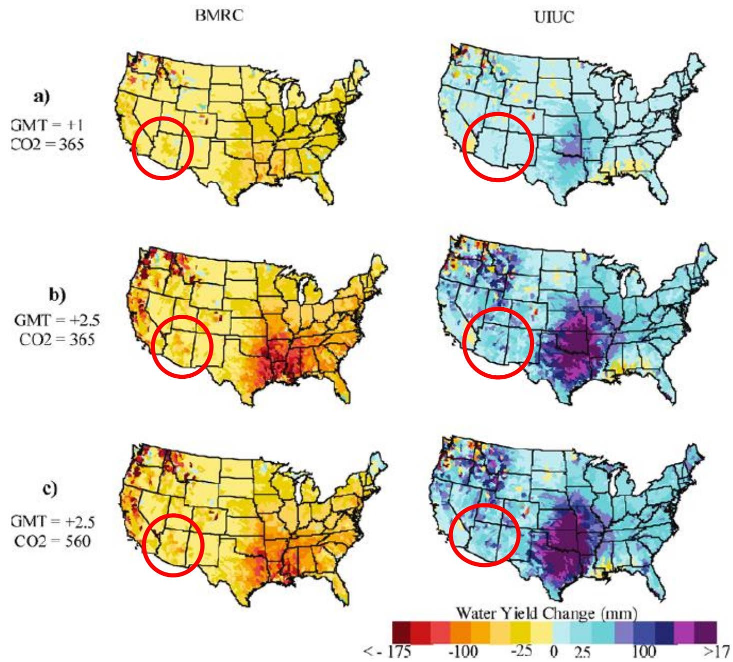


Figure 3.22. Projected change in water yield (from historical baseline), under various climate change scenarios based on two GCM projections. The Lower Colorado Region is within the red oval (Thomson et al., 2005).

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 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 CDM Smith (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 from Hagemann et al. (2013), for the Lower Colorado Region show an overall decrease in runoff by up to approximately 120 mm per year for their future planning horizon (2071 – 2100) compared to the recent historical baseline (1971 – 2000) (**Figure 3.23**), assuming an A2 emissions scenario. Changes in seasonal runoff are similar, showing a decrease in runoff between 0 and 10 mm, with fall changes showing slight potential increases in runoff up to 10 mm. (**Figure 3.24**).

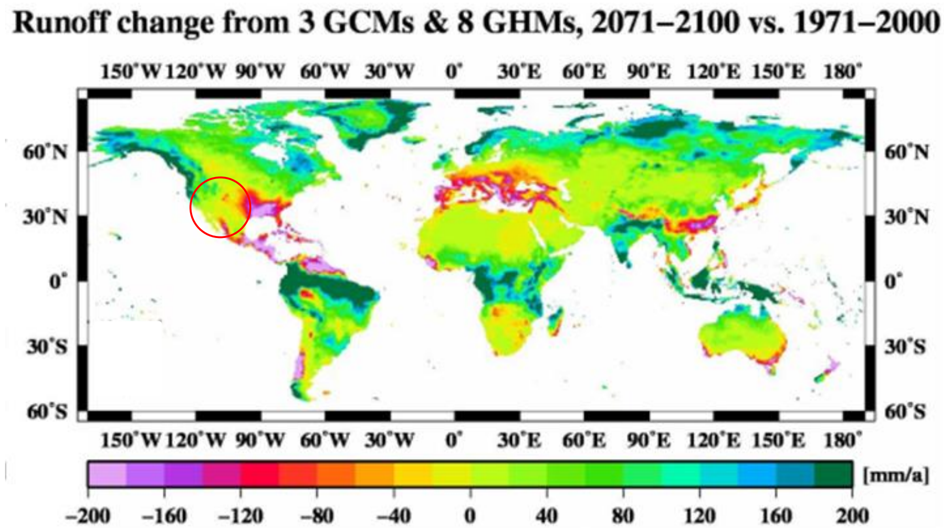


Figure 3.23. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Lower Colorado Region is within the red oval (Hagemann et al., 2013).

