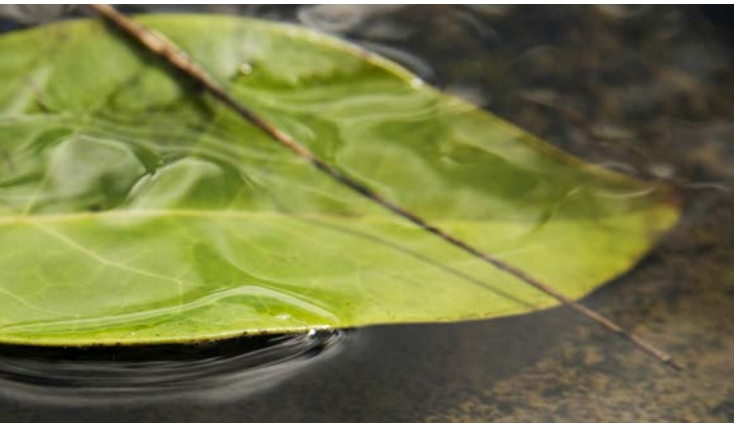

Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

TEXAS-GULF REGION 12

FINAL

May 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

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

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Texas-Gulf Region	Observed Hydrology	Business Line
Water Resources Region 12	Projected Climate	Climate Vulnerability
Observed Climate	Projected Hydrology	Regional Climate Synthesis

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TEXAS-GULF REGION 12

May 5, 2015

CDM Smith
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Water Resources Region 12: Texas-Gulf Region

1. Introduction

U.S. Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the *Response to Climate Change Program* at the scale of 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 12, the Texas-Gulf Region, the boundaries for which are shown in **Figure 1.2**. The Albuquerque, Ft. Worth, Dallas, and Galveston USACE districts each include territory within the region.

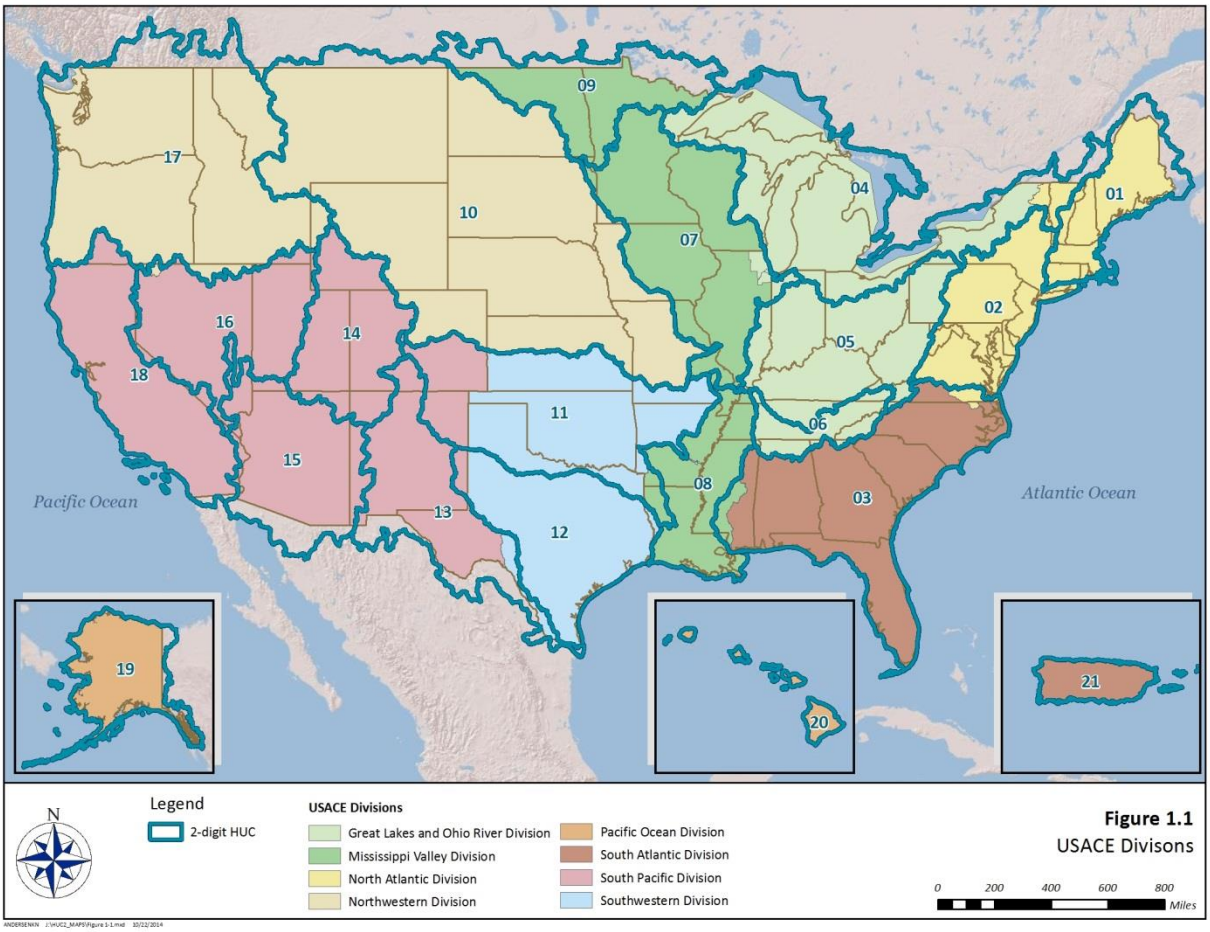


Figure 1.1. 2-digit Hydrologic Unit Code Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.

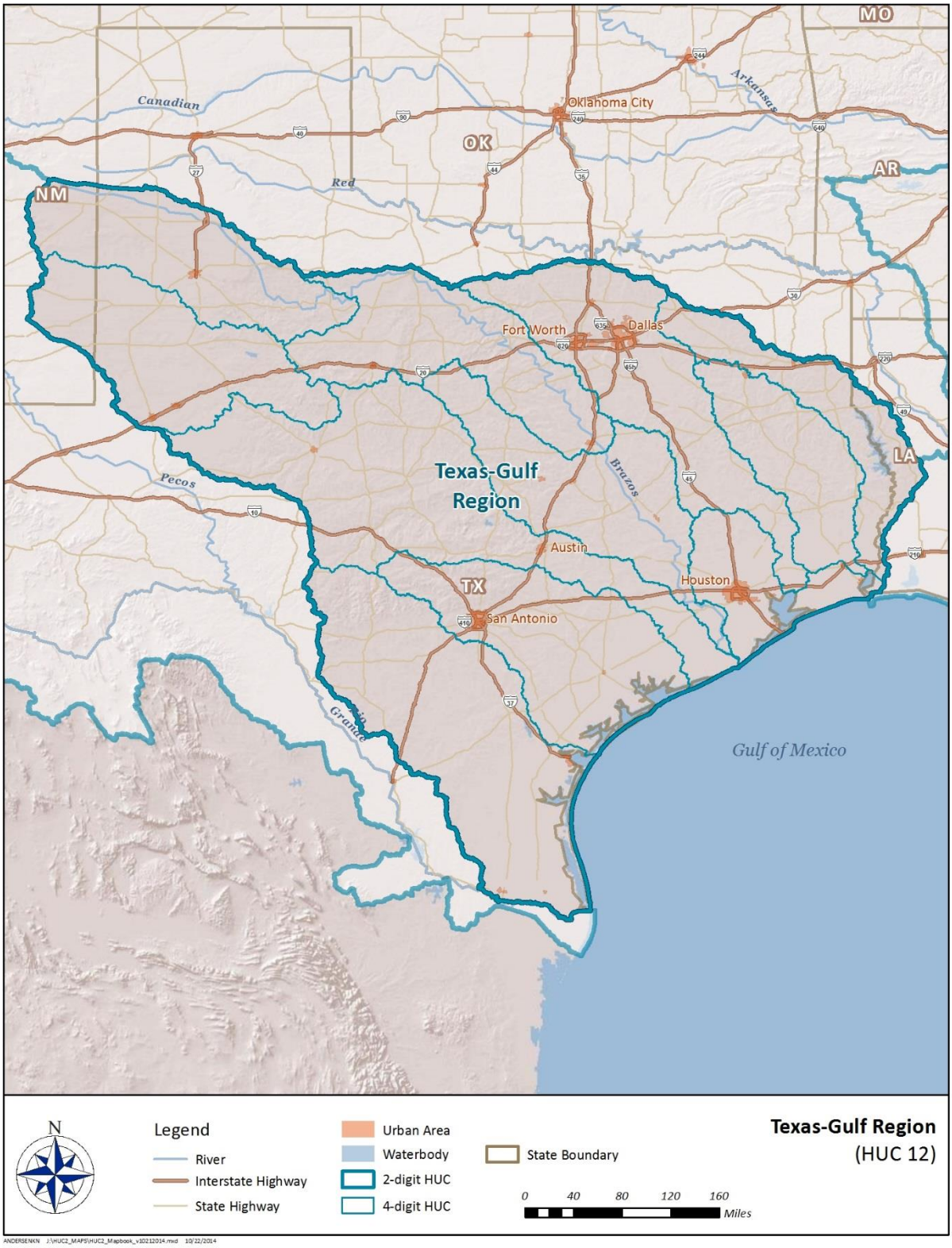


Figure 1.2. Water Resources Region 12: Texas-Gulf Region Boundary.

1.1 A Note on the Water Resources Region Scale

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

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

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

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit USGS 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 scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Region scale both to be guides into the climate change literature and to support the informational analyses USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 12, 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 12 are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014), this section is not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth's climate systems are complex and influenced by multiple natural and

unnatural (i.e. anthropogenic greenhouse gas emissions) forcings. When additional detail is needed, the reader is referred to the specific references cited, including the third National Climate Assessment (NCA) which includes not only regional assessments but also foundational resources related to climate science literacy.

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

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

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

The results presented below indicate mild upward trending in both precipitation and streamflow in the Texas-Gulf Region. There is also a reasonable consensus that air temperatures have not changed significantly in the recent past and in contrast with the rest of the county may actually show a decreasing trend.

