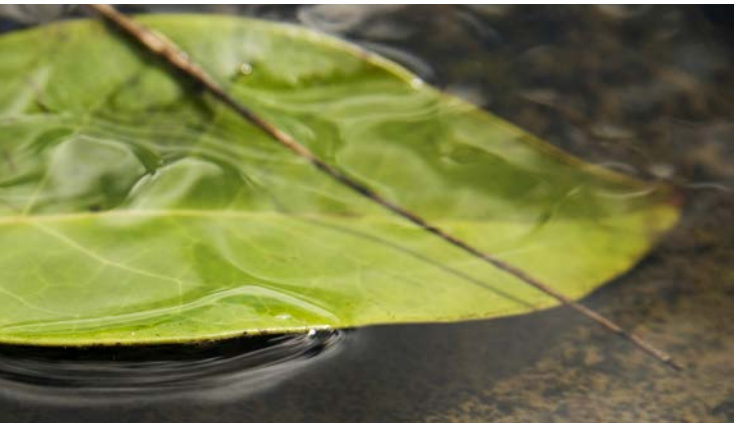

Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

RIO GRANDE REGION 13

FINAL

May 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

REPORT DOCUMENTATION PAGE

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1. REPORT DATE *(DD-MM-YYYY)*
18-05-2015

2. REPORT TYPE
Civil Works Technical Series

3. DATES COVERED *(From - To)*
2014 - 2015

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

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

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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- Support from CDM Smith

5d. PROJECT NUMBER

5e. TASK NUMBER
147

5f. WORK UNIT NUMBER

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

8. PERFORMING ORGANIZATION REPORT NUMBER
CWTS-2015-11

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

10. SPONSOR/MONITOR'S ACRONYM(S)

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

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the Rio Grande 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

Rio Grande Region	Observed Hydrology	Business Line
Water Resources Region 13	Projected Climate	Climate Vulnerability
Observed Climate	Projected Hydrology	Regional Climate Synthesis

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	U		

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Standard Form 298 (Rev. 8/98)
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Adobe Professional 7.0

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

RIO GRANDE REGION 13

May 18, 2015

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

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Suggested Citation:

USACE (2015). Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions – Water Resources Region 13, Rio Grande. Civil Works Technical Report, CWTS 2015-11, USACE, Washington, DC

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Water Resources Region 13: Rio Grande

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 2-digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty one Water Resources Regions included in this series of reports is shown in **Figure 1.1** along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and watershed vulnerability assessment tools.

This report focuses on Water Resources Region 13, the Rio Grande Region, the boundaries for which are shown in **Figure 1.2**. The region encompasses portions of the Albuquerque and Fort Worth USACE districts.

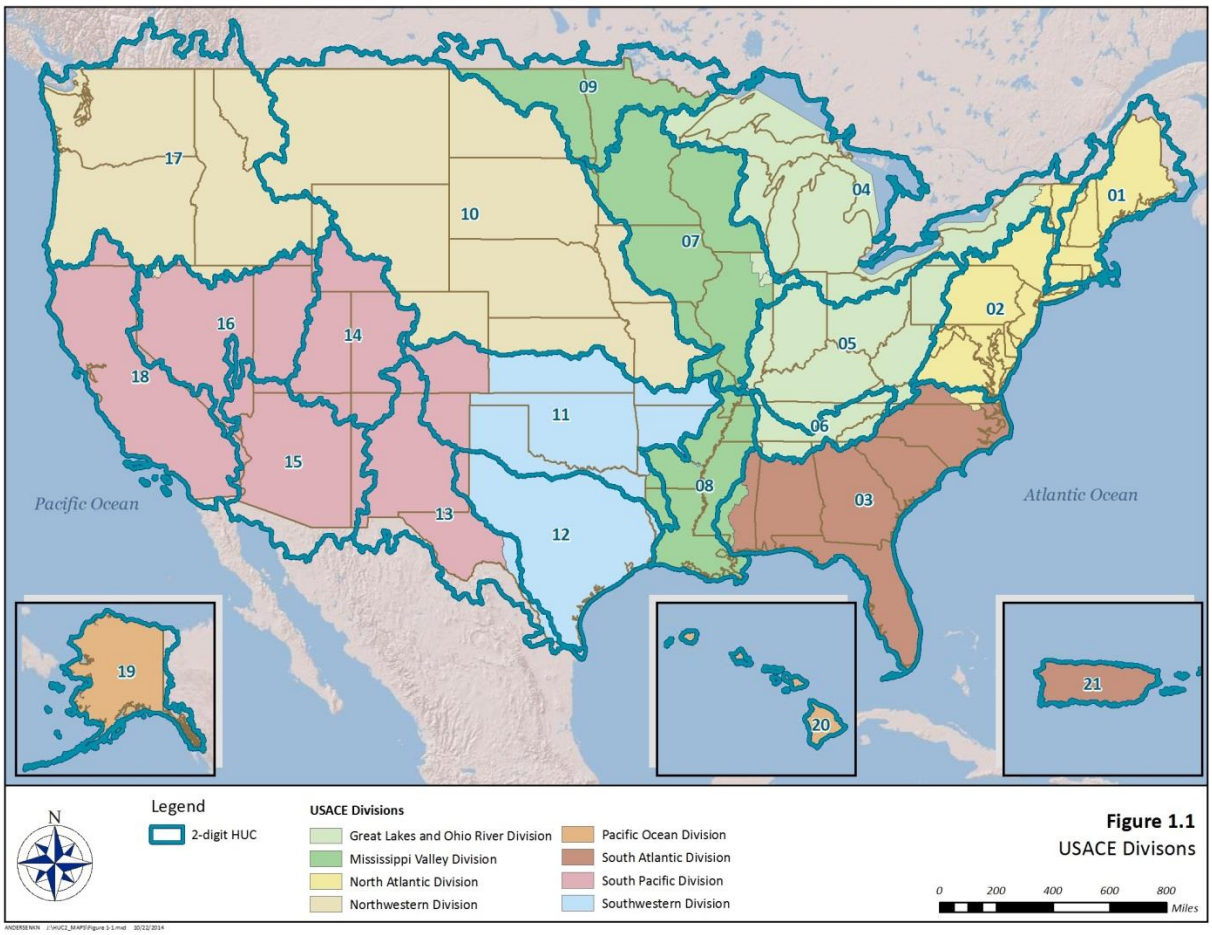


Figure 1.1. 2-digit Water Resources Region Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.

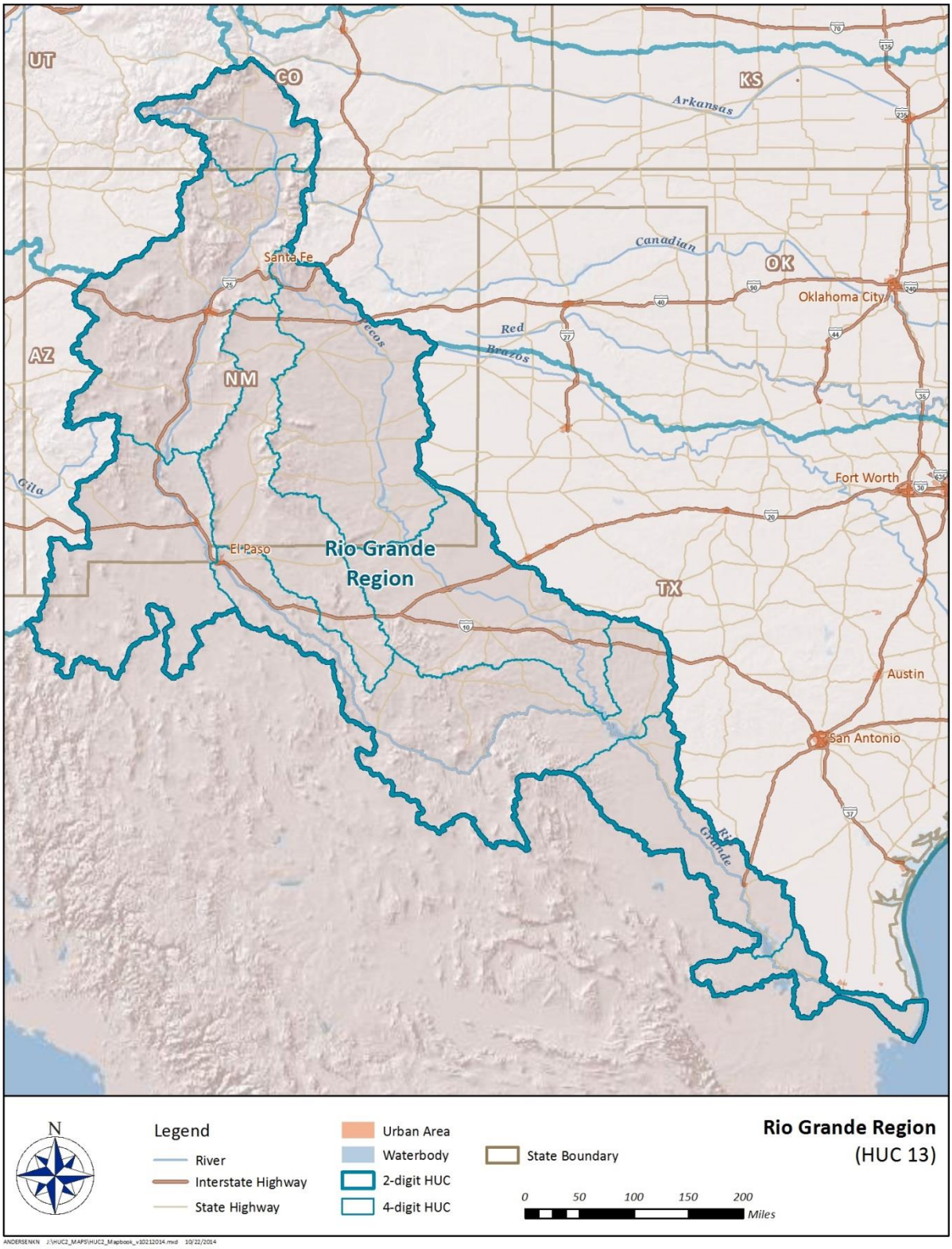


Figure 1.2. Water Resources Region 13: Rio Grande Region Boundary.

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 assessment USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 13, 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 13 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 Water Resources Region 13 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 Water Resources Region 13 (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), drought indices, and soil moisture.

The Rio Grande Region is topographically and geographically diverse. The Rio Grande Region can be divided into two parts: the Upper Rio Grande (above Elephant Butte Dam) and the Lower Rio Grande (Elephant Butte Dam to the Gulf of Mexico). The Upper Rio Grande is snowmelt dominated, with smaller, flashy late-summer storm flows; the Lower Rio Grande is operated for irrigation with spring runoff held at Elephant Butte Reservoir (and adjoining Caballo Reservoir) in southern New Mexico for irrigation season use by Texas. Flows in the Lower Rio Grande are supplemented by flows from the Rio Conchas, Mexico, where flood flows result primarily from summer rainfall events. The complex topography of the region juxtaposes much cooler, humid high elevation climates with warmer, more arid lowland climates. Latitude is also important, with winter limited winter precipitation south of Albuquerque, while contributing a large share of the annual total in the mountain headwaters areas of northern New Mexico and southern Colorado.

The major controls on inter-annual variation in temperature and precipitation in the Rio Grande Region are imperfectly understood. Winter precipitation, in areas receiving any, is affected by sub-decadal scale variations in El Niño-Southern Oscillation, which refers to cyclical patterns of sea surface temperature and air pressure in the tropical Pacific that controls the availability of warm surface waters to serve as sources of atmospheric moisture in the eastern Pacific. In El Niño years, warm sea temperatures encourage increased winter precipitation and the formation of large snow packs; in La Niña years, cool sea surface temperatures in the tropical eastern Pacific reduce the availability of atmospheric moisture to the Southwest, resulting in low winter precipitation and small snow packs (Sheppard et al., 2002).

Multidecadal changes in Pacific Ocean temperatures known as the Pacific Decadal Oscillation (PDO) can enhance or suppress the effects of El Niño and La Niña, particularly in concert with changes in Atlantic sea surface temperatures (McCabe et al., 2004). Controls on the interannual variability of the North American Monsoon are imperfectly understood, but relate in part to the

intensity of surface heating during the summer and the amount of available moisture in source areas of the Gulf of Mexico and the tropical eastern Pacific. Likewise, the number and intensity of hurricanes in any given season, and the likely distribution of their landfall has proved elusive to predict.

Trends and observations have varying coverage over the region and therefore, the results from the studies presented herein are limited. From the studies that cover the region, the results presented below indicate an increasing trend in temperature for the Rio Grande Region. However, clear consensus does not exist for precipitation trends. Additionally, studies of regional streamflow reviewed here present a slight decreasing trend in streamflow, but overall literature consensus was also low.

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 Rio Grande Region and studies focused more specifically and exclusively on the region. Some national studies have sparse data coverage or are limited by topographical diversity and therefore lack truly representative findings for the Rio Grande Region. Those studies are included and are noted as such. Results from both national and regional types of studies 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 Rio Grande Region, no such trend is identified for the region in the winter (December-February), a slight warming trend in the spring (March-May), while a slight cooling trend is shown for the summer (June-August) and fall (September-November) with an exception at the mouth of the Rio Grande River. The authors do not provide information on statistical significance of the presented observed trends. A later study by Westby et al. (2013), using data from the period 1949 – 2011, presented similar findings, presenting both increasing and decreasing trends for the same portions of the region for this time period (**Figure 2.2**). Their cooling trend, however, was not statistically significant at a 95% confidence interval (C.I.).

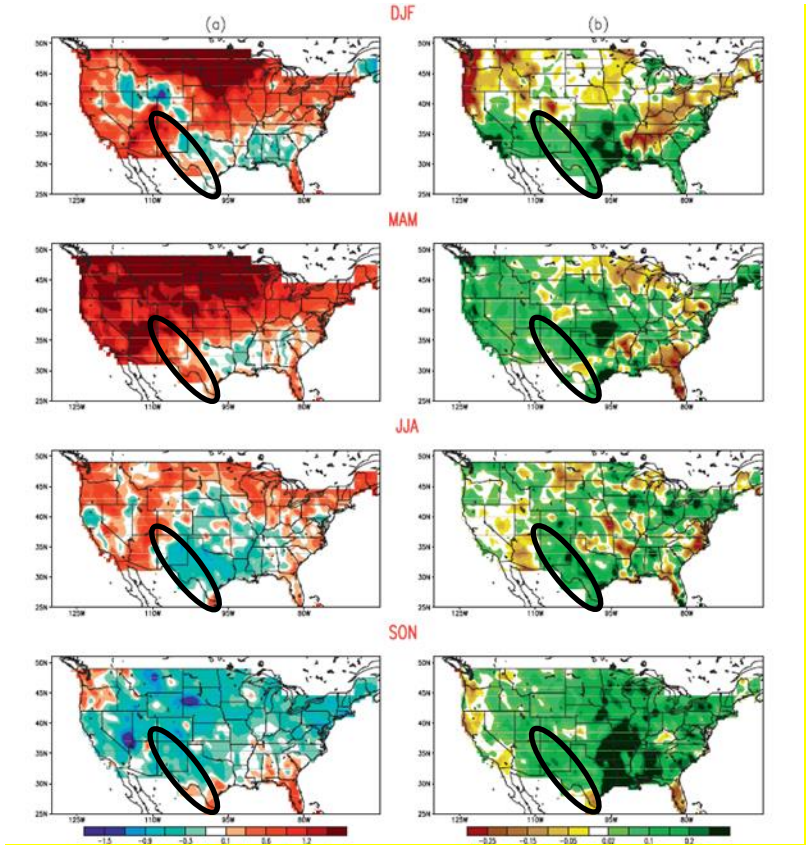


Figure 2.1. Linear trends in surface air temperature (a) and precipitation (b) over the United States, 1950 – 2000. The Rio Grande Region is within the black oval (Wang et al., 2009).

