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Condensing Water Availability Models

Desalination and Long-Haul Water Transfer as a Water Supply for Dallas, Texas

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Climate Change Impacts on Texas Water: A White Paper Assessment of the Past, Present and Future and Recommendations for Action

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Abstract: Texas comprises the eastern portion of the Southwest region, where the convergence of climatological and geopolitical forces has the potential to put extreme stress on water resources. Geologic records indicate that Texas experienced large climate changes on millennial time scales in the past, and over the last thousand years, tree-ring records indicate that there were significant periods of drought in Texas. These droughts were of longer duration than the 1950s "drought of record" that is commonly used in planning, and they occurred independently of human-induced global climate change. Although there has been a negligible net temperature increase in Texas over the past century, temperatures have increased more significantly over the past three decades. Under essentially all climate model projections, Texas is susceptible to significant climate change in the future. Most projections for the 21st century show that with increasing atmospheric greenhouse gas concentrations, there will be an increase in temperatures across Texas and a shift to a more arid average climate. Studies agree that Texas will likely become significantly warmer and drier, yet the magnitude, timing, and regional distribution of these changes are uncertain. There is a large uncertainty in the projected changes in precipitation for Texas for the 21st century. In contrast, the more robust projected increase in temperature with its effect on evaporation, which is a dominant component in the region's hydrologic cycle, is consistent with model projections of frequent and extended droughts throughout the state.

For these reasons, we recommend that Texas invest resources to investigate and anticipate the impacts of climate change on Texas' water resources, with the goal of providing data to inform resource planning. This investment should support development of 1) research programs that provide policy-relevant science; 2) education programs to engage future researchers and policy-makers; and 3) connections between policy-makers, scientists, water resource managers, and other stakeholders. It is proposed that these goals may be achieved through the establishment of a Texas Climate Consortium, consisting of representatives from academia, industry, government agencies, water authorities, and other stakeholders. The mission of this consortium would be to develop the capacity to provide decision makers with the information needed to develop adaptation strategies in the face of future climate change and uncertainty.

Keywords: climate change, drought, paleoclimate

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FOREWORD

"Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems."

These words, from the *Intergovernmental Panel on Climate Change Technical Paper VI: Climate Change and Water* (Bates et al. 2008), sound a sufficiently sobering call for more research, more deliberation, and more informed actions in efforts to mitigate predicted climate change impacts on Texas' water resources. And now, bolstering the vital importance of serious and timely attention to these matters, a report issued in December 2008 by the U.S. Climate Change Science Program suggests that earlier projections may have underestimated the climatic changes that could take place by 2100 and that the United States faces the possibility of much more rapid climate change by the end of the century than previous studies have suggested (Clark and Weaver 2008).

"Climate Change Impacts on Texas Water," produced by the Environmental Science Institute and the Jackson School of Geosciences at the University of Texas at Austin, focuses on the impacts and uncertainties of climate change on Texas and its water resources. Understanding climate change impacts on water resources is critical because of the implications of these impacts for many other important sectors, including agriculture, energy, ecosystems, and public health. The paper provides an excellent presentation of potential global climate change effects on Texas' water resources; identifies future scientific research efforts deemed necessary to develop more reliable climate projections; and proposes recommendations designed to enhance further collaborations between research scientists, regional and state water managers, policy-makers, consultants, and the public. If implemented, these recommendations can lead to potential policy changes and resource management decisions that may help prepare Texas for climate change impacts on its water resources.

Almost all climate model projections show that Texas is extremely susceptible to significant future climate variability and has the strong potential of extreme stress on its water resources. This fact, coupled with a rapid and concurrent population growth, will likely push water supply and demand issues in the state, especially in the urban areas, to the "breaking point." Texas has one of the world's most robust economies, but if sound, scientifically based water infrastructure and water management strategies are not implemented, Texas could face serious social, economic, and environmental consequences.

Given the possibilities that perfectly legitimate, science-based scenarios present or imply, Texas must act now to develop and implement feasible and effective measures to mitigate climate change impacts on its water resources. Texas has the world's greatest concentration of experts in energy research, finance, law, science, engineering, and business development. All this knowledge and all these skills can be applied to make Texas a world leader in addressing climate change and its predictable impacts. *Climate Change Impacts on Texas Water* is an excellent example of the application of such knowledge and expertise.