2.1. Temperature

Although no studies were found on observed temperature trends specific to the Texas-Gulf Region, a number of regional and national studies on the subject were identified in this review. Results of these national studies relevant to the Texas-Gulf Region are discussed below.

A 2009 study by Wang et al. examined historical climate trends across the continental United States. Gridded (0.5 degrees x 0.5 degrees) mean monthly climate data for the period 1950 – 2000 were used. The focus of this work was on the link between observed seasonality and regionality of trends and sea surface temperature variability. The authors identified positive statistically significant trends in recent observed mean air temperature for most of the U.S. (**Figure 2.1**). For the Texas – Gulf Region, no such trend was detected. In fact a mild cooling trend (or no trend) for most of the water resources region, particularly for the summer months (June – August), is presented. However, the western portion of the water resources region was found to have slight warming trend in the spring (March – May). However, a more recent study by Liu et al. (2012) noted that the cooling trend for their study region (which includes the Texas-Gulf Region along with the Southeast U.S.) appears to end in the mid-1970's and is followed by a warming trend from about 1976 onward.

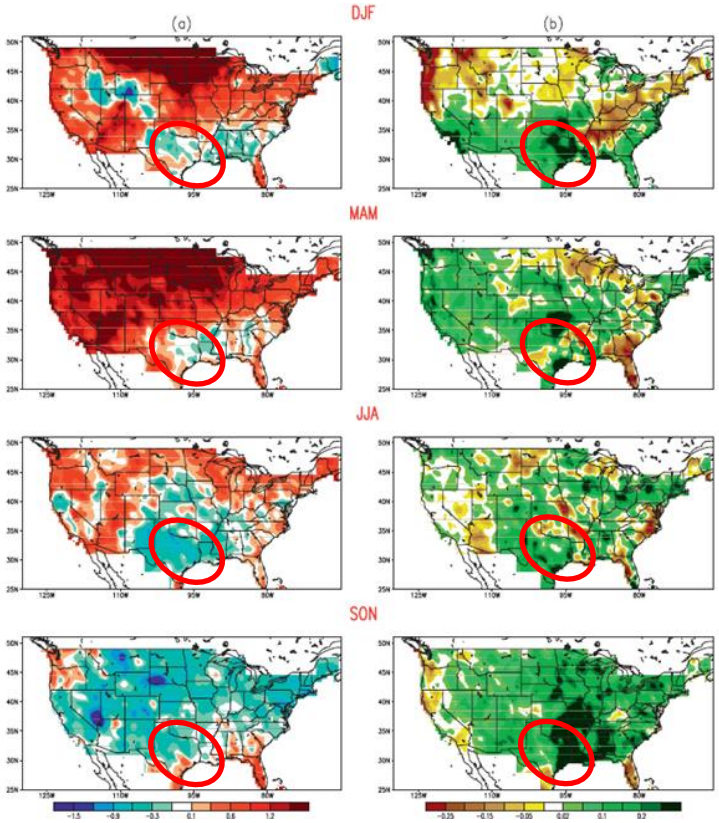


Figure 2.1. Linear trends in (a) surface air temperature and (b) precipitation over the United States, 1950 – 2000. The Texas-Gulf Region is within the red oval (Wang et al., 2009).

Grundstein and Dowd (2011) investigated trends in one day extreme maximum and minimum temperatures across the continental U.S. based on daily temperature data compiled by the National Climatic Data Center (NCDC) for 187 stations across the country for the period 1949 - 2010. For the Texas-Gulf Region, they found a statistically significant increasing trend in the number of one day extreme minimum temperatures and the number of one day extreme maximum temperatures. The authors also compared trends based on a dataset containing years 1949-2010 and a dataset containing years 1949-1995. Trends for extreme maximum temperature were found to be more prevalent and bigger in magnitude for the dataset containing years 1949-2010. This examination of extreme temperatures contrasts with the findings of Wang et al. (2009) and Westby et al. (2013) which evaluated seasonal mean temperatures and presented observed cooling trends for the region.

In support of the recently released third NCA, Kunkel et al. (2013) summarized historical climate trends for the Great Plains region which is inclusive of Texas-Gulf Region in its southern extent. The NCA defines the Great Plains as the states of Montana, North Dakota, South Dakota, Wyoming, Nebraska, Kansas, Oklahoma, and Texas. For this region as a whole historical data shows that annual temperatures over the past 20-years have been above average when compared to a baseline period of 1901 to 1960 (Kunkel et al., 2013). The authors specifically quantified a statistically significant (95% confidence level) increasing trend of 0.09°F per decade in the Southern Great Plains (including the Texas-Gulf Region) using data from 1895-2011.

Schwartz et al. (2013) investigated changes in spring onset for the continental U.S. Their particular focus was on changes in the seasonality of plant growth as dictated by changing temperature regimes. The authors used historical data from over 22,000 stations across the United States, obtained from the NCDC with periods of record extending through 2010. Their findings indicate that for the Texas-Gulf Region, spring onset is generally occurring at least a few days later for the current period (2001 – 2010) compared to an earlier baseline reference decade (1951 – 1960) (**Figure 2.2**). Though, a select number of locations are showing an earlier spring onset of a few days. In other words, an apparent small shift in seasons has been identified for the Texas-Gulf Region, with spring warming generally occurring later than in the past for post locations. These findings are in general agreement with the findings of Wang et al. (2009) and Westby et al. (2013).

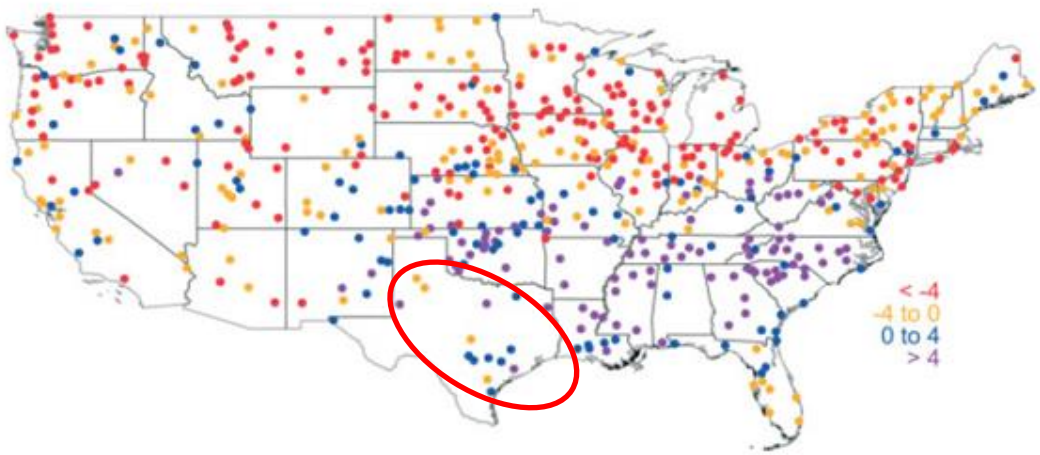


Figure 2.2. Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The Texas-Gulf Region is within the red oval (Schwartz et al., 2013).

Key point: A slightly decreasing trend in observed mean air temperature in the Texas-Gulf Region was identified, though consensus regarding this trend is relatively low. Extreme temperatures were found to be trending upwards among the few available studies on this subject in the region.

2.2. Precipitation

Palecki et al. (2005) examined historical precipitation data from across the continental United States. They quantified trends in precipitation for the period 1972 to 2002 using NCDC 15-minute rainfall data. For inland study regions that include a portion of the Texas-Gulf Region, statistically significant decreases in summer storm intensity (mm per hour) and fall storm duration were identified. Additionally, statistically significant decreases in summer 15-minute maximum intensity and increases in winter 15-minute maximum intensity were observed. For the study area inclusive of the northern gulf region (i.e. Houston), the authors found a statistically significant increase in fall storm total precipitation and winter storm intensity. In other words, the authors generally found statistically significant decreasing trends in storm intensities and duration for the study areas inclusive of the inland Texas-Gulf Region and increasing trends in total precipitation and intensity for the coastal areas.

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 Texas-Gulf Region, the authors identified a moderate to significant increasing trend in precipitation, particularly in coastal areas of the Texas-Gulf Region (**Figure 2.1**).

A 2011 study by McRoberts and Nielsen-Gammon used a new continuous and homogenous data set to perform precipitation trend analyses for sub-basins across the United States. The extended data period used for the analysis was 1895 – 2009. Linear positive trends in annual precipitation were identified for most of the U.S., including the Texas-Gulf Region (**Figure 2.3**). For this region, the trend in annual precipitation indicates an increase on the order of 2 – 15% per century.

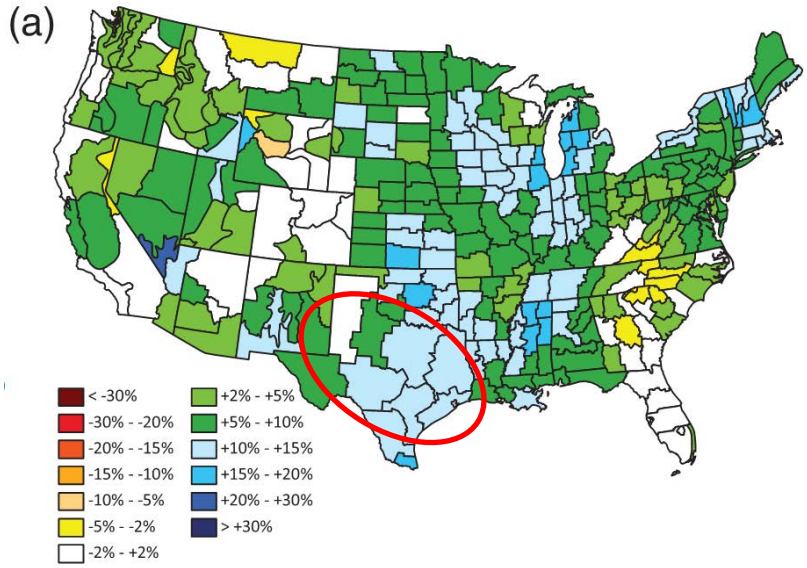


Figure 2.3. Linear trends in annual precipitation, 1895 – 2009, represented as a percent change per century. The Texas-Gulf Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

Changes in extreme precipitation events observed in recent historical data have been the focus of a number of studies. Studies of extreme events have focused on intensity, frequency, and/or duration of such events. Wang and Zhang (2008) used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. Statistically significant increases in the frequency of the 20-year storm event were quantified across the southern and central U.S., in both the recent historical data and the long term future projections (described below). For the Texas-Gulf Region, significant changes in the recurrence of this storm were identified for the period 1977 to 1999 compared to the period 1949 to 1976. An increase in frequency of approximately 33 – 100% was quantified.