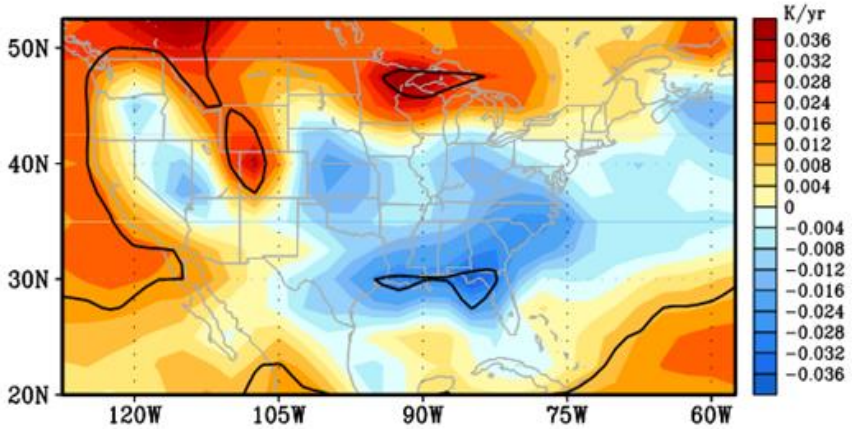


Figure 2.2. Mean winter (December through February) temperature trends from 1949 – 2011 (K/year). Black contours indicate statistical significance at the 95% confidence level. The Rio Grande Region is within the red oval (Westby et al., 2013).

MacDonald (2010) demonstrated that the increase in average annual temperatures from 2001 – 2009 compared to 1951 – 1960 (**Figure 2.3**) was 0.5 – 1.5 standard deviations above the 20th century average in New Mexico and southern Colorado, and between 0.0 – 1.0 standard deviations in the southern portion of the study area in Texas. The author used data from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory, Physical Sciences Division and mapped the changes in temperature by state climate divisions. Details on statistical significance were not provided in the study.

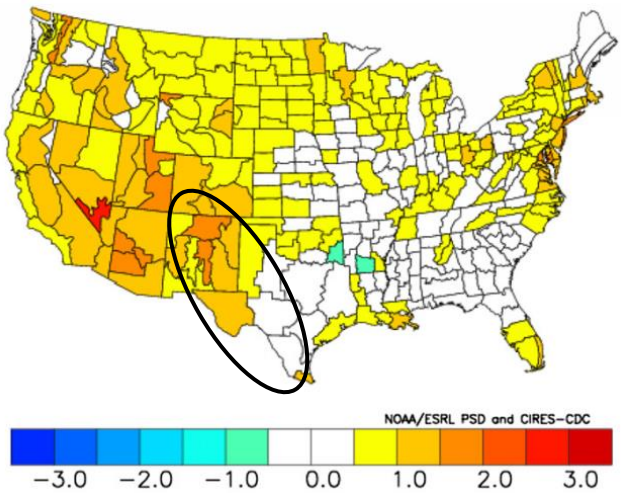


Figure 2.3. Composite standardized temperature anomalies for 2001 – 2009 relative to 1895 – 2000. The Rio Grande Region is within the black oval (MacDonald, 2010).

Another national study by Tebaldi et al. (2012) evaluated average annual historic decadal changes in temperatures. Based on data from 1912 – 2011, in New Mexico, temperatures warmed at an average rate of 0.122 °C (0.22 °F) per decade, but at a faster rate of 0.377 °C (0.68 °F) per decade since 1970. The same pattern of faster recent warming was also observed in annual average daytime maximum high temperature (T_{max}) and annual average nighttime minimum temperature (T_{min}). The rate of temperature change was statistically significant (95% C.I.) for New Mexico, but was not statistically significant for Texas or Colorado.

Grundstein and Dowd (2011) investigated trends in one-day extreme maximum and minimum 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. For the Rio Grande Region, they found a statistically significant (95% C.I.) increasing trend in the number of one-day extreme minimum and maximum temperatures for the three stations in the study area.

Similarly, Hoerling et al. (2013) assessed weather and climate variability and trends in the Southwest using observed climate and paleoclimate records comparing the last 100 years to the last 1,000 years. The authors quantified trends in annually averaged daily temperature and daily maximum temperature as estimated from station data for which there were at least 90 years of available data during the period between 1901and 2010. In the Rio Grande Region, a statistically significant (95% C.I.) increase of both average annual daily temperature and daily maximum temperature was identified within a range of 0.5 – 2.0 °C (0.9 – 3.6 °F) for both metrics.

The third NCA report (Walsh et al., 2014) presents historical annual average temperatures for the Rio Grande Region. The Rio Grande Region falls within the areas categorized as Great Plains South and the Southwest as described in the section about recent U.S. temperature trends. For the southern portion of the Rio Grande Region, historical data generally shows mild warming of average annual temperatures in the early part of the 20th century, followed by a few decades of cooling, and is now showing indications of warming. In the northern part of the study region, historical data shows an increase in warming over the past 60 years. Temperatures have increased throughout a significant portion of the Rio Grande Region, up to 2 °F (1.1 °C), as illustrated by **Figure 2.4** (Walsh et al., 2014). This is consistent with an increasing trend in annual average temperatures within the Rio Grande Region reported by MacDonald (2010), Tebaldi (2012), and Hoerling (2013).

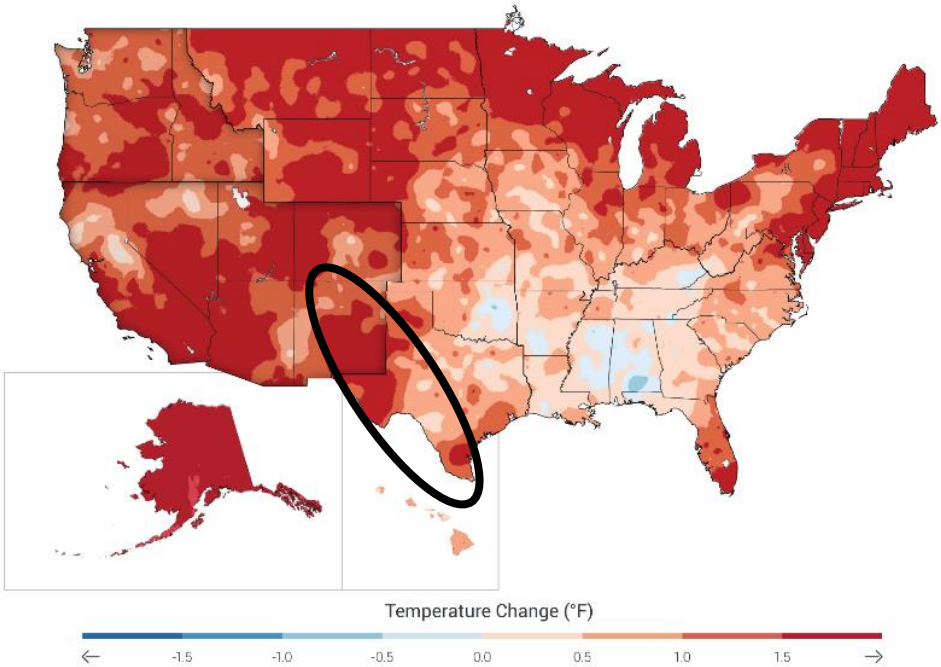


Figure 2.4. Changes in average temperatures for 1991 – 2012 compared to 1901 – 1960. The Rio Grande Region is within the black oval. (Walsh et al., 2014).

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 Rio Grande Region, spring onset is occurring between zero to four days later for the current period (2001 – 2010) compared to an earlier baseline reference decade (1951 – 1960) (**Figure 2.5**). Data are limited for the Rio Grande Region and are reason for uncertainty in findings in this study at different topographical and geographical areas within the region. In other words, an apparent small shift in seasons has been identified at those NCDC stations across the Rio Grande Region with spring warming occurring later than in the past.

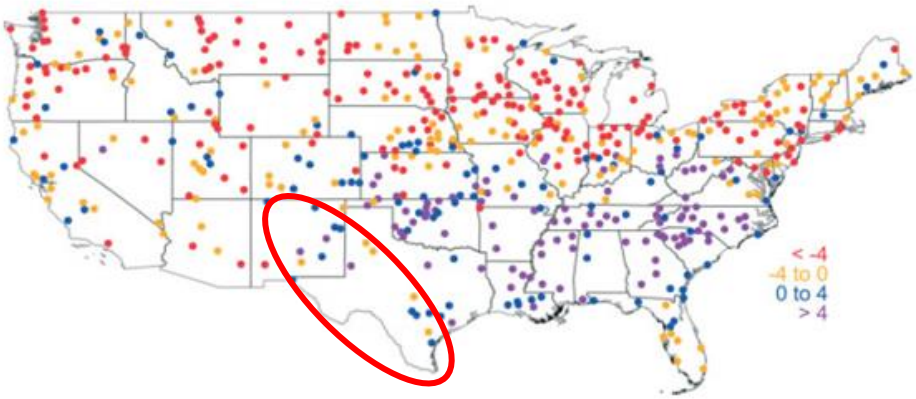


Figure 2.5. Change in spring onset (first leaf date), in days for 2001-2010 compared to 1951 – 1960. The Rio Grande Region is within the red oval (Schwartz et al., 2013).

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 compared to average of 1901 – 1960. Only values significant (> 95% C.I.) are reported (Kunkel et al., 2013).

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

In the study area above Albuquerque (Upper Rio Grande), Saunders and Maxwell (2005) evaluated climate disruption of the Western U.S. and its water supply using data from the NOAA Climate Division Series. As part of their study, they compared average monthly temperatures of the period 1995 – 2004 with average monthly temperatures of the period 1961 – 2000 (**Figure 2.6**). The figure shows increases of average monthly temperatures of 2.2 – 4.2 °F (1.2 – 2.3 °C) in winter and increases in the April through November period of less than approximately 1.6°F (0.9 °C) in all months but May. Details on statistical significance were not provided in the study.

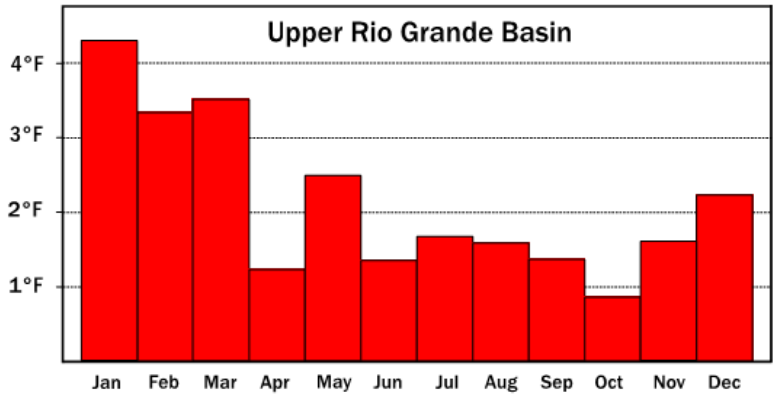


Figure 2.6. Average monthly temperatures in 1995 – 2004, compared to historical average monthly temperatures in 1961 – 1990 (Saunders and Maxwell, 2005).

Rates of warming in high elevation areas may be considerably greater than the regional average. Rangwala and Miller (2010) used data from the National Weather Service and the US Department of Agriculture (USDA) Natural Resource Conservation Service Snowpack Telemetry (SNOTEL) in the San Juan Mountains within the Upper Rio Grande Region. They detected a rate of warming (90% C.I.) of 1°C (1.8°F) between 1895 and 2005 with most of the warming occurring between 1990 and 2005.

In the adjacent San Luis Valley, a regional analysis of annual average temperatures identified an increase (C.I. >95%) of 1.1 °C (1.9 °F) for the period 1957 – 2006. Temperature trends were presented in 30-, 50-, and 75-year time periods, when available, across the state of Colorado (Ray et al., 2008). A study by Mix et al. (2012) presented information on the San Luis Valley with temperature data from seven climate stations by focusing on the growing season and related monthly temperatures. Increases in daily mean, maximum, and minimum temperature were approximately 0.3 – 1.4 °C (0.5 – 2.5 °F), 0.3 – 1.7 °C (0.5 – 3 °F), and 0.5 – 1.6 °C (0.9 – 2.9 °F), respectively. The temperature increases (95% C.I.) occurred at nearly all of the study stations for each month within the growing season.

A 2013 study performed by the USACE Albuquerque District analyzed climate trends for the Upper Rio Grande Region above the Elephant Butte Dam, NM. For the period 1971 – 2012, long term trends in temperature in the study area showed an average rate of increase (90% C.I.) of 0.35 °C (0.63 °F) per decade on a regional scale. Data indicated a faster increase in nighttime minimum temperatures (T_{min}) of 0.37 °C (0.67 °F) per decade, and a slower increase in daytime maximum temperatures (T_{max}) of 0.25 °C (0.45 °F). The study showed that while daytime and nighttime warming were approximately similar in low elevation areas, daytime warming was low and nighttime warming was pronounced in high elevation mountain settings, which are critical for snowpack accumulation. The study also divided temperature data into two time periods: 1971 – 2000 vs. 2001 – 2012 and showed that the rate of warming of T_{min} and T_{max} in mountainous settings has doubled over time, while the rate of warming in low elevation settings has slowed.

Nielsen-Gammon (2011) performed a study evaluating the changing climate for the state of Texas, focusing on temperature and precipitation. Individual stations from the U.S. Historical Climatology Network dataset were utilized to inform regional and seasonal climate variations. In the Rio Grande Region below El Paso, TX, the December-February average temperatures (using a nine-year running mean) have increased approximately 2.2 °C (4 °F) since 1960. A longer term trend is evident in Far West Texas (El Paso area), larger negative temperature departures from the mean (comparatively cooler) early in the century and larger positive departures from the mean (comparatively warmer) towards century's end. Spring (March-April) and fall (October-November) average temperatures do not show a particular trend, indicating no significant change in the length of the growing season in this region. As in winter, temperatures in Far West Texas have a tendency to show a more definitive trend than elsewhere in Texas, being relatively cooler early in the 20th century and warmer towards the end. Summer (May-September) temperature trends are comparable to those of winter, with a definitive warming trend after 1970. At a century-scale, Far West Texas is warming faster than any other region of Texas with temperatures increasing at 0.6 – 1.2 °C (1.1 – 2.2 °F) per century. A very slight warming is evident in South Texas (near Brownsville, TX and the mouth of the Rio Grande River) and a very slight cooling in between. Details on statistical significance were not provided in the study.

Norwine et al. (2007) investigated the climate trends in South Texas for the period of 1900 – 2000 for 21 climate stations within the region. The authors observed that mean annual temperatures generally trended upward through the first half of the 20th century, trended downward for about 25 years between 1950 and 1975, declined slightly across the period of 1931 to 2001, but have since climbed from 1980 to 2000. Details on statistical significance were not provided in the study.

Key point: Temperatures in the region have shown a relatively steady rise beginning in the early 20th century. An increasing trend was observed in mean, minimum, and maximum temperatures although less pronounced during the fall and winter seasons. Spatial variation, differences in climate and elevation contribute to magnitude of variation. The consensus view is that recent increases in temperature in the region exceed observations in the historic record beginning in the late 19th century.