Larry R. Soward, Former Commissioner
Texas Commission on Environmental Quality

SUMMARY OF RECOMMENDATIONS

Based on our study, we find that climate change may have significant impact on the future of Texas' water resources and that large uncertainties exist regarding the nature and extent of the changes and impacts. Understanding the changes in climate, the impacts, and the uncertainties will require new initiatives to conduct policy-relevant scientific research. As a guide to this research process, we make the following series of recommendations:

1. Establish a Texas Climate Consortium (TCC), consisting of representatives from academia, industry, federal, state and local agencies, water resource managers, and other stakeholders. The proposed TCC will be administered by the Texas Water Development Board (TWDB). The proposed mission of the consortium includes: a) to serve as a state-level equivalent to the Intergovernmental Panel on Climate Change (IPCC) to bring together experts and stakeholders to investigate and report on the latest climate science to help inform policy and management, b) to identify high-priority science and policy topics related to Texas' climate change and water resources, and c) to identify resources needed for research and education.
2. Incorporate large droughts of the past into water planning. Whereas the current use of the 1950s drought as the drought of record has provided a baseline for water resource planning, paleoclimate studies indicate that longer-term "megadroughts" occurred in the past. An investment in research to improve the temporal and spatial resolution and accuracy of proxies for paleoclimate reconstructions will provide a more extended and accurate drought history for Texas. This research can be used to determine whether droughts that better represent the extremes documented in the 13th and 16th century should be considered in water planning.
3. Develop a statewide, real-time monitoring network of climate and hydrologic variability so that the response of water resources to extreme climate events can be determined.
4. Improve the applicability of climate models for the Texas region by supporting research to improve methods

to use global climate model results for "downscaling" to model projections for regions in Texas and assess the sources of uncertainty in climate model projections to determine how well models can simulate observed climate variability at diurnal to decadal time scales and how well they can replicate processes that control Texas climate (e.g., generation of tropical storms, winter cold fronts).

5. Continue to advance the use of adaptive management strategies for Texas' water resources.
6. Determine the impacts and calculate the costs of projected climate change to the state's economy, including the long-term costs of not planning for changes in water availability due to climate change.
7. Advance research on the relationship between Texas' water supply and energy use and incorporate the findings into water planning.
8. Encourage and support development of K-12 and university-level education programs on the science and policy of climate change and water resources to inform and inspire future researchers, policy-makers, and citizens.

INTRODUCTION

In April 2008, the conference *Forecast: Climate Change Impacts on Texas Water 2008* was held at the State Capitol in Austin, Texas. It was cosponsored by the Environmental Science Institute and the Jackson School of Geosciences at The University of Texas at Austin, the River Systems Institute at Texas State University, and the Texas Water Resources Institute at Texas A&M University. The conference focused on what we know and what we need to gain knowledge about regarding the effect of climate change on Texas' water availability and on the Texas communities and ecosystems that depend on reliable sources of water. The conference featured presentations by scientists who study climate change and who investigate how climate change may affect Texas and our water resources.

The future of Texas' water supplies is difficult to predict with confidence because of the large number of factors that influence precipitation and water storage. At the same time, state-of-the-art research is currently available to help inform policy decisions, but more research is needed to fully address policy and planning needs. This white paper first reviews what is known about how global climate change may affect Texas' water resources. We then outline research steps necessary to build more reliable regional climate projections. We conclude by providing a set of recommendations for research that may be useful for guiding potential policy changes and resource management decisions.

Our intention in writing this white paper is to further interactions between research scientists, regional and state water managers, policy-makers, consultants, and the public, as they pertain to assessing the impacts of climate change on Texas' water resources. The goal of the recommendations is to help the state build resilience in the face of an uncertain future, a future where the only certainty is that future climate conditions in Texas will not resemble those experienced over the past century. By acknowledging this uncertainty and developing robust, relevant tools capable of quantifying future uncertainty, we believe it is possible to prepare the state of Texas for successful adaptation to future climate change and its impacts on water resources.