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 Texas-Gulf Region, the analysis showed generally increasing, and statistically significant, trends in total annual precipitation and the number of precipitation days per year (**Figure 2.4**). However, contrasting trends (both decreasing and increasing) were identified for precipitation intensity associated with extreme events (e.g. 90th percentile precipitation days). Generally, extreme precipitation event trends were found to be slightly increasing for the coastal areas and slightly decreasing for the inland areas of the Texas-Gulf Region. The authors note that the trends identified are not necessarily linear, with an apparent increase in the rate of change in the latter part of the century for most of the trends. These trends were determined to be significant at the 90% confidence interval.

a)annual precipitation

b) 90th percentile daily precipitation

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

d) number of precipitation days per year

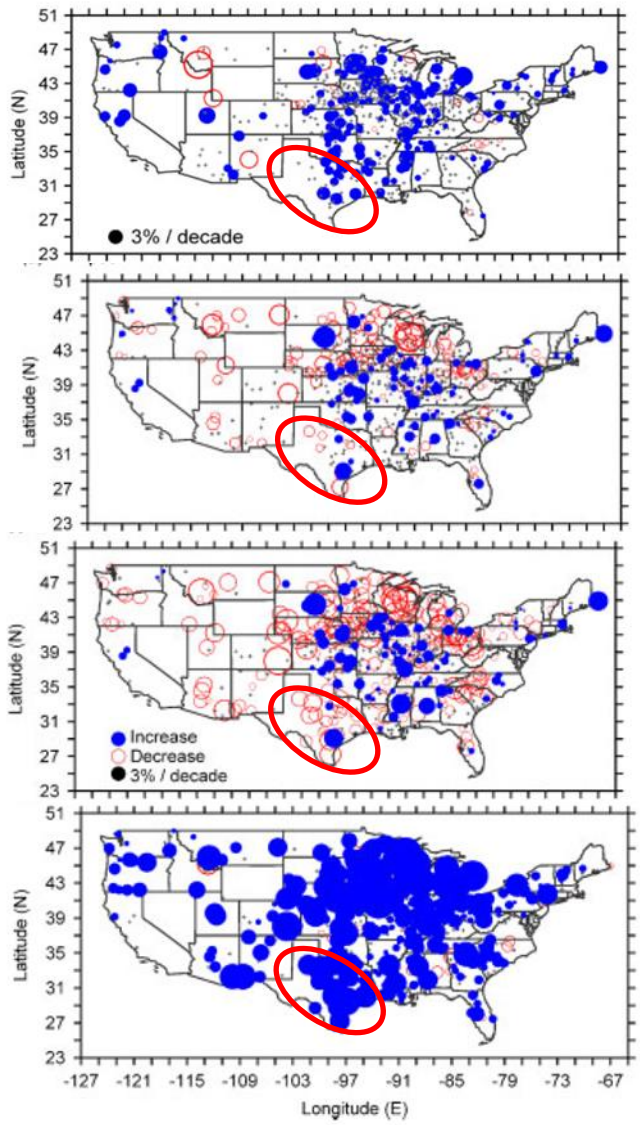


Figure 2.4. Historical precipitation trends in the 20th century. a.) annual totals, b.) 90th percentile daily, c.) precipitation intensity (annual total/number of precipitation days), and .d) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The Texas Gulf Region is within the red oval (Pryor et al., 2009).

2.3. Hydrology

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

Mauget (2004) analyzed 42 daily streamflow gages throughout the U.S., three of which are located within the Texas-Gulf Region (Brazos River, Guadalupe River, and Frio River). The authors quantified a significant increase in surplus flow days and a decrease in drought incidence in the Guadalupe and Frio Rivers for the latter part of the record compared to earlier years. The Brazos River was observed to have slightly decreasing surplus days and slightly increasing drought incidences for the latter part of the record compared to earlier years. Xu et al. (2013) identified similar hydrologic trends for multiple stream gages in the Texas Gulf Region. This study used the Model Parameter Estimation Experiment (MOPEX) data set for the period 1950 to 2000. Additional information on the MOPEX can be found in Duan et al. (2006). Statistically significant positive trends in both annual streamflow and baseflow were identified for a small number of stations within the region. It should be noted that the majority of the Texas-Gulf Region stations included in the study showed no significant trends in streamflow. These authors attribute the observed trends to a combination of climate change and human landscape impacts.

In general agreement with the findings described above, Kalra et al. (2008) found increasing trends in streamflow for unimpaired gages located throughout the Texas-Gulf Region for the period 1951 to 2002. These authors looked at both annual total flows and seasonal flows (spring/summer vs. fall/winter). Increasing trends were observed for the water year (October – September) as well as the fall/winter season. No trend was observed in the spring/summer season.

Villarini et al. (2013) evaluated annual maximum peak discharge for 62 stations within Texas. The authors tested the stationarity assumption utilizing statistical techniques on the historical data set in order to assess abrupt and gradual changes. The results of this analysis showed that trends in maximum streamflow were primarily due to abrupt changes caused by river regulation (e.g. construction of dams).

Key point: A mild upward trend in mean streamflow in the study region has been identified by multiple authors but a clear consensus is lacking.

2.4. Summary of Observed Climate Findings

The general consensus in the recent literature points toward mild increases in annual precipitation and streamflow in the Texas-Gulf Region over the past century. In some studies, and some locations, statistically significant trends have been quantified. In other studies and locales within the region, apparent trends are merely observed graphically but not statistically quantified. Some evidence has been presented of increased frequency in the occurrence of extreme storm events Wang and Zhang (2008). However, in the literature, observed precipitation extremes were found to have spatial variability. The inland portion of Texas-Gulf Region generally showed decreasing trends while the coastal portion of the Texas-Gulf Region generally showed increasing trends for observed precipitation extremes.

In contrast to most of the rest of the country, there is little evidence of increasing mean air temperature trends in the study region. However, there is some evidence of changes in the frequency or intensity of extreme temperature events (Grundstein and Dowd, 2011) in the region.

3. Projected Climate Trends

While historical data is essential in understanding current and future climate, nonstationarity in the data (i.e. a changing climate) dictates the use of supplemental information in long term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2008). Consequently, the scientific and engineering communities have begun using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. While significant uncertainties are inherent in these model projections, the models, termed global climate models (GCMs), are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the Texas-Gulf Region identified in a review of recent peer-reviewed literature. The information presented should be considered an overview and, similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth's climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of "climate futures" so each study's assumed emission scenario(s) are noted. When additional detail is needed the reader is referred to the specific references cited, including the third NCA which includes not only regional assessments, but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

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

Results of this review indicate a strong consensus in the scientific literature that air temperatures will trend sharply upward over the next century in the Texas-Gulf Region. There is much less consensus on the future trending, or lack thereof, of total precipitation, although many studies agree that storm intensity and extended drought conditions will both likely trend upward in the future. A limited number of hydrologic projections for the region generally indicate downward

trends in future streamflow, due largely to increased evapotranspiration as a function of rising temperatures.

3.1. Temperature

GCMs have been used extensively to project future climate conditions across the country. At a national scale, model projections generally show a significant warming trend throughout the 21st century, with a high level of consensus across models and modeling assumptions. There is much less consensus on future patterns of precipitation. Results of studies inclusive of the Texas-Gulf Region typically fall in line with both of these generalizations. Spears et al. (2013) states that, for the Great Plains Region (which includes the Texas-Gulf Region); confidence in future temperature projections is much higher than that for precipitation projections.

Maximum air temperature projections were investigated by Liu et al. (2013) using a single GCM and assuming an A2 greenhouse gas emissions scenario (worst case). The results of their study, specific to the Texas-Gulf Region, show a projected increase in maximum air temperature of 2 to 5 ºC for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (**Figure 3.1**). They also project an increase in the Keetch Byrum Drought Index (KBDI), a measure of soil moisture deficit, for the Texas-Gulf Region.

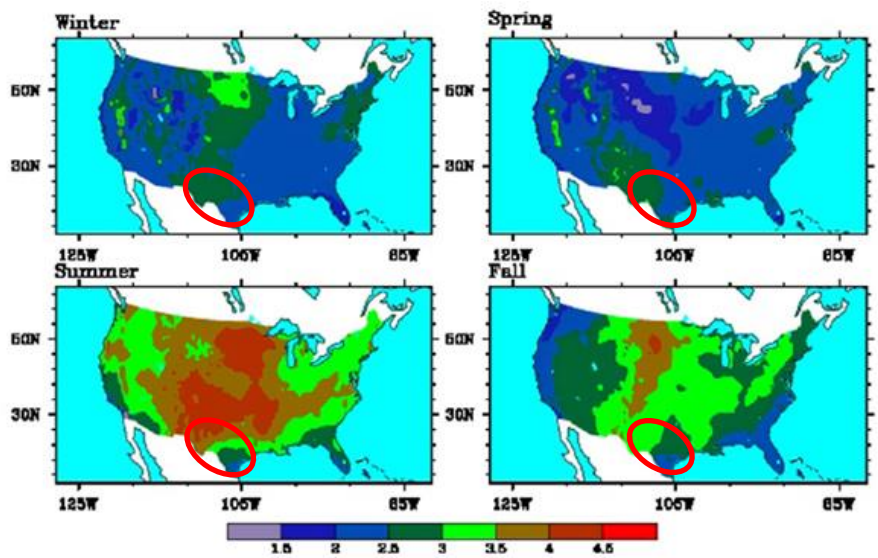


Figure 3.1. Projected changes in seasonal maximum air temperature, ºC, 2041 – 2070 vs. 1971 – 2000. The Texas-Gulf Region is within the red oval. (Liu et al., 2013).