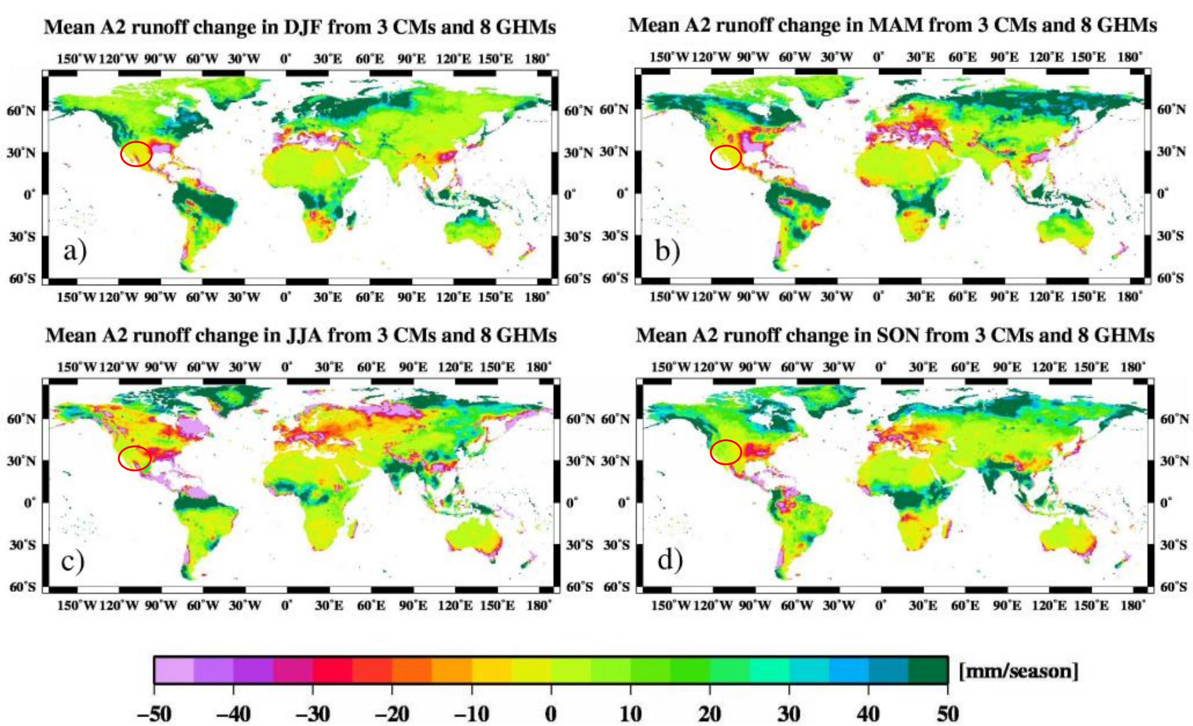


Figure 3.24. Ensemble seasonal (a. winter b. spring c. summer d. fall) mean runoff projections (mm/season) for A2 greenhouse gas emissions scenario, changes in seasonal runoff, 2071 – 2100 vs 1971 – 2000. The Lower Colorado Region is within the red oval (Hagemann et al., 2013).

A regional study by Cayan et al. (2013) evaluated projected changes in annual runoff based on sixteen simulations of a variable infiltration capacity (VIC) hydrologic model for the high emissions scenarios, comparing future conditions (2041 – 2070) to historic conditions (1971 – 2000). Projected annual median runoff is spatially and temporally variable within the Lower Colorado Region. In general, most areas within the Lower Colorado Region show a decreasing trend in annual median runoff, with pocket areas in southern Nevada and southern California showing increasing trends in runoff (**Figure 3.25**).

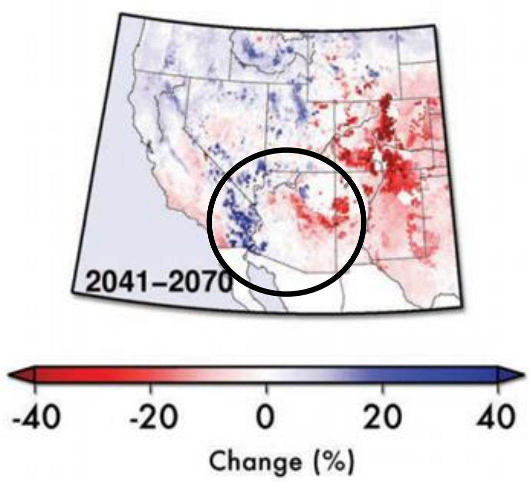


Figure 3.25. High emissions scenario projected changes in annual median runoff for 2041 – 2070 compared to historical runoff (1971 – 2000). The Lower Colorado Region falls generally within the black oval. (Cayan et al., 2013).