2.2. Precipitation

Multiple authors have identified slight increasing trends in total annual precipitation in recent historical records for the study region. Grundstein (2009) identified statistically significant (95% C.I.) increasing trends in soil moisture for two climate division stations in New Mexico (**Figure 2.7**) based on annual data from 1895 to 2006. Soil moisture is a function of both supply (precipitation) and demand (evapo-transpiration [ET]), and therefore is an effective proxy for both precipitation and ET. A statistically significant trend in soil moisture index and annual precipitation was quantified for at most three of the stations within the Rio Grande Region. Data are spatially limited, however, for the region. A slight increase in soil moisture was identified, but little or no change in precipitation was identified.

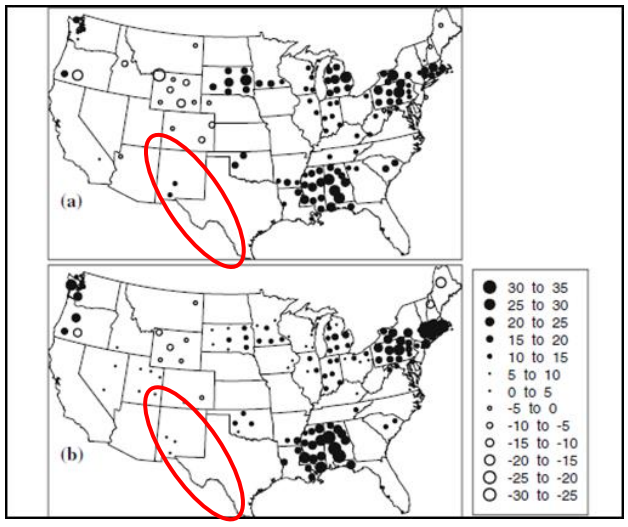


Figure 2.7. Statistically significant linear trends in (a) soil moisture index (unitless) and (b) annual precipitation (cm) for the continental U.S., 1895 – 2006. The Rio Grande Region is within the red oval (Grundstein, 2009).

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 Rio Grande Region, the authors identified a mild increasing trend in winter and summer, but a slight decrease trend in precipitation during spring and fall, specifically in the southern portion of the Rio Grande Region. (**Figure 2.1**). 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 sub-basins across the United States. The extended data period used for the analysis was 1895 – 2009. Linear positive trends in annual precipitation were identified for most of the U.S. (**Figure 2.8**). For the Rio Grande Region, results indicate increasing (2 – 20% per century) trends in annual precipitation, especially at the southern tip of Texas. The authors do not provide information on statistical significance of the presented observed trends.

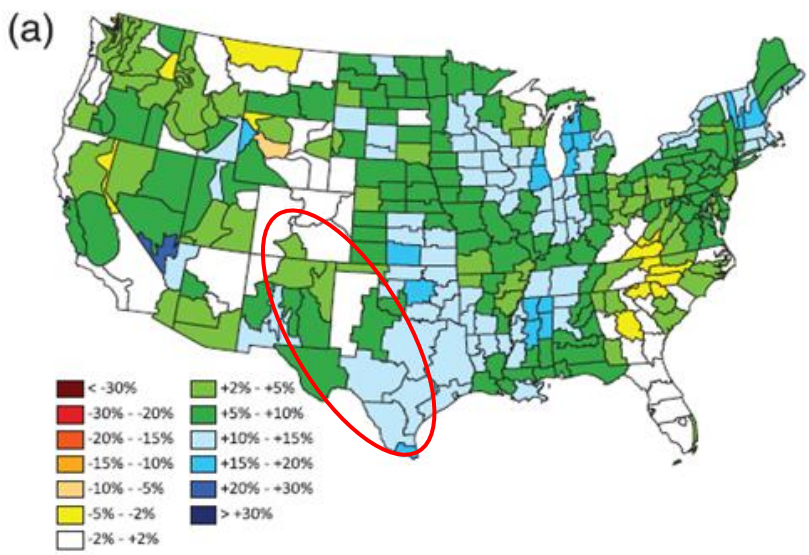
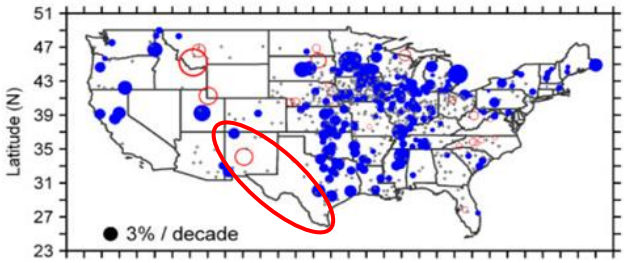


Figure 2.8. Linear trends in annual precipitation, 1895 – 2009, percent change per century. The Rio Grande Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

Palecki et al. (2005) examined historical precipitation data from across the continental United States. They quantified trends in precipitation for the period 1972 to 2002 using NCDC 15-minute rainfall data. For the Rio Grande Region, a statistically significant increase (90 – 95% C.I.) in summer and fall mean storm intensity (total precipitation divided by storm duration) was identified for the region. A statistically significant increase was identified for 15-minute maximum intensity during the summer, and a decrease in fall/winter storm duration and storm total precipitation.

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 Rio Grande Region, the analysis showed a mixed result for annual precipitation (**Figure 2.9 a**), with some locations exhibiting an increasing trend and others a decreasing trend. Results showed a generally decreasing, and statistically significant, trend in extreme high precipitation events (90th percentile daily) and precipitation intensity, but an increase in the number of precipitation days per year (**Figure 2.9 b, c, and d**). These trends were determined to be significant at the 90% confidence interval. 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

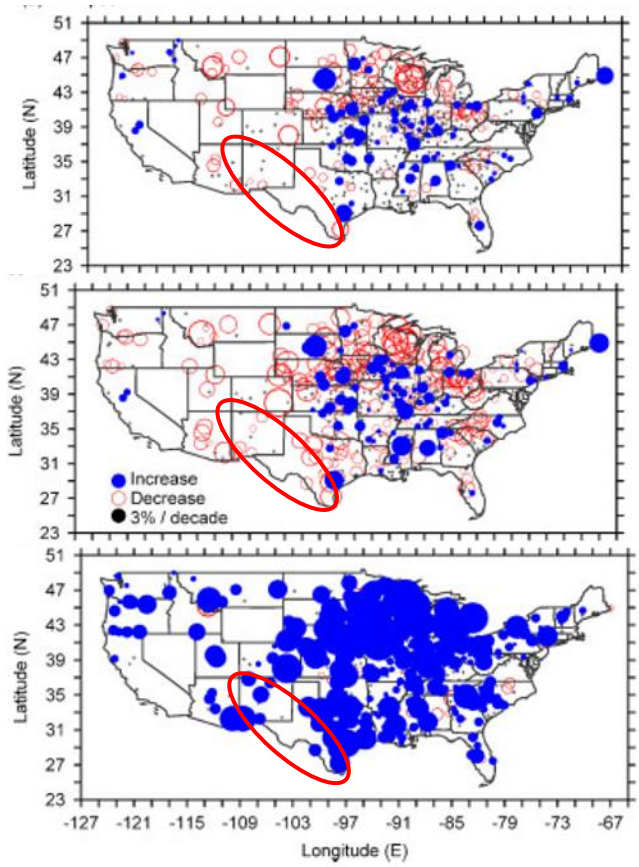


Figure 2.9. Historical precipitation trends (20th century) in a) annual totals, b) 90th percentile daily, c) precipitation intensity (annual total/number of precipitation days), and d) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The Rio Grande Region is within the red oval (Pryor et al., 2009).

Changes in extreme precipitation events observed in recent historical data have been the focus of a number of studies. Studies of extreme events have focused on intensity, frequency, and/or duration of such events. Wang and Zhang (2008) used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. Statistically significant increases in the frequency of the 20-year storm event were quantified across the southern and central U.S., in both the recent historical data and the long term future projections (described below). For the Rio Grande Region, there appears to be a significant change in the recurrence of this type of storm event for the period 1977 – 1999 compared to the period 1949 – 1976. The occurrence of daily precipitation at the 20-year return level has been doubled between the two time periods for the central portion of the Rio Grande Region.

Villarini et al. (2013) identified statistically significant ($p \leq 0.05$) increasing trends in the frequency of occurrence of heavy rainfall in a region inclusive of the Rio Grande Region for multiple climate stations with at least 50 years of historical record. While significant trends were

identified for a number of stations in the region, an even greater number of stations in the Rio Grande Region exhibited no significant trends.

Since 2001, large portions of the southwest and west Texas have experienced drought, with particularly widespread and severe drying in 2002, 2003, 2007, 2009, 2011 and 2012. The authors identify a general, but episodic, decline in regional participation (**Figure 2.10a**). During these extremes, precipitation in the Rio Grande Region ranged from 20% below the 20th century average in the Upper Rio Grande to 10% above the average in the Lower Rio Grande (MacDonald, 2010). Similar in interpretation, the mean regional Palmer Drought Severity Index (PDSI) was lower than average in the Upper Rio Grande versus the Lower Rio Grande region, but that in West Texas, there was minimal departure from the average (**Figure 2.10b)**. The author used data from the NOAA Earth System Research Laboratory, Physical Sciences Division to map spatial and temporal contexts of drought across the U.S. Details on statistical significance are not provided.

a) Annual precipitation

b) Mean PDSI

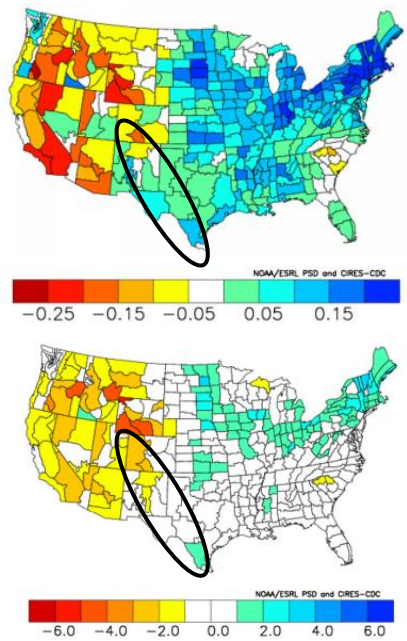


Figure 2.10. a) Composite standardized precipitation anomalies for 2001-2009 relative to 1895-2000. b) mean PDSI value for the period 2001-2009. The Rio Grande Region is within the black oval (MacDonald, 2010).

Trends in the frequency and severity of droughts in the southern U.S. were the subject of studies by Chen et al. (2012) and Cook et al. (2014). In the first study, historical data (1895 – 2007) were used to identify trends in drought, as defined by the standard precipitation index (SPI). The SPI is a metric of precipitation only and neglects the impacts of ET on droughts (Chen et al., 2012). The authors were not able to identify significant trends in the frequency, intensity, or duration of droughts in the study region. The second set of authors used 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 a portion of the Rio Grande Region, the authors identified a decline in the number of droughts per century, although the finding is not considered a statistically significant ($p = 0.11$) decline in drought frequency (droughts per century) over the

past 1,000 years; in addition, the authors identified a marginally significant increase in soil moisture, as defined by the PDSI, over the same period (**Figure 2.11**).

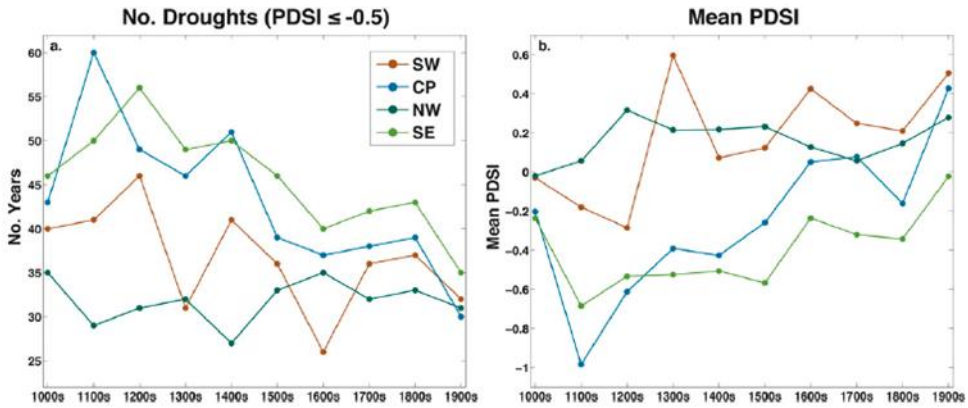


Figure 2.11. Trends in number of droughts per year per century (left) and mean PDSI across all years of each century. The Rio Grande Region is within the Southwest (SW) (Cook et al., 2014).

A number of recent studies have focused more specifically on the southwest-south central region of the U.S., including the Rio Grande Region. As above, regional investigations have targeted trends, or changes, in annual precipitation and the occurrence of extreme events.

In the 20th century, the Southwest has experienced dramatic swings in precipitation due to natural cycles in Atlantic and Pacific sea surface temperatures. The period 1905 – 1930 had wetter winters than average, from 1931 – 1941 precipitation was approximately average, and from 1942 – 1964 it was drier than average. Peak dryness occurred during the drought from 1950 – 1956, when average annual precipitation remained below the long term average. Average years from 1965 through 1975 were followed by the period from 1976 through 1997/1998 when warm, wet winters and erratic summer precipitation were the norm (Gutzler, 2003; Sheppard et al., 2002; Swetnam and Betancourt, 1998). Gutzler used data from the Western Regional Climate Center to show a time series of annual water-year precipitation for average annual precipitation from 1896 – 2002 and discussed periods and severity of drought for the region, whereas Sheppard et al. describes droughts and short-term fluctuations in PDSI based on a 3-year average using tree-ring constructed PDSI since 1700 through 2002. The three sets of authors confirm that periods of peak dryness occurred during the 1950s with a long period of below-average moisture availability. The studies do not discuss statistical significance of these trends.

As mentioned above, Hoerling et al., (2013) used observed climate and paleoclimate records to analyze the last 100 years of climate variability in comparison to the last 1,000 years to assess trends in the Southwest U.S. The authors compared the basin-mean precipitation of 2001 – 2010 to 1941 – 2000 and determined that the Rio Grande at El Paso, TX had a positive 3% difference. In contrast, the authors also concluded that the decade 2001-2010 had the second-largest area affected by drought (after the period 1951 – 1960), the decade was the fourth driest in the Southwest of all decades from 1901 – 2010, and that the frequency of extreme daily precipitation events over the Southwest during 2001 – 2010 showed little change compared to the 20th century

average (high/medium-high confidence). The study area covered by the Hoerling et al. study includes the Rio Grande Region and the trends reported are relatively indicative of the trends impacting the region. However, some National Weather Service Historical Climatology Network stations in west and south Texas show increases of 5-20%, respectively, primarily in the fall, for the period 1895 – 2006 (Nielsen-Gammon, 2011). The Nielsen-Gammon study did not discuss statistical significance of this trend.

The third NCA report (Walsh et al., 2014) presents observed precipitation changes for the Rio Grande Region. As described above, the study area is categorized as Great Plains South and the Southwest detailed in the section describing recent U.S. precipitation trends. The observed changes in precipitation are mixed, with some areas within the Rio Grande Region having increased while others have decreased since 1900. Details on statistical significance are not provided. These conclusions are founded upon research performed by Kunkel et al. (2013) who also described that despite recent drought years, no statistically significant trends in annual water year, seasonal precipitation, extreme precipitation, or frequency of extreme precipitation events were detected from 1895/1896 through 2010/2011 for the six-state Southwest region (NOAA, 2013b), including Colorado and New Mexico. Seasonal time series show no trends for winter, spring and summer; fall shows a slight upward, but not statistically significant, trend. Precipitation on the Southern Great Plains, including Texas, shows no significant trend in any season (NOAA, 2013a).

Key point: Despite recent drought years, observed trends in precipitation or frequency of extreme events are varied and no significant trends have been identified. Similar to temperature trends, spatial variation and differences in elevation contribute to some variation in interpretation.

2.3. Hydrology

Studies of trends and non-stationarity in streamflow data collected over the past century have been performed throughout the continental U.S., some of which are inclusive of the Rio Grande Region. In addition, changes to snowpack, snowmelt, and runoff volume are important in the snowmelt-dominated portion of the Rio Grande Region above Elephant Butte Dam. Two important variables with regard to snowpack are the quantity of precipitation falling as snow, and the amount of water contained in a given volume of snow (snow water equivalent). These studies typically focus on the mainstem of the Rio Grande, or where long-term stream gages or instruments exist. Changes to the mainstem of the Rio Grande are more likely to be dominated by changes to snowpack and snowmelt, whereas tributary watersheds may be more sensitive to changes in summer precipitation.

A recent study of annual records of unimpaired streamflow stations with data from 1951 to 2010 showed an increasing trend (Sagarika et al., 2014). For the one streamflow station within the upper region of the Rio Grande Region, an increasing trend was seen in fall, winter, and spring. There was no discernible trend for summer streamflows. Observed streamflow trends were also evaluated at the Water Resources Region scale by Kalra et al. (2008). The study utilized recorded streamflow data from 639 stations (unimpaired) to assess trends and step changes based on a study period of 1951 – 2002. Streamflow was evaluated based on water year and also seasonally for autumn/winter and spring/summer. The authors identified an increasing trend

(95% C.I.) in streamflow during the water year and fall/winter, but not during the spring/summer for six unimpaired gages located throughout the Rio Grande Region.

Hoerling et al., (2013) analyzed naturalized or near-natural streamflows amounts for the southwest region's river basins, including the Rio Grande; data are from the International Boundary and Water Commission (U.S. Section). During the first decade of the drought in 2001 – 2010, flows in the Rio Grande at El Paso, TX were about 23% lower than the period from 1941 – 2000, even though overall precipitation in the basin was 3% above normal. The Rio Grande at this location is nearly 100% irrigation flows from the Caballo Reservoir. The low flows resulted from less precipitation, warm temperatures, and to some extent, water-management impacts that were not completely accounted for in the natural streamflow records. Hoerling et al. (2013) also report that streamflow timing for the snowmelt-fed streams of the Southwest. A trend was identified of earlier timing of annual streamflow from 1950 – 1999 compared to 2001 – 2010. In the Rio Grande Region, an estimated 5 to 20-day difference in streamflow timing was reported (95% C.I.). Statistical significance of observed streamflows was not discussed in the study.

Studies have discussed that changes in snowmelt are occurring. There has also been a long-term decline in the ratio of winter-total snow water equivalent (SWE) to winter total precipitation, particularly where winter wet-day minimum temperatures averaged were warmer than -5°C for the period 1949 – 2004. The changes were most pronounced in spring (Knowles et al., 2006). Changes in snowpack and snowmelt have begun to be evident in spring runoff flows. Southwestern flood magnitudes over the last 85 years have declined strongly, with the strongest decreases along the Rio Grande River (Hirsch and Ryberg, 2011). The authors selected 200 stream gages and fit the annual peak streamflow to a regression model in an attempt to quantify changes of flood magnitudes in relation to CO_2 concentrations. Statistical significance was not discussed in the study.

Other processes associated with aridity can affect the rate of snowmelt. Increased aridity is likely to reduce vegetation cover, leaving soil exposed to erosion by wind and water. On the Colorado Plateau, researchers measured dust emissions from different vegetation communities. The communities were selected as analogs for vegetation changes expected with increasing aridity. The researchers found that increased temperatures due to climate change will increase wind erosion across the Colorado Plateau, leading to much higher dust emissions in areas with low vegetation cover and low rates of biological soil crust (Munson et al., 2011). The dust can move large distances, and can readily be blown onto areas of mountain snow, changing snowfield albedo (reflectivity) and thereby helping to accelerate spring snowmelt (Seager and Vecchi, 2010). The authors of this study performed an analysis of 15 coupled climate models that demonstrated a reduction of winter season precipitation coupled with warming, which is causing a decline in mountain snow mass and an advance in the timing of spring snow melt. The arid regions of the southwest are a major dust source and projected drying could lead to increased dust deposition that will exacerbate the snowpack reduction driven by temperature increases and thus can affect changes in spring runoff and water supply reservoirs. Statistical significance was not discussed in this study.

The third NCA report (Garfin et al., 2014) presents observed streamflow changes for the southwest U.S. and includes a portion of the Rio Grande Region. Over the past 50 years, there has been a reduction in the amount of snow measured on April 1 as a proportion of the precipitation falling in the corresponding water-year (October to September), which affects the

timing of snowfed rivers. The implication of this finding is that the lower the proportion of April 1st SWE to the water-year-to-date precipitation, the more rapid the runoff, and the earlier the timing of center-of-mass of streamflow in snowfed rivers. Other studies have resulted in similar conclusions. The observational record of 1948 – 2002 reveals a steady advance in the initiation of snowmelt across a network of streamflow gages in the western United States and across the Rio Grande Region (Stewart et al., 2005). The data show earlier beginning (spring pulse onset) of snowmelt and advances in the center of mass of the annual hydrograph (peak spring runoff) by one to three weeks (90% C.I.).

In another study evaluating the shifts in snowmelt-dominated areas, Fritz et al. (2011) split the observational period of 61 years into two periods and compared the percentage of snowmelt runoff pulses (i.e., the center of mass of flow-weighted timing). The results corroborated the Stewart et al. (2005) study and identified a similar (i.e., earlier) onset of streamflows in the region. Statistical significance was not discussed in the study.

Key point: An overall decreasing trend is identified based on this region's streamflow and related snowmelt data with some uncertainty in seasonal trends. Additionally, there is consensus that an earlier onset of snowmelt-driven streamflow has been observed.

2.4. Summary of Observed Climate Findings

Mountain climates are complex and may vary over short distances due to aspect and topographical differences, which influence temperature and precipitation. The variation across the Rio Grande Region, in environment/habitat, elevation, and topography, may lead to a variety of conclusions with regards to observed climate variables. These complexities may lead to some locations within each dataset to exhibit trends that are different the rest of the sites, and they may reflect real, local climate differences (Reclamation, 2013). In addition, some observed temperature and precipitation studies are based on low elevation datasets and may underestimate changes at higher-altitude critical locations and thus, water supplies.

Evidence has been presented in the recent literature of a relatively steady rise in annual temperature in the Rio Grande Region beginning in the early 20th century. An increasing trend was observed in mean, minimum, and maximum temperatures, although this trend was less pronounced during the observed fall and winter seasons. Spatial variation, differences in climate and elevation contribute to some variation in results. The consensus view is that recent increases in temperature in the region exceed observations in the historic record beginning in the late 19th century. Temperature increases were greater in areas to the south and at lower elevation. Increases in minimum temperatures coupled with potential decreases in precipitation are important because these two factor contribute to a longer growing season and decrease period of snowpack accumulation in winter months (Reclamation, 2013).

Despite recent drought years, no distinguishable trend in precipitation or frequency of extreme events was identified. In the 20th century, the Southwest has experienced dramatic swings in precipitation due to natural cycles in Atlantic and Pacific sea surface temperatures. The authors listed herein provide discussion on seasonal changes, especially changes associated with storm intensity. In addition, the magnitude of change is variable.

A slight decreasing trend is identified based on this region's streamflow and related snowmelt data with variable interpretation of results associated with trends for certain seasons. The slight decreasing trend for runoff and streamflow is likely a result of the variable trends associated with precipitation and an increasing trend in temperatures. Changes to the mainstem of the Rio Grande are more likely to be dominated by changes to snowpack and snowmelt, whereas tributary watersheds may be more sensitive to changes in summer precipitation. Based on the studies that focused on snowpack and snowmelt, there is an implication that precipitation and temperature changes have created an earlier onset of snowmelt-driven streamflows.

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 are actively using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed global climate models (GCMs), are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the Rio Grande 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 water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate a strong consensus in the scientific literature that air temperatures will increase over the next century in the Rio Grande Region. The studies also show that there is a consensus on a small decrease in streamflows within the region. There is much less consensus on the future trending, or lack thereof, in projected changes to precipitation.

3.1. Temperature

GCMs have been used extensively to project future climate conditions across the country. At a national scale, model projections generally show a significant warming trend throughout the 21st century, with a high level of consensus across models and modeling assumptions. There is much less consensus on future patterns of precipitation. Results of studies inclusive of the Rio Grande 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 Rio Grande Region, show a projected increase in winter and spring maximum air temperature of 2.5 – 3.5 ºC (4.5 – 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 2.0 – 4.5 ºC (3.6 – 8.1 ºF) for summer and fall temperatures.

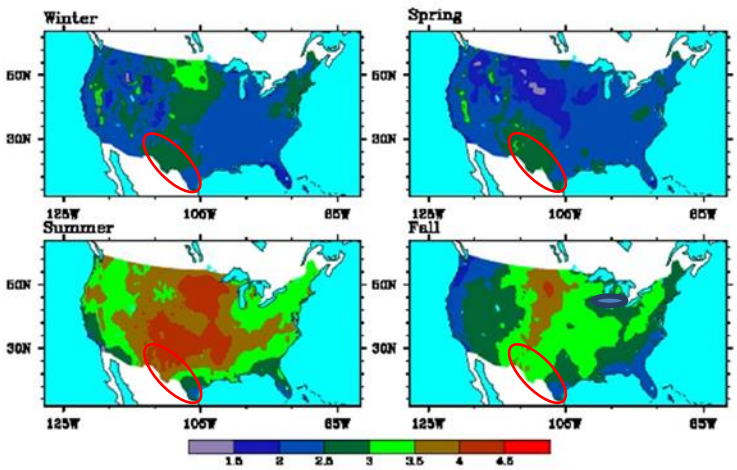


Figure 3.1. Projected changes in seasonal maximum air temperature, ºC, 2055 vs. 1985. The Rio Grande Region is within the red oval (Liu et al., 2013).

Similar results are presented by Scherer and Diffenbaugh (2014). These authors apply a multi-member ensemble GCM, assuming an A1B (middle of the road or "business as usual") emissions scenario, to the continental U.S. For the Southwest and Great Plains region of the country, including the Rio Grande 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 – 5 ºC (7.2 – 9 ºF) in the summer and 3.2 – 3.4 ºC (5.8 – 6.1 ºF) in the winter, compared to a 1980 – 2009 baseline period. These results agree well with those described previously for Liu et al. (2013).

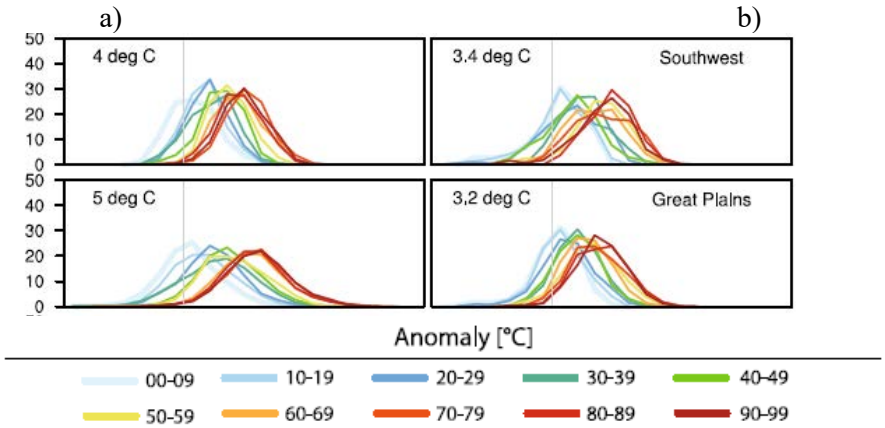


Figure 3.2. Probability distributions of GCM Projections of daily maximum temperatures for Years 2000 – 2100 by decade, Southwest and Great Plains region a) summer months: June – August, b) winter months: December – February. Colors indicate the decade of the 21st century. Probabilities on the vertical 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 Rio Grande Region, results show a shift from semiarid/arid climate type in the latter decades of the 20th century to a much larger proportion of arid climate type areas with some areas remaining warm/hot arid by the period 2041 – 2070 (**Figure 3.3**).

a) Historical observed (1971-2000)

b) GCM projections (2041 – 2070)

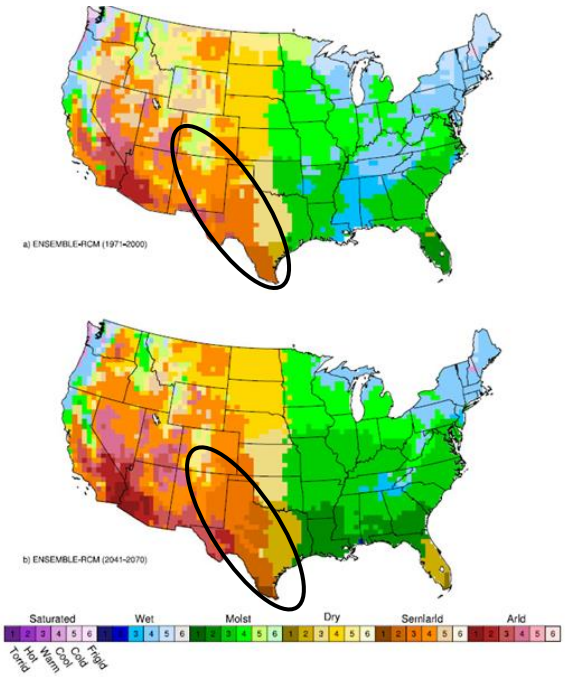


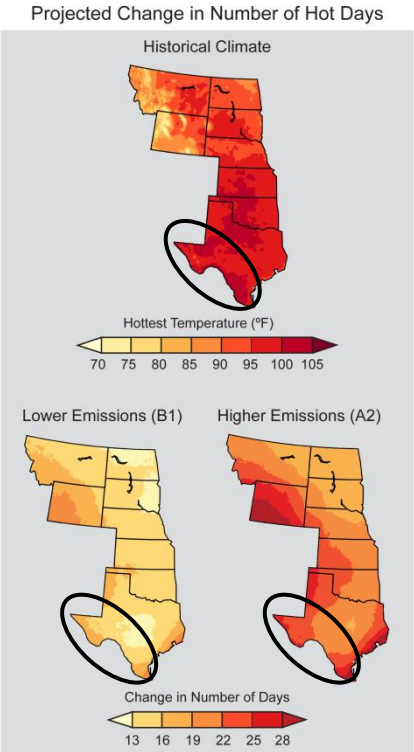
Figure 3.3. Revised Thornthwaite climate types projected by regional climate models. The Rio Grande Region is within the red oval (Elguindi and Grundstein, 2013).

Projections of changes in temperature extremes have been the subject of many 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 region of the southwestern U.S., specifically in the Rio Grande Region, the authors identified a slight increase in the projected extreme temperature range (0.5 ºC [0.9 ºF] range of annual high minus annual low temperature), a moderate increase in a heat wave duration index (increase of 3 to 4 days per year that temperatures continuously exceeds the historical norm by at least 5 ºC [9 ºF]), and an increase in the number of warm nights (6 to 8% 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. The authors state that a general significant increase of heat waves is observed.

Similar results are presented by Kunkel et al. (2010). In this study, two different downscaled GCMs were applied to the continental U.S., assuming high greenhouse gas emissions scenarios (A2 and A1F), with a focus on summer heat wave occurrence and intensity. For the Rio Grande Region, projections indicate a 3 – 6 ºC (5.4 – 10.8 ºF) increase in three-day heat wave temperatures and a 70 to 85-day increase in the annual number of heat wave days for a 2090 planning horizon compared to a recent historical baseline.

The third NCA generally supports the findings above. The NCA presents information on a regional basis. The Rio Grande Region spans two of these regions: the Southwest (Garfin et al., 2014) and Great Plains (Shafer et al., 2014) regions. The U.S. climate model projections presented in this report indicate a statistically significant increase in both the number of extreme heat days over the next century and annual average temperature (**Figure 3.4**).

a) Extreme heat days



b) Changes in average annual temperature

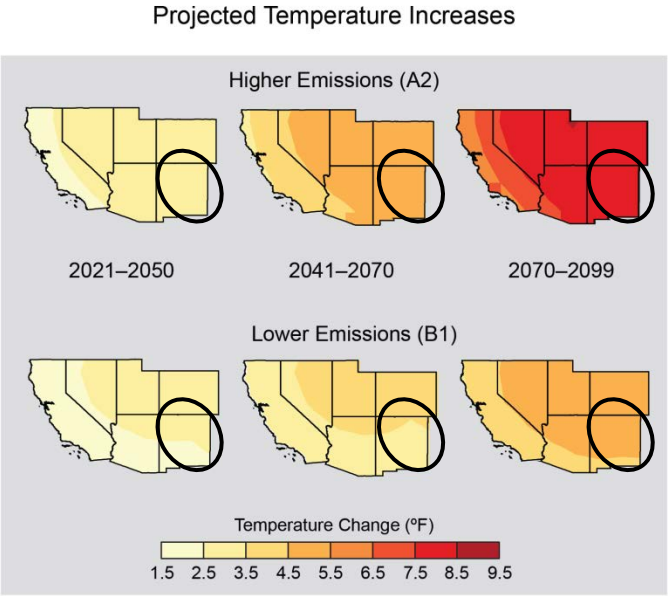


Figure 3.4. GCM projections of change in a) extreme heat days in the Great Plains (Shafer et al., 2014) and b) in average annual temperature in the Southwest (Garfin et al., 2014). The Rio Grande Region is within the black oval.

For the Southwest as a whole, compared to the period 1971 – 2000, models used in the most recent national climate assessment project (Cayan et al., 2013b; USGCRP, 2013):

- Under the low future emissions model scenario (known as B1), there will be an increase of 16 to 19 days hot days while under the higher future emissions model scenario (known as A2), there will be an increase of 19 to 25 hot days.

- For the period 2021 – 2050, warming under the B1 scenario is likely to range from 1 – 3°F (0.6 – 1.7°C) and under the A2 scenario from 2 – 4 °F (1.1 – 2.2 °C).

- For the period 2041 – 2070, warming under the B1 scenario is likely to range from 0.6 – 1.4°F (0.3 – 0.8 °C) and under the A2 scenario from 2 – 6 °F (1.1 – 3.3 °C).

- For the period 2070 – 2099, warming under the B1 scenario is likely to range from 2 – 6°F (1.1 – 3.3 °C) while under the A2 scenario, the projections are 5 – 9 °F (2.8 – 5 °C).

Seasonal differences in warming are likely, although the high variation among models reduces confidence in specific results (Cayan et al., 2013). Increases in summer temperatures are likely to be greater than for other seasons, with mean increases across modeled scenarios around 3.5°F (1.9°C) in 2021 – 2050, 5.5 °F (3.0 °C) in 2041 – 2070, and 9 °F (5 °C) in 2070 – 2099. The least amount of warming is anticipated for the winter months, with an average increase of 2.5°F

(1.4°C) in 2021 – 2050 increasing to almost 3.9°F (1.9°C) in 2070 – 2099. The authors state medium-high confidence for the key findings.

In a 2007 study, Hurd and Coonrod used three global climate models driven by the A1B scenario to model hydrology and streamflow changes for the periods 2020 – 2039 and 2070 – 2089 in the Rio Grande Region. The three models are chosen because one represents a slightly "wetter" projection, one a slightly "drier" projection and one a "middle of the road precipitation" projection. In their models, average annual temperatures increased by 1.7 – 3.2 °F (0.9 – 1.8 °C) by 2030 (**Figure 3.5**) and by 5.5 – 7.9 °F (3.1 – 4.4 °C) by 2080 (**Figure 3.6**). Temperature increases are projected to be greatest in summer under the dry scenario, presumably reflecting changes in summer cloudiness resulting from a reduced monsoon.

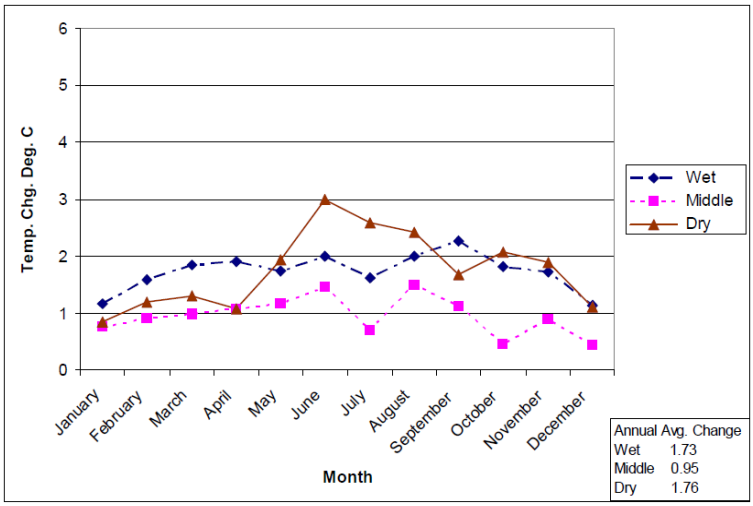


Figure 3.5. Three scenarios for temperature change projected for the Rio Grande Region in 2020 – 2039 (Hurd and Coonrod, 2007).

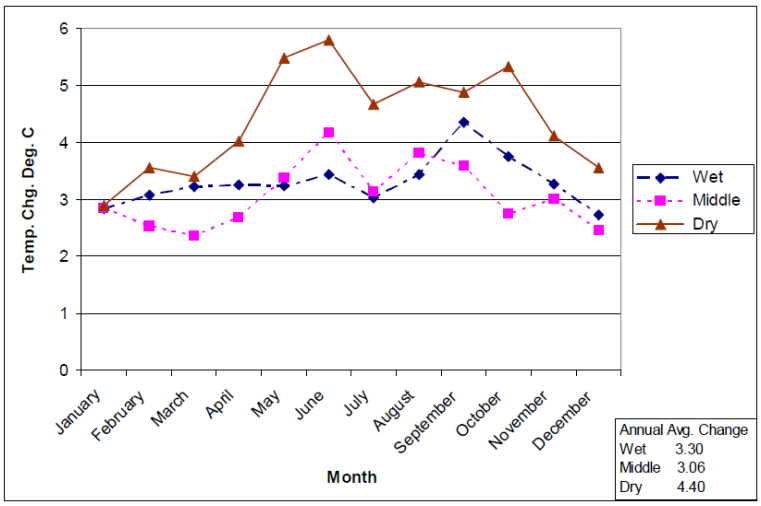


Figure 3.6. Three scenarios for temperature change projected for the Rio Grande Region in 2070 – 2089 (Hurd and Coonrod, 2007).

A relatively fine-grained analysis was recently conducted by NOAA, in support of the National Climate Assessment (NOAA, 2013b), using downscaled Coupled Model Intercomparison Project 3 (CMIP3) models and the more recent North American Regional Climate Change Assessment Program (NARCCAP) models. In maps of average annual temperature change using the CMIP3 multi-model mean simulations, the Upper Rio Grande Region warms 7.5 – 8.5 °F (3.1 – 4.4 °C) by 2070-2099 under the higher emissions (A2) scenario, and 4.5 – 5.5 °F (2.5 – 3.1 °C) by 2070-2099 under the lower emissions (B1) scenario (NOAA, 2013b). These changes are considered significant. In addition, the NARCCAP simulations show that the largest average temperature increases of 5.5 – 6.0 °F (3.1 – 3.3 °C) are likely to occur in summer and to a lesser degree, temperature increases in fall, winter, and spring.

Additional projections of temperature change come from studies focusing specifically on Colorado (Ray et al., 2008) and New Mexico (Gutzler, 2006). Ray et al. also used downscaled, global climate models to project annual mean temperatures. For Colorado as a whole, an increase in annual temperature of 1.5 to 3.5 °F (0.8 – 1.9 °C) by 2025 relative to 1950-1999 average temperatures is expected, with increases of 2.5 – 5.5 °F (1.4 – 3.1°C) expected by 2050. The authors also noted that summer temperatures are anticipated to increase faster than winter temperatures. Gutzler used data from the average of eighteen GCMs forced by the A1B scenario to create a New Mexico statewide average result. The GCM statewide average suggest substantial increases in temperature of over 5.4 °F (3 °C) are far greater than temperature increases experienced during the period of instrumental record by the end of the century. Gutzler reported that in the northern part of New Mexico, model simulations suggested accelerated summertime warming in the future and up to 7.6 °F (4.2 °C) during the summer (**Figure 3.7**).

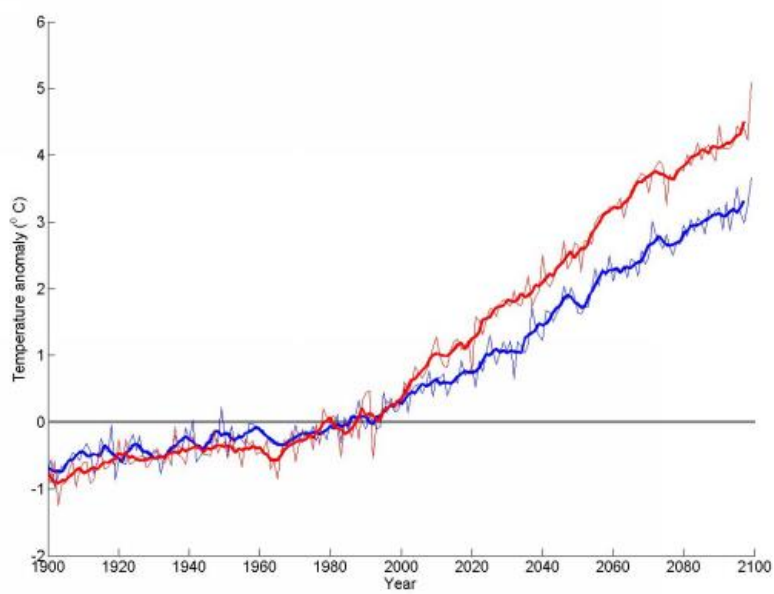


Figure 3.7. GCM projections of seasonal temperature changes in New Mexico in the 21st century for summer (red line; June-August) and winter (blue line; December-February), compared with model climatology (1971-2000) (Gutzler et al., 2006).

For the San Juan Mountains, Cozzetto et al. (2011) used a series of downscaled models driven by the A2 (high emissions) scenario. They compared the average temperatures and precipitation for the baseline period of 1971 to 2000 against the model reference period of 2041 to 2070. In

summer, fall and winter, daytime high temperatures were expected to increase faster than nighttime low temperatures, but the pattern is reversed in the spring (**Table 3.1**).

Table 3.1. Model projections for the San Juan Mountains, average of 2041 to 2070 compared to 1971 to 2000, median values of model runs (Cozzetto et al., 2011).

	Change in T_{max} (°C)	**Change in T_{min} (°C)**	**Change in Precipitation (%)**	**Change in Precipitation (cm)**
Winter	2.5	3.2	4.0	0.5
Spring	2.8	2.5	-5.0	-1.0
Summer	3.7	3.1	-17.0	-2.3
Fall	3.2	2.7	-9.0	-1.3

An increasing trend in average annual temperature was also predicted for the Lower Rio Grande Region. Based on models from the National Center for Atmospheric Research, the average projection is for a mean annual temperature increase of 6 – 8 °F (3.3 – 4.4 °C) by 2100 (Norwine et al., 2007). Statistical significance is not discussed in the study. Another study used a multi-model ensemble (also from the National Center for Atmospheric Research) for the A1B scenario. The authors projected an increase of about 1 °F (0.6 °C) for the period 2000-2019 compared to the 1980 – 1999 baseline period, 2°F (1.1°C) for the period 2020-2039, and close to 4 °F (2.2 °C) for the period 2040 – 2059 (Nielsen-Gammon, 2011). The range of model values for the 2040-2059 is from 2 – 5.5 °F (1.1 – 3.1 °C). Statistical significance is not discussed in the study.

Regional differences in warming are evident in model projections of temperature change for the Great Plains states, including Texas, which show a gradation of change in the Lower Rio Grande, with greater warming in dryer west Texas and less warming in more humid south Texas (NOAA, 2013a). Under the A2 (high emissions) scenario, compared to the baseline 1971-2000 period, the period 2041 – 2070 is projected to be, on average, 4.5 – 5.0 °F (2.5 – 2.8 °C) warmer while coastal south Texas may warm by 3.5 – 4.0 °F (1.9 – 2.2 °C). Seasonal temperature projections (NOAA, 2013a) indicate little difference in winter warming by 3 – 3.5 °F (1.7 – 1.9°C) across the Lower Rio Grande, and similar warming in spring with slightly greater warming in the west. Summer and fall, however, are projected to have much larger contrasts in warming, with west Texas warming by 4.5 – 5.5 °F (2.5 – 3.1 °C) compared to south Texas, which is projected to warm by 4 – 4.5 °F (2.2 – 2.5 °C) during these seasons.

Climate change in the Lower Rio Grande below the Falcon Dam was also modeled by the U.S. Bureau of Reclamation (2013) using the results of 112 gridded climate and hydrology projections developed for the planning year of 2070 with a time span of 2056-2085. The outputs are average monthly precipitation and surface air temperature generated from a suite of 16 CMIP3 models forced by the three Intergovernmental Panel on Climate Change (IPCC) future greenhouse gas emissions scenarios (A2, A1B, and B1). The baseline period for comparison is the 1990s. The spatial resolution of the model is approximately 12 x 12 kilometers. Projections from the Variable Infiltration Capacity (VIC) model were used to predict climate factors. The spatial plots (**Figure 3.8**) are developed on a water year basis for the reference decade (1990s) and the mean annual temperature is calculated for each of the 10 water years. The mean annual temperature is then subsequently averaged to calculate the decadal average of the mean annual temperature to determine the magnitude change. The results show that the Lower Rio Grande is

expected to get hotter through successive decades (2020s, 2050s, and 2070s) than it was in the 1990s reference decade.

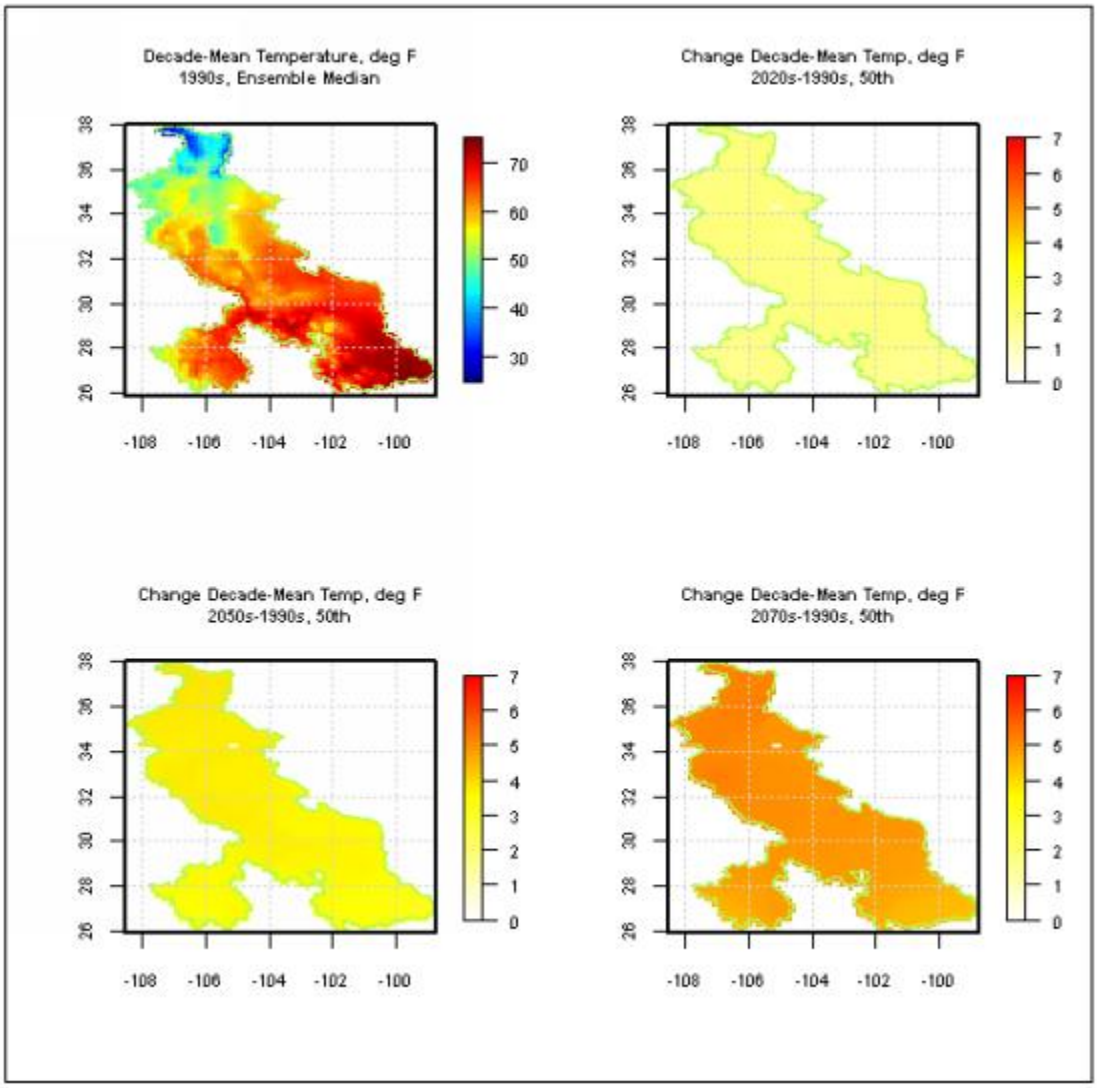


Figure 3.8. Spatial distribution of simulated decadal mean temperatures for the Lower Rio Grande. The vertical axes represent latitude, while the horizontal axes represent longitude. The coloration represents median magnitude change vs. the baseline decade, the 1990s (U.S. Bureau of Reclamation, 2013).

Key point: Strong consensus exists in the literature that projected temperature in the study region show a sharp increasing trend over the next century. There is also consensus that there is a projected increase in overnight temperatures and daytime high temperatures.

3.2. Precipitation

In line with projections for the rest of the country, projections of future changes in precipitation in the Rio Grande 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 decrease in annual precipitation between 80 to 180 mm per year for the Rio Grande Region (**Figure 3.9**).

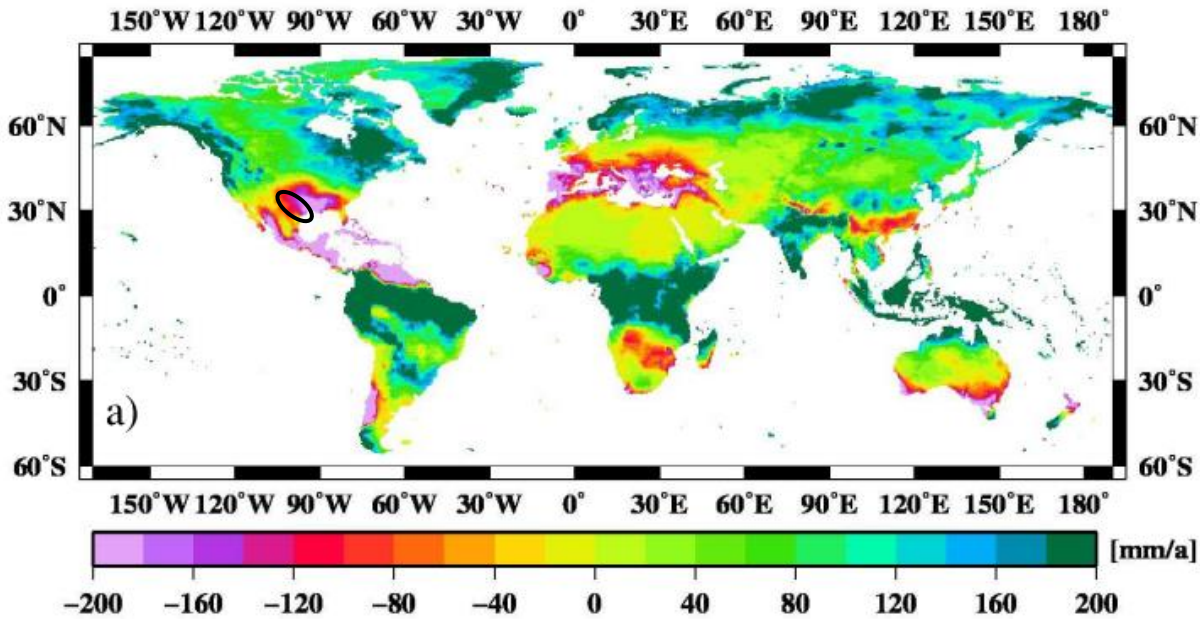


Figure 3.9. Projected (2071-2100) changes in annual precipitation compared to baseline, 1971-2000, conditions, mm/year. The Rio Grande Region is within the black oval (Hagemann et al., 2013)

The Liu et al. study (2013) of the U.S., described above, quantified both slight decreases in winter and spring and increases in summer and fall in precipitation associated with a 2041-2070 planning horizon, relative to a recent historical baseline (1971-2000, centered around 1985), for the southwestern U.S., including the Rio Grande Region (**Figure 3.10**).

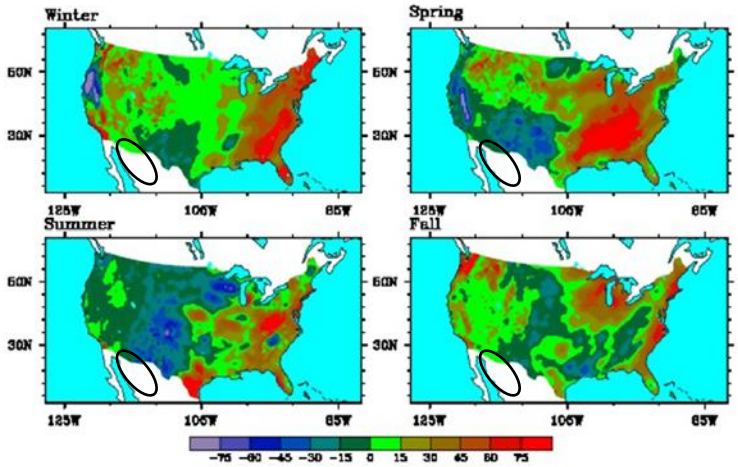


Figure 3.10. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The Rio Grande Region is within the black oval. (Liu et al., 2013).

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 the southwest-south central U.S. and a 2080-2099 planning horizon with historical baseline data (1980-1999). They report slight decreases or no change in the number of high (> 10 mm) precipitation days for the region, a slight increase in the number of storm events greater than the 95th percentile of the historical record, and a slight increase in the daily precipitation intensity index (annual total precipitation divided by number of wet days). In other words, the projections forecast a slight increase in the intensity of storm events by the end of the 21st century for the general study region with spatial variability in the future frequency of such events.

Wang and Zhang (2008) 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 (1 to 2 times) in the recurrence of the current 20-year 24-hour storm event for their future planning horizon (2050-2099) in the Rio Grande Region (**Figure 3.11**).

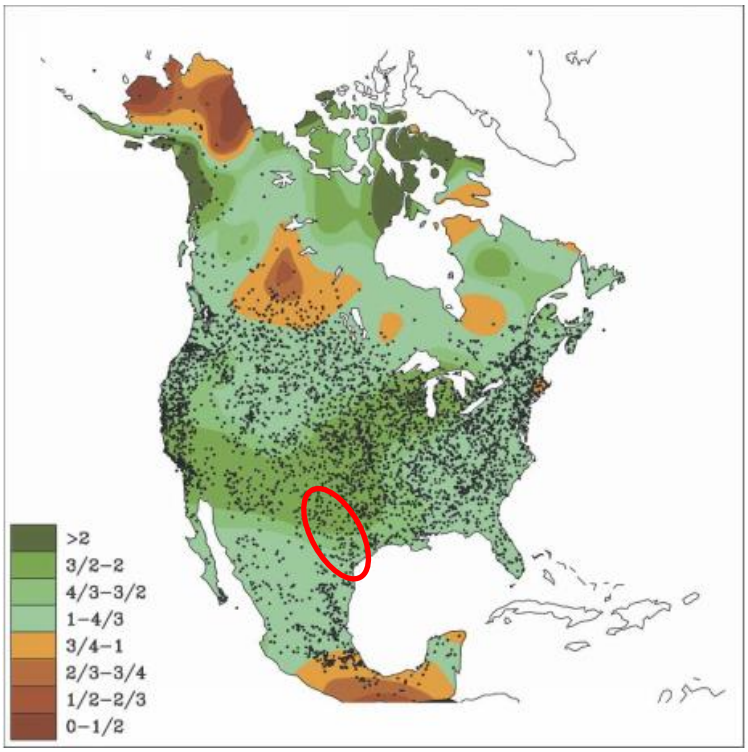


Figure 3.11. Projected risk of current 20-year 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The Rio Grande Region is within the red oval (Wang and Zhang, 2008).

Researchers at the U.S. Global Change Research Program project a 10 to 20% decline in precipitation by 2080-2090 primarily in the winter and spring, resulting from the northward (poleward) shift of mid-latitude winter storm tracks bringing the Southwest into the subtropics year-round. Land and ocean warming should bring more moisture into New Mexico during the summer months, providing stronger monsoons, but this is only projected by some models. The

third NCA (Walsh et al., 2014) reports findings similar to the study above. In winter and spring, the models project a 10 to 20% decline in seasonal precipitation for 2071-2099 (compared to 1970-1999) under the A2 emissions scenario with model agreement that projected changes are significant. Summer and fall had relatively similar changes, but the projections were not consistent among models. In the Southern Great Plains section of the NCA report, a small relative change in precipitation was identified relative to natural variations within the Rio Grande Region (Shafer et al., 2014). In addition, the U.S. climate model projections presented in this report also indicate a statistically significant increase in annual maximum precipitation. The annual maximum precipitation is defined as the average amount of precipitation falling on the wettest day of the year for the period 2070-2099 as compared to 1971-2000 under a scenario that assumes continued emissions increases.

Cook and Seager (2013) analyzed the response of the North American Monsoon (NAM) to increased greenhouse gas forcing using the emissions scenario RCP 8.5 (high greenhouse gas concentration levels) using CMIP5. Changes in total season rainfall are small and insignificant, however, the study concludes there may be a projected shift in seasonality toward delayed onset in the seasonal cycle. By the end of the 21st century, early monsoon season (June-July) precipitation significant declines, a change that is largely balanced by late season (September-October) increases. This shift is likely to have a societal and ecological effect. The Rio Grande Region depends on rainfall during the summer monsoon season to benefit crops and surrounding ecosystems. There are consequences of a delayed seasonal increase in precipitation that may also increase the intensity or frequency of flood events.

In the Upper Rio Grande, projected changes to precipitation have no greater certainty than the projections for the Southwest as a whole. Global climate models driven by the A2 (high emissions) scenario project an annual precipitation decrease in New Mexico by 2100 of 4.8% (**Figure 3.12**), driven mainly by decreases in winter precipitation, but offset slightly by gains in summer precipitation (Gutzler et al., 2006).

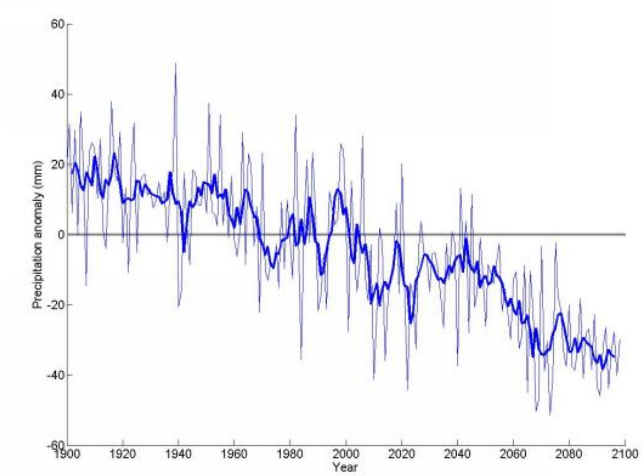


Figure 3.12. GCM projections of annual precipitation changes in New Mexico in the 21st century compared with model climatology (1971-2000) (Gutzler et al., 2006).

In the San Juan Mountains, small gains in winter precipitation are more than offset by declines in precipitation over the remainder of the year (**Table 3.1**, above) (Cozzetto et al., 2011). Hurd and

Coonrod (2012) performed a study evaluating changes in the Upper Rio Grande using data from a suite of GCMs representing the A1B scenario. Model agreement did not exist for mean annual change in precipitation.

Additionally, modeling by the U.S. Bureau of Reclamation for the Lower Rio Grande suggests a gradual decline in precipitation over the region to 2099 (U.S. Bureau of Reclamation, 2013). The range of uncertainty discussed in this report appears to largely be the same over time. Model projections for Texas under the A2 (high emissions) scenario show a drying in west Texas and slight precipitation increase in south Texas for the period 2041-2070 compared to 1971-2000 (NOAA, 2013a). West Texas is drier in all seasons of the year, while extreme south Texas near the mouth of the Rio Grande is drier in winter, spring and summer. Yet, fall precipitation is anticipated to increase between 10 and 15%. However, there was limited model agreement on these changes. Statistical significance was not discussed in the study.

Key point: Little consensus exists among models in projected changes of total annual precipitation in the Rio Grande Region. Some suggest that the precipitation trends will remain unchanged, or will decline slightly over the 21st century. Projected changes in seasonal precipitation are also variable. Precipitation may become more concentrated in larger precipitation events.

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 southeastern 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 3.13**) and for individual Water Resources Regions. For the Rio Grande 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.

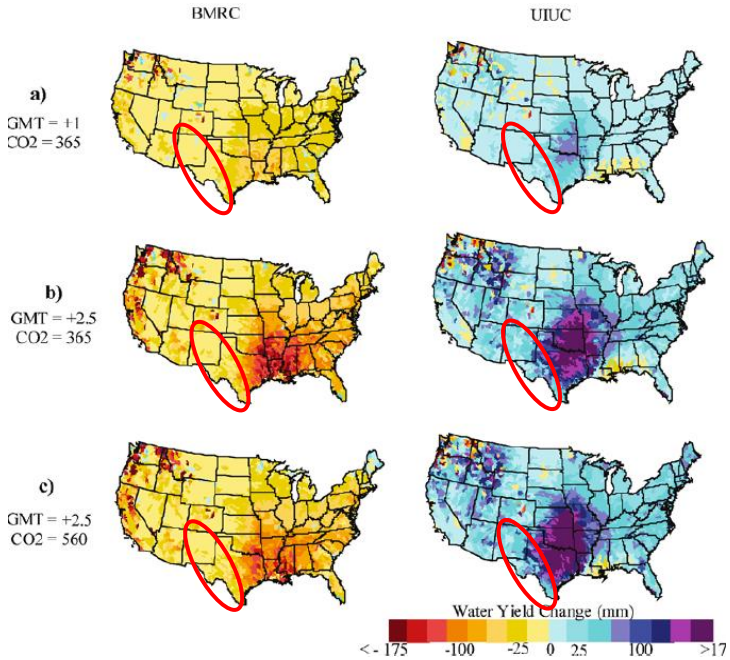


Figure 3.13. Projected change in water yield (from historical baseline), under various climate change scenarios based on 2 GCM projections. The Rio Grande Region is within the red oval (Thomson et al., 2005).

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 Rio Grande Region show an overall decrease in runoff by approximately 20-40 mm per year for their future planning horizon (2071-2100) compared to the recent historical baseline (1971-2000) (**Figure 3.14**), assuming an A2 emissions scenario. Similar changes in seasonal runoff are expected year round (**Figure 3.15**).

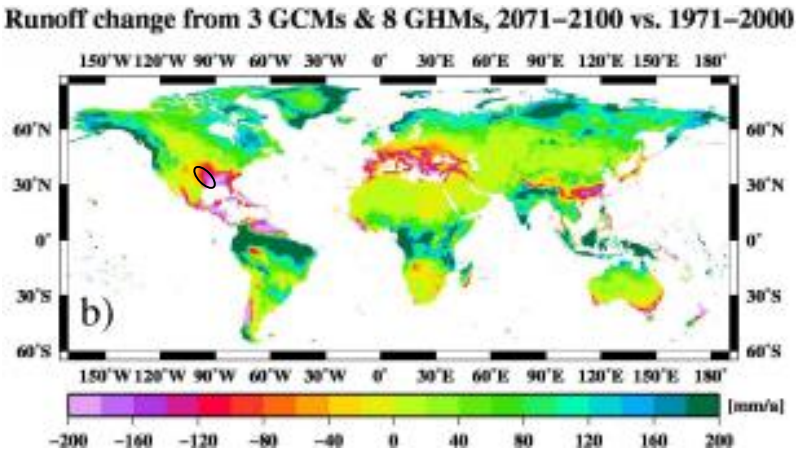


Figure 3.14. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Rio Grande Region is within the black oval (Hagemann et al., 2013).

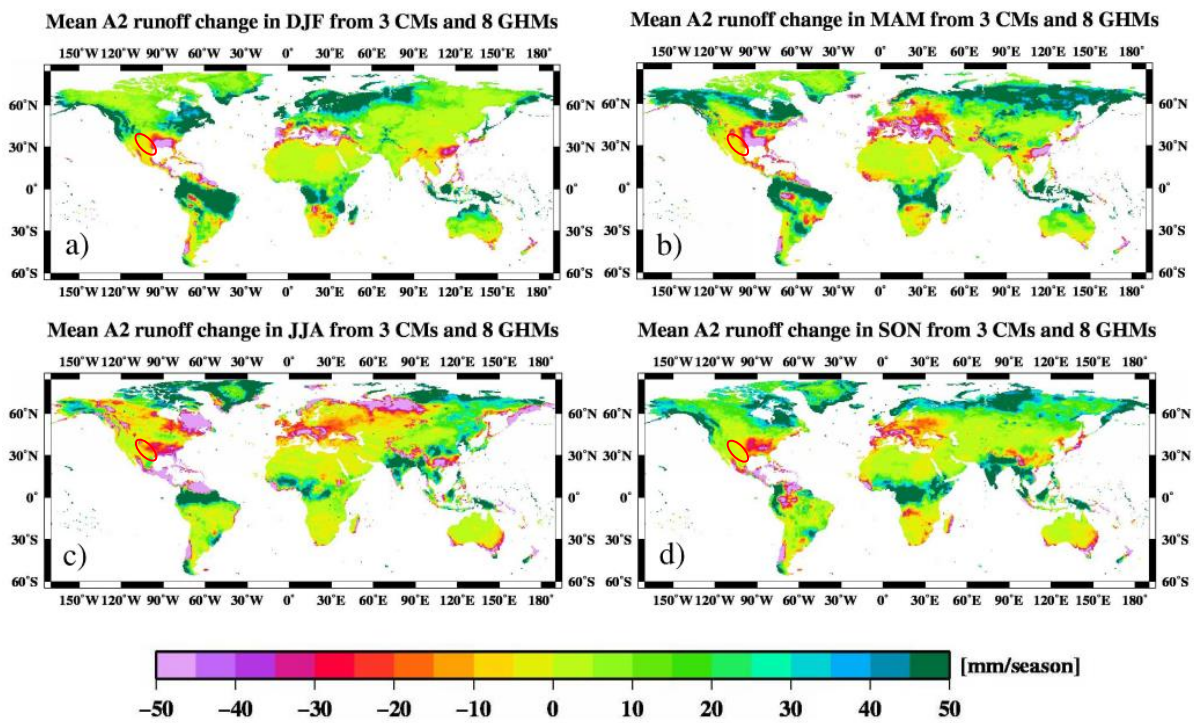


Figure 3.15. Ensemble seasonal (a. winter b. spring c. summer d. fall) mean runoff projections (mm/season) for A2 greenhouse gas emissions scenario, changes in seasonal runoff, 2071-2100 vs 1971-2000. The Rio Grande Region is within the red oval (Hagemann et al., 2013).

In the chapter of the NCA that discusses the southwestern United States (Garfin et al., 2014), a decrease in snowpack is projected in the Rio Grande River headwaters. Decreased snowpack, as measured by SWE, is strongly related to the amount of runoff and associated natural inflows to snowpack supplied rivers such as the Rio Grande River headwaters. Projected SWE for the

Southwestern United States are summarized below (**Figure 3.16**). Each bar chart's size is proportional to the amount of snowfall experienced by each state. On a state-by-state basis, the graphic demonstrates the projected snow water equivalent, and for the Rio Grande Region, with its headwaters in Colorado, where the snow is most likely, snowpack is also expected to decrease in the latter part of the century. Note that the charted summary for New Mexico may also include the Gila and San Juan River Basins.

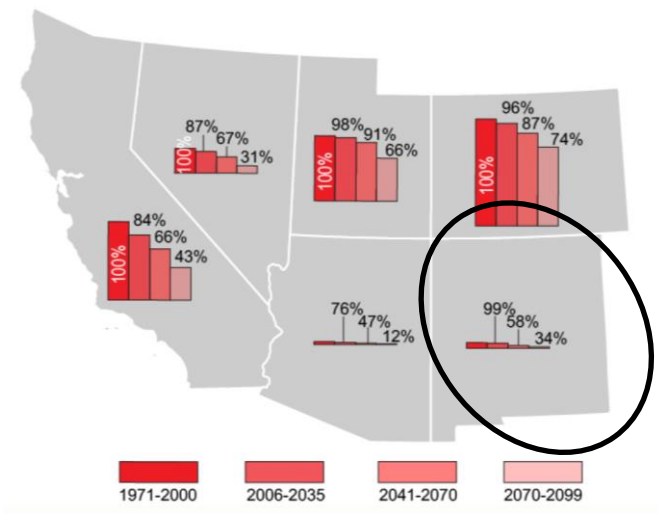


Figure 3.16. Projected snow water equivalent in the southwestern United States. The Rio Grande Region is within the black oval (Garfin et al., 2014).

Since the headwaters of the Rio Grande are located in a region that will likely see no increases in winter precipitation as well as significant declines in precipitation for the rest of the year (USGCRP, 2009), it is probable that projected declines in flow in the Rio Grande will equal or exceed those for the Colorado River (Cayan et al., 2013a). Regional climate models driven by the A2 (high emissions) scenario indicate that the snowpack may be non-existent south of 36°N (approximately the latitude of the City of Española, New Mexico) by 2100 (Gutzler et al., 2006). The same study showed reductions in snow water equivalence of approximately one-third to one-half (approximately 50-200 mm of water) compared to the 1961-1985 average in the San Juan Mountains, which result in reduced spring runoff into rivers and reservoirs by the late 21st century. As stated in the observed climate trend discussion, many of the studies focus on the mainstem of the Rio Grande River. The mainstem is more likely to be affected by changes associated with snowpack and snowmelt whereas smaller, tributary regions are more likely to be affected by changes in summer precipitation and flows.

Reduced flows in the rivers of the Southwestern U.S. are robustly predicted by most models. Flows in the Colorado River are likely to be reduced by 10 to 30% (Barnett and Pierce, 2009). Because of earlier spring snowmelt and higher evaporation rates, it is projected that the total Colorado Basin storage in regional reservoirs could decline by as much as 40% by 2070-2098 (Christensen et al., 2004; Leung et al., 2004). This directly impacts water supply in the Rio Grande because a portion of stream flows in the Upper Rio Grande consists of New Mexico's share of Colorado River water diverted to the Rio Grande through the San Juan-Chama diversion project. In addition, changes in Rio Grande Region flows are likely to be comparable to changes

in the Colorado River, suggesting similar reductions to the regional water supply. Changes in spring runoff have future planning implications for irrigation and water allocations in the Rio Grande Region.

Increased temperatures, greater evapotranspiration, changes in the form and distribution of precipitation across the year are anticipated to reduce stream flows, both spring runoff flows and summer baseline flows. In addition, periods of drought are anticipated to be longer and more severe than observed in the 20th century (Cayan et al., 2010), with average conditions comparable to the drought of the 1950s emerging by the end of the century (Wehner et al., 2011). Changes in ET and soil moisture may cause habitat loss in certain areas.

Average annual runoff is likely to decline by as much as 11-20% in the Upper Rio Grande by the 2070s (Reclamation, 2011) (up to 28.7% in 2080 [Hurd and Coonrod, 2007]), accompanied shifts in the timing of spring runoff to earlier in the year. These declines are likely to be largest during the spring runoff period due to reductions in peak runoff flows, advances in runoff timing, and increased evaporation (Gutzler et al., 2006). Evaporation at reservoirs is likely to be higher under warmer temperatures, accelerating loss of water from the system. In South Texas, reservoir evaporation is projected to be 116% of normal in average years, and 137% of normal in drought years by 2050 (Ward, 2011). Statistical significance was not discussed in this study.

Hurd and Coonrod (2012) performed a study evaluating changes in the Upper Rio Grande using data from a suite of GCMs representing the A1B scenario. They used a conceptual rainfall-runoff model to determine a water balance between surface runoff and sub-surface flow. The authors report that lower runoff totals and a shift toward a greater share of runoff occurs earlier, which reflects both earlier snowmelt, lower snowfall, and diminished snowpack in the headwater regions of the Rio Grande Region. Statistical significance was not discussed in this study.

Recent modeling of flows in the Upper Rio Grande by the U.S. Bureau of Reclamation, USACE, and Sandia National Labs projects that native flows in the Rio Grande are like to decrease by approximately one third by 2100 and peak flows would shift earlier in the year from June to May, with most flow decreases between June and September (U.S. Bureau of Reclamation, 2013).

The third NCA report section discussing water resources (Georgakakos et al., 2014) provides a summary of changes regarding annual and seasonal streamflow projections based on the B1, A1B, and A2 CMIP3 scenarios for the Upper Rio Grande Region. The Rio Grande Region is projected to experience gradual runoff declines during this century with a slight decrease in the winter months and a substantial decrease in the summer months (**Figure 3.17**). Projections are shown for annual, cool, and warm seasons for three future decades (2020s, 2050s, and 2070s) relative to the 1990s.

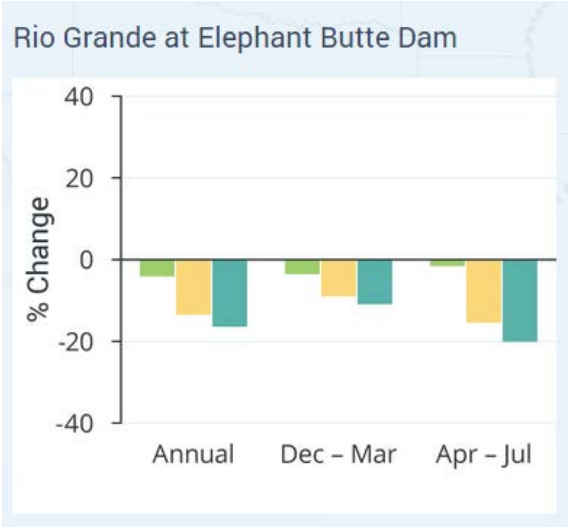


Figure 3.17. Projected change in annual and seasonal average runoff at the Rio Grande at Elephant Butte Dam. The percentage change in average runoff is shown with projected decreases shown below the zero line (Georgakakos et al., 2014).

The U.S. Bureau of Reclamation provides a similar graphic for the Lower Rio Grande for the same representation of change in average annual and seasonal runoff as the third NCA report's graphic for the Upper Rio Grande (**Figure 3.18**) (U.S. Bureau of Reclamation, 2013). The average runoff is calculated for three future decades from the reference 1990s decade. The change in runoff for the 2020s decade is nominal in the Lower Rio Grande, but notable in the 2070s.

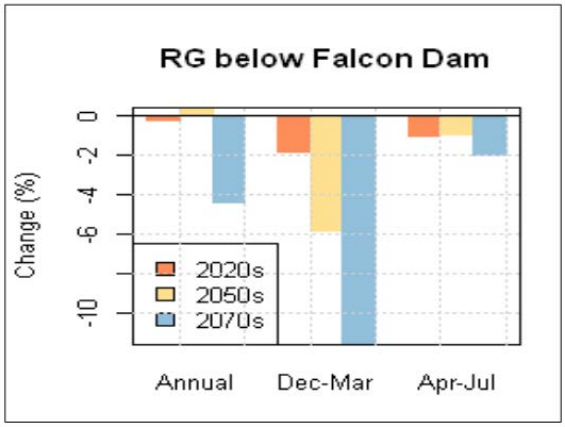


Figure 3.18. Projected change in annual and seasonal average runoff at the Rio Grande at Falcon Dam. The percentage change in average runoff is shown with projected decreases shown below the zero line. Note that the scale of percent change is different than Figure 3.17 (U.S. Bureau of Reclamation, 2013).

Key point: There is a consensus that there is a projected decreasing trend in streamflow for the study region through the next century.

3.4. Summary of Future Climate Projection Findings

As previously mentioned, the Rio Grande Region is characterized by a broad topographical and geographical diversity. This being said, observed and precipitation trend studies are based on low elevation datasets and may underestimate the changes seen at higher altitude locations.

By the end of the century, temperatures in the Upper Rio Grande are anticipated to increase by about 9°F over twentieth century values under high emissions scenarios, and by close to 5.4°F under the B1 (low emissions) scenarios. There is consensus that temperature increases will be greater in summer and fall. Changes in precipitation are likely to affect net warming across the year because evaporation and condensation processes consume energy that would otherwise go to land surface heating, and also indirectly affect warming through the density and composition of vegetation cover and the persistence of snow cover.

Overall, models project that precipitation in the Rio Grande Region will remain unchanged, or will decline slightly over the 21st century. More precipitation likely will fall as rain, less will fall as snow. Precipitation may become more concentrated in larger precipitation events. Projections for precipitation are limited by uncertainties in factors driving variability due to the natural cycles of the ocean surface temperatures. Additional uncertainties arise with respect to the impacts of the loss of Arctic sea ice, the reductions in Northern Hemisphere snow cover, and the poleward expansion of the subtropical dry zone, all three of which appear to be occurring at a rate faster than predicted by current global circulation models. Seasonal and annual drought is anticipated to be a persistent feature of climate across the Rio Grande Region. Temperature driven increases in evaporation are projected to lead to sustained dryer climate conditions, particularly in winter such that the average climate of the southwest by mid-21st century will resemble that found during a multi-year drought today.

The Rio Grande Region is projected to experience gradual runoff declines during this century (Georgakakos et al., 2014). During the winter months, the region will experience little change to slight decreases in runoff. Conversely, the warm season runoff is projected to decrease substantially. Recent modeling of flows in the Upper Rio Grande by the U.S. Bureau of Reclamation, USACE, and Sandia National Labs projects that native flows in the Rio Grande are likely to decrease by approximately one third by 2100 (U.S. Bureau of Reclamation, 2013). The model simulations consistently project decreasing snowpack, an earlier and smaller spring snowmelt runoff, and an increase in the frequency, intensity, and duration of both droughts and floods. Accelerated warming of high-altitude regions is a result that is not captured by GCMs or downscaled models due to the finer spatial scale, but these findings suggest that current models may even underestimate rates of future snowpack loss.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in **Figure 3.19**.

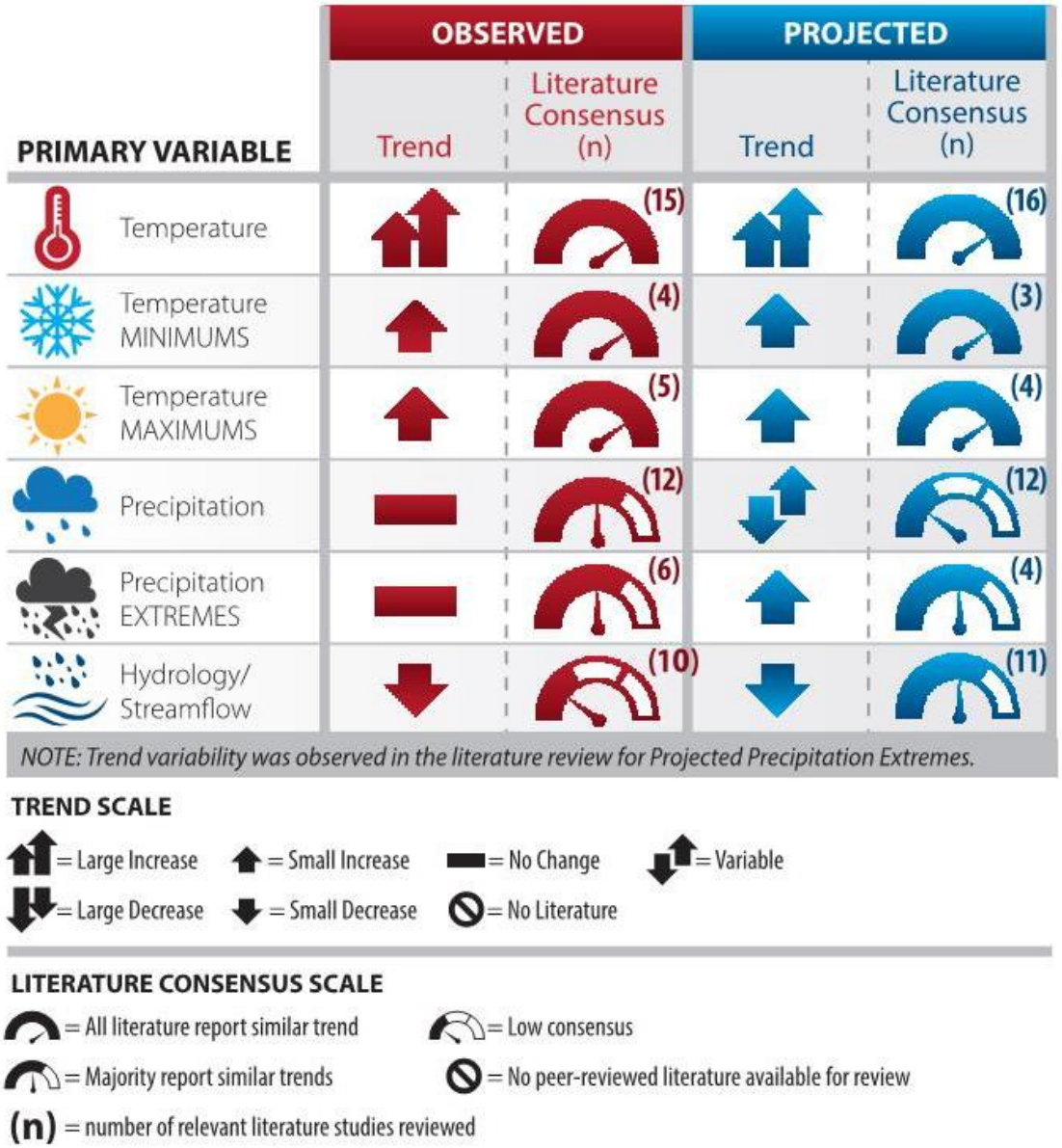


Figure 3.19. Summary matrix of observed and projected climate trends and literary consensus.

4. Business Line Vulnerabilities

The Rio Grande Region encompasses the majority of New Mexico, southern Colorado, and west/southwest Texas above the Rio Grande River. 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
- Hydropower
- Recreation
- Emergency Management
- Regulatory
- Military Programs

USACE implements flood risk management projects in the region to reduce risks associated with flooding. Increased precipitation event intensity 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, and possibly more frequent flood events in the region comparable to the September 2013 flood event.

USACE also maintains and operates several reservoirs 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 Rio Grande 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 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.

The hydropower facilities in the Rio Grande Region at Abiquiu and Elephant Butte Dams may be affected my climate change. Increased air temperatures may cause seasonal drought situations and the streamflow in the region is expected to decrease. This may reduce the amount of electricity that may be generated by the hydropower plants.

Recreational facilities in the Rio Grande 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 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 Rio Grande Region. These types of storms are capable of intense precipitation and winds. Since these may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

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

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services 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 5.4-9°F by the middle of the 21st century. The number and temperature of 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 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. • Implications for the operation of hydropower plants, likely resulting in a decrease in power generation. **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
Cayan DR, Tyree M, Kunkel KE, Castro C, .., Rajagopalan B, Rangwala I, Duffy P (2013a)																X				
Cayan DR, Tyree M, Kunkel KE, Castro C, Gershunov A, .., Rajagopalan B, Rangwala I, Duffy P (2013b)											X	X	X							
Chen G, Tian H, Zhang C, Liu M, Ren W, Zhu W, Chappelka AH, Prior SA, Lockaby GB (2012)				X			X													
Cook BI, Smerdon JE, Seager R, Cook ER (2014)				X			X													
Cozzetto K, Rangwala I, Neff J (2011)											X	X	X	X						
Elguindi N, Grundstein A (2013)											X									X
Fritze H, Stewart IT, Pebesma E (2011)						X														
Garfin GM, Franco G, Blanco H, Comrie AC, Gonzalez T, Piechota T, Smyth R, Waskom R (2014)						X					X					X				
Georgakakos A, Fleming P, Dettinger M, Peters-Lidard TC, Richmond K, White K, Yates D.(2014)																X				
Grundstein A (2009)				X				X												
Grundstein A, Dowd J (2011)		X	X																	
Gutzler DS (2003)				X																
Gutzler DS, Garfin G, Zak B (2006)											X		X	X	X	X				
Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, … , Voss F, Wiltshire AJ (2013)														X		X				
Hirsch RM, Ryberg KR (2011)																X				
Hoerling MP, Dettinger M, Wolter K, Lukas J, Eischeid J, Nemani R, Liebmann B, Kunkel KE (2013)											X		X	X		X				
Hurd BH, Coonrod J (2007)											X									
Hurd BH, Coonrod J (2012)														X		X				
Kalra A, Piechota T, Davies R, Tootle G (2008)						X														
Knowles N, Dettinger MD, Cayan DR (2006)																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																
Liu Y, Goodrick SL, Stanturf JA (2013)													X	X	X					
MacDonald GM (2010)	X			X	X															
McRoberts DB, Nielsen-Gammon JW (2011)				X																
Milly PC, Dunne KA, Vecchia AV (2005)											X									
Mix K, L. LV, Rast W (2012)	X	X	X																	
Nielsen-Gammon J (2001)	X			X																
NOAA (2013a)				X							X	X	X	X						
NOAA (2013b)				X							X	X	X							
Norwine J, Harriss R, Yu J, Tebaldi C, Bingham R (2007)																				
Palecki MA, Angel JR, Hollinger SE (2005)		`			X															
Pryor SC, Howe JA, Kunkel KE (2009)					X															
Rangwala I, Miller JR (2010)	X																			
Ray AJ, Barsugli JJ, Averyt KB, Wolter K, Moerling M, Doesken N, Udall B, Webb RS (2008)	X										X									
Sagarika S, Kalra A, Ahmad S (2014)						X														
Saunders S, Maxwell M (2005)	X																			
Scherer M, Diffenbaugh N (2014)											X	X	X							
Schwartz MD, Ault TR, Betancourt JL (2013)									X											
Shafer M, Ojima D, Antle JM, Kluck D, McPherson RA, Petersen S, Scanlon B, Sherman K (2014)											X		X	X						
Sheppard PR, Comrie AC, Packin GD, Angersbach K, Hughes MK (2002)														X			X			
Stewart IT, Cayan DR, Dettinger MD (2005)																X				
Swetnam TW, Betancourt JL (1998)														X	X					
Tebaldi C (2006)												X	X		X		X			
Tebaldi C, Adams-Smith D, Heller N (2012)	X	X	X																	
Thomson AM, Brown RA, Rosenberg NJ, Srinivasan R, Izaurralde RC (2005)																X				
Reclamation (2011)															X					
Reclamation, USACE, Sandia Labs (2013)											X			X	X					
USGCRP (2009)														X		X				
USGCRP (2013)											X	X	X							
USACE (2013)	X																			
Villarini G, Smith JA, Vecchi GA (2013)				X	X															
Walsh J, Wuebble D, Hayhoe K, Kossin J, Kunkel K, Stephens G, …, Kennedy J, Somerville R (2014)	X			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					
Westby RM, Lee Y-Y, Black RX (2013)	X	X																		

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Cayan DR, Tyree M, Kunkel KE, Castro C, Gershunov A, Barsugli J, Ray AJ, Overpeck JT, Anderson M, Russell J, Rajagopalan B, Rangwala I, Duffy P (2013b) The Southwest climate of the future - projections of mean climate. in Garfin G (ed.) Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. NCA Regional Input Reports. Island Press, Washington, D.C., p. 509.

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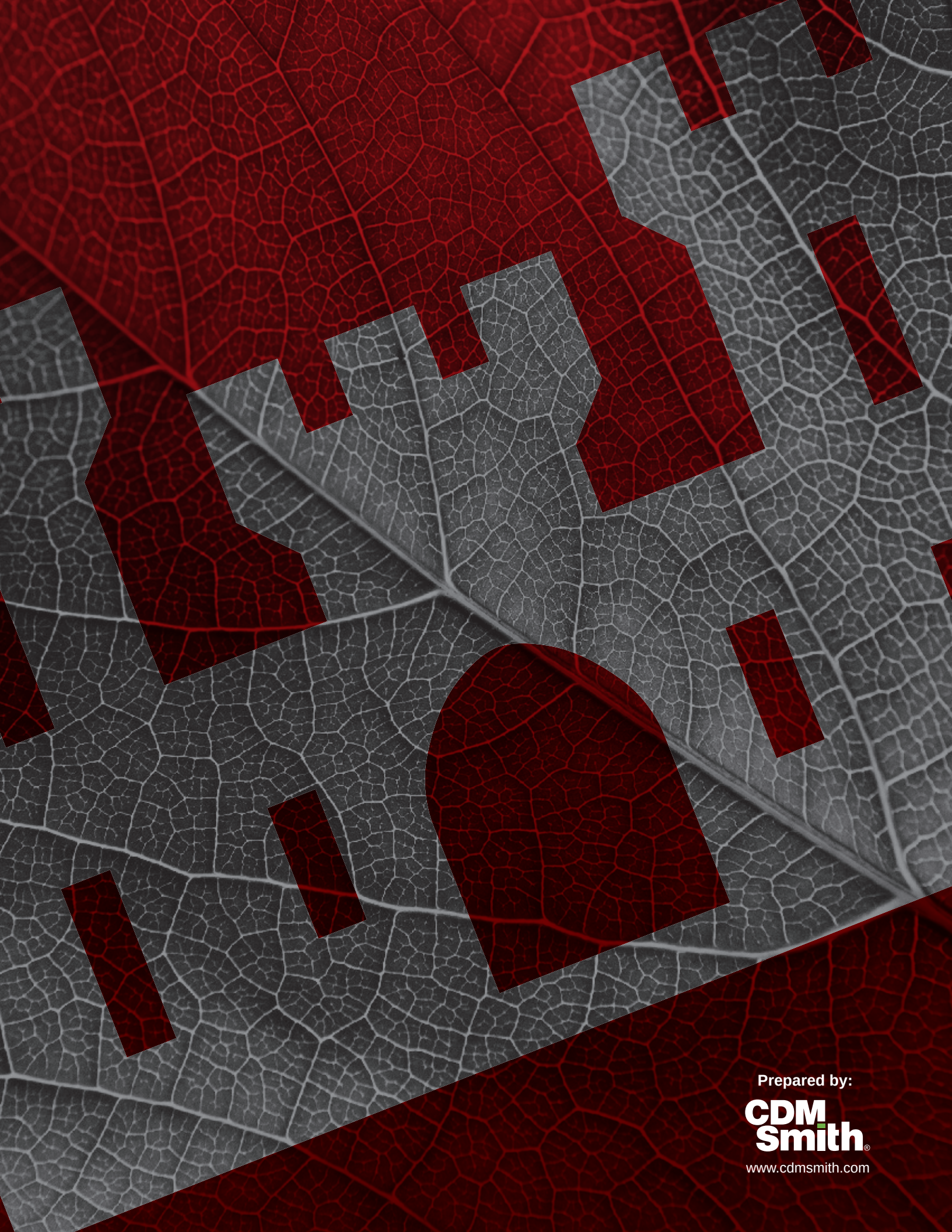

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