We recognize that the problems associated with climate change impacts on Texas' water resources go beyond the subjects considered in this white paper. For example, steps to mitigate climate change, such as energy conservation, developing alternative energy and carbon sequestration, and efforts to increase water conservation, are only generally treated here. These are all considered in detail in other available and well-referenced reports (e.g., IPCC 2007c; US EPA 2008; Bates et al. 2008). The focus of this white paper is the impacts of climate change in Texas on the state's water resources.

CURRENT UNDERSTANDING OF CLIMATE CHANGE IMPACTS ON WATER RESOURCES

Water resources around the world are already stressed by rapid population increases, rising demand, and limited supply. In many regions, climate change will exacerbate existing stresses, leading to increased competition for water resources and raising the specter of water shortages. Exactly how climate change will affect a specific region's water resources is dependent on physical and social characteristics unique to each region. The Southwest has been characterized as one of seven geopolitical "danger zones" in the world, due to both vulnerability to significant future climate change and rapidly growing populations and cities (Sachs 2008). Using Seager et al.'s (2007) definition, the "Southwest" is all land between 125°W and 95°W and 25°N and 40°N. This includes most of Texas. Here we summarize the current understanding of principal climate change impacts on water at the global and national scale. We then build on this discussion to provide a more detailed discussion of Texas-specific impacts.

General impacts of climate change on water resources

The potential impacts of climate change on water resources at the global and national scale have been described in recent reports by the Intergovernmental Panel on Climate Change and the U.S. Global Change Research Program (IPCC 2007b; Bates et al. 2008; USGCRP 2009). At the global scale, a number of projected impacts of climate change on freshwater resources include (Bates et al. 2008):

- Changes in the availability of drinking water, resulting from shifting patterns of precipitation and evaporation, rapidly shrinking glaciers and snowpack that provide water to over half of the world's population, and changing water demands
- More frequent and intense extreme events, including floods and droughts
- Increased risk to coastal areas due to rising sea level, storm surge floods, and increasing ocean temperatures
- Increases in water pollution and shifts in aquatic biology resulting from increased water temperatures
- Both growth and shrinkage in water boundaries resulting from rising sea level, changing precipitation patterns, and changing flow to lakes and streams

Climate change impacts specific to Texas water: Past, present, and future

Texas climate

Texas is located in climate zones that transition from the humid Southeast United States to the arid Southwest United States. The state's climate is characterized by a north-south gradient in minimum annual temperature and a strong east-to-west moisture gradient, from 145 cm of rainfall per year (57 inches/yr) in the east to less than 25 cm/yr (10 inches/yr) in the west (Fig. 1). The climate of Texas is influenced by a complex range of atmospheric processes, physiographic features, and moisture sources (Fig. 2). The North American Cordillera funnels cold air southward into Texas, whereas the Gulf of Mexico serves as Texas' main moisture source and a moderating influence on temperature on the land surface (Nielsen-Gammon 2010). The Pacific Ocean is a less frequent moisture source for the region. Along the region's coast to the southeast, tropical storms and hurricanes are infrequent but important weather systems. Texas experiences great extremes in rainfall, and large rainfall events may be triggered by a variety of mechanisms, including synoptic-scale and coastal fronts, topography, and large-scale ascent (Nielsen-Gammon et al. 2005). This range of sources and interacting processes produces significant variability in the intra- and interannual patterns of rainfall in Texas, making the prediction of recharge to aquifers and runoff to streams challenging. Texas spans 26 to 37 °N latitude, and as a result, the state's climate is influenced by the descending limb of the Hadley atmospheric circulation cell. This is one of several factors that produce semi-arid conditions in the western part of the state (Griffiths and Ainsworth 1981; Bomar 1995). In addition to these regional factors, Texas' climate is also influenced by more remote connections with other regions such as the tropical Pacific Ocean, where sea surface temperatures control El Niño-Southern Oscillation climate phenomena that influence rainfall and temperature in Texas. El Niño episodes typically bring higher than average rainfall to Texas, whereas La Niña episodes typically bring below average rainfall.

Among the factors that make Texas susceptible to drought are the aridity caused by high pressure associated with Hadley circulation, variations in the strength and position of the Bermuda High, and the influence of La Niña events (Fig. 1). Failure of the Southwest Monsoon, which brings warm moist air in July and August from the Pacific Ocean to northwest Mexico, Arizona, and New Mexico, can also result in drought in Far West Texas (Nielsen-Gammon 2010).