Median runoff, specifically for the period of April through July, is projected to decrease primarily throughout the Lower Colorado Region. April 1 SWEs are projected to primarily decrease dramatically in particular areas throughout the Lower Colorado Region, whereas June 1 soil moisture is projected to change variably throughout the Lower Colorado Region, with areas of southern Nevada and southern California showing increasing soil moisture, and remaining areas of the Lower Colorado Region showing decreased soil moisture (**Figure 3.26**). The authors did not provide specific information on confidence levels for these parameters in this study.

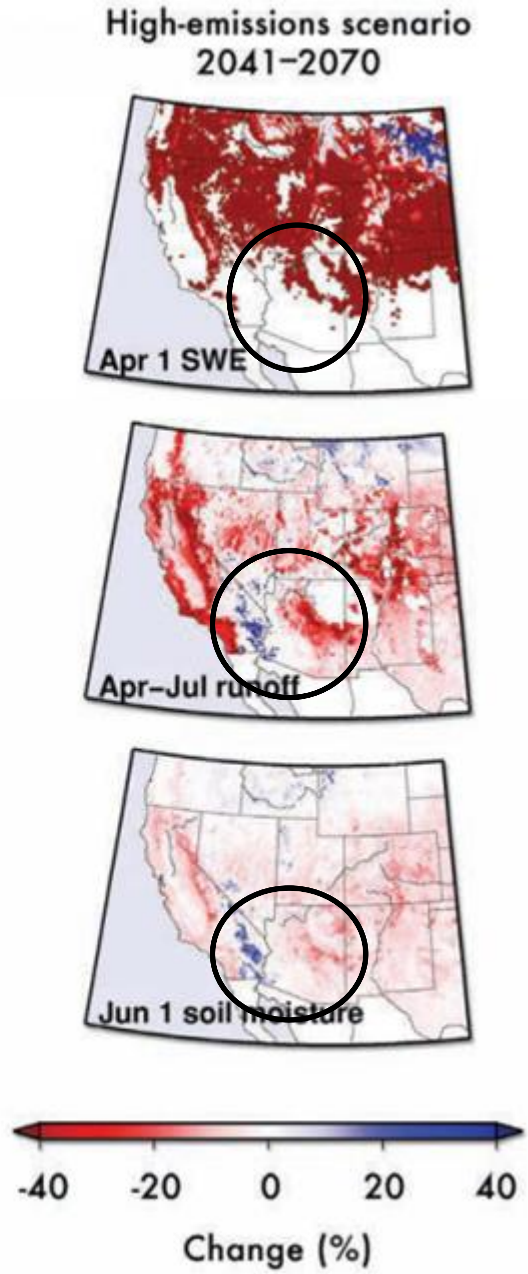


Figure 3.26. High emissions scenario changes in projected (2041 – 2070) compared to historical (1971 – 2000) snow water equivalents (top) April – July median runoff (middle) and June 1 soil moisture (bottom). The Lower Colorado Region falls generally within the black ovals. (Cayan et al., 2013).

Also on a regional scale, the National Climate Assessment's chapter which focuses on the southwest (Garfin et al., 2014) projects a decrease in snowpack for the southwestern United States, including the Lower Colorado Region. Decreased snowpack, as measured by SWE, is strongly related to the amount of runoff and associated natural inflows to snowpack supplied rivers, as is the case in many of the rivers within the Lower Colorado Region. Projected SWE for the Southwestern United States are summarized in **Figure 3.27**.

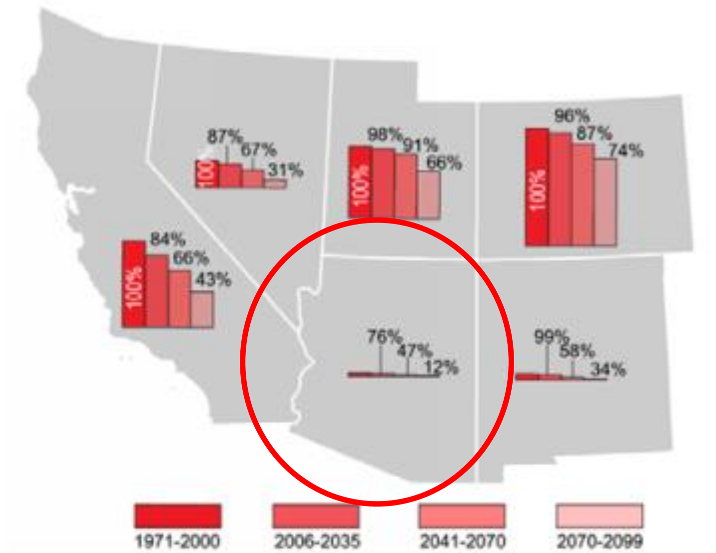


Figure 3.27. Projected snow water equivalent in the southwest United States. The Lower Colorado Region is generally within the red oval (Garfin et al., 2014).