Similar results are presented by Ashfaq et al. (2010) and Scherer and Diffenbaugh (2014). The first set of authors apply a single regional climate model to project future climate change across the continental U.S. In comparing future projections (2071 – 2100) to historical climate (1961 – 1990), they quantify changes in summer daily maximum temperature of 4 to 6 ºK for the Texas-Gulf Region. Projected changes in winter daily maximum temperatures for the region range from 3 to 4 ºK. The second set of authors apply a multi-member ensemble GCM, assuming an A1B (middle of the road) emissions scenario, to the continental U.S. For the Great Plains region of the country, including the Texas-Gulf 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 5 ºC in the summer and 3.2 ºC in the winter, compared to a 1980 – 2009 baseline period. These results agree well with those described previously for Liu et al. (2013).

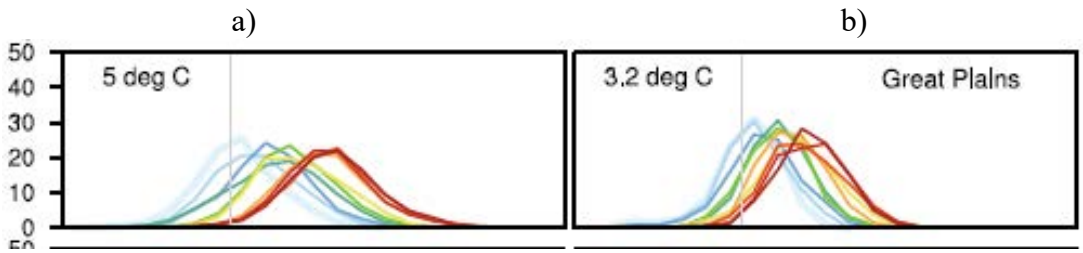


Figure 3.2. Probability distributions of GCM Projections of daily maximum temperatures for Years 2000 – 2100 by decade, Great Plains region (a. summer months: Jun – Aug, b. winter months: Dec – Feb). Colors indicate different decades of the 21st century. Probabilities on the vertical axis are in the 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 Texas-Gulf Region, results show a shift from mostly warm dry or warm semi-arid climate type in the latter decades of the 20th century to a hot dry or semi-arid climate type by the period 2041 - 2070 (**Figure 3.3**).

a) historical observed (1971 – 2000)

b) GCM projections (2041 – 2070)

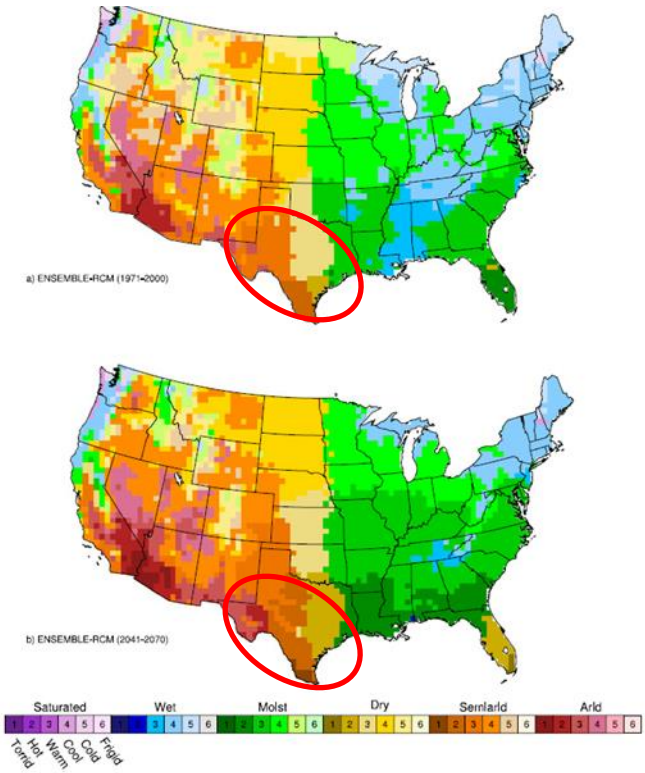


Figure 3.3. Revised Thornthwaite climate types projected by regional climate models. Texas-Gulf Region is indicated by the red oval (Elguindi and Grundstein, 2013).

Projections of changes in temperature extremes have been the subject of many recent studies performed at a national and international scale. 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 southern Great Plains region of the U.S., inclusive of the Texas-Gulf Region, the authors identified small increases in the projected extreme temperature range (annual high minus annual low temperature), a moderate increase in a heat wave duration index (increase of 3 to 4 days per year that temperatures continuously exceeds the historical norm by at least 5 ºC), and a moderate increase in the number of warm nights (c. 6 to 7% increase), compared to the baseline period.

Similar results are presented by Kunkel et al. (2010). In this study, two different downscaled GCMs were applied to the continental U.S., assuming high greenhouse gas emissions scenarios (A2 and A1F), with a focus on summer heat wave occurrence and intensity. For the Texas-Gulf Region, projections indicate a 4 to 6 ºC increase in three-day heat wave temperatures and a 50 to 80 day increase in the annual number of heat wave days for a 2090 planning horizon compared to a recent historical baseline.

At a regional scale, a comprehensive study by Liu et al. (2012) applied the full suite of Coupled Model Intercomparison Project, 3rd release (CMIP3, http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/) GCM projections to the Southern Impacts Planning Program region. This region includes the states of Oklahoma, Texas, Arkansas, Louisiana, Tennessee, Missouri, Kentucky and Mississippi (and therefore encompasses the entire Texas-Gulf Region). The suite of GCM projections includes 16 different models run applied for three greenhouse gas emission scenarios. Projections show statistically significant ($p = 0.001$) increasing trends in temperature for all three emission scenarios. Average annual temperatures in the study region are projected to increase by 2 to 5 ºC by the end of the 21st century, depending on the assumed emission scenario (**Figure 3.4**). The largest changes in temperature are projected for the fall and summer seasons.

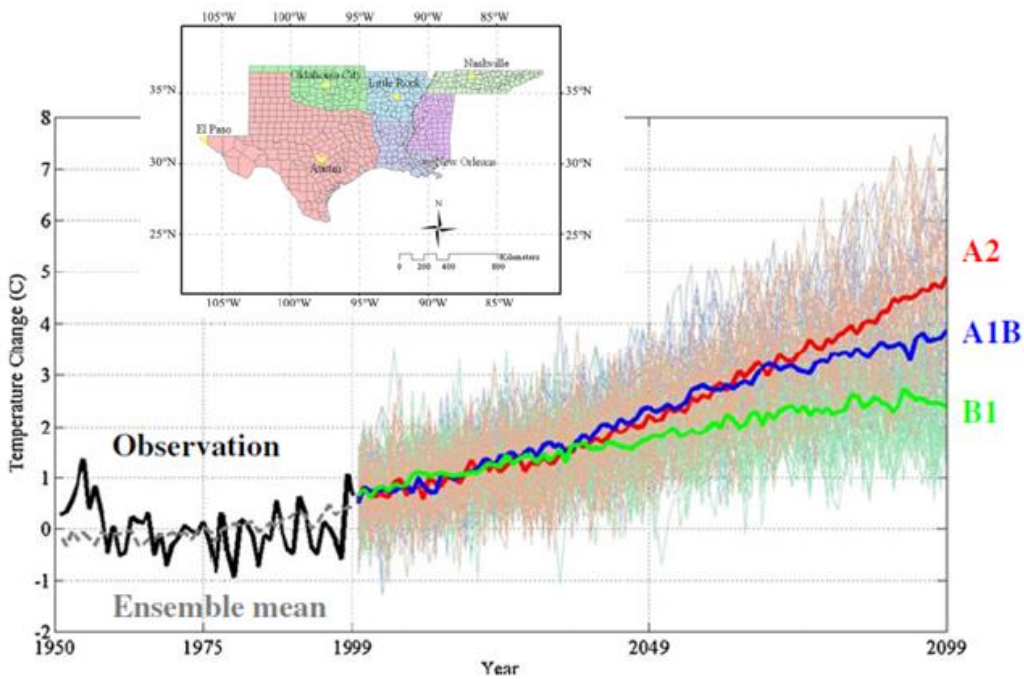


Figure 3.4. CMIP3 GCM Projections of Southern States Planning Region (Inset): Changes in Mean Annual Temperature, 1950 – 2099 (Liu et al., 2012).

Gutzler and Robbins (2010) applied an ensemble of 18 GCMs, forced by a middle of the road (A1B) emissions scenario, to project temperature, precipitation, and drought changes for the western U.S. through 2100. Results for Texas (**Figure 3.5**) indicate a projected change in annual average temperature of approximately 2.5 to 3.5 ºC for the last quarter of the 21st century compared to the last quarter of the 20th century.

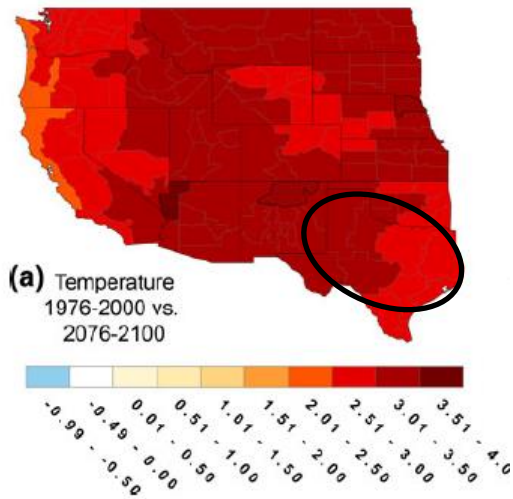


Figure 3.5. GCM projections of annual average temperature change, western United States. The Texas-Gulf Region is within the black oval (Gutzler and Robbins, 2010).

Smith et al. (2005) present GCM projections for the Texas-Gulf Region specifically. These projections highlight the uncertainties in climate modeling. Predictions range from -0.2 to +3 ºC change in winter mean daily temperature and +0.5 to +3 ºC change in summer mean daily temperatures by the middle of the 21st century, compared to a recent historical baseline.

The third NCA (Ojima et al., 2014) supports the projections of extreme temperature regimes presented above. Climate model projections for the Great Plains region of the U.S. presented in this report indicate a sharp increase in the number of extreme heat days and warm nights by the middle of the 21st century (**Figure 3.6**) for the Texas-Gulf Region. The number of extreme heat days is projected to increase by 10 – 15 days under the low greenhouse gas emissions scenario (B1) and by 20 – 28 days under the high greenhouse gas emissions scenario (A2). The number of extreme warm nights is projected to increase by 25 – 40 nights under the low emissions scenario and by 40 – 50 nights under the high emissions scenario.

a) extreme heat days

b) extreme warm nights

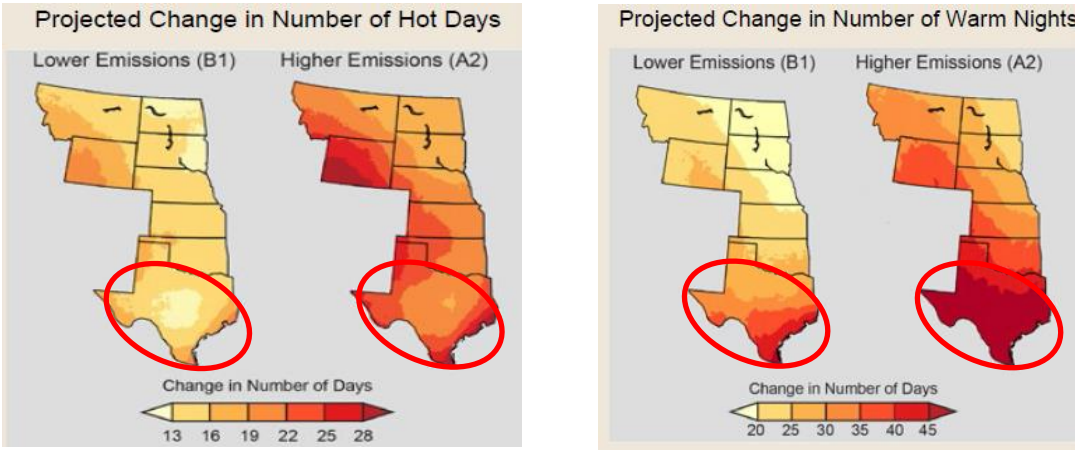


Figure 3.6. GCM projections of temperature change in the Great Plains region. The Texas-Gulf Region is within the red oval (Ojima et al. 2014).

Key point: Strong consensus exists in the literature that projected temperatures in the study region show a sharp increasing trend over the next century.

3.2. Precipitation

In line with projections for the rest of the country, projections of future changes in precipitation in the Texas-Gulf Region are variable and generally lacking in consensus among studies or across models. The Liu et al. study (2013), described above, quantified significant increases in summer and spring precipitation associated with a 2055 planning horizon, relative to a recent historical baseline (1971 – 2000, centered around 1985) , for the Texas-Gulf Region (**Figure 3.7**). Smaller increases, or even slight decreases, are projected for the other seasons. However, the authors also project increases in the severity of future droughts for the region (results not shown), as projected temperature and ET impacts outweigh the increases in precipitation. The middle of the road (A1B) ensemble of projections applied by Gutzler and Robbins (2010) show mild decreases (< 2 mm year^{-1}) in annual average precipitation for Texas (**Figure 3.8**) for the last quarter of the 21st century compared to the last quarter of the 20th century. Like the Liu et al. study, the authors also project future drought indices for the region, as a function of changing climate, that indicate reduced soil moisture and more drought-prone conditions.

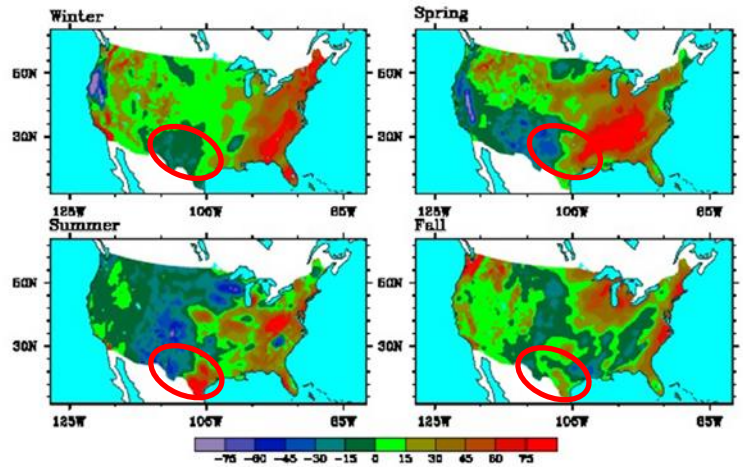


Figure 3.7. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The Texas-Gulf Region is within the red oval (Liu et al., 2013).

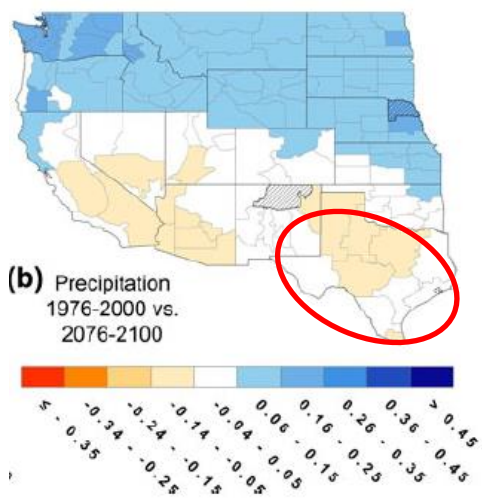


Figure 3.8. GCM projections of annual average precipitation change (mm month^{-1}), western United States. The Texas-Gulf Region is within the red oval (Gutzler and Robbins, 2010).

Liu et al. (2012) were not able to detect significant trends in GCM projections of future precipitation in the study region. The ensemble projections do exhibit increased year-to-year variability in rainfall totals, with frequent forecasts of higher peak rainfall and lower minimum rainfall compared to the historical (1950 – 2000) baseline data (**Figure 3.9**). Austin (TX) precipitation projections of the 21st century exhibit a small increase under some model scenarios and a small decrease under others (**Figure 3.10**), compared to historical baseline.

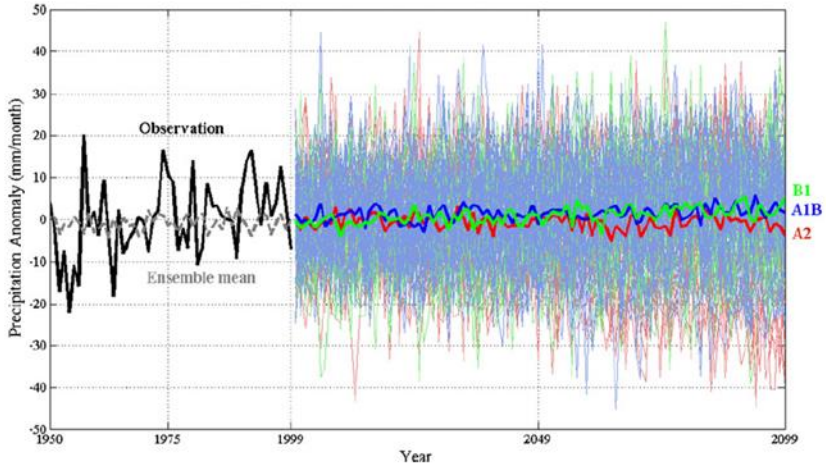


Figure 3.9. CMIP3 GCM projections of Southern States Planning Region: total annual precipitation. (Liu et al., 2012).

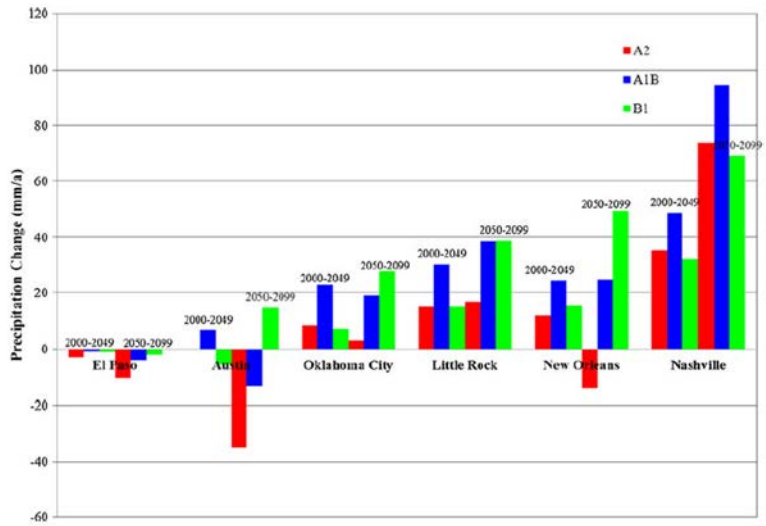


Figure 3.10. CMIP3 ensemble mean projections of precipitation changes in the 21st century (compared to 1950 – 2000 historical period) (Liu et al., 2012).

Future projections of storm events are the subject of studies by Tebaldi (2006) and Wang and Zhang (2008). The first authors compared an ensemble of GCM projections for the southeast U.S. and a 2090 planning horizon with historical baseline data (1980 to 1999). They report small decreases in the number of high (> 10 mm) precipitation days for the region, but a small increase in the magnitude of the 95th percentile storm events and the daily precipitation intensity index (annual total precipitation divided by number of wet days). In other words, the projections forecast small increases in the intensity of storm events by the end of the 21st century for the general study region. It is unclear whether these projected changes are statistically significant for the Texas-Gulf Region. In addition to the historical data trend analyses by Wang and Zhang (2008) described above, these authors also used downscaled GCMs to look at potential future changes in precipitation events across North America. They used an ensemble of GCMs and a single high emissions scenario (A2) to quantify a significant increase (c. 30 to 50%) in the recurrence of the current 20 year 24-hour storm event for their future planning horizon (2075)

and the general Texas-Gulf Region. The projected increases in storm frequency presented by Wang and Zhang (2008) appear to be more significant than those projected by Tebaldi (2006), but there is agreement on the general trend. Projected increases in extreme storm events are in agreement with global modeling results, as described in Spears et al. (2013) which consistently suggest a trend toward more intense and extreme precipitation for the globe as a whole.

Study findings described above are generally supported by the recently released third NCA (Ojima et al., 2014). Results presented in this study for the lower Great Plains Region (inclusive of Texas) indicate small future increases in the number of heavy precipitation events (mid-21st century compared to recent historical past) but also increases in the number of future consecutive dry days (**Figure 3.11**).

a.) number of heavy precipitation days b.) number of consecutive dry days

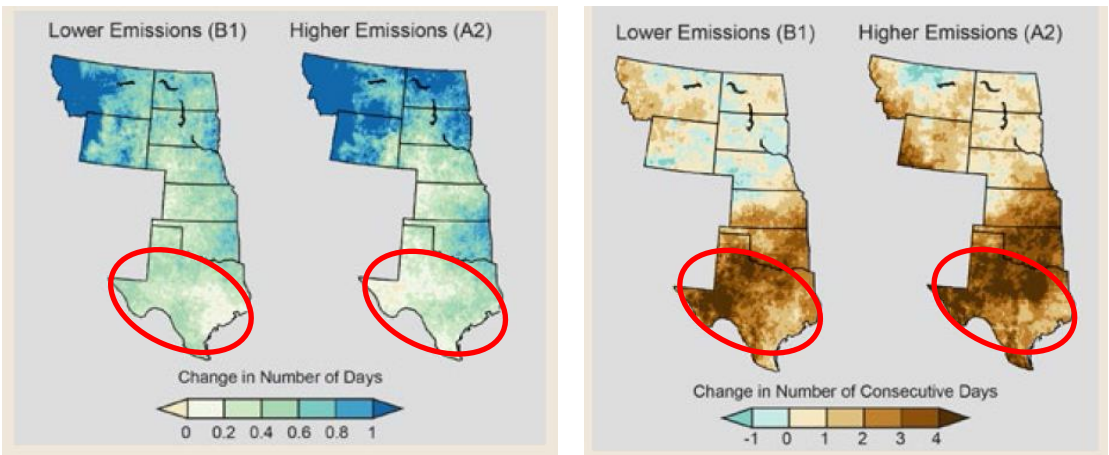


Figure 3.11. Ensemble projections of future precipitation (mid-21st century vs. historical baseline). The Texas-Gulf Region is within the red oval (Ojima et al. 2014).

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

3.3. Hydrology

A number of 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 Texas-Gulf Region. No regional studies of future hydrology projections, specific to Texas, were found in this review.

Thomson et al. (2005) applied two GCMs, across a range of varying input assumptions, in combination with the macro-scale Hydrologic Unit Model to quantify potential changes in water yield across the United States. Results are presented for both continuous spatial profiles across the country (**Figure 3.12**) and for individual watersheds. For the Texas-Gulf Region, 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.

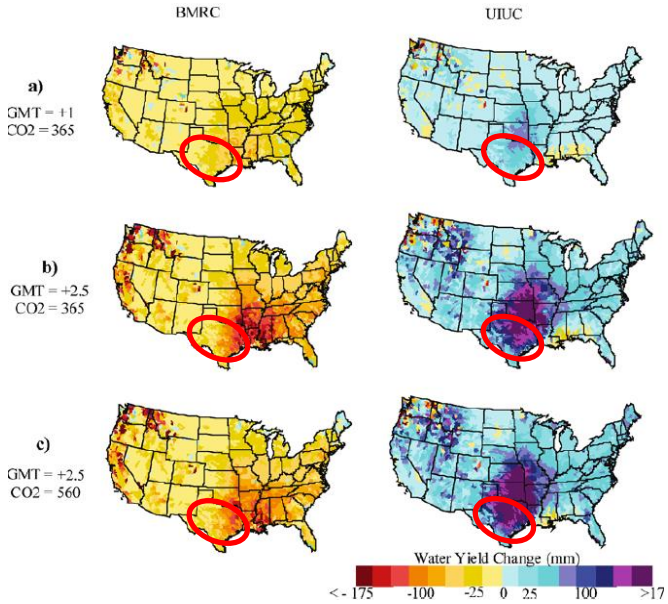


Figure 3.12. Projected change in water yield (from historical baseline), under various climate change scenarios based on 2 GCM projections. The Texas-Gulf Region is within the red oval. Global mean temperature increase (in °C) and atmospheric CO_2 concentrations (ppm) are indicated on the left side for each of the three scenarios (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 CDMSmith (2012), indicate that the uncertainty associated with macro-scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections for the general Texas-Gulf Region show an overall decrease in runoff by approximately 10 to 100 mm per year for their future planning horizon (2071 – 2100) compared to the recent historical (1970 – 2000) baseline (**Figure 3.13**), assuming an A2 emissions scenario.

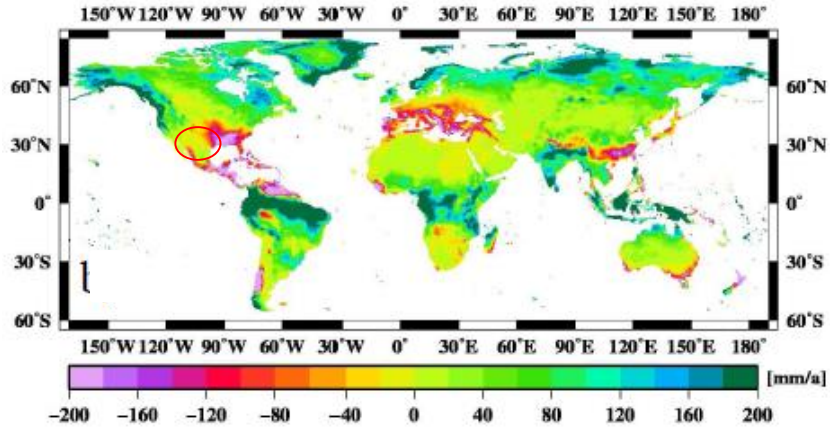
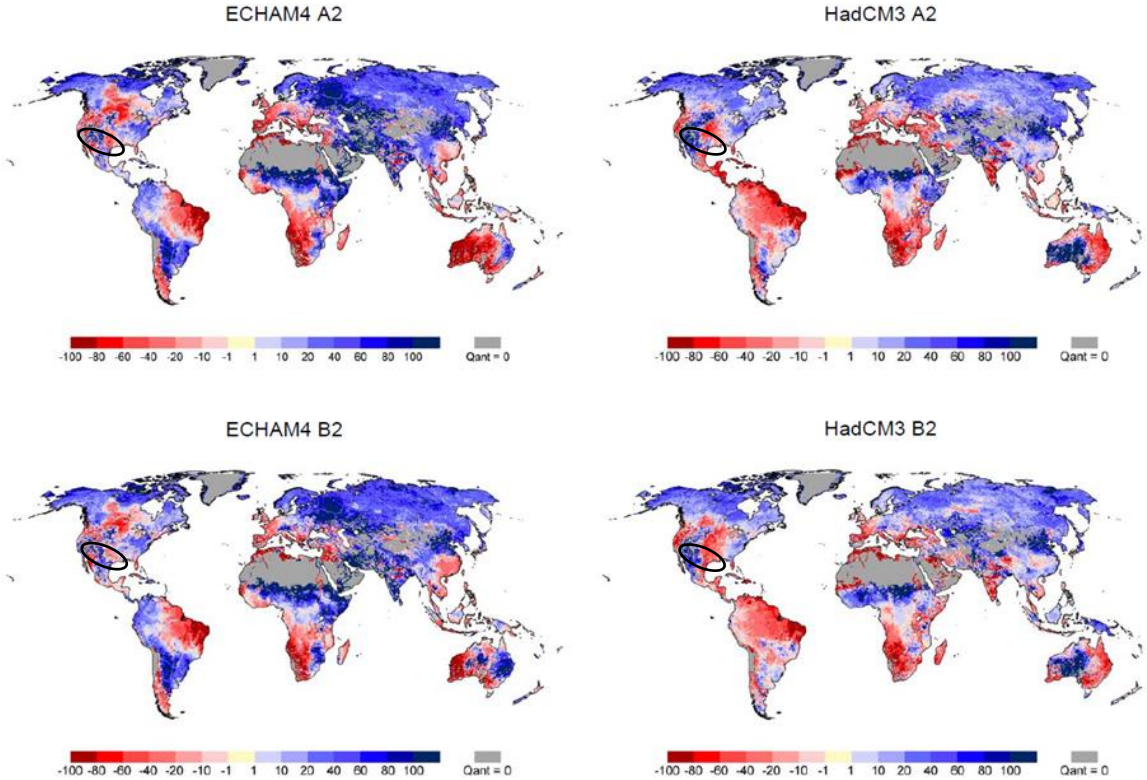


Figure 3.13. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Texas-Gulf Region is within the red oval (Hagemann et al., 2013).

Döll and Zhang (2010) present similar results in their global modeling study focused on climate change impacts on ecologically relevant flow indices. As above, these authors used a combination of GCMs and a macro scale hydrologic model (WaterGap) to project hydrology across a coarse spatial resolution (0.5 degree x 0.5 degree grid). They used two different GCMs simulating two bracketing emission scenarios (A2 and B2). Globally, they quantified a shift of peak flow by at least one month (earlier) for one third of the global land area, a significant increase in mean annual flow for approximately half of the land area, and a significant decrease in mean annual flow for approximately one quarter of the land area. Only small differences between the two emissions scenarios were noted. They demonstrate that climate change is expected to have as much, or more, of an impact to ecologically relevant flow characteristics as dams and withdrawals over the next century. For the general Texas-Gulf Region, projections show mild (relative to global results) impacts to both low and average annual flows (**Figure 3.14).** Projected regional impacts include primarily small (c. 10 to 20%) decreases in both metrics for their 2055 planning horizon, compared to historical baseline.

a) percent changes in river low flows (Q_{90}), A2 and B2 emissions scenarios



b) percent changes in average annual runoff, B2 emissions scenario

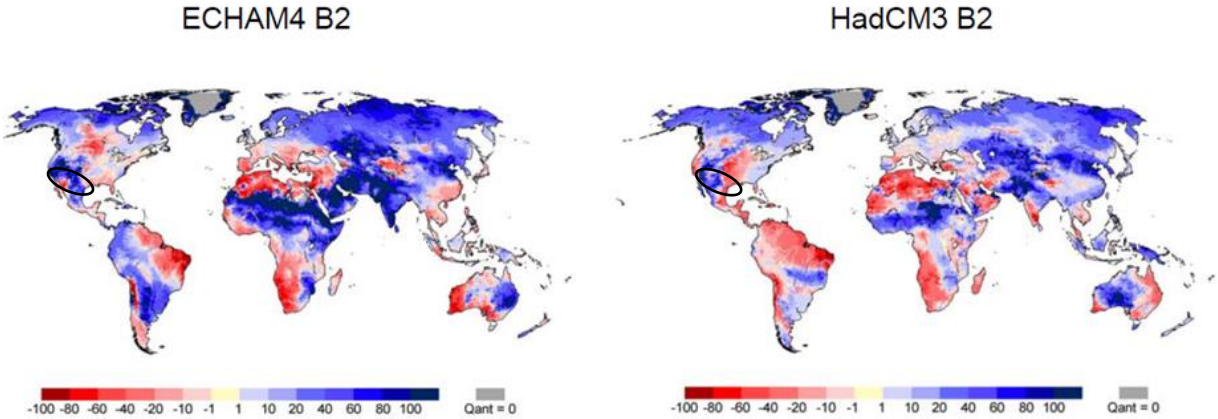


Figure 3.14. Projected changes in global hydrology (2041 – 2070 vs. 1961 – 1990). The Texas-Gulf Region is within the black oval (Döll and Zhang, 2010).

The U.S. Bureau of Reclamation has developed a comprehensive set of hydrologic runoff projections for the western U.S. corresponding to each of the 112 different downscaled CMIP3 GCM projections (Brekke, 2011). Both the climate and runoff projections are available at:

http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

The hydrologic projections were generated using a macro-scale generalized hydrologic model, the Variable Infiltration Capacity (VIC) model, seeded with climate forcing variables (temperature and precipitation). The projections are particularly useful for assessing relative changes in runoff or flow that might be caused by projected changes in climate. Results of this work (**Figure 3.15**) specific to the Texas-Gulf Region show primarily decreases in 21st century projected flows compared to the historical baseline (1990's). Projection ensemble median changes are all < 10% for the 2050's comparison, but extend to > 20% change (eastern edge of the Texas-Gulf Region) for the 2070's comparison.

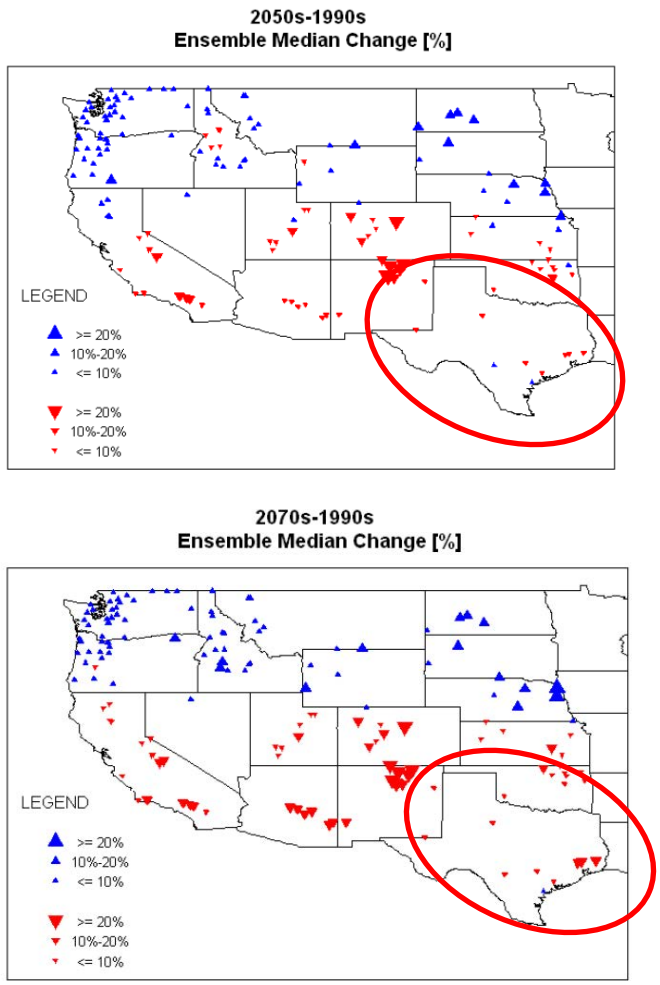


Figure 3.15. Ensemble median runoff projections, changes in annual runoff. The Texas-Gulf Region is within the red oval (Brekke, 2011).

Key point: A small number of reviewed studies, in general agreement, indicate a mildly decreasing trend in streamflow for the study region through the next century.

3.4. Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the study region, and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of approximately 3 to 5 ºC by the latter half of the 21st century for the Texas-Gulf Region. The largest increases are projected for the summer months. Reasonable consensus is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long-term future compared to the recent past.

Projections of precipitation in the study region are less certain than those associated with air temperature. On the whole, the region appears to sit on a divide between a generally projected wetter east and a projected dryer west. There is reasonable consensus in the literature, however, that the frequency and intensity of large storm events in the region will increase in the future. Multiple studies reviewed here also indicate increasing frequency and severity of future droughts in the region.

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

The trends and literary consensus of observed and projected primary variables noted above have been summarized for reference and comparison in the following figure (**Figure 3.16**).

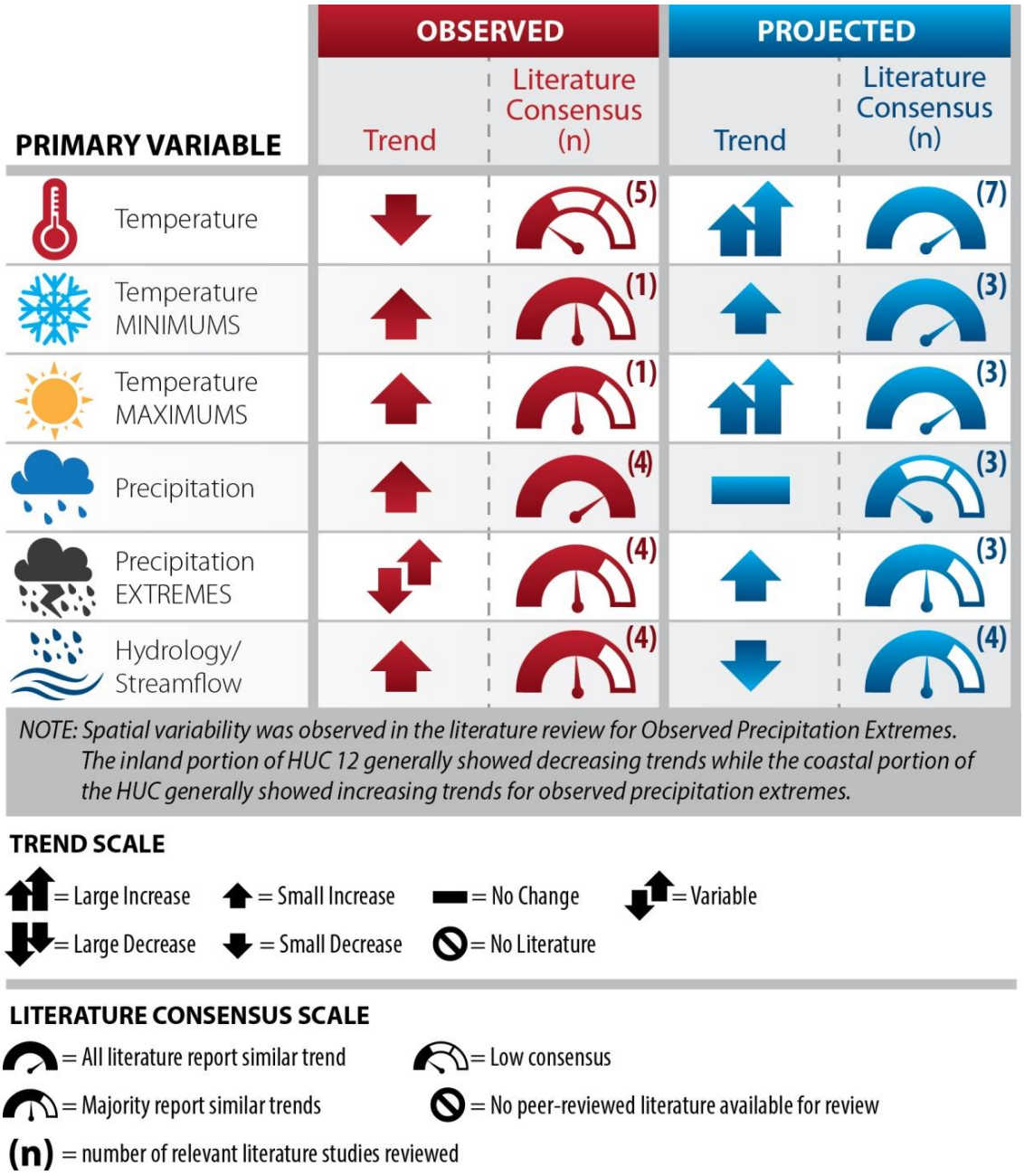


Figure 3.16. Summary Matrix of Observed and Projected Climate Trends and Literary Consensus.

4. Business Line Vulnerabilities

The Texas-Gulf Region encompasses the majority of Texas, including the Gulf Coast and a small portion of eastern New Mexico. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE's missions, a set of primary USACE business lines were identified. They include:

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

Navigation is one of the primary missions of USACE in the Texas-Gulf Region. Three of the top ten Federal channels which serve ports exist in this region in Houston, Beaumont, and Corpus Christi; these ports have more foreign import from cargo ships than any other in the country. By the middle of the century, the frequency and intensity of large storm events and associated flooding are also expected to increase. In addition, the Texas-Gulf Region may experience increases in ambient air temperature and a broader range of extremes in water availability, which has implications for water levels and thus the ability for vessels to navigate and dock at ports.

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

USACE also maintains and operates several fresh water supplies to maintain water quality in the region. It is likely that future water availability will be limited, and shortage will be most pronounced in the western part of the region, resulting in an increasing frequency and severity of droughts. In addition, the contrast between increasing mean air temperatures along with increased frequency and magnitude of heat waves, versus the increase of storm intensity and frequency will make managing competing water needs a challenge, especially when water demand is high and water supply is low.

USACE implements several ecosystem restoration projects in the Texas-Gulf Region to restore, protect, and manage the native habitats in the region. Increased air temperatures and increased frequencies of drought, will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures are associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies. Increased storm

intensities coupled with prolonged periods of drought conditions in the Texas-Gulf Region, may pose complications to planning for ecosystem needs and lead to variation in flows.

There are several hydropower plants in the Texas-Gulf Region that are owned or operated by USACE. Large storm events are expected to increase in the region, which may be beneficial for hydropower plants in the region, as flooding and increased river flows may lead to increased power generation. However, in extreme cases excess flooding may present some operational issues at these projects. Conversely, flows and reservoir levels may be reduced due to high temperatures and drought conditions, which reduce the amount of power that may be generated by the hydropower plants.

Recreational facilities in the Texas-Gulf Region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature along extended heat waves in the summer months and the increased frequency 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 Texas-Gulf Region. These types of storms are capable of intense precipitation, winds, and storm surge in coastal areas. Since these may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

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

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

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. The interrelationships between business lines must be recognized as an essential component of future planning efforts when considering the best

methods or strategies to adapt. **Figure 4.1** summarizes the projected climate trends and impacts on each of the USACE business lines.

CLIMATE VARIABLE	VULNERABILITY
Increased Ambient Temperatures	Increased ambient air temperatures throughout the century are expected to create the following vulnerabilities on the business lines in the region: • Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Decrease in flows may result from periods of drought and reduced streamflow has implications for maintain water levels in the rivers. • Risk of wildfires during hot and dry conditions may cause an increased risk of wildfires, especially in heavily forested and dry areas. Flora and fauna that are not drought resistant can also be impacted by longer drought conditions, which may reduce opportunities for recreational wildlife viewing. **BUSINESS LINES IMPACTED:**
Increased Maximum Temperatures	Air temperatures are expected to increase 3-5˚C in the latter half of the 21st century. This is expected to create the following vulnerabilities on business lines in the region: • Increased water temperatures leading to water quality concerns, particularly for the dissolved oxygen (DO) levels, growth of nuisance algal blooms and influence wildlife and supporting food supplies. • Increased evapotranspiration. • Human health risk increases from extended heat waves, impacting recreational visitors and increasing the need for emergency management. **BUSINESS LINES IMPACTED:**
Increased Storm Intensity and Frequency	Extreme storm events may become more intense and frequent over the coming century which are expected to influence the following vulnerabilities on business lines in the region: • Increased flows and runoff, 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 groundwater recharge rates, as residence times are shortened within areas where evapotranspiration takes place during high intensity events. • Increased 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 evapotranspiration 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 fpr competing sources such as hydropower generation, navigation and ecosystem management, may present some significant, additional challenges to an already complex water resource system. • Reduced ability for vessels to navigate and dock at ports. • Reduced amount of power that may be generated by the hydropower plants. **BUSINESS LINES IMPACTED:**

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

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

Figure 4.1: Summary of Projected Climate Trends and Impacts on USACE Business Lines

Appendix A: References Climate/Hydrology Summary Table

	Observed										Projected									
References	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Ashfaq M, Bowling LC, Cherkauer K, Pal JS, Diffenbaugh NS (2010)											X	X	X							
Brekke (2011)																X				
Brommer DM, Cerveny RS, Balling Jr RC (2007)				X																
CDM Smith (2012)																X				
Chen G, Tian H, Zhang C, Liu M, Ren W, Zhu W, Chappelka AH, Prior SA, Lockaby GB (2012)	X						X													
Döll P, Zhang J (2010)																X				
Duan Q, Schaake J, Andreassian V, Franks S, Goteti G, …, Wagener T, Wood EF (2006)						X														
Elguindi N, Grundstein A (2013)											X									X
Grundstein A, Dowd J (2011)		X	X																	
Gutzler DS, Robbins TO (2010)											X			X						
Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, Hanasaki N, …, Wiltshire AJ (2013)														X		X				
Kalra A, Piechota TC, Davies R, Tootle GA (2008)						X														
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Liu L, Hong Y, Hocker JE, Shafer MA, Carter LM, Gourley JJ, Bednarczyk CN, Yong B, Adhikari P (2012)	X	X	X								X									
Liu Y, Goodrick SL, Stanturf JA (2013)													X	X			X	X		
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Milly PC, Betancourt JL, Falkenmark M, Hirsch R, Kundzewicz Z, Lettenmaier D, Stouffer R (2008)											X									
Ojima DS, Schafer MA, Antle JM, Kluck D, McPherson R, Petersen S, Scanlon BR, Sherman K (2014)												X	X	X						
Palecki MA, Angel JR, Hollinger SE (2005)				X																
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Wang J, Zhang X (2008)				X	X									X	X					
Westby RM, Lee Y-Y, Black RX (2013)	X																			
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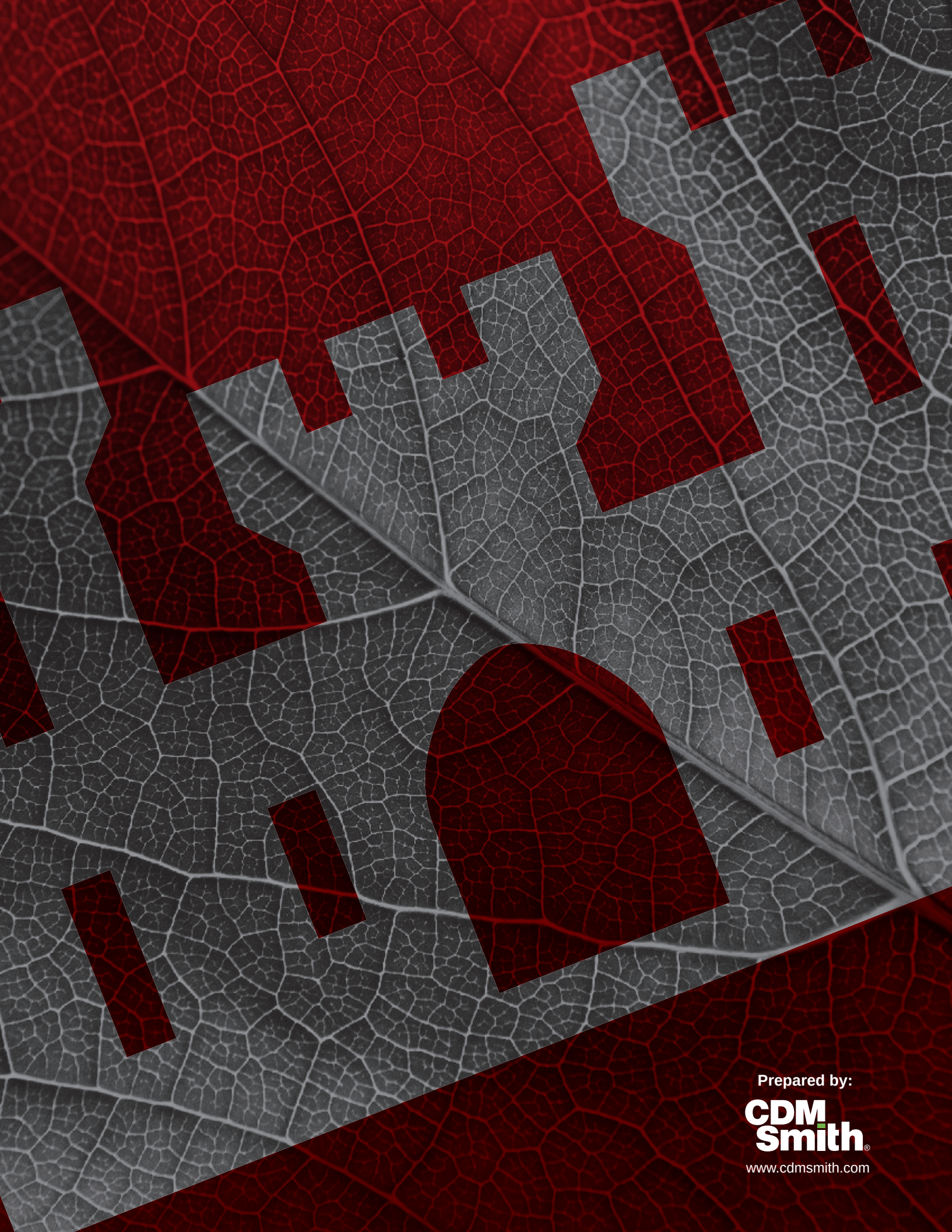

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