Past climate change in Texas

Climate change that is driven by natural processes occurs over many time scales. According to the IPCC (2007a), atmospheric warming over the 20th and 21st centuries is "unequivocal," and is "very likely" (greater than 90% probability) to have been driven by a combination of natural and anthropogenic processes. To place this warming into a broader context, geologic materials are analyzed that preserve information about past climate and can thus serve as "proxies" for time periods prior to instrumental measurement of temperature and rainfall. These paleoclimate proxies indicate that Texas experienced large changes in the past, on millennial time scales that in some cases follow global-scale glacial to interglacial cycles. These inferred changes are based on the analysis of sedimentary deposits, fossils, cave mineral formations, and other proxies (Toomey et al. 1993; Musgrove et al. 2001; Cooke et al. 2003). These studies produce a consistent reconstruction of central Texas as a much wetter and cooler region, covered by thicker soils, during the late Pleistocene time period, between approximately 25,000 and 15,000 years before present.

Instrumental records document variations in climate and hydrology based on observations, using devices such as thermometers and rain gauges. These records are generally limited to little more than a century and have formed a basis for water resource management and planning. The 1950s drought is commonly used as the worst-case-scenario for drought planning. Climate records have been extended further back in time using proxies such as tree rings, which can track annual variations in climate, and have been used to reconstruct precipitation, drought, and streamflow for past centuries to several millennia. These proxy records, which have been generated for many areas of the United States including Texas, place the 20th century events, such as the 1950s drought, into a long-term context. It can be concluded from these studies that the 20th century contains only a subset of the climatic variability that is evident over past centuries.

The magnitude of the 1950s drought is not unprecedented, and reconstructions show that more severe and sustained droughts occurred prior to the 20th century. For example, a reconstruction of Rio Grande headwaters flow using tree rings documents a drought in the late 1800s with 11 consecutive years of below-average flows (Woodhouse and Lukas 2006). Central and west Texas tree-ring reconstructions provide evidence for the occurrence of droughts that rivaled or exceeded the drought of the 1950s in this region. The most severe of these droughts occurred in west Texas during much of the 13th century (Fig. 3A), and in central Texas during the last half of the 16th century and at the turn of the 18th century (Cleaveland 2006). The 16th century included a period of "megadrought" that was nearly continental in scale (Stahle et al. 2000; Cleaveland 2006). Climate reconstructions in combination with climate model results suggest cool sea surface temperatures (SSTs) in the eastern equatorial Pacific Ocean as a driving mechanism for these megadroughts (Cook et al. 2008). An observational and model analysis of the major North American droughts in the Great Plains of the 20th century indicates that there is a regional sensitivity in the apparent driving mechanisms for these droughts (Hoerling et al. 2009). 20th century drought severity in the southern portion of the Great Plains (i.e., Texas) is strongly linked to Pacific equatorial SSTs, whereas drought severity in the northern portion is not. These climate observations and proxy records indicate that significant variability in water availability has occurred even in the absence of anthropogenic climate change.

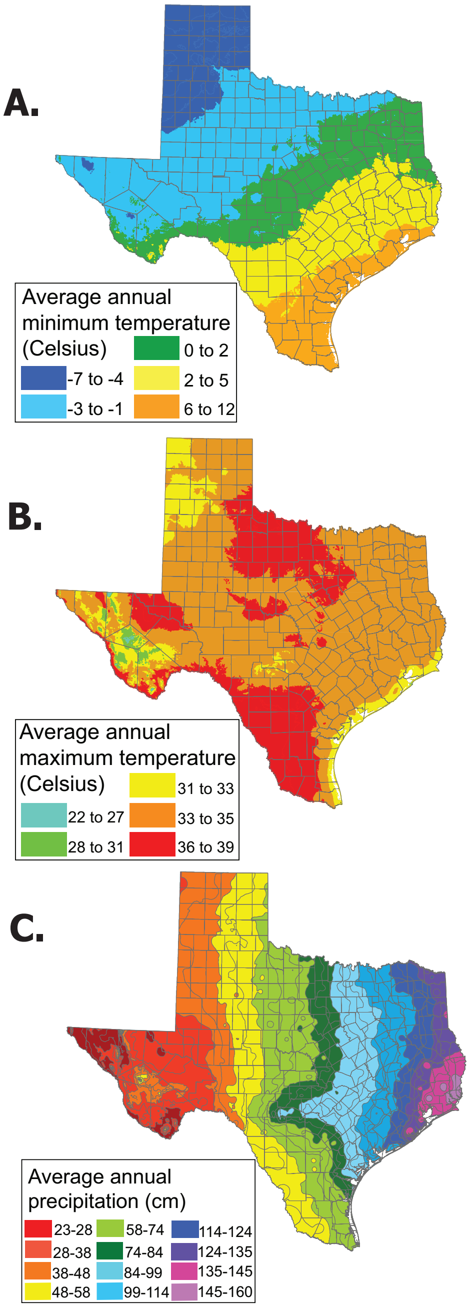

Fig. 1. A. Average annual minimum temperature; B. Average annual maximum temperature; C. Average annual rainfall (cm) for Texas. Data are from USDA National Resources Conservation Service for the time period 1971 to 2000 (USDA NRCS 2006).

In addition to multiyear droughts, the reconstructions of past climate discussed above also document slow, multidecadal variations in climate. This low-frequency variability is a challenge for water management approaches that consider climate as relatively stationary. Superimposed over the natural low-frequency variability will be trends in climate due to anthro-

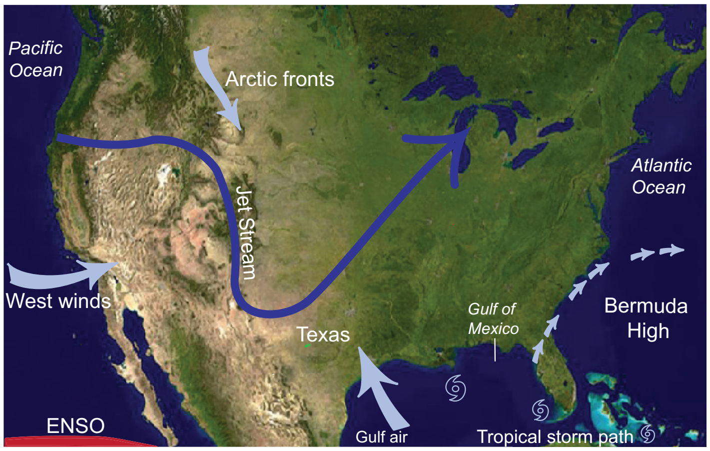

Fig. 2. Atmospheric processes in North America that influence the variability of Texas climate. Red 'ENSO' region schematically represents the northeast extent of the El Nino–Southern Oscillation climate phenomenon, which drives changes in sea-surface temperature in the tropical Pacific Ocean and which can influence rainfall and temperature variability in Texas. Modified from TWDB (2007).

pogenic influences that are expected to contribute to future changes in Texas' climate (Fig. 3). We therefore recommend that planning take into account a broader range of scenarios by considering both the natural variability of the extended records of paleoclimate data, along with 20th century records and 21st century projections. This recommendation necessitates reassessment of the use of the most severe drought in the instrumental record, which is the 1950s drought for most of Texas, as the worst-case scenario. Research collaboration among scientists, planners, and decision makers should be conducted to determine how best to incorporate the information from the paleoclimatic data into future planning. Such research should assess the need for improving the temporal and spatial resolution, temporal extent, and accuracy of proxies for paleoclimate reconstruction. More accurately determining such paleoclimate information from such proxies will allow the development of a more comprehensive climate history for Texas.

Recent temperature trends

During the last 130 years, measurements of observed surface temperatures of the Earth have shown warming globally and regionally, with increases in global mean temperature of almost one degree C (almost 2 °F). This warming is less than the 4–7 °C warming that occurred since the Last Glacial Maximum (around 21,000 years before present) to the pre-industrial era, but it has occurred at a rate that is ten times faster (IPCC 2007a, Chap. 6). The IPCC supported its 2007 announcement that global warming was unequivocal by showing that state-

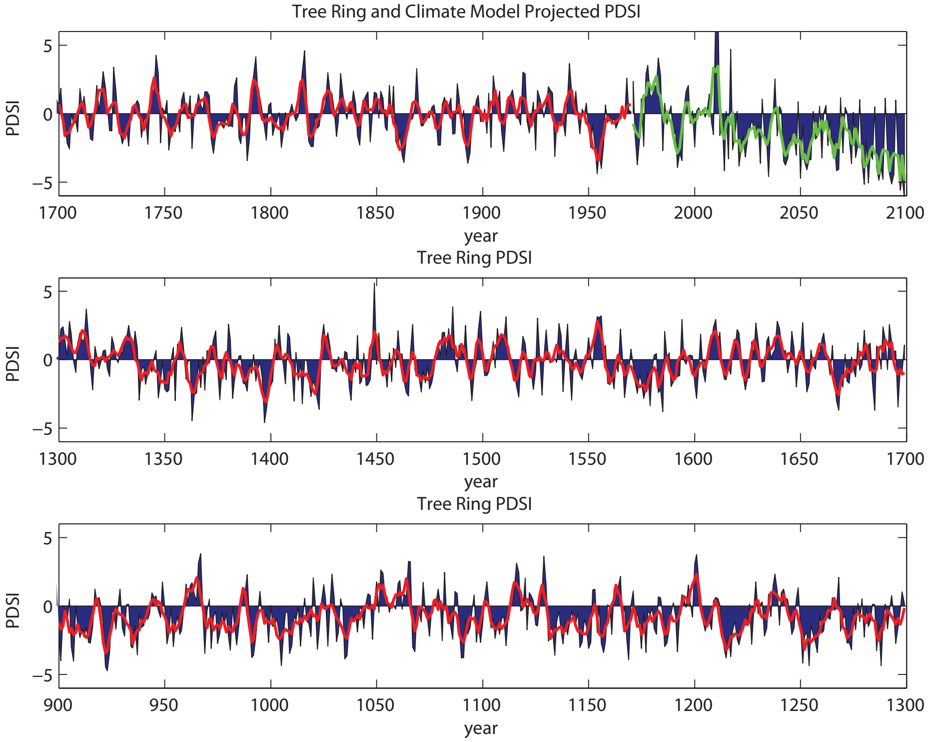

Fig. 3A. Drought history for the time period 900-1970 (red time series, based on tree-ring data), and one possible drought projection for the 21st century (green time series, based on climate model results) for west Texas. The Palmer Drought Severity Index (PDSI) is a measure of drought that incorporates rainfall and temperature information (Palmer 1965; Wells et al. 2004). The utility of the PDSI and other indices for drought is evaluated by the IPCC (2007a, Chap. 3). The PDSI tree-ring reconstruction is from the North American Drought Atlas (Cook and Krusic, 2004). Climate model data are from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 multi-model dataset. The model data are from downscaled regional climate projections from coarser-scale global climate model results, as described in Maurer et al. (2007). The featured projection is for IPCC emissions scenario A2, using the Canadian Global Climate Model (CGCM) projections of monthly mean temperature and precipitation and converted to PDSI using the self-calibrating algorithm of Wells et al. (2004). The red and green curves are 4-year running means of the PDSI index given in dark blue. The IPCC emissions scenarios involve a range of projected rates of economic growth, population growth, and balances between fossil and alternative fuels, as described in IPCC (2000). The A2 group of scenarios involves high-population growth and slow technological change in terms of energy use, and is also referred to as the "business as usual" group of scenarios.

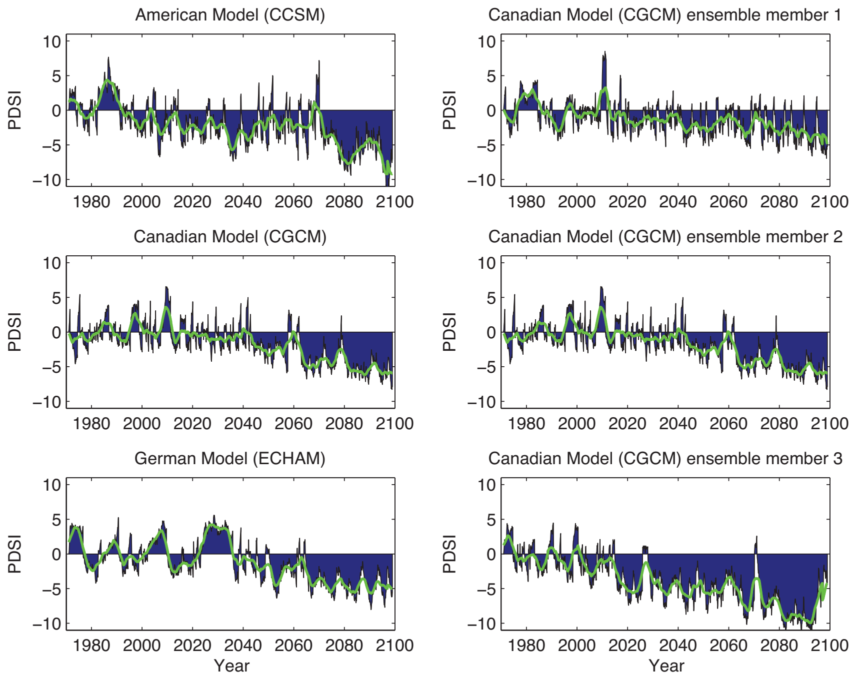

Fig. 3B. Climate model projections of the PDSI for west Texas over the next 100 years under emissions scenario A2 for three different climate models: the American CCSM model (top left), Canadian CGCM model (middle left), and German ECHAM model (bottom left); and for three different runs of the Canadian model for different initial conditions (three panels in right column). There is uncertainty in the severity of the drying as indicated by the spread in predictions among the American, Canadian, and German models. It is important to note that climate models do not provide information about the precise timing of particular drought or flooding events. This is illustrated by the right column, which presents three ensemble members (a kind of repeat experiment) from the Canadian model that were initialized with different starting conditions. Taking into account the range of uncertainties associated with the different models, the results indicate that west Texas has the potential to become much drier than it is at present.

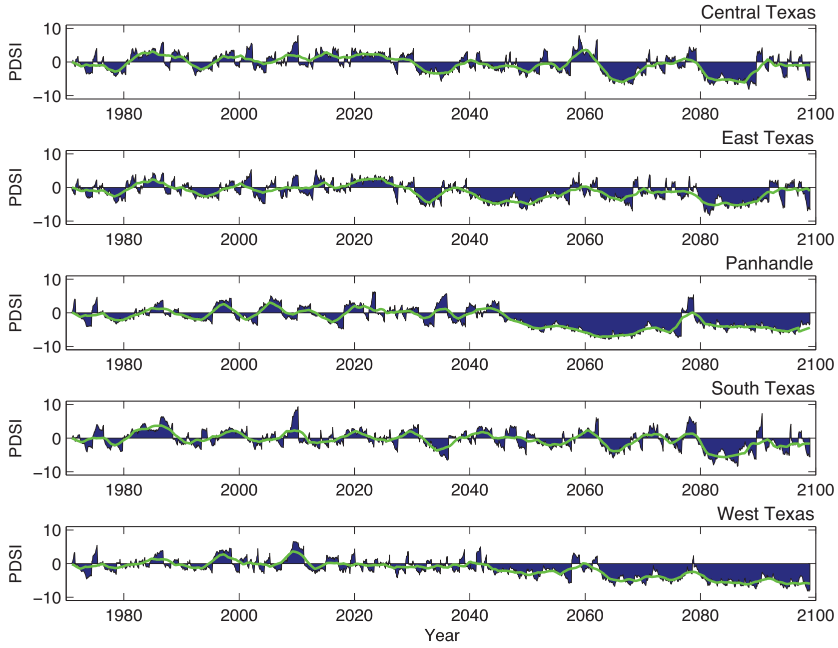

Fig. 3C. Climate model projections of the PDSI, based on the Canadian CGCM model for each of five regions in Texas.

of-the-art climate models were able to reproduce the observed temperature trends only when they included natural solar and volcanic forcings together with the anthropogenic increase of greenhouse gases (Fig. 4). This inability of the models that lack anthropogenic forcings to reproduce observed temperature trends is largest over the past three decades. Although the average change in surface temperature has been only 1°C, the warming across the globe has not been evenly distributed. Larger warming is concentrated at the poles and over the continents, so that local climate change may be significantly different from the global average change. Similarly, surface temperature is projected to increase unevenly, with larger changes over