A study by Christensen et al. (2007), as discussed in Section 3.1, evaluated the impacts of climate change on hydrology in the Colorado River Basin. The results of the VIC model, which forced the Colorado River Reservoir Model (CRMM) was based on the results of 11 GCMs. Two emissions scenarios were evaluated: A2 (unconstrained growth) and B1 (elimination of global emission increases by 2100). Three future periods were evaluated (2010 – 2039, 2040 – 2069, and 2070 – 2099) compared to the baseline historic period (1950 – 1999). Spatially and temporally averaged results indicate a general decrease in runoff within the Colorado River Basin. **Figure 3.28** illustrates the ensemble average spatial change in mean annual runoff compared to the baseline period. Within the Lower Colorado Region specifically, some areas show a slight increase (up to 25 mm/year) while other areas show a decrease (up to a reduction of 50 mm/year).

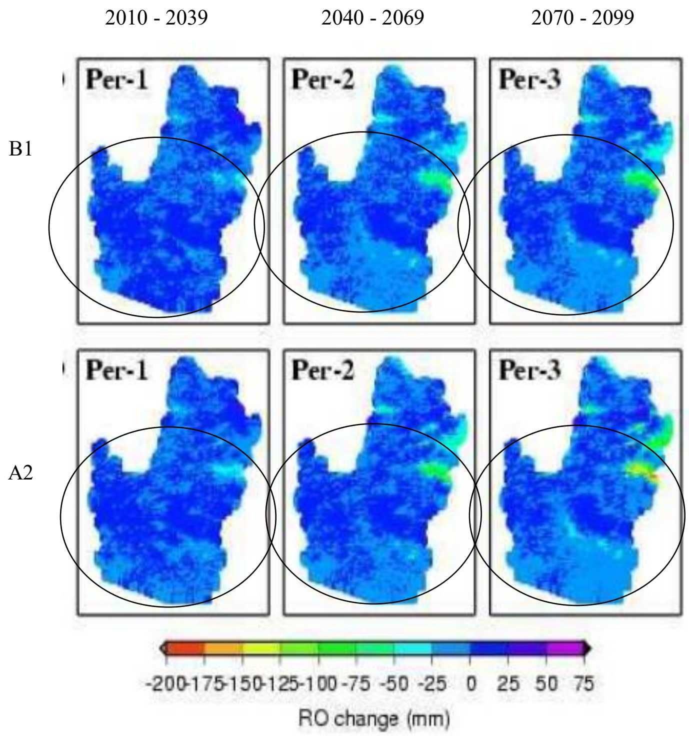


Figure 3.28. Annual average runoff changes (averaged from 11 GCMs) for 2010 – 2039 (left), 2040 – 2069 (middle), and 2070 – 2099 (right) compared to the baseline period (1950 – 1999) for the B1 (top) and A2 (bottom) emissions scenarios. The Lower Colorado Region is generally within the black circles (Christensen et al., 2007).

Monthly variations in projected runoff in **Figure 3.29** show that runoff is projected to increase slightly in the spring months followed by a larger decrease during summer months. Runoff is projected to be relatively consistent with little change across future winter and fall months. **Figure 3.30** shows that for the Colorado River below Imperial, AZ, located at the southwestern corner of the Lower Colorado Region, the highest flows are experienced during spring and summer months. The Colorado River streamflow at Imperial, AZ is projected to decrease over time. This projection is consistent with other regional studies.

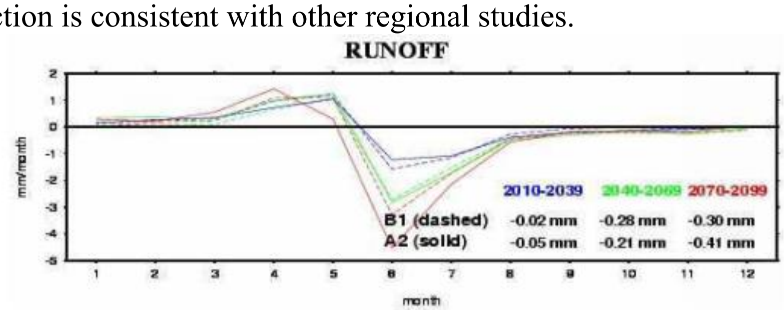


Figure 3.29. Monthly changes in runoff (averaged from 11 GCMs and spatially averaged across the Colorado River Basin) under the B1 (dashed) and A2 (solid) emissions scenarios for three projected time periods compared to the baseline period (1950 – 1999) (Christensen et al., 2007).

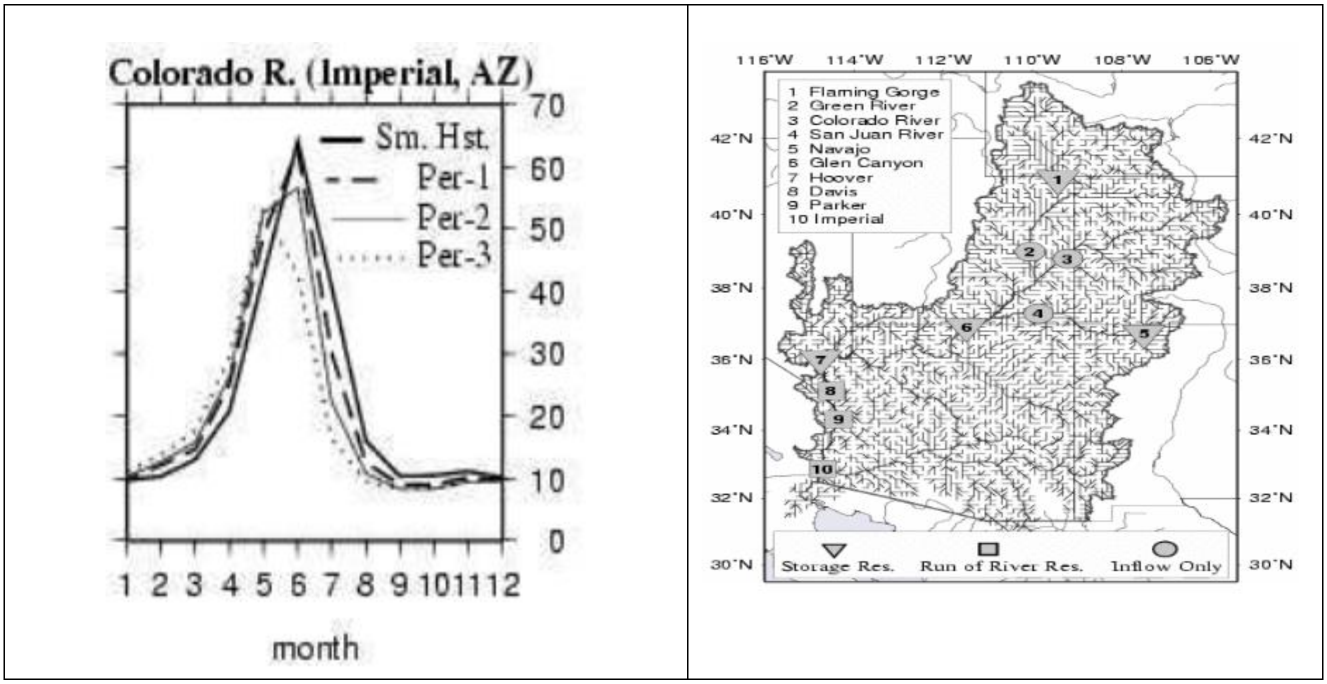


Figure 3.30. Mean monthly hydrograph (left) for the Colorado River below Imperial, AZ (located at location 10 on the map on the right) and simulated streamflow in thousands of cubic feet per second (KCFS) are shown for the 1950 – 1999 baseline period (Sm. Hst.), 2010 – 2039 (Per_1), 2040 – 2069 (Per_2), and 2070 – 2099 (Per_3) (Christensen et al., 2007).

On a smaller scale, hydrology in the San Pedro Basin, located in southeastern Arizona, within the Lower Colorado Region, was the basis of the study by Serrat-Capdevila et al. (2007). The study used 17 global circulation models which were spatially downscaled and simulated under four different IPCC climate change scenarios (A1, A2, B1, and B2) from 2000 – 2100. A three-dimensional transient groundwater-surface water flow model was used to simulate hydrology in the region. Results of the study show that recharge rates within the San Pedro Basin will decrease 17 – 30% over the next century depending on the emissions scenario. Baseflow within the Sand Pedro River shows a reduction of up to almost 50% by 2100.

Similarly, Ellis et al. (2008) studied the future runoff levels of the Salt and Verde River Basins in central Arizona, located within the Lower Colorado Region. The study used a Thornwaite-Mather climate water budget model, which is based on inputs from six global circulation models, and nine IPCC emissions scenarios to predict runoff conditions of 2050. The study concluded, given the variability of the models and the climate scenarios, runoff rates in 2050 could range from 50 to 127% of historic levels. The projections primarily indicate a decrease in runoff for this region.

Key point: Streamflow and associated runoff is projected to generally decrease in the Lower Colorado Region.

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 2.5 to 6 ºC (4.5 to 10.8 ºF), with extreme temperature projections increasing by the latter half of the 21st century for the Lower Colorado Region. The largest increases are generally projected for the summer months. 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 study region are less certain than those associated with air temperature. Results of the studies reviewed here are roughly evenly split with respect to projected increases versus decreases in future annual precipitation, with many showing spatial and seasonal variability in precipitation trends. There is, however, moderate consensus among the reviewed studies that future storm events in the region will be more intense and more frequent compared to the recent past.

The literature presents a relatively clear consensus with respect to hydrologic projections. Projections generated by coupling GCMs with macro-scale hydrologic models show decreasing trends in runoff and/or streamflows in the study region.

A number of studies reviewed here employed probabilistic modeling methods to capture and quantify some of this projection uncertainty, resulting from both climate and runoff modeling steps. These methods frame output in the form of probability distributions that can viewed as characterizations of likelihood of occurrence (risk) or levels of consensus among modeling scenarios.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in **Figure 3.31**.

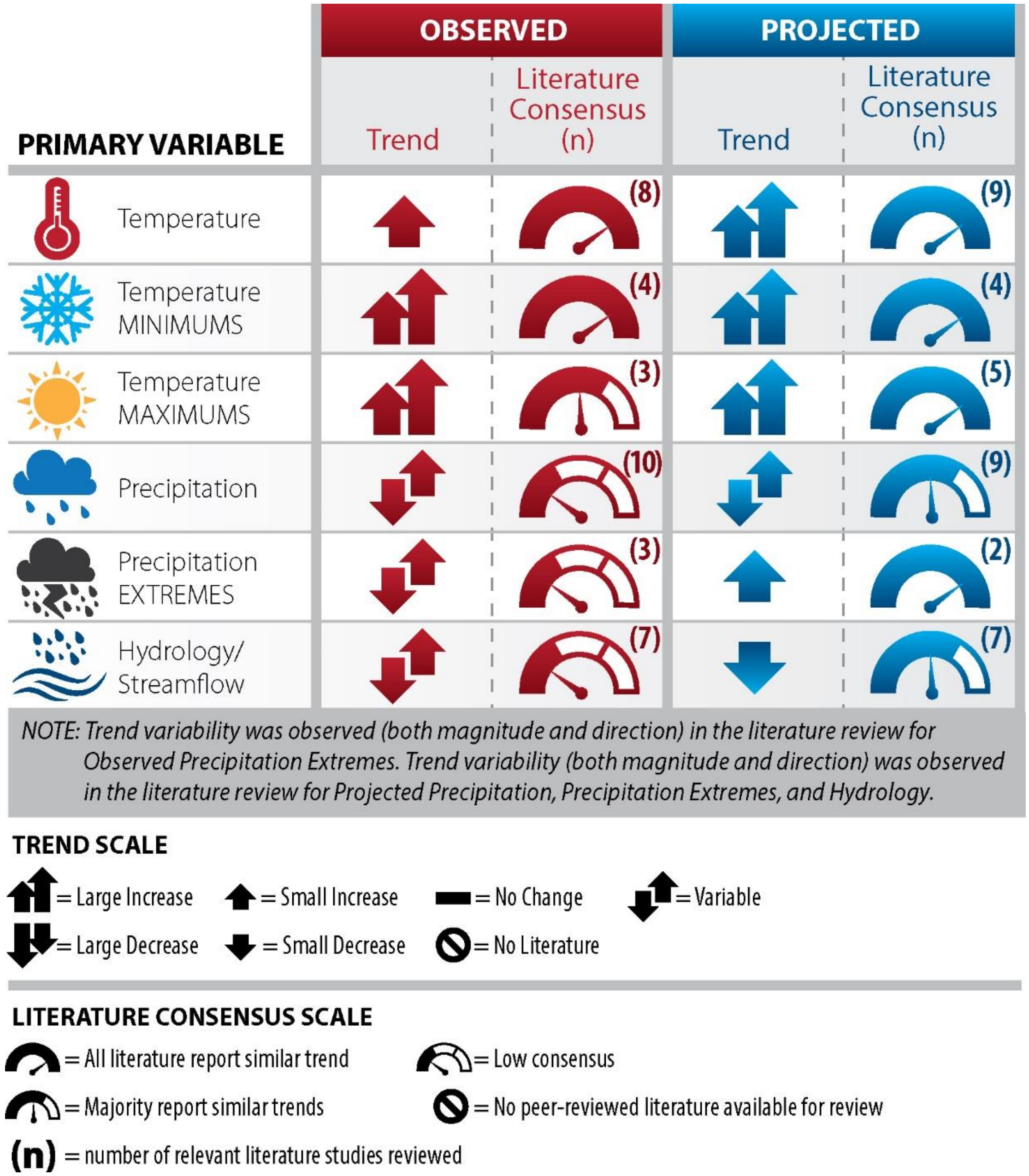


Figure 3.31. Summary matrix of observed and projected climate trends and literary consensus.

4. Business Line Vulnerabilities

The Lower Colorado Region encompasses the majority of Arizona, the western edge of New Mexico, and small portions of Nevada, Utah, and California. 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 to limit flooding. Increased precipitation event intensity and frequency is predicted for the region. This may cause increased 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.

USACE also maintains and operates 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 and the 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 ecosystem restoration projects in the Lower Colorado Region. Increased ambient air temperatures, including increasing high and low temperatures, 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 and frequencies may pose complications to planning for ecosystem needs and lead to variation in flows. However, flows are expected to decrease overall, in part due to a reduced snowpack.

Recreational facilities in the Lower Colorado Region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature along extended heat wave duration in the summer months and the increased intensity and frequency 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 Lower Colorado Region. These types of storms are capable of intense precipitation and winds. Since these may occur more frequently and be more intense, 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 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	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 arid 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 by the middle of the 21st century. The number and temperature of heat waves should also 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 runoff during an 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							
Cayan DR, Tyree M, Kunkel KE, Castro C, Gershunov A, Barsugli J, Overpeck J, …, Rangwala I, Duffy P (2013)											X	X	X	X		X				
CDM Smith (2012)																X				
Christensen N, Lettenmaier DP (2007)											X		X	X		X				
Cook BI, Smerdon JE, Seager R, Cook ER (2014)				X			X	X												
Das T, Hidalgo HG, Pierce DW, Barnett TP, Dettinger MD, Cayan DR, Bonfils C, Bala G, Mirin A (2009)						X														
Dettinger MD (2012)												X		X						
Dominguez F, Cañon J, Valdes J (2010)												X		X						
Elguindi N, Grundstein A (2013)											X			X						X
Ellis AW, Hawkins TW, Bailing RC, Gober P (2008)																X				
Garfin G, Franco G, Blanco A, Comrie A, Gonzalez P, Piechota T, Smyth R, Waskom R (2014)	X					X					X			X	X	X				
Grundstein A (2009)				X				X												
Grundstein A, Dowd J (2011)		X	X																	
Gutzler DS, Robbins TO (2010)											X			X			X	X		
Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, ..., Voss F, Wiltshire AJ (2013)														X		X				
Hoerling MP, Dettinger M, Wolter K, Lukas J, Eischeid J, Nemani R, Liebmann B, Kunkel KE (2013)	X	X	X	X		X														
Kalra A, Piechota T, Davies R, Tootle G (2008)						X														
Kunkel KE, Liang X-Z, Zhu J (2010)											X		X							
Kunkel KE, Stevens LE, Stevens SE, Sun L, Janssen E, Wuebbles D, Redmond KT, Dobson JG (2013)	X	X	X	X	X							X	X							
Liu Y, Goodrick SL, Stanturf JA (2013)													X	X						
MacDonald GM (2010)	X			X																
McRoberts DB, Nielsen-Gammon JW (2011)				X																
Milly PC, Dunne KA, Vecchia AV (2005)											X									
Mote PW, Hamlet AF, Clark MP, Lettenmaier DP (2005)	X			X																
Palecki MA, Angel JR, Hollinger SE (2005)				X	X															
Pryor SC, Howe JA, Kunkel KE (2009)				X	X															
Reclamation, US Borough of (2012)						X														
Sagarika S, Kalra A, Ahmad S (2014)						X														
Scherer M, Diffenbaugh N (2014)											X	X	X							
Schwartz MD, Ault TR, Betancourt JL (2013)	X								X											
Seager R, Vecchi GA (2010)														X						
Serrat-Capdevila A, Valdés JB, Pérez JG, Baird K, Mata LJ, Maddock T (2007)																X				
Tebaldi C (2006)												X	X		X		X			
Tebaldi C, Adams-Smith D, Heller N (2012)	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., ..., Kennedy J, Somerville R (2014)	X			X																
Wang H, Schubert S, Suarez M, Chen J, Hoerling M, Kumar A, Pegion P (2009)	X	X	X	X																
Wang J, Zhang X (2008)				X	X									X	X		X			
Weiss JL, Overpeck JT (2005)		X																		
Westby RM, Lee Y-Y, Black RX (2013)		X																		
Xu X, Liu W, Rafique R, Wang K (2013)						X														

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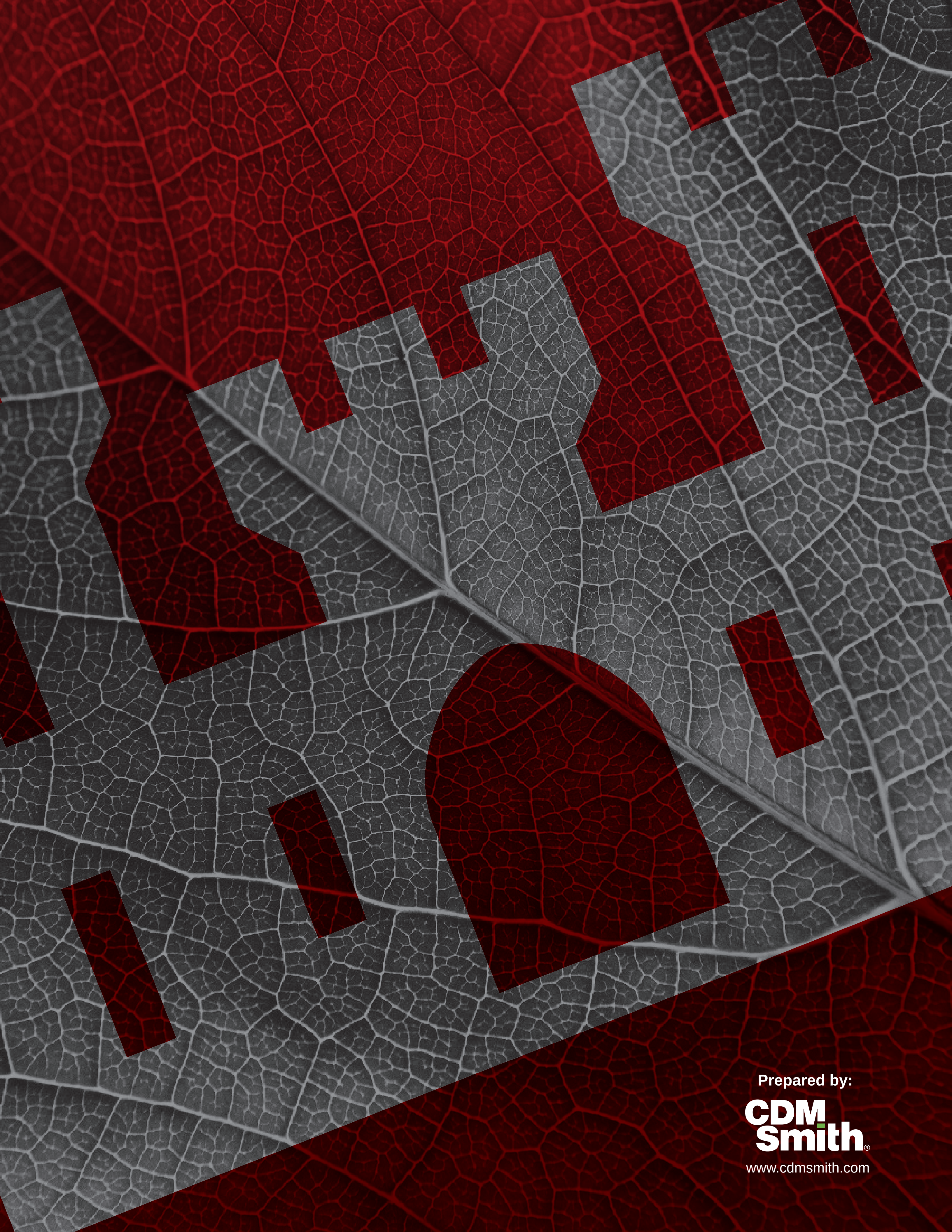

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