Final Report

A Framework for Assessing Impacts of Climate Change

Prepared for

Lower Colorado River Authority

and San Antonio Water System

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Executive Summary

Overview

The LCRA-SAWS Water Project is being studied as a long-term water supply project designed to meet municipal, industrial, agricultural and environmental flow needs within two rapidly growing regions in central Texas. Analyses are well underway to locate and size facilities, forecast future demand and conservation levels, calculate yield and evaluate potential impacts. These analyses are critical for determining the viability of the project, as well as for supporting necessary state and federal permit applications.

Models used to calculate water availability and environmental flow requirements have been developed largely within existing frameworks based on hydrologic data available from historic events. This is a reasonable approach used by water planners across the country as well as by many regulatory agencies for permit review. In light of the project's eighty year planning horizon, contractual obligations associated with this particular project, comments from the project's Science Review Panel and increased public and regulatory awareness of the climate change issue, LCRA tasked CH2M HILL to explore predictions of climate change in the region and methods to assess its impact on the LCRA-SAWS Water Project. Specifically, the scope of study includes:

- A literature review that summarizes the status of current knowledge of climate change;
- A summary of the literature on the current status of knowledge on how global climate change may affect Texas, particularly within the central and gulf coast regions; and
- Recommendations for the technical path forward to assess the potential effects of global climate change on the project.

Predictions Regarding Climate Change

Most of the scientific literature indicates that significant changes are occurring and will continue to occur in key parameters by which global climate is measured: precipitation, evapotranspiration, sea level rise and drought/flood cycles. The extent of such change will likely be determined by both long-term natural processes as well as anthropogenic (man-made) activities. Less rigorous analyses regarding regional variations and implications of such global changes have been conducted across the nation, but some research focused on Texas and its gulf coast region has been documented in the literature.

- Research regarding temperature changes in Texas has been inconclusive, although the climatologists generally concur that updated modeling would likely confirm a continued warming trend, ranging from 1.8°C to 4.0°C (3.2°F to 7.2°F) by the end of the century with potentially higher temperatures if uncertainty factors are applied.

- Within the gulf coast region, sea level rise cannot be described without also considering the combined effect of coastal land subsidence. Assuming a conservative estimate of 0.10 meters (0.33 feet) per century average rate of subsidence (UCS 2001, Penland et al. 1989),

the "relative" sea level rise (sea level rise plus land subsidence) would range from 0.28 to 0.69 meters (0.92 to 2.26 feet) by the end of the century.

- Based on the multi-model analyses by the Intergovernmental Panel on Climate Change (IPCC, 2007), southwest Texas may experience 5% to 20% decreases in average annual precipitation, north and northeast Texas may experience increases on the order of 5%, and there is no consensus for much of the rest of the state. The general findings of this work suggest that western states will likely experience more severe drying conditions due to the impact of temperature increases on the evaporative demands, even in areas where slight increases in precipitation are projected. However, when precipitation does occur, the events are likely to be more extreme.

The scientific research regarding climate change is evolving very quickly. The International Panel on Climate Change issues reports every five years and the US Global Change Research Program is developing a report that was initially scheduled for release in 2004. Information provided by these and other reports may provide additional guidance for assessing potential effects of climate change during the project's planning period.

Methods for Assessing Potential Change

General trends indicate that dry areas and seasons will tend to become drier and wet areas and seasons will tend to experience more rainfall than that experienced historically. Additionally, drought and flood cycles will tend to become more frequent and of greater magnitude than historical data would predict. The precise geographical and temporal extent of these changes cannot be predicted with certainty. Further, the implications of these changes for water resources cannot be precisely forecast.

None-the-less, approaches to planning for water supply projects can be adopted so that change can be anticipated and steps taken to manage for likely changes. Over the long run, water resources managers can benefit from institutionalizing processes that provide for:

- Planning and forecasting a range of changes of the key parameters;
- Assessing the potential impacts of long-term changes in climate;
- Developing structural and operational strategies to minimize the risk of changes on water supply;
- Implementing those strategies; and
- Monitoring their success and updating the plan.

A number of methods for predicting change exist. The level of effort and time required to develop and utilize the different methodologies varies. Some of the methods have not yet matured to the point that they would provide a reasonable confidence in their utility or their accuracy, such as "downscaling" global models to a finer regional "grid." Such models will be developed and their accuracy improved over time by climate centers and universities conducting necessary research. While these refined tools are being developed for Texas, water resource managers can develop and employ techniques to assess potential implications of climate change and develop strategies to minimize the risks associated with such changes.

Recommended Analytical Approaches for the LCRA-SAWS Water Project

An analytical framework for assessing impacts and vulnerabilities of the project due to potential changes in climate is needed to provide context and direction for managers and for various technical analyses; to maintain consistency of the treatment of climate changes throughout the assessment; to describe the integrated nature of the analyses; and to formally describe impacts, uncertainties, and risks. The proposed overall analytical framework, described in this report, consists of the following processes/actions:

- Define evaluation criteria;
- Select analytical approach;
- Select climate change scenarios;
- Downscale climate changes to regional level;
- Adjust climatic inputs to analytical tools used in various technical studies;
- Determine natural and human system responses;
- Assess impacts and vulnerabilities; and
- Develop and apply adaptation strategies to minimize risk.

Specific recommendations include:

- The analysis should focus on the development of broad-based evaluation or performance criteria (e.g., changes in the salinity regime of the bay) rather than specific threshold criteria (e.g., a specific salinity concentration measured at a specified location). These types of criteria allow greater flexibility and a broader understanding of impacts over time.

- The selected approach will depend on the analytical methods of existing tools and on stakeholder acceptance and understanding of statistical methods. Based on our current understanding of the existing analytical tools being used for the analyses during the study period for the LCRA-SAWS Water Project, we recommend that a scenario approach be pursued initially. If the entities involved would like a more rigorous analysis in the future, the modeling tools and methods would need to be modified to perform an uncertainty/risk analysis. By utilizing the scenario approach initially, a range of implications can be forecast such that the benefits of a more robust assessment can be better gauged.

- Potential future conditions were developed by the IPCC and documented in the Special Report on Emission Scenarios. Each of these scenarios had associated emissions concentrations which were used as data input into various global circulation models used by the California Department of Water Resources in the July 2006 progress report regarding incorporating climate change into water supply planning. These climate scenarios appear reasonable for capturing the range of potential changes in climate variables. We recommend that these climate scenarios be utilized in analyses for the project.

- Additional contact should be made with the scientific community to understand if downscaling of the models used in the IPCC's Fourth Assessment Report may already be available for Texas or which institute/agency could provide these services. If the models are not developed and populated with data, downscaling may be more

appropriately part of a long-range strategy to manage the lower Colorado River watershed rather than applied to this project. During the 2007 legislative session, a bill was proposed that would have directed the Texas Water Development Board to assess the implications of climate change on water resources in Texas. Such an assessment may provide a future avenue for regional modeling that would encompass a larger area.

- Regional scale climate change behavior should be transferred to local scale historical data using modeling techniques that create "perturbation ratios" or additional factors that are applied to historical data. These data sets could then be used as input to simulate run-off, evaporation and other inputs to water availability in the future resulting from such changes in key parameters.
- With a revised set of input data based on the calculated ratios, the project study teams can then use current modeling tools to assess surface water availability (WAM/WRAP), agricultural and urban demands, changes to the Matagorda Bay ecosystem, groundwater system response and water quality changes.

1.0 Introduction

The LCRA-SAWS Water Project is being studied as a long-term water supply project designed to meet municipal, industrial, agricultural and environmental flow needs within two rapidly growing regions in central Texas. Analyses are well underway to locate and size facilities, forecast future demand and conservation levels, calculate yield and evaluate potential impacts. These analyses are critical for determining the viability of the project, as well as for supporting necessary state and federal permit applications.

Models used to calculate water availability and environmental flow requirements have been developed largely within existing frameworks based on hydrologic data available from historic events. This is a reasonable approach used by water planners across the country as well as by many regulatory agencies for permit review. In light of the project's eighty year planning horizon, contractual obligations associated with this particular project, and increased public and regulatory awareness of the climate change issue, LCRA and SAWS are evaluating the possible implications of climate changes on the project is advisable.

In March, 2007, LCRA tasked CH2M HILL to explore predictions of climate change in the region and methods to assess its impact on the LCRA-SAWS Water Project. Specifically, the scope of study includes:

- A literature review that summarizes the status of current knowledge of climate change;
- A summary of the literature on the current status of knowledge on how global climate change may affect Texas, particularly with the central and gulf coast regions; and
- Recommendations for the technical path forward to assess the potential effects of global climate change on the project.

More specifically, the scope of study emphasizes the potential range of impacts from climate change on key parameters affecting water resources including precipitation, evapotranspiration, sea level change and the magnitude and frequency of flood and drought events as these factors may affect water supply.

2.0 State of the Science

A growing body of evidence indicates that Earth's atmosphere is warming. Records show that surface temperatures have risen about 0.7°C since the early twentieth century and that 0.5°C of this increase has occurred since 1978 (National Academies of Sciences [NAS] 2006a summary, U.S. Global Change Research Program [USGRP] 2001). Observed changes in oceans, snow and ice cover, and ecosystems are consistent with this warming trend (NAS 2006a; IPCC 2001, 2007). The temperature of Earth's atmosphere is directly related to the concentration of atmospheric greenhouse gases. Growing scientific consensus suggests that that climate change will be inevitable as the result of increased concentrations of greenhouse gases and related temperature increases (IPCC 2001, 2007; Kiparsky and Gleick 2003).

The science and methodologies associated with predicting climate change are evolving rapidly. Those literature sources that are the most current, provide information associated with the area of focus for this review and provide a good synthesis of data were used in this report.

2.1 Climate Change Overview

Earth's climate has exhibited variability and has changed over time. The extremes of the 100,000-year ice-age cycles and "mega-droughts" have been well-documented. The period of the last 10,000 years has been generally warm and stable, and the last millennium, over which current societies have developed, has been one of the most stable climatological periods observed (California Environmental Protection Agency [CalEPA] 2006). Observations in the 20th century indicate rapid climate change (IPCC 2001, 2007; NAS 2006a). The National Academy of Sciences (2006b) recently supported the conclusion that it is likely that the past few decades exhibited higher global mean surface temperatures than during any comparable period of the preceding four centuries. Additionally, 11 years between 1995 and 2006 rank among the 12 warmest years in the instrumentation record (1850 - 2006) for global surface temperature (IPCC 2007).

2.1.1 Some Definitions

In common terms, one can think of "climate" as the "average weather" conditions over some extended period. The IPCC (2001) provides a more rigorous definition of climate as the "statistical description in terms of the mean and variability of relevant parameters over a period of time ranging from months to thousands or millions of years." Parameters measured are most often surface variables such as temperature, precipitation, and wind. Data are typically averaged in 30-year periods as defined by the World Meteorological Organization. "Climate change" is the shift in the average weather, or trend, that a region experiences. This change may be due to natural processes, or to anthropogenic factors that affect the composition of the atmosphere. Thus, climate change cannot be represented by single annual events nor individual anomalies. That is, a single large flood event or particularly hot summer is not an indication of climate change, while a series of floods or

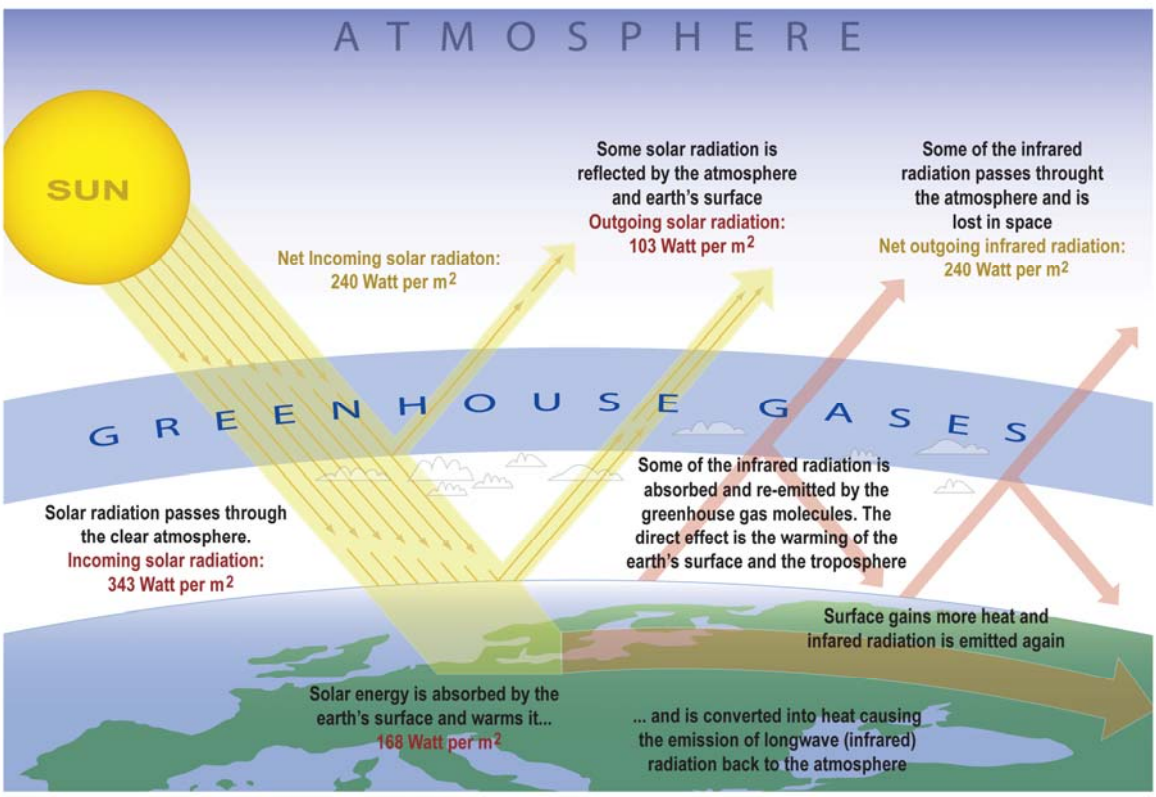
warm years that statistically change the average precipitation or temperature over time may indicate climate change.

"Climate variability", refers to the deviation from the average climate. For example, an individual year that is drier or hotter than average would indicate variability, but may not indicate a shift in the trend as would be defined as climate change.

2.1.2 Mechanics of Climate Change

The temperature on Earth is regulated by a system commonly described as exhibiting the "greenhouse effect." The greenhouse effect is a natural phenomenon in which atmospheric gases, primarily water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3), allow solar radiation to pass through the atmosphere and warm Earth's surface. As Earth's surface warms, infrared radiation is emitted back to the atmosphere. Greenhouse gases in the atmosphere absorb some of this radiation and re-emit it back to Earth, causing the surface to gain more heat (NAS 2006a) (Figure 1). Changes in atmospheric gases can result in changes in Earth's temperature, thus influencing climate.

FIGURE 1.
The Greenhouse Effect (adapted from NAS 2006a)



Changes in the atmospheric abundance of greenhouse gases, as well as modifications to the land surface, alter the energy balance of the climate system. Greenhouse gases are contributed to the atmosphere by both natural and anthropogenic sources. Evidence suggests that the rates of contribution of greenhouse gases to the atmosphere were in balance with mechanisms for their removal prior to the early 1800's (North et al., 1995). Data

on atmospheric carbon dioxide concentration indicate a cyclical pattern. The concentration of carbon dioxide (CO_2) in the atmosphere has risen about 30% since the late 1800's and is now higher than it has been in at least the last 400,000 years (USGRP 2001) (Figure 2). While there is debate as to the causes of increasing concentrations of carbon dioxide, the climate effects and implications for water resource planning remain. Rising concentrations of CO_2 (Figure 3) and other greenhouse gases are intensifying Earth's natural greenhouse effect. Global projections of population growth and assumptions about energy use indicate that the CO_2 concentration will continue to rise, likely reaching between two and three times its late-19th-century level by 2100 (USGRP 2001).

FIGURE 2.
Carbon Dioxide in Earth's Atmosphere over Time (Source: NAS 2006a)

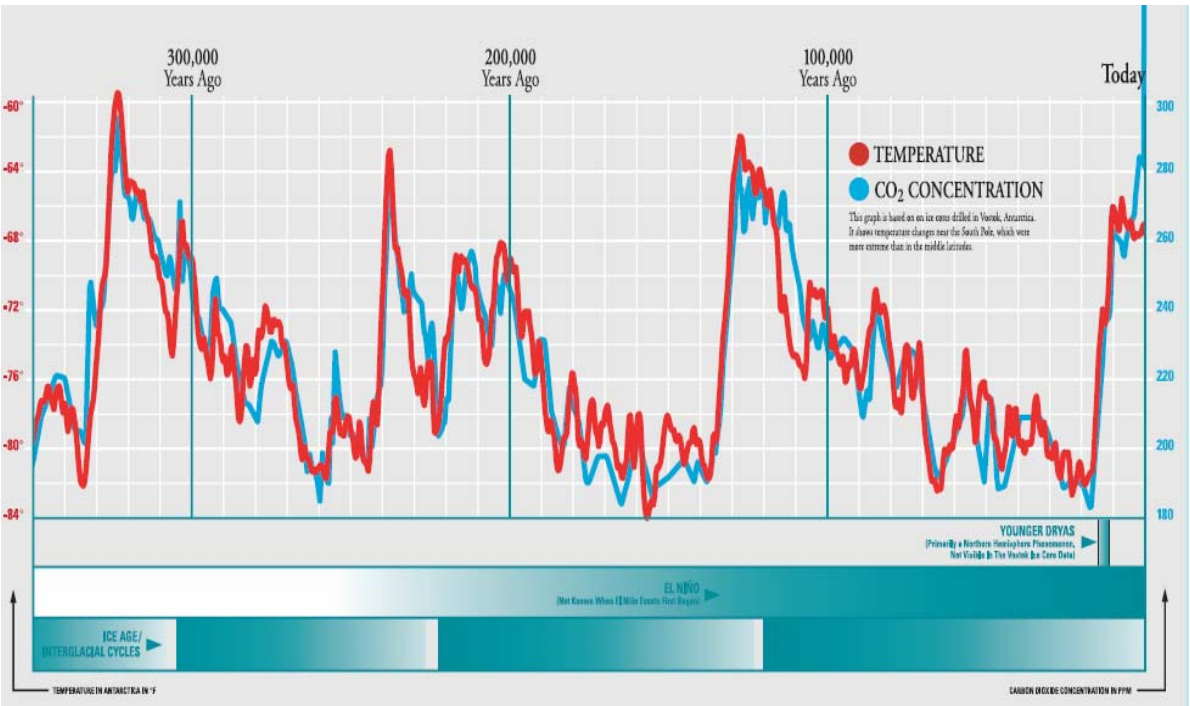
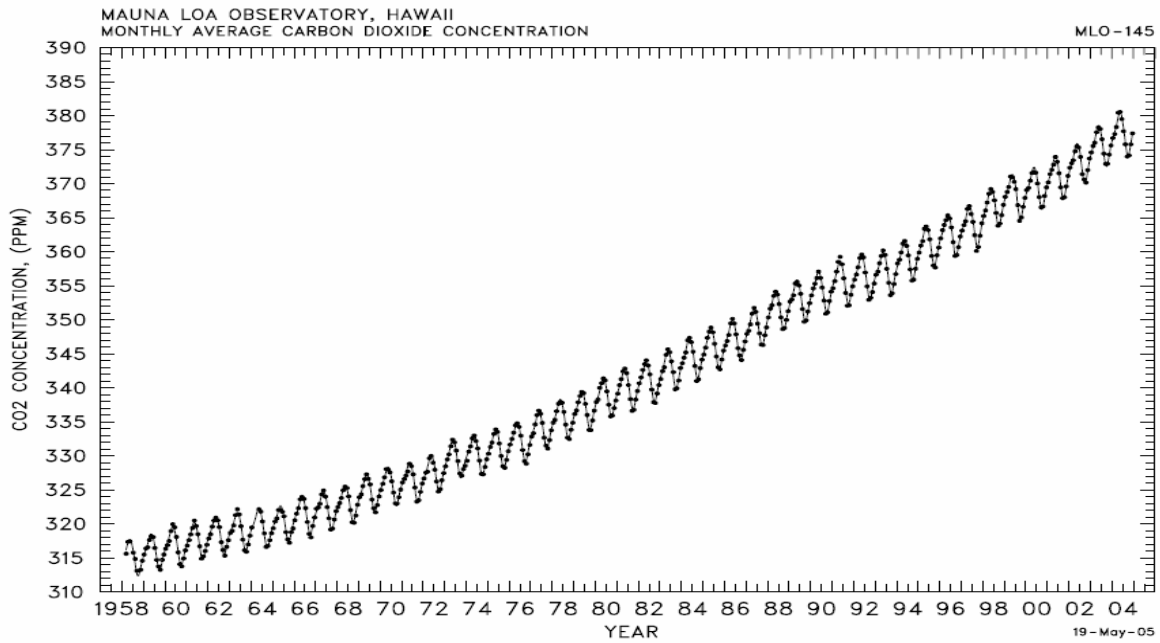


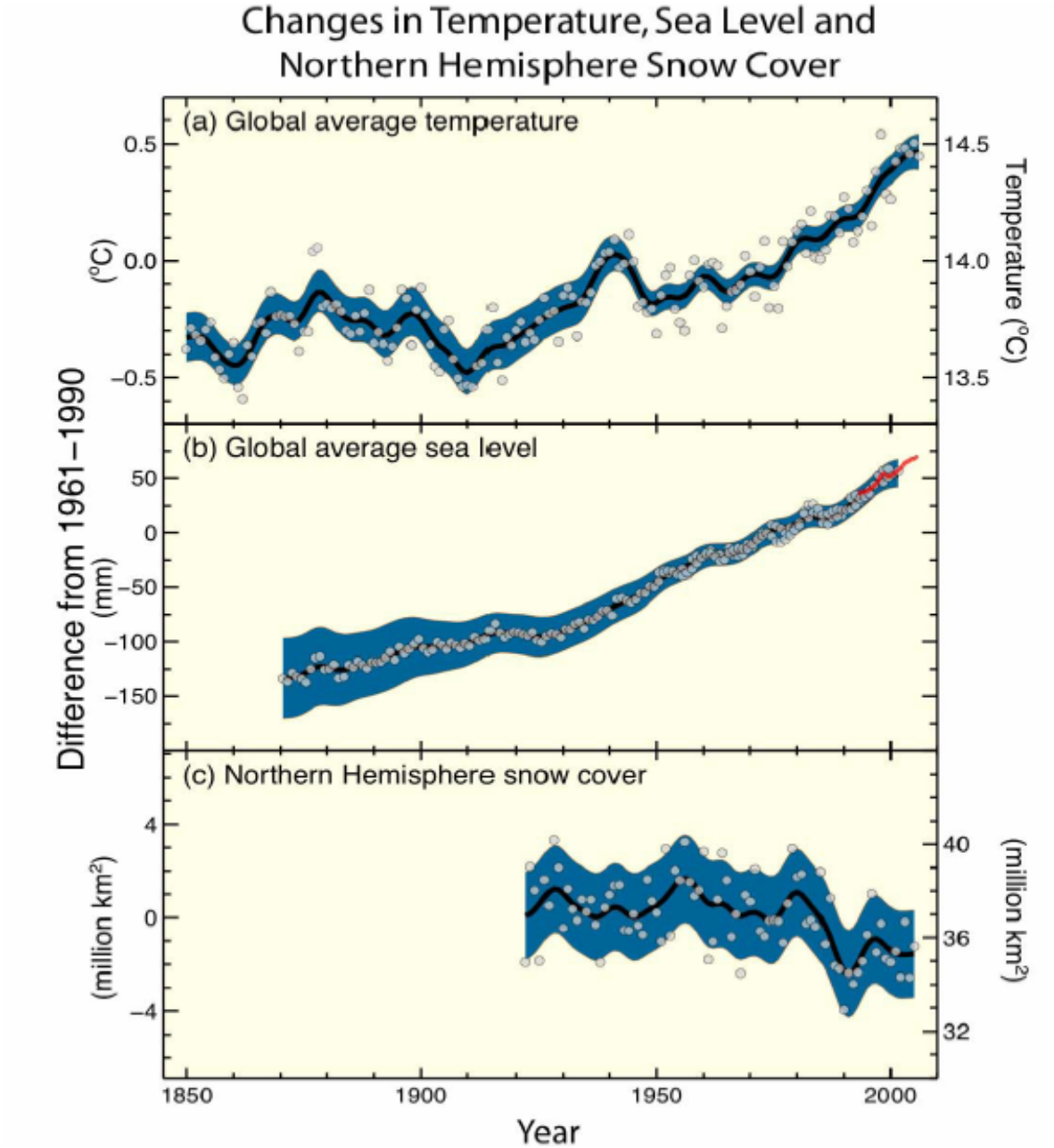
FIGURE 3.
Monthly Average Carbon Dioxide Concentration, 1958 – 2004 (Source: Carbon Dioxide Analysis Center, 2007)



2.2 Reported Observations of Recent Climate Change

To provide a scientifically sound basis for global policymaking, the United Nations Environment Programme (UNEP) and the World Meteorological Organization in 1988 established an international consortium of scientists to review and assess the state of climate change science. This consortium, the Intergovernmental Panel on Climate Change (IPCC), has published three comprehensive assessments (in 1990, 1996, and 2001) and has released a summary of the fourth assessment (February 2007), each based on extensive reviews of published and peer-reviewed research on all aspects of global warming. In its most current assessment (IPCC 2007), significant observations of climate variables from around the globe support the conclusions that average global temperatures have increased, that sea levels have risen, and that the extent of snow and ice cover in the northern hemisphere has decreased (IPCC 2007) (Figure 4).

FIGURE 4.
Changes in Temperature, Sea Level and Northern Hemisphere Snow Cover (Source: IPCC 2007)



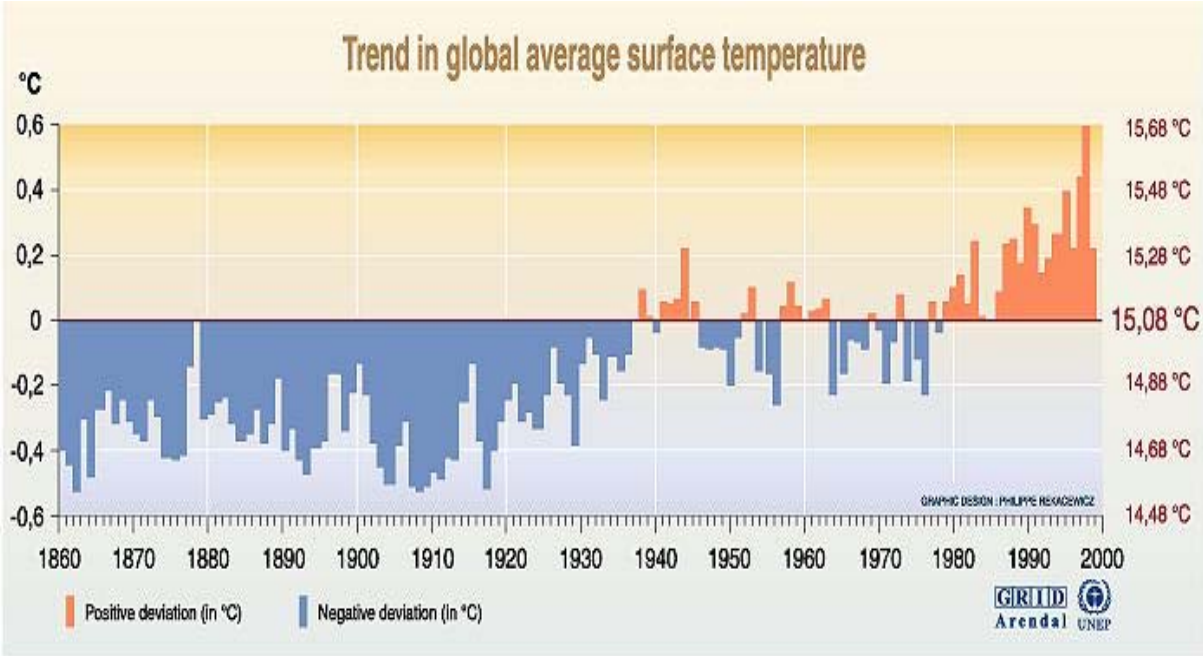
Note: Temperature data is available from the 1850's; sea level data from the 1870's and snow cover data from the 1920's.

2.2.1 Temperature

The IPCC (2007) reports that eleven of the last twelve years (1995 -2006) are in the top twelve warmest years during the period of record for global surface temperature (1850-2006) (Figure 5). The global warming trend over the last 50 years is estimated to be 0.13°C (3.2°F) per decade and is nearly twice that for the last 100 years. The observational trends

have also indicated that warming, consistent with that attributable to human activities, has occurred on every continent except Antarctica (Figure 6).

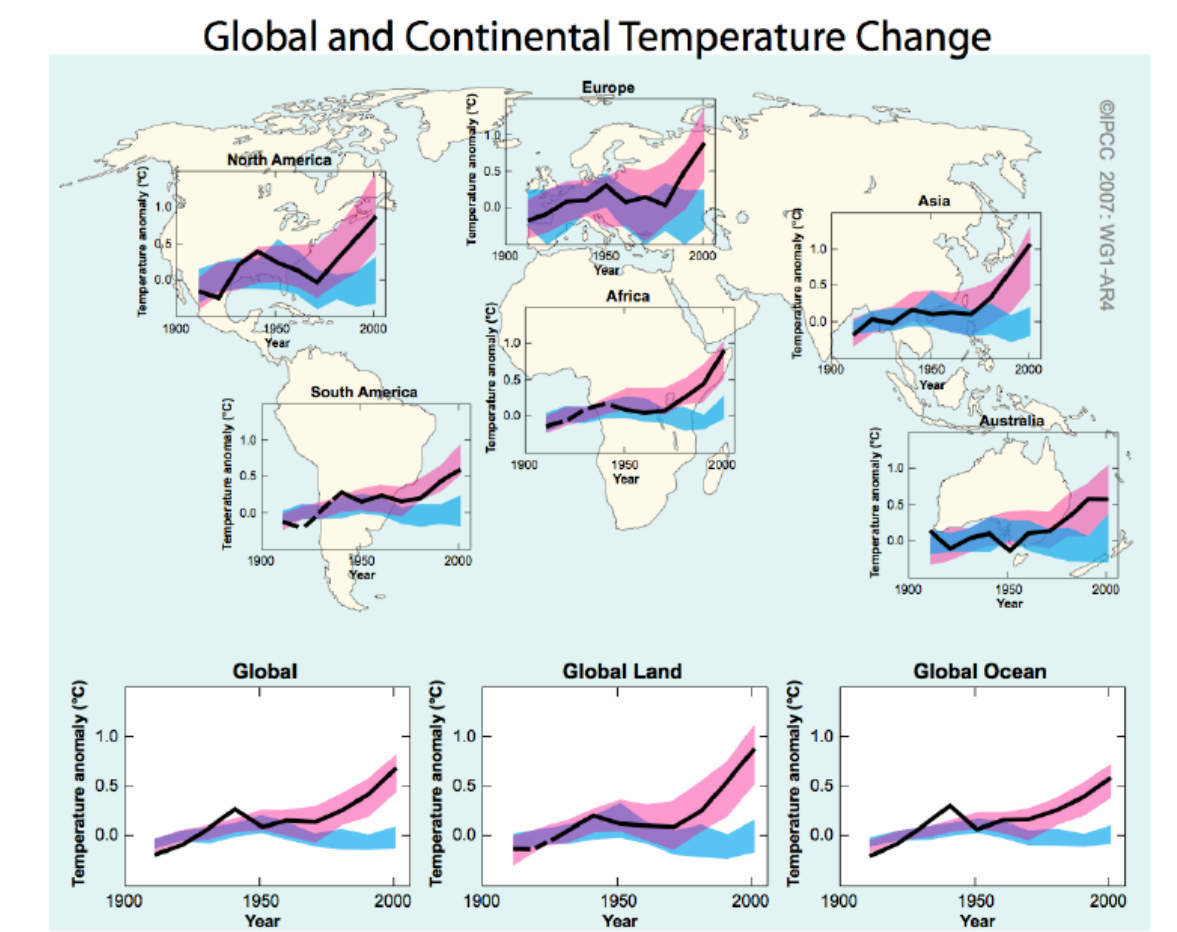
FIGURE 5.
Trend in Global Average Surface Temperature (Source, University of East Anglia: 1999; obtained from UNEP Vital Climate Graphics http://www.grida.no/climate/vital/trends.htm)



Source: School of environmental sciences, climatic research unit, university of East Anglia, Norwich, United Kingdom, 1999.

The figure shows the combined land-surface air and sea surface temperatures (degrees Centigrade) from 1861 to 1998, relative to the average temperature between 1961 and 1990.The mean global surface temperature has increased by about 0.3 to 0.6°C (0.5 to 1.1°F) since the late 19th century and by about 0.2 to 0.3°C (0.4 to 0.5°F) over the last 40 years, which is the period with most reliable data. Recent years have been among the warmest since 1860 - the period for which instrumental records are available.

FIGURE 6.
Global and Continental Temperature Change (Source: IPCC 2007)

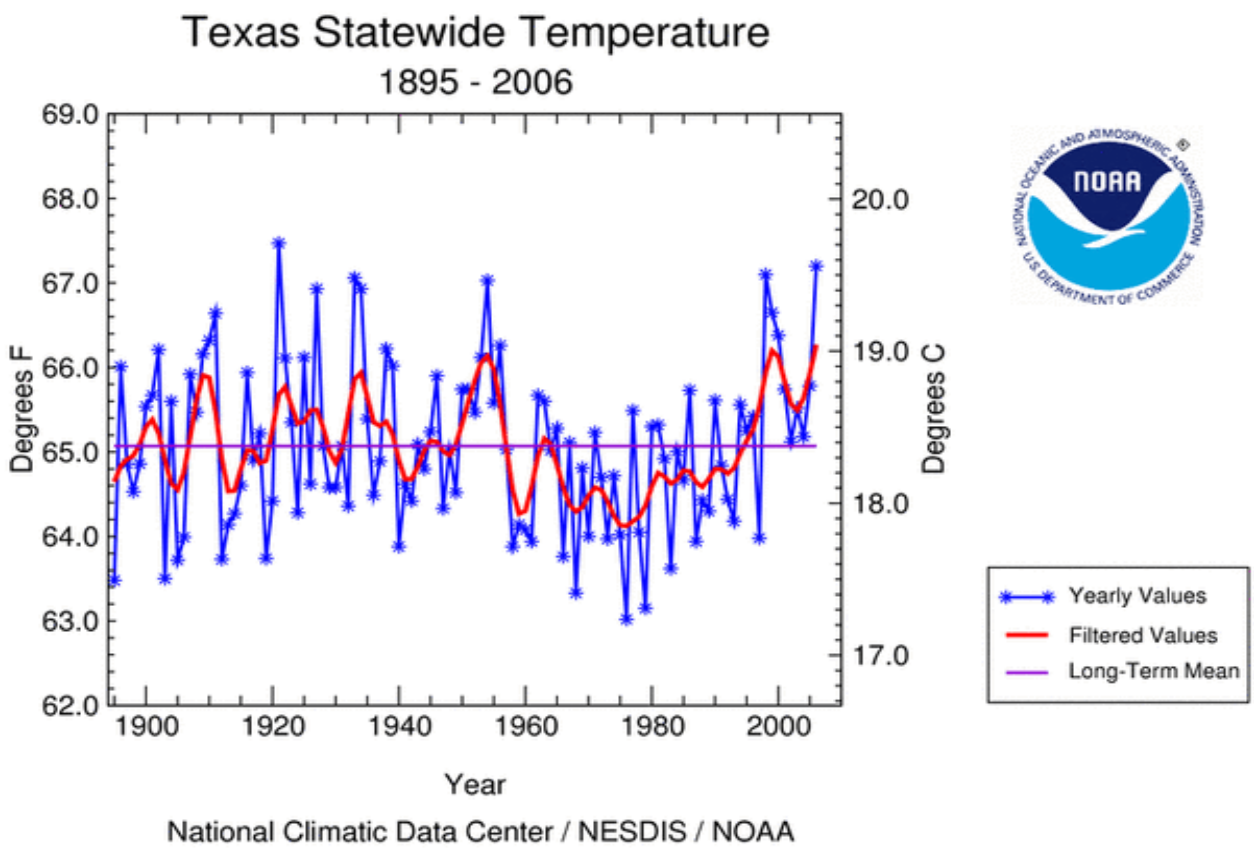


Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906–2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic factors. (Source: IPCC 2007).

Although the global and continental air temperatures show a strong trend toward warming, the picture is not as clear in Texas. North analyzed annual mean temperature trends for Texas for the period of 1888 – 1989 (North et al. 1995). The Union of Concerned Scientists (UCS 2001) provided slightly broader coverage of the gulf coast region for the period of 1895 – 2000. Both analyses indicated a slight cooling during the 1960's and 1970's as compared to the reported warming in most of the United States during that period. North et al. suggested that the most likely reason for the differences between the reported national trends and observations for Texas is that the natural variability of this smaller region (rather than continental scale) could mask an underlying trend. The Union of Concerned Scientists suggest that observations are not inconsistent with global warming, that a warming trend did occur in the gulf coast record between the 1920s and 1949, and that the region has been warming since the late 1960s. A 2007 analysis of temperature trends in Texas by National

Oceanic and Atmospheric Administration (NOAA) (2007) confirms the warming trend since the 1960s reported by the Union of Concerned Scientists (Figure 7). Note recent yearly values on the high end are similar to those prior to the 1960's, but that the lower yearly values are at or above the long-term mean. Consistent with a long-term warming trend, but potentially just a single event, the year 2006 is reported to be the 2nd warmest in Texas since 1895.

FIGURE 7.
Texas Statewide Temperature, 1895-2006 (NOAA 2007, obtained from http://www.ncdc.noaa.gov/oa/climate/research/2006/ann/us-summary.html)



The filtered value in this figure represents decadal-scale variations (using a nine-point binomial filter). The long-term mean includes the period 1895 through 2006.

2.2.2 Sea Level Rise

Observations since 1961 show that the average temperature of the global ocean has increased at depths of up to 3000 meters and that the ocean has been absorbing more than 80% of the heat added to the climate system (IPCC 2007). This warming causes seawater to expand, contributing to sea level rise. The global average sea level rose at an average rate of 1.8 millimeters per year (mm/yr, or approximately 0.07 inches/year) from 1961 to 2003. The

rate increased to about 3.1 mm/yr (0.122 inches/year) from 1993 to 2003. Whether the higher rate for 1993 to 2003 reflects climate variability which is observed every ten or so years, or an increase in the longer-term trend is unknown.

The total 20th century global average sea level rise is estimated to be 0.17 meters (6.7 inches). A recent assessment for the State of California (California Department of Water Resources [CDWR] 2006) indicates that the observed relative sea level rise in that state was consistent with those reported for global increases.

Although sea level rise is difficult to measure in the gulf region as a result of simultaneous deltaic and coastal subsidence, the U.S. Global Change Research Program, National Assessment Synthesis Team (USGRP 2001) found that high tidal flood elevations have increased by approximately 0.3 meters (about 12 inches) since 1852. The rate of relative sea level rise (sea level rise plus subsidence) for Galveston and Port Isabel, Texas were reported to range from approximately 3.3 mm/yr (0.13 inches/year) in Port Isabel to 6.2 mm/yr (0.244 inches/year) at Galveston (Penland et al. 1989). The reported subsidence rates, when corrected for sea level rise, range from 1.0 to 5.0 mm/yr (0.04 to 0.2 inches per year) for the coast of Texas (Port Isabel to Galveston, respectively).

2.2.3 Precipitation

On a global scale, long-term trends in precipitation amounts from 1900 to 2005 have been observed over many regions of the world. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Precipitation, however, is highly variable, both spatially and temporally, and continues to be an area of uncertainty for many regions of the world. Changes in precipitation and evaporation over the oceans are suggested by freshening of mid and high latitude waters, together with increased salinity in low latitude waters (IPCC 2007). The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapor.

The observed precipitation trends for Texas for the 20th century show considerable variability (Figure 8). Northern Texas (in the Panhandle area) and southwestern Texas have exhibited slight reductions in precipitation over the 20th century while much of the rest of Texas has experienced slight increases in precipitation (USGRP 2001). This figure underscores that precipitation is inherently highly variable. Trend analysis performed by the National Oceanographic and Atmospheric Administration (NOAA 2007) indicates an observed increase in precipitation for most of Texas with increases greater in the east and negligible to slight increases in the west (Figure 9).

EXHIBIT 8.
Precipitation Change in United States during 1900's (Source: USGRP 2001)

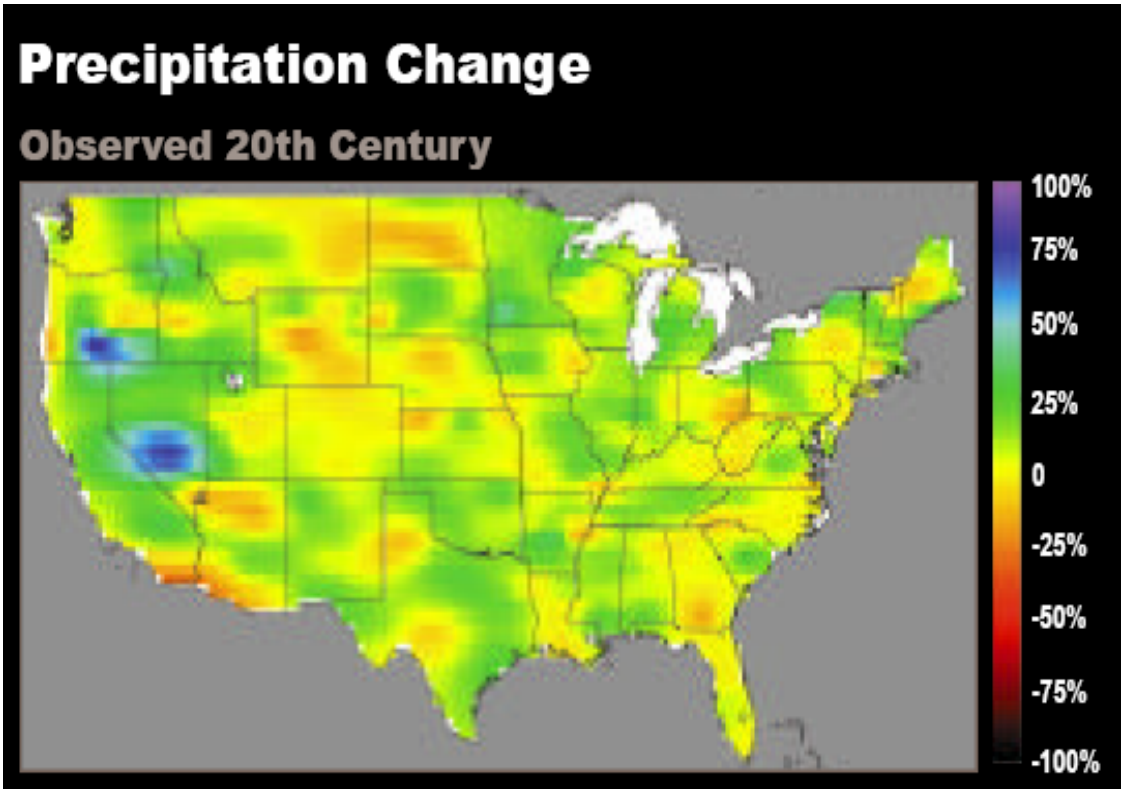
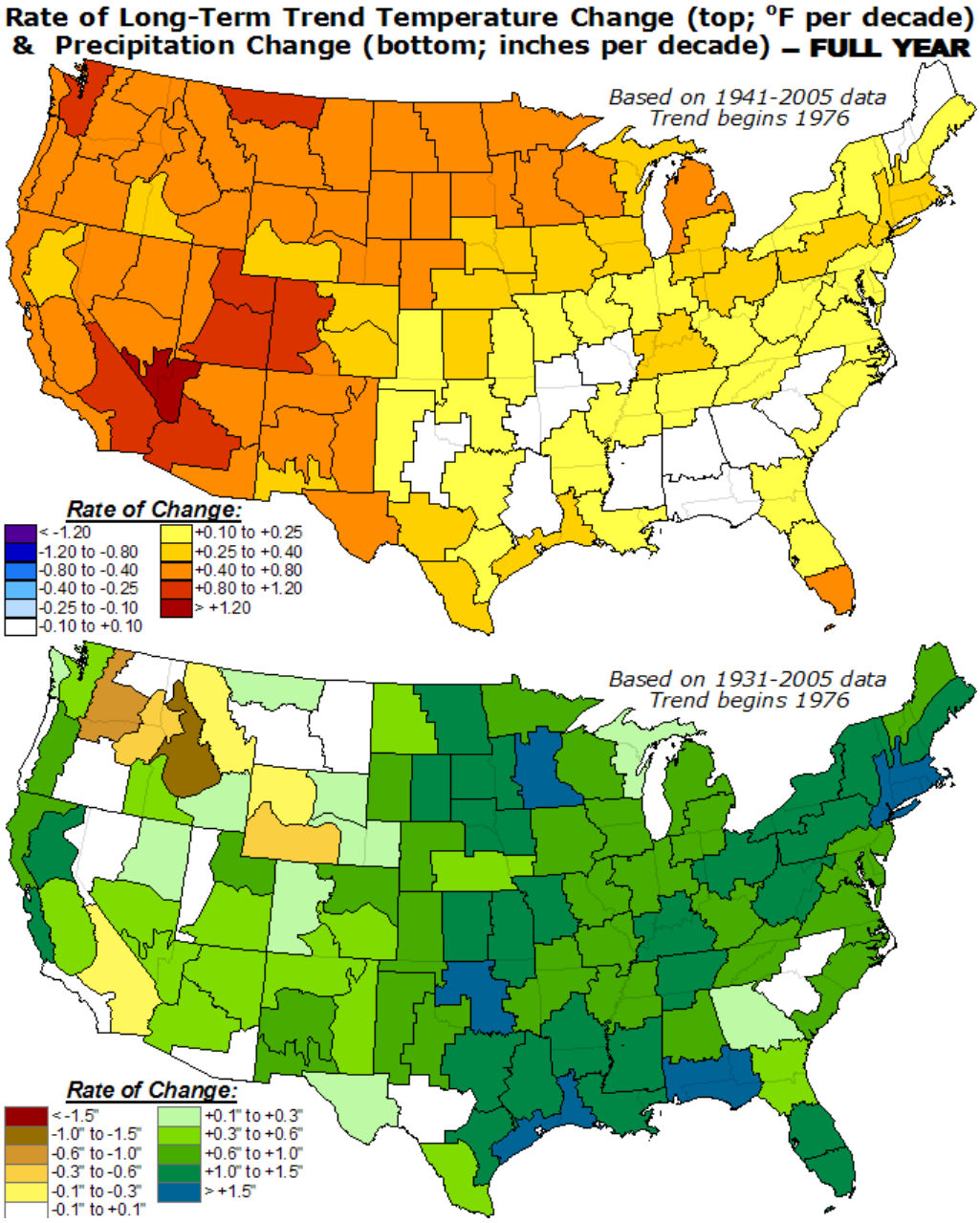


FIGURE 9.
Long-Term Linear Trend Rates for Annual Temperature and Precipitation in the U.S. (Source: Climate Prediction Center http://www.cpc.ncep.noaa.gov/trndtext.shtml)



2.2.4 Climate Variability and Extreme Events

Consistent with increased warming of land surface and oceans, the hydrologic cycle is expected to become more variable. That is, those areas that are trending toward drier seasonal rainfall rates are experiencing more droughts, and those areas trending toward greater rainfall are experiencing more significant flood events.

Recent findings included in the IPCC Fourth Assessment Report (2007) indicate that droughts have become longer and more intense, and the frequency of heavy precipitation

events has increased over most land areas. While there is also some evidence of an increase of intense tropical cyclone activity in the north Atlantic since 1970, there is no clear trend in the annual numbers of tropical cyclones.

An important aspect of climate extremes is related to excessive drought or wet periods. A recent analysis by Dai et al. (1998) shows increases in the overall areas of the world affected by either drought or excessive wetness. The IPCC (2007) reports that increased drying linked to higher temperatures and decreased precipitation has contributed to a change in drought frequency, extent, and severity. There is also evidence that regions influenced by the El Niño -Southern Oscillation phenomenon will experience greater variability associated with changes in this index (Dai et al. 1988; IPCC 2001). While weather in Texas is influenced by El Niño -Southern Oscillation (North et al. 1995) and would be expected to become more variable, no specific studies regarding potential effects on the gulf coast region were identified as the submittal of this report in the spring of 2007. Examination of drought during the 20th century in the U.S. shows that there is considerable variability, with the droughts of the 1930s and 1950s dominating any long-term trend (Easterling et al. 2000). Recent investigation of longer-term variability over the past 2000 years using paleoclimatic data (proxy data such as tree-rings to indicate climate over geologic periods) indicates that large droughts, such as those experienced in the 1930s can be expected to occur once or twice a century in the central United States, and that multi-decadal mega-droughts extending over larger areas occur every few hundred years (Woodhouse and Overpeck 1998).

Although long-term trends in drought are more difficult to discern from the limited available data, the area of the U.S. experiencing excessive wetness appears to be increasing, particularly since the 1970s (Easterling et al. 2000). Recent work aimed at predicting future drought severity (Hoerling 2007), however, suggests that even areas experiencing modest precipitation increases could experience drought as a result of the overwhelming effect of heat-related moisture loss due to evaporation and evapotranspiration.

Data suggest that areas experiencing significant increases or decreases in monthly or seasonal precipitation are also experiencing a change in the amount of precipitation falling during heavy and extreme precipitation events. Over these areas, there have been changes in both the seasonal totals and the frequency of 1-day heavy precipitation events. In either case, however, the heavy precipitation changes were always disproportionately large (Easterling et al. 2000).

2.3 Projections of Future Changes in Climate

2.3.1 Climate Change Scenarios

Given the relationship between anthropogenic sources of atmospheric gases that affect temperature and climate change, projections of future climate conditions will vary based on assumptions about future global socio-economic activities. The IPCC Special Report on Emissions Scenarios (SRES) developed a set of possible emissions scenarios based on different potential global development futures. Four basic “futures” were developed, each having several variations. Once the future scenarios were developed, green house emissions values were assigned to the various scenarios. These scenarios attempt to bracket the range

of fossil fuel use, regional political and social conditions, technologies, population, and governance and associated emissions that could result in the future. The focus for this report includes those factors affecting the parameters used to measure global climate change. In Table 1, each future will be referred to as a "scenario" or "scenario family".

TABLE 1.
Four Potential Global Scenarios (Source: IPCC Special Report of Emission Scenarios, 2000 and California Department of Water Resources, 2006)

"SCENARIO FAMILY" (Special Report on Emission Scenarios)	DESCRIPTION	KEY CHARACTERISTICS
A1	Second highest green house emissions	• Population growth is relatively low • Global economic growth occurs rapidly • New and more efficient technologies introduced rapidly
A2	Highest green house emissions	• High population growth • Regional economic growth which is somewhat slower that A1 • Fragmented technological changes
B1	Lowest green house emissions	• Population growth is relatively low as in Scenario A1 • Rapid economic growth moving towards service and information orientation • Sustainable technology introduced Economic growth moves rapidly • Natural resource consumption is reduced
B2	Second lowest green house emissions	• Moderate population growth • Intermediate levels of economic growth • Less rapid and more diverse technological development

Each of the four storylines, or scenario families, with key characteristics were developed and then modeled using 6 different models to create 40 separate scenarios. The IPCC selected a "marker", or representative scenario to represent each of the scenario families. For example, the marker for scenario family A1 is scenario A1B. Within scenario A1, variants were created to reflect intensive fossil fuel use (A1FI) and non-fossil fuel use (A1T).

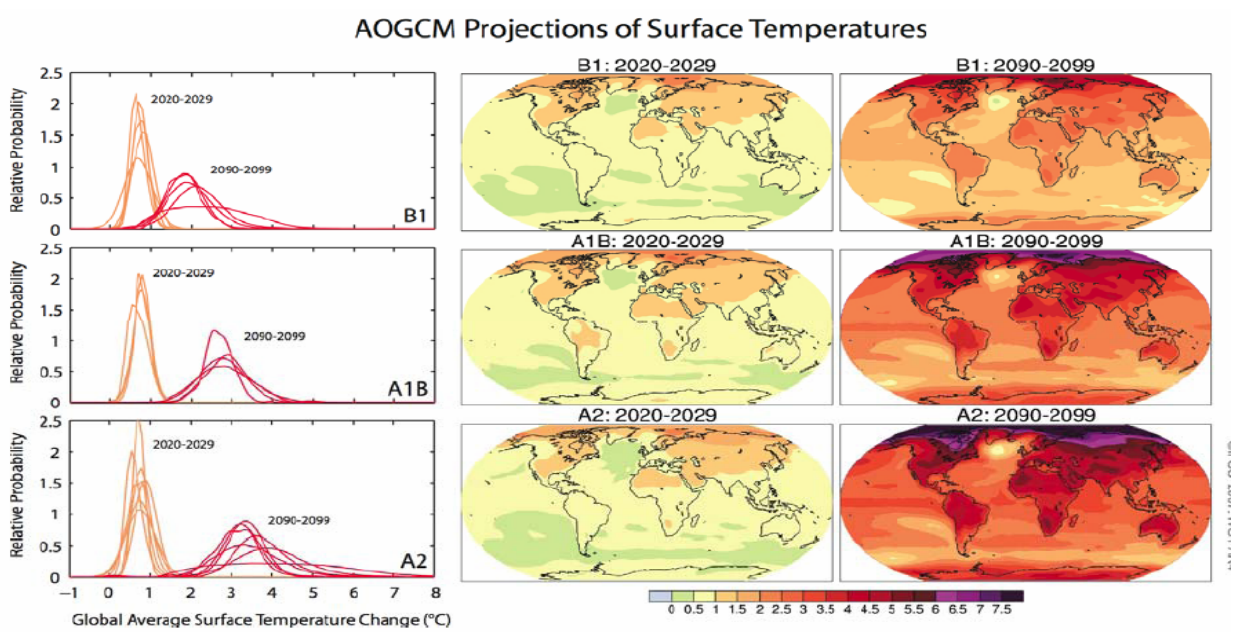
Projections of possible future climate changes are made by applying atmospheric-oceanic global circulation models to each the emission scenarios described above. In the most recent projections of potential climate changes (IPCC 2007), over 20 global circulation models were applied to each scenario, including the Parallel Climate Model (PCM) from the National Center for Atmospheric Research (NCAR) and the U.S. Department of Energy (DOE), and the Geophysical Fluids Dynamics Laboratory (GFDL) CM2.1 model from the National

Oceanographic and Atmospheric Administration . Using historical data for temperature and other parameters as a baseline, the global circulation models, driven by the emission scenarios, produce projections of global climate change variables such as temperature, sea level, precipitation, droughts, and floods. The results also depict the range of uncertainty in future conditions and understanding of Earth's climate system, thus providing important information to the decision-maker that can be used to develop adaptation and mitigation approaches to address climate change effects. Predictions on each of the variables will be described in the following sections.

2.3.2 Projected Temperature Changes

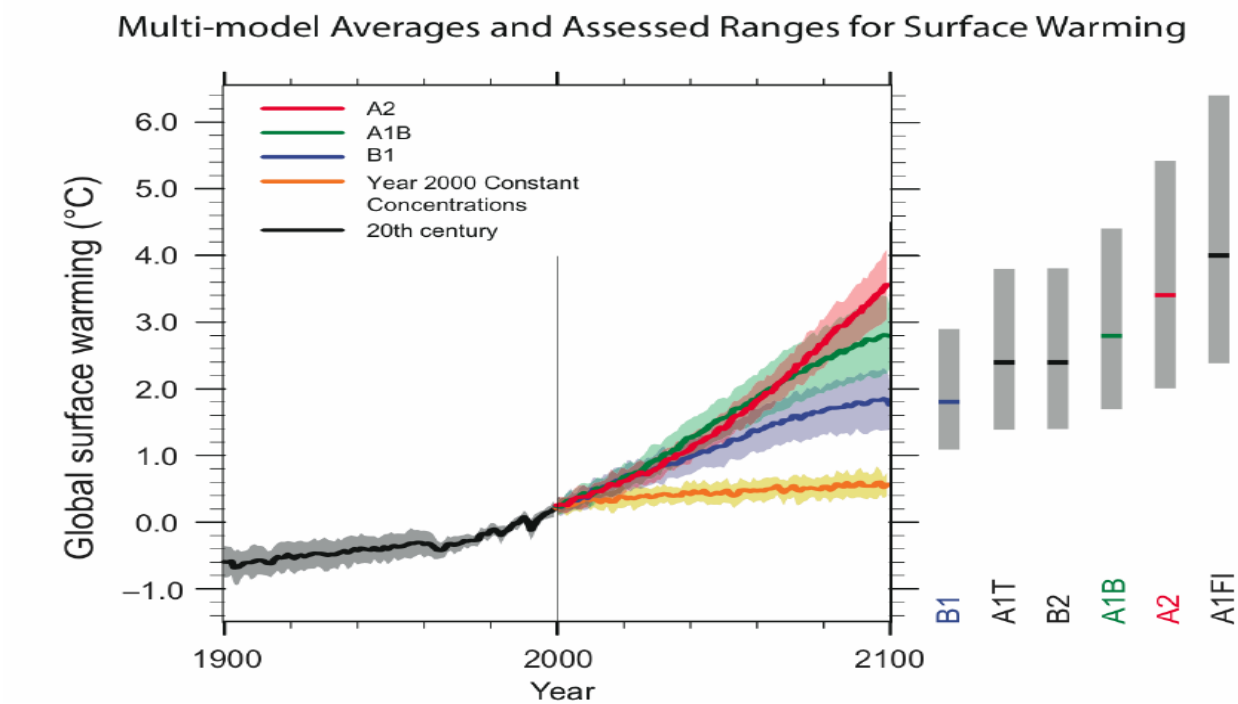
Multi-model projections indicate future global warming of about 0.2 °C (0.36°F) per decade for the next two decades for all of the scenarios described in Table 1. Even if the concentration of all greenhouse gases and aerosols had been held constant at 2000 levels, a warming of about 0.1 °C (0.18°F) per decade would be expected (IPCC 2007). Note that temperature projections through about 2030 are relatively insensitive to the emission scenario selected for analysis because the climate system, influenced primarily by oceans and atmosphere greenhouse gas concentrations, responds slowly. Estimates of globally averaged surface air warming in longer term projections, however, range from 1.8°C (3.2°F) for the low emission scenario to 4.0°C (7.2°F) for the high scenario relative to the mean for 1980-1999. The uncertainty, however, suggests that the range of warming could be as low as 1.1°C (2.0°F) and as high as 6.4°C (11.5°F). The direction (increase) of future temperature change is consistent throughout the globe and across scenarios and depicts significantly greater warming toward the arctic region (Figures 11 and 12).

FIGURE 11.
Global Climate Model Projections of Surface Temperature (Source: IPCC 2007)



As described in more detail in Table 1, scenario A1B was used by the IPCC as illustrative of the A1 Scenario Family.

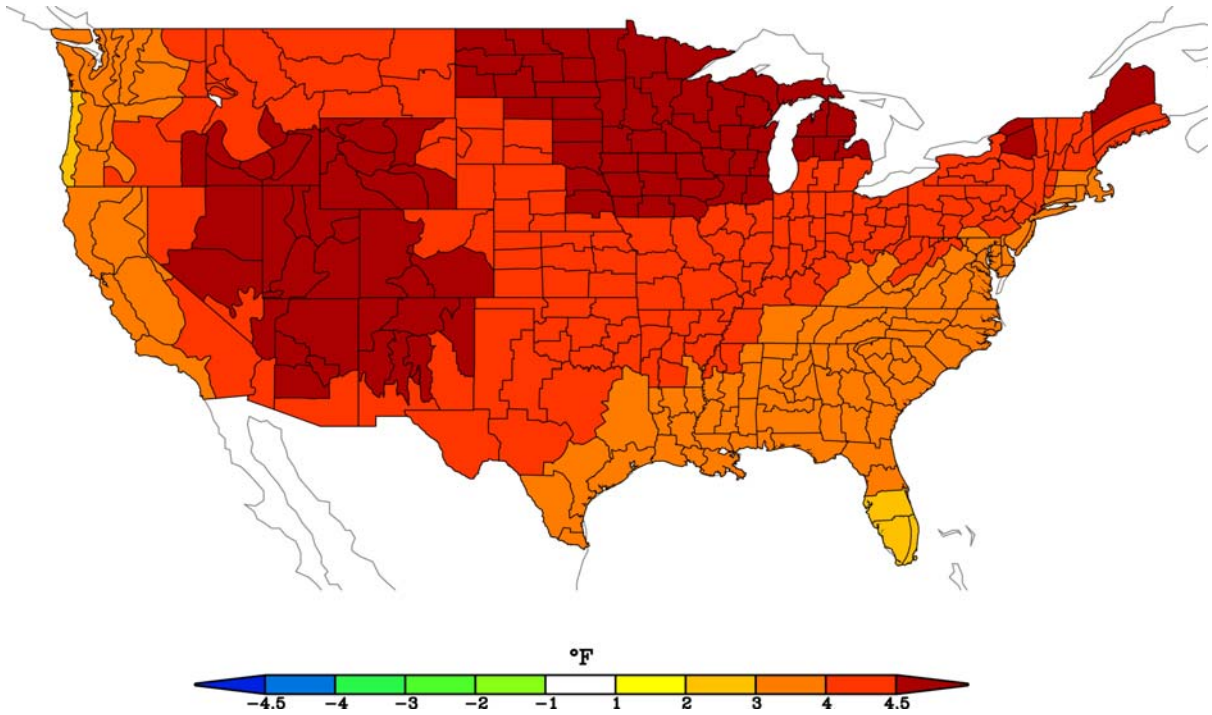
FIGURE 12.
Multi-Modal Averages and Assessed Ranges for Surface Warming on Global Scale (Source: IPCC 2007)



Note that IPCC developed each of the four "futures" with variations. Each of the basic scenarios is labeled A1, A2, B1, and B2 as indicated in Table 1. Scenario A1B is the "marker" or representative scenario used for the A1 scenario "family." A1T is the scenario with low fossil fuel use, while A1FI represents a fossil fuel intensive future.

Projected temperature changes in Texas are similar to that represented as the global average change and may range from just under 2°C (4°F) to about 4°C (8°F)(Figure 13).

FIGURE 13.
Change in Annual Temperature 2035-2060 (Source: Hoerling and Eischeid 2006)



2.3.3 Projected Sea Level Rise

Global average sea level increases are projected to accelerate relative to the rise experienced in the late 20th century. Sea levels are projected to increase by 0.18 to 0.38 meters (0.59 to 1.25 feet) by the end of the century under the low emission scenario and by 0.26 to 0.59 meters (0.85 to 1.93 feet) for the high emission scenario (IPCC 2007). These increases in sea level projected in the Fourth Assessment Report (AR4) are somewhat smaller than those projected in the Third Assessment Report (TAR) (IPCC 2001 and USGRP 2001), a difference largely related to improved information about uncertainties and contributions. Within the gulf coast region, sea level rise cannot be described without also considering the combined effect of coastal land subsidence. Assuming 0.10 meters (0.33 feet) per century of subsidence (UCS 2001, Penland et al. 1989), the "relative" sea level rise (sea level rise plus subsidence) would range from 0.28 to 0.69 meters (0.92 to 2.26 feet) by the end of the century as compared to 1980-1999 conditions.

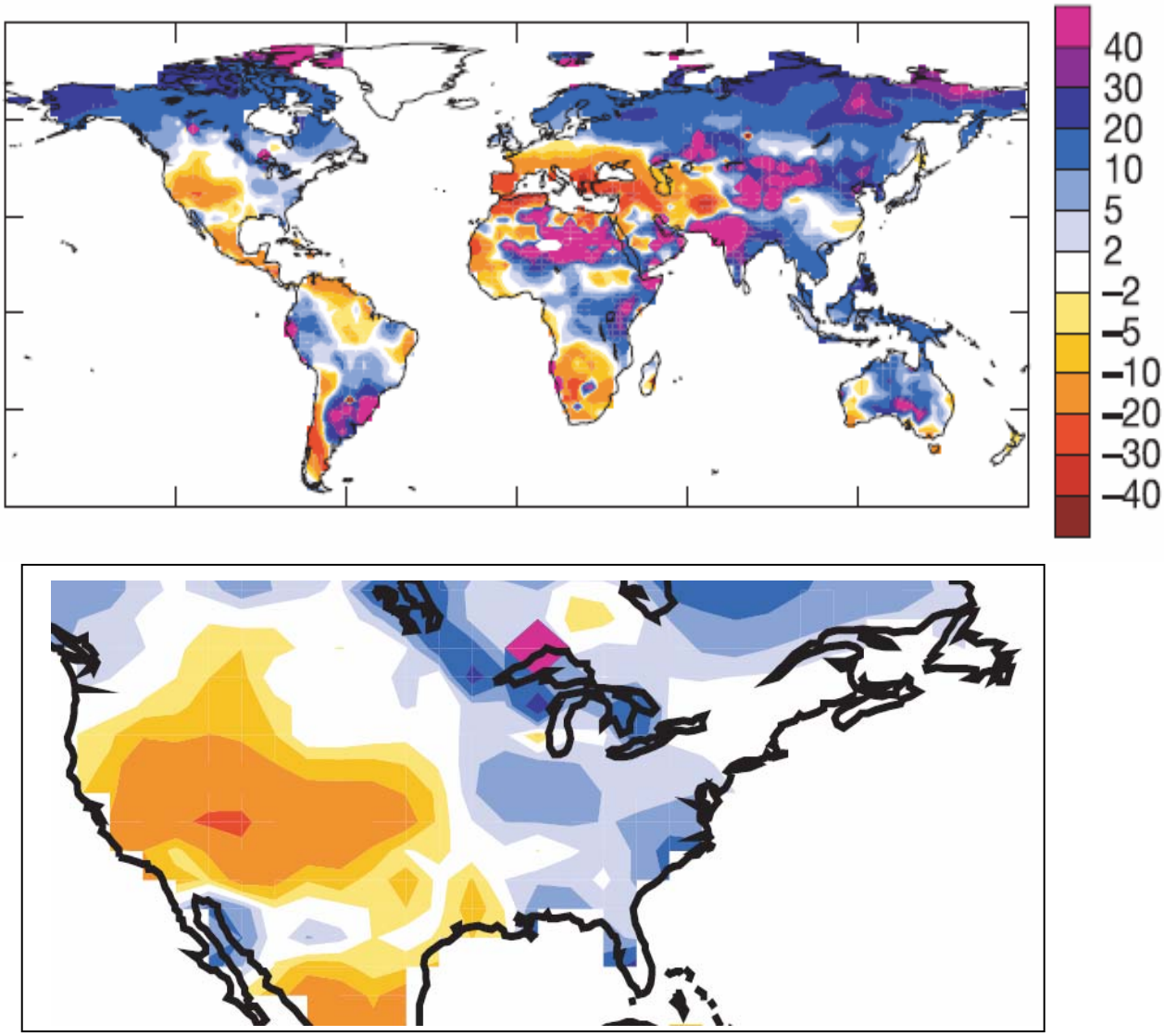
The sea level rise estimates provided above do not include possible rapid dynamic changes in ice flow that would contribute to significantly larger increases. These larger values cannot be excluded, but the current understanding is insufficient to assess the likelihood or upper bound on sea level rise (IPCC 2007).

2.3.4 Projected Precipitation Changes

Globally, higher temperatures should lead to higher rainfall because a warmer climate will contribute to higher rates of evaporation and a more active hydrologic cycle. However, the spatial distribution of moisture and precipitation changes is complex and drives regionally distinct trends. On a global scale, a poleward shift in storm tracks is projected to continue that trend observed in the last half century (IPCC 2007; Yin 2005). As a result, increases in the amount of precipitation are very likely at high-latitudes, while decreases are likely in most subtropical land regions (IPCC 2007). The prediction of changes in precipitation patterns continues to carry great uncertainty, and there remains a lack of consensus for many regions. However, recent scientific opinion appears to support the broad notion that "wet regions get wetter and dry regions get drier" (Held and Soden 2006; North, personal communication).

Based on the multi-model analyses of the IPCC (2007), southwest Texas may experience 5% to 20% decreases in average annual precipitation, north and northeast Texas may experience increases on the order of 5%, and there is no consensus for much of the rest of the state. Downscaling of the combined multi-model analyses would provide a better regional representation of the projections if developed and refined for Texas. A recent analysis of large-scale water availability using the most recent climate scenarios and models (Milly et al. 2005) indicates that mid-latitude central and western United States will experience decreases in streamflow (Figure 14). The range of streamflow changes in this study are on the same scale as the precipitation changes described previously.

FIGURE 14.
Projected Relative Percent Change in Runoff for 2041-2060 Compared to 1900-1970 Runoff (Source: Milly et al. 2005): Global view (top) and United States view (bottom).



2.3.5 Projected Changes to Climate Variability and Extreme Events

A long-standing concern has been the possibility of increased drought in the future as a result of increased greenhouse gases in the atmosphere. Increased heating ("global warming") produces increased drying and hence, evaporation, if moisture is available. Because evaporation generally exceeds precipitation across the United States in the summer months of July and August, increased summer continental drought is the primary risk. Drier soils and less recycled moisture in the atmosphere present a recipe for increased intensity, frequency, and duration of drought. These general mechanisms are found to occur in the new version of the model developed by NOAA's Geophysical Fluids Dynamics Lab (Trenberth et al. 2004).

A more vigorous hydrologic cycle, observed in the recent half century, is expected to continue over the next century. Dai et al. (1998) found increasing size and severity of droughts associated with this activity, while Easterling et al. (2000) also related increases in extreme precipitation events. Recent work by Hoerling (2007) provides an assessment of soil moisture and drought indices in the Southwest and across the United States (Hoerling and Escheid 2006) (Figure 15). Figure 15 references the Palmer drought index which is used by NOAA and many others as a way to determine the severity of a long-term drought. It uses a formula that incorporates local temperature and rainfall data, where "0" is normal for that area and drought severity is shown as negative numbers. The general findings of this work suggest that western states will likely experience more severe drying conditions due to the overwhelming impact of temperature increases on the evaporative demands, even in areas where slight increases in precipitation are projected (Figure 16).

FIGURE 15.
Projected Change in Palmer Drought Index, 2035-2060 (Source: Hoerling and Eischeid 2006)

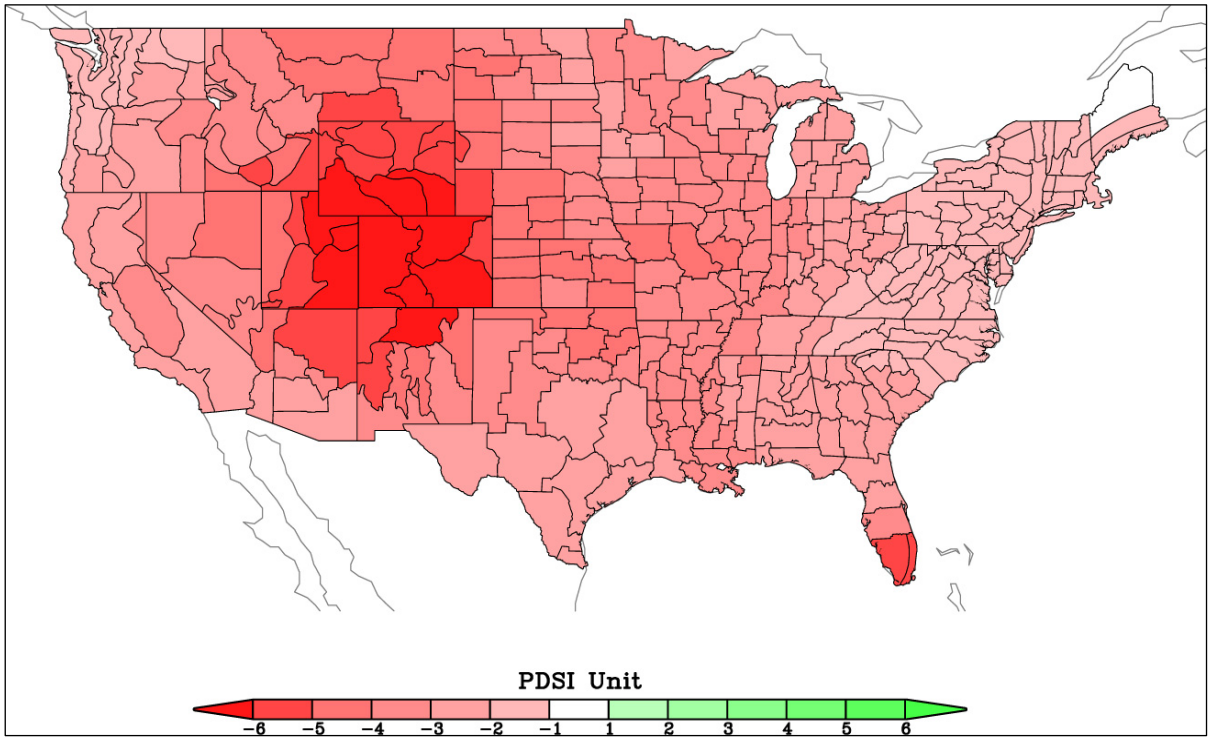
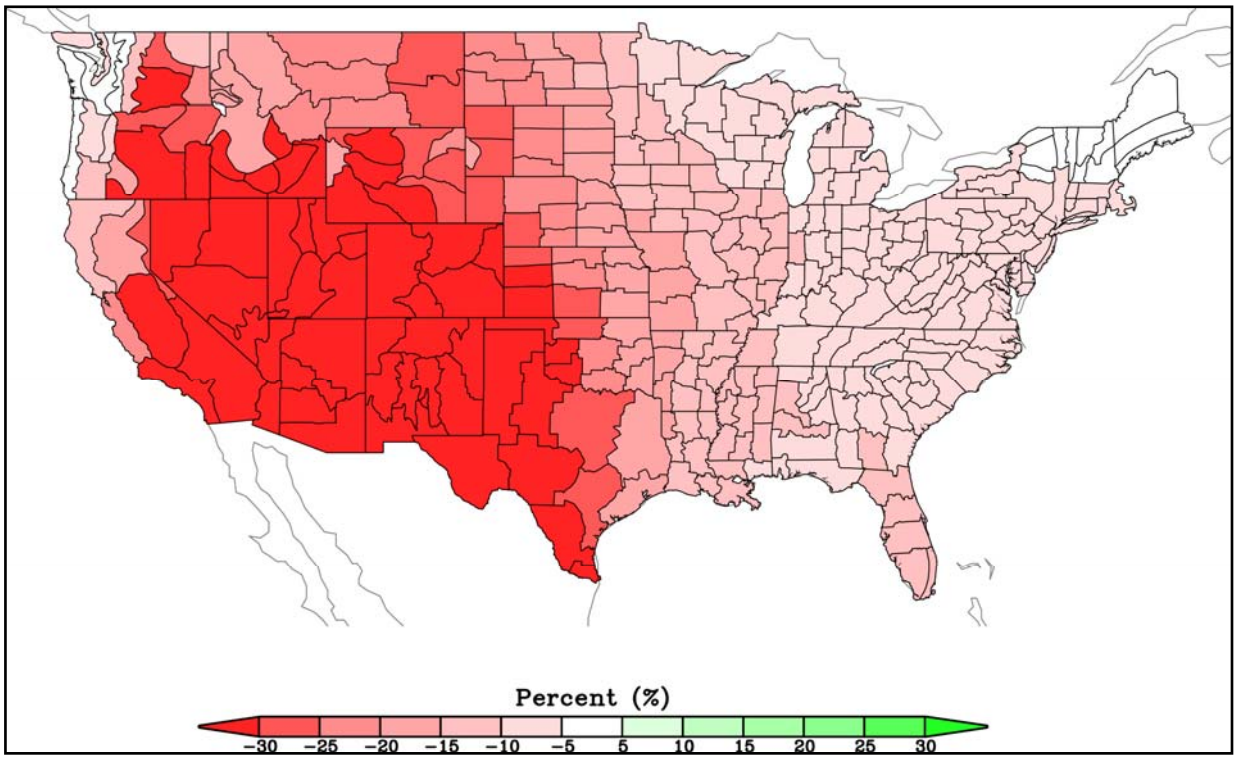


FIGURE 16.
Projected Change in Annual Precipitation minus Potential Evapotranspiration, 2035-2060 (Source: Hoerling and Eischeid 2006)



2.3.6 Abrupt Climate Change

When most people think about climate change, they imagine gradual increases in temperature and only marginal changes in other climatic conditions, continuing indefinitely or even leveling off at some time in the future. It is assumed that human societies can adapt to gradual climate change. However, recent climate change research has uncovered a disturbing feature of Earth's climate system: it is capable of sudden, violent shifts. Abrupt climate change is the subject of reports commissioned by the National Academy of Science (National Research Council 2002, 2005) and the U.S. Department of Defense (Schwartz and Randall 2003). Thus, in addition to the gradual (albeit accelerated) climate changes projected by current climate models, one needs to be aware of the possibility of much more sudden climate shifts.

Climate change will not necessarily be gradual, as assumed in most climate change projections, but may instead involve relatively sudden jumps between very different conditions. A mounting body of evidence suggests that continued increasing greenhouse gas emissions may push the oceans past a critical threshold and into a different future (CalEPA 2006).

2.4 Potential Climate Changes Affecting Texas

The table below summarizes how climate changes potentially will affect the Texas region. The values should be treated as an initial step in verifying possible impacts to Texas water resources, but significantly more detail may be provided through downscaling of global circulation model results to the region of interest when they have been refined to improve accuracy.

TABLE 2.
Summary of Key Climate Indicators and Potential Changes for Texas/ Gulf Coast Region

Climate Change Variable	Potential Magnitude of Change	Time Period	Range of Uncertainty	References
Temperature Increase	1.8 – 4.0 °C (3.2-7.2°F)	By 2100 related to 1980-99 mean	Absolute range between 1.1 °C and 6.4 °C (2 -11.5°F)	IPCC 2007
Sea Level Rise	0.18 – 0.59 m (0.59-1.93 ft.)	By 2100	0.10 m (0.33 ft.) per century adjustment for subsidence – could be higher. No assumptions of rapid changes to ice flow that could have significant effect on sea levels	IPCC 2007 UCS 2001 Penland et al. 1989
Precipitation Change	5-20% decreases in southwest; possible 5% increases in north/northeast; no consensus for much of state	By 2100	Downscaling would be required for better discretization	IPCC 2007
Precipitation minus Potential Evapo-transpiration (P-E)	Greater than 15% decrease throughout the state; greater than 25% decrease in central and west Texas	2035-2060	Downscaling would be required for better discretization	Hoerling and Eischeid 2006 Milly et al. 2007 Seager et al. 2007
Climate Variability	More severe droughts, response to more persistent El Niño activity More severe storm intensity Greater extremes			IPCC 2007 Easterling et al. 2000 Dai et al. 1998 Hoerling, 2007 Seager et al. 2007

3.0 Potential Impacts on Water Resources

Analysis of current projections of potential global-scale changes to key climate variables (temperature, precipitation, evaporation, and drought/flood events) for the Texas gulf coast area forms a foundation for identifying possible effects on water resources within the lower Colorado River watershed. Table 3 summarizes those potential impacts.

TABLE 3.
Potential Impacts of Climate Change on the Lower Colorado River Watershed

Climate Change Variable	Potential Impact to Water Resources	Key Issues
Temperature Increase	• Increased evaporation/evapotranspiration rates resulting in increased agricultural, industrial, municipal, and watershed demands • Longer agricultural growing season, greater productivity if water available • Changes in crop mix • Reduced baseflows as soil moisture is depleted earlier in the summer • Increased river, lake, and bay water temperatures • Reduced Dissolved Oxygen saturation in rivers and lakes • Increased algal productivity and eutrophication in lakes • Potential basin-wide salt management issues • Possible increased occurrence of foreign invasive species • Long-term changes in watershed vegetation • Increased wildfire potential • Dependence of power generation on temperature	• Changes in consumptive use demands (irrigation, industrial, municipal, and surface water evaporation) affecting water projected to be developed through conservation measures • Need to revisit temperature effects on evaporation as North suggests that previous analysis may not be appropriate • Water quality degradation and effects on ecosystem
Sea Level Rise	• Increased potential for seawater intrusion in coastal aquifers or brackish water supplies • Greater freshwater flow needs in tidal estuaries or bays to maintain salinity regime or changes could so alter the bay resulting in reduced need for freshwater inflows to the bay • Change in hydrodynamics and salt transport in estuaries and bays • Increased coastal flooding • Increased vulnerability of coastal infrastructure due to increased storm intensity • Significant disruption of ecosystems due to changing salinity regimes • Barrier islands compromised or submerged • Habitat shifts within bay boundaries • Scour/deposition patterns shift	• Ecosystem response due to changed salinity regimes • Fate of barrier islands and coastal protection for bay • Freshwater flow needs with increased landward salinity gradient

Climate Change Variable	Potential Impact to Water Resources	Key Issues
Precipitation and Runoff Changes	• Changes in precipitation and associated runoff or changes in seasonal distribution • More extremes in rainfall/runoff patterns • Reduced recharge to aquifers • Changes in total water availability • Increased flooding/sedimentation and potential re-allocation of reservoir storage for flood control purposes • Altered infiltration patterns due to precipitation totals or intensity affecting groundwater recharge • Decreased soil moisture may increase soil infiltration resulting in lower runoff and streamflows for the same precipitation (North et al.)	• Reductions in runoff and surface water availability • Sizing of off-channel reservoirs and pumps • Changes in agricultural demand due to changes in rainfall patterns • Reduced water available for diversion to LCRA-SAWS project due to reduced runoff and priority of run-of-river permit holders • Groundwater availability affected by reduced recharge rates
Evaporation increase and (P-E) decrease	• Loss of supply from reservoirs • Increased evaporation/evapotranspiration rates resulting in increased agricultural, municipal, and watershed demands • Less runoff due to increased evapotranspiration from plants and crops and lower soil moisture • Higher municipal demands for landscape irrigation as well as higher demands for agricultural users	• Reduced water available from upstream reservoirs and planned off-stream lakes • Changes in consumptive use demands affecting water projected to be developed through conservation measures
Climate Variability	• More active hydrologic cycle • Greater variability in annual inflow patterns likely to lead to more extreme droughts • Increases in frequency of both severe drought or wet spells • Evidence that regions influenced by El Niño will experience associated greater variability	• Sufficiency of “drought of record” for planning • Reliability of water supplies available for LCRA-SAWS project • Change in extreme precipitation events affecting sizing of facilities
Abrupt Climate Change	• Abrupt sea level rise due to rapid changes in glacial melting • Abrupt change in ocean currents or melting permafrost causing rapid changes in global temperatures	• Beyond current ability to predict • Impacts likely to be larger than which could be addressed on a project by project basis

4.0 Framework for Addressing Climate Change for LCRA-SAWS Water Project

4.1 Long-Term Framework

Climate change represents a planning problem facing decision-makers at local, national and global levels. The degree and nature of the impacts of climate change are potentially large but uncertain, cutting across multi-faceted issues in planning. Richard Alley, the leading U.S. climate change scientist, describes the fundamental issues:

> "Policymakers look to climate change science to answer two big questions: what could we do to prepare for the impacts of climate change, and what steps might be taken to slow it?" (NAS 2006a)

The second question "what steps may be taken to slow climate change?" is termed "mitigation" as these measures attempt to mitigate for the causes of climate change. This question is beyond the scope of this report. However, the first question dealing with "what could we do to prepare for the impacts of climate change?" is termed "adaptation" and is the focus of the report. Understanding the impacts and developing adaptation measures are the primary focus of many water resources planning efforts.

Faced with climate changes that are both uncertain and long-term in nature, a useful approach facilitates incorporation of new information, new technology and new adaptations into water resources projects. In general, the framework for this approach includes:

- Planning
- Assessing impacts and vulnerabilities
- Developing adaptive strategies
- Implementing strategies
- Monitoring results and updating the plan

4.1.1 Plan

Current analyses suggest that the global climate is changing and increases in frequency and magnitude of both drought and wet spells are expected. Climate models indicate that regions that are influenced by the El Niño effect, such as the central and gulf coast regions of Texas, will experience greater variability in future climatic patterns than they have experienced in the past (Dai et al., 1988; IPCC 2001).

The water resources industry has often relied on recent past climate for which data are available as a reasonable representation of the range of likely future conditions. Because climate science is predicting greater variability than that captured in the period of record for most watersheds, it may be appropriate to begin to develop new methodologies for assessing impacts and risk associated with water supply on a watershed basis. These tools are not yet developed for application on a regional or project-by-project basis; however, the time may be ripe for such enhancement of the planning process.

In the interim, methods may be employed to forecast a range of implications to assist decision-makers and stakeholders in identifying and assessing potential impacts, evaluating trade-offs and developing adaptation strategies as change happens. Regardless of methods and approaches, it is important to initiate a planning process to begin to understand the relationship of the climate to the system response or performance. The planning for climate change can be similar to that which is applied to address other pressures on natural resources such as population growth. This report is an important first step in the planning process.

4.1.2 Assess Impacts and Vulnerabilities

The two approaches used to forecast impacts of climate change are through assessment of impacts or through assessment of project/system vulnerability. These can be used independently or in concert with each other. Impacts refer to both positive and negative changes in significant project/system/or related parameters. Impacts simply describe the degree of change from a baseline condition. Vulnerabilities refer to the degree to which the stated performance of a project/system may become at risk. Both impacts and vulnerabilities are important in assessing climate change effects on water resources management.

4.1.3 Develop Adaptation Strategies

Adaptation strategies refer to those structural or management changes that minimize the risk identified during the assessment phase. Structural modifications could include providing for greater storage in either reservoirs or aquifer storage and recovery systems, or larger diversion works to capture flood flows or recharge enhancement features to detain run-off for groundwater banking. Management opportunities for adapting to potential climate change include those programs or operational changes that manage demand in response to changing climate patterns. For example, if forecast changes include greater frequency of dry periods that are likely to result in greater agricultural demands, then programs such as dry-year options to transfer water use from the agricultural to municipal sector may be appropriate. Similarly, developing incentive programs to shift peak industrial or municipal demands from summer to winter may make sense if greater winter rainfall is forecast or occurs.

Incorporating risk management assessment into decision-making regarding facilities and their management is an important adaptation strategy. This suggests developing phase-in alternatives for projects if, for example, precipitation patterns fluctuate from historic trends upon which facilities' sizing is based and additional storage would produce required project yield.

Similarly, finding synergies among existing and planned projects and management strategies may minimize the risk of the effects of climate change. For example, recharge enhancement projects identified as potential structural strategies could be coupled with regional banking agreements for those times when groundwater production is needed to supplement a surface water project.

4.1.4 Implement Strategies

Based on the planning criteria, results of analyses, and assessment of various structural and management changes, decisions can be made about which adaptive strategies to implement. Methods of measuring their effectiveness should be established prior to or during the early phases of implementation. Specific focus should be given to adaptive management principles and concepts that would minimize the risk, maximize the flexibility, and reduce the initial committed costs of projects.

4.1.5 Monitor and Update

The effectiveness of the implemented strategies should be measured and tracked. Additionally, the assessment of likely impacts should be updated as the ability to accurately forecast the impacts of climate change on those key parameters affecting water resources evolves. As predictions change, the process to engage stakeholders, determine acceptable bounds for system performance and to identify meaningful adaptive strategies should continue.

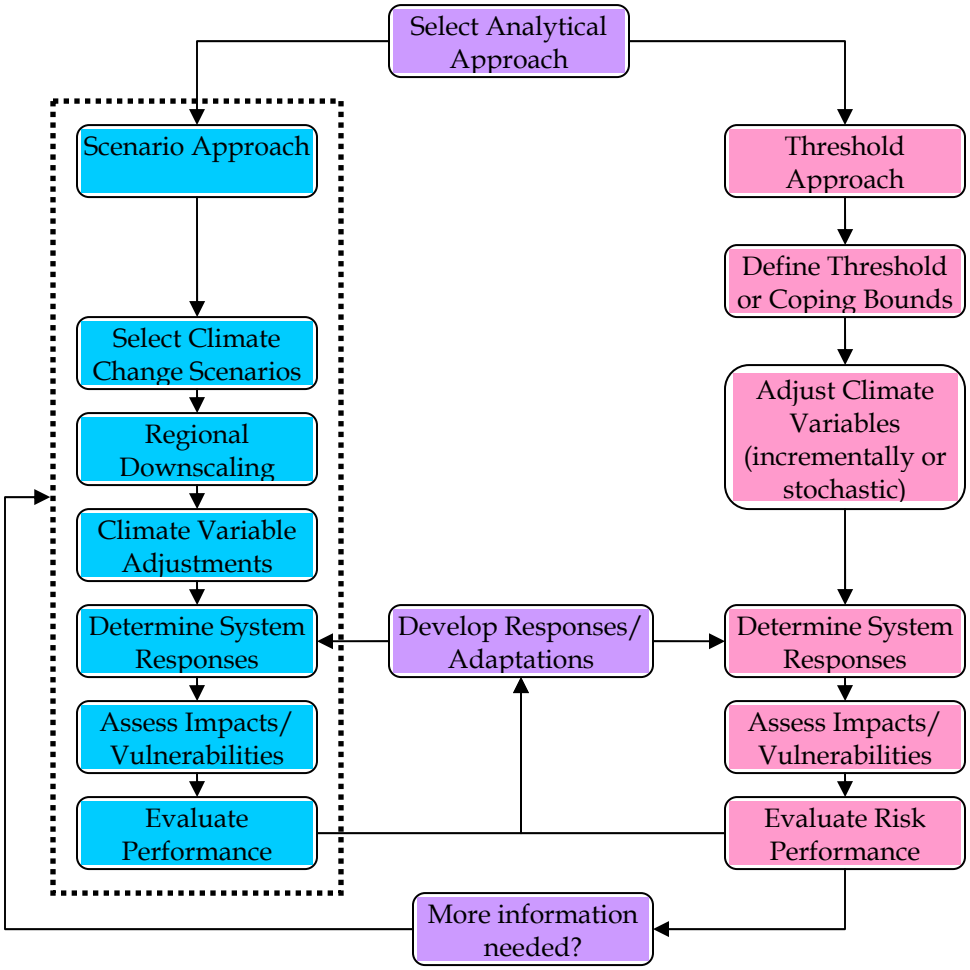
4.2 Analytical Framework for LCRA-SAWS Water Project

An analytical framework for assessing impacts and vulnerabilities of the project due to potential changes in climate is reported here. The analytical framework is needed to provide context and direction for managers and for various technical analyses, to maintain consistency of climate change assumptions throughout the assessment, to describe the integrated nature of the analyses, and to formally describe impacts, uncertainties, and risks. The overall analytical framework, described in detail below, consists of the following processes/actions:

- Define either evaluation/performance or more specific threshold criteria
- Select analytical approach
- Select climate change scenarios
- Downscale climate changes to regional level (using climate models, or statistical methods or macroscale hydrologic models)
- Adjust climatic inputs to analytical tools used by the project's study teams
- Determine natural and human system responses
- Assess impacts and vulnerabilities
- Develop and apply adaptation strategies to minimize risk

The overall framework and information flow is illustrated in Figure 17.

FIGURE 17
Regional Assessment Process Framework



4.2.1 Evaluation or Threshold Criteria

Evaluation or performance criteria should be established very early in the process to provide a formal measurement of the system impacts caused by changes in climate. Examples of potential evaluation criteria for the LCRA-SAWS project include changes in the reliability of surface water availability for the project or changes in the salinity regime of Matagorda Bay. Alternatively, threshold criteria could be established and used to estimate the vulnerability of various project/system components due to climate changes. Examples of threshold criteria include maintaining at least 90% reliability of project supplies or experiencing salinity intrusion of no more than one mile.

- *Recommendation*: We recommend that the analysis of potential implications of climate change focus on the development of broad-based evaluation or performance criteria (e.g., changes in the salinity regime of the bay) rather than specific threshold criteria (e.g., a specific salinity concentration measured at a specified location). These types of criteria allow greater flexibility and a broader understanding of how impacts over time

are consistent with the legislative criteria and approach used in current project analyses. Threshold criteria could be subsequently applied, if desired.

4.2.2 Analytical Approach

Two analytical approaches have been applied to analyze the effects of climate change on water resources projects: the ***scenario*** approach and the ***threshold*** approach. Each approach has advantages and disadvantages, and often hybrid forms are applied.

The scenario approach, considered a "top-down" approach, utilizes the mean values of specific climate change scenarios to describe the bookends, or range, of potential climate changes. These changes are then used to drive individual deterministic assessments of the system impacts. The results of this analytical approach are system impacts at the mean of the selected scenarios. The scenario approach was applied by the California Department of Water Resources (2006) in their initial assessment of potential changes to water management in that state. A similar, less rigorous, approach was applied in North et al. (1995) for assessing impacts in Texas. A simplified version of this approach can be thought of as "screening" or "sensitivity" in that the main goal is to characterize the relative system response due to specific changes in climatic inputs. In the "screening" approach the treatment of climate change is usually considered on a coarse scale. The advantage of the scenario approach is that it conforms rather well to most standard impact assessments in which one or more alternatives are compared to a base condition and it is also more likely be implementable without significant changes to existing modeling tools. The disadvantage of the scenario approach is that it ignores the uncertainty associated with climate change scenarios. Even the uncertainty associated the individual selected scenarios is not addressed because typically only the mean value is carried forward.

The threshold approach, considered a "bottom-up" approach, starts with the system and evaluates its adaptive capability compared to a threshold. The response of the system to a range of climate variable changes can be performed either incrementally or through stochastic methods. The adaptive capability of the system, range of adaptation before threshold reached, can then be assessed and compared to the potential impacts that may be caused by climate change scenarios. It is more likely, however, that this approach would be used in a hybrid form where initial climate scenario estimates would be used to test the adaptive capability of the system and refined after initial vulnerabilities are identified. Since the threshold approach often is associated with risk assessment, the entire range of possible climate scenarios may be addressed through probability or possibility distributions. Probabilistic methods (e.g., Monte Carlo) are then applied to sample the distributions many times (usually on the order of several hundred to thousands of times) and solve the system response for each unique climate trace. The results of this analytical approach are descriptions of the statistical probability of system impacts and can be utilized in more formal risk analysis. The advantage of this approach is that it preserves the uncertainty associated with climate scenarios, provides a potentially more robust set of information, and can be directly applied in risk analyses. The disadvantage of this approach is that it generally is significantly more computationally intensive, often requires modification to existing deterministic modeling tools, and requires careful preservation of the joint probabilities of different climate variables.

Recommendation: The selected approach will be largely dependent on the analytical methods of existing tools and on stakeholder acceptance and understanding of statistical methods. Based on our current understanding of the existing analytical tools being used for the analyses on the LCRA-SAWS Water Project, we recommend that a scenario approach be pursued initially. If the selection of climate change scenarios proves unwieldy or is believed to be too sensitive, a threshold approach may be adopted initially. If the entities involved would like a more rigorous analysis in the future, the modeling tools and methods would need to be modified to perform an uncertainty/risk analysis. By utilizing the scenario approach initially, a range of implications can be forecast such that decisions regarding the benefits of a more robust assessment of uncertainty analyses can be better gauged.

4.2.3 Climate Change Scenarios

Climate change scenarios are a function of both socio-economic assumptions and atmospheric-oceanic global climate model predictions. Guidance provided from scientists at the Scripps Institute of Oceanography (CalEPA 2006) led to the selection of two moderate climate change scenarios for use in analyses of impacts to water resources in California in the 2006 "progress" report to the governor published by the Department of Water Resources. These two scenarios are the higher emission scenario and the lower emission scenario. The results for these scenarios, as simulated by the two U.S.-supported climate models, Parallel Climate Model and NOAA's Geophysical Fluids Dynamics Laboratory model, are used to characterize the range of possible climate changes.

Alternatively, under the threshold approach increments, or distributions, of climate variable changes may be used to bound the range of possible climate change effects. In this case, the changes are not specifically tied any particular Special Report on Emissions Scenarios scenario, but are assumed to capture the range that may be possible under these scenarios.

Recommendation: The climate scenarios and global climate models selected for use in analyses in California appear reasonable for capturing the range of potential changes in climate variables. We recommend that these climate scenarios be utilized in analyses for the project.

4.2.4 Regional Downscaling

The global climate model predictions provide results for assessing impacts for the planet. The grid for these models is necessarily coarse. Downscaling is often applied to map the results of the global climate models to the specific region of interest. The regional downscaling usually involves a macroscale dynamic model (i.e. the Variable Infiltration Capacity [VIC] model from the University of Washington or the simplified water budget model developed by Ward [1993] for Texas), or statistical relationship that transfers the changes identified by global climate model results to that observed or simulated at the regional scale. Relationships are developed between observed parameters at the regional or local scale to the appropriate parameters at the global climate model scale under the historic simulations. These relationships are then assumed to apply for future changes; transferring the global climate model results to local-scale effects. This is particularly important for variables that are spatially heterogeneous or have significant orographic influences (affected by the land terrain). Precipitation changes often require downscaling for assessment of watershed scale impacts. Temperature changes, however, often can translate directly from

the atmospheric-oceanic global climate models without significant limitations. Guidance from climate centers or academic institutions is suggested to determine the best approach and whether much of this has already been performed for Texas.

Recommendation: We recommend that additional contact be made with the scientific community to understand what downscaling of the models used for the Fourth Assessment Report from the IPCC (AR4 models) may already be available for Texas or which institute/agency could provide these services. If the models are not currently developed and populated with data, regional downscaling may more appropriately be part of a long-range strategy to manage the lower Colorado River watershed rather than applied to project-specific analyses.

4.2.5 Adjust Climatic Inputs to Analytical Tools

Based on the results of the climate change scenarios and regional downscaling (if required), the climatic inputs to the analytical tools need to be adjusted to reflect anticipated future conditions. A common approach is to develop perturbation ratios or addition factors (Miller and Bashford 2001, Wurbs et al. 2006; CDWR 2006) to transfer regional scale climate change behavior to local scale historical data. The ratios or addition factors are derived by determining the relative change in the regional climate variable from the average value for the variable over a reference period (usually 30 years). The use of the macroscale hydrologic or statistical models is often used to generate these ratios. These factors are derived for each model grid cell overlying the region of interest and are developed on a seasonal basis (usually monthly). Revised input data sets can then be developed for the analytical tools by adjusting the historical inputs by the ratios and factors developed for the individual climate scenario.

Recommendation: We recommend that the methods suggested by Miller et al. (2001) and applied by California Department of Water Resources (2006), Wurbs et al. (2006), and others be applied for the water availability modeling. The adjustments would apply to both supply and demand components.

4.2.6 Determine System Responses (Apply Models)

Determination of system responses, at this point, is no different than current practice of assessing future system response. The modeling tools traditionally used to assess surface water availability, agricultural and urban demands, ecosystem response, groundwater system response, etc., all will have adjusted climatic inputs and the response can be ascertained from the results. For example, adjusted climatic inputs into the Water Availability Model will produce a modified availability of surface water, adjusted evaporation/evapotranspiration rates will result in modified agricultural and urban water demands, and adjusted temperatures and sea level rise will serve as modified boundary conditions to the bay hydrodynamic and water quality models.

4.2.7 Assess Impacts and Vulnerabilities

Based on the integration of results of the various system modeling tools, the impacts and vulnerabilities to the project can be assessed. The changes to the project supplies, reliability, ecosystem, economics, etc. can be compared to the evaluation or threshold criteria

established earlier and assessments can be made regarding the significance of the impacts or whether system/project vulnerability has been significantly increased.

4.2.8 Evaluate Adaptation Strategies to Minimize Risk

Depending on the assessment of impacts and vulnerabilities, project or system adaptation strategies may be considered to reduce the risk of decreased project performance related to potential changes in climate conditions. Once initial impacts and risks have been assessed and adaptation strategies developed, the analytical tools may need to be applied again to evaluate the suitability and efficacy of the strategies.

4.3 Summary of Recommendations

Due to the inherent uncertainty of the implications of climate change on water supply, a framework that plans for change, develops strategies to adjust to that expected change and reassesses whether the strategy is working as intended is recommended for the watershed. This approach would foster the development of tools that could transfer global data to the regional/local level.

While this approach is considered, we have specific recommendations for the technical analysis for the LCRA-SAWS Water Project.

- We recommend that the analysis focus on the development of broad-based evaluation or performance criteria (e.g., changes in the salinity regime of the bay) rather than specific threshold criteria (e.g., salinity concentration measured at a specified location). These types of criteria allow greater flexibility and a broader understanding of impacts over time.
- The selected approach will depend on the analytical methods of existing tools and on stakeholder acceptance and understanding of statistical methods. Based on our current understanding of the existing analytical tools being used for the analyses on the LCRA-SAWS Water Project, we recommend that a scenario approach be pursued initially. If the entities involved would like a more rigorous analysis in the future, the modeling tools and methods would need to be modified to perform an uncertainty/risk analysis. By utilizing the scenario approach initially, a range of implications can be forecast such that the benefits of a more robust assessment of uncertainty analyses can be better gauged.
- The climate scenarios and models selected for use in analyses in California in the 2006 Department of Water Resources "progress" report to the governor appear reasonable for capturing the range of potential changes in climate variables. We recommend that these climate scenarios be utilized in analyses for the project.
- We recommend that additional contact be made with the scientific community to understand if downscaling of the models used in the IPCC's Fourth Assessment Report may already be available for Texas or which institute/agency could provide these services. If the models are not developed and populated with data this may be more appropriately part of a long-range strategy to manage the lower Colorado River watershed rather than applied to the project analysis.

- We recommend that macroscale hydrologic models (such as VIC or the simplified water budget model by Ward [1993]) or statistical methods be developed to accept global climate model-scale results and translate into local scale hydrologic variables. Perturbation ratios or addition factors can then be applied to modify the historic hydrologic data. These data sets could then be used as input to simulate run-off, evaporation and other inputs to water availability in the future resulting from such changes in key parameters.
- With a revised set of input data based on the calculated ratios, the project study teams can then use current modeling tools to assess surface water availability (WAM/WRAP), agricultural and urban demands, changes to the Matagorda Bay ecosystem, groundwater system response and water quality (if desired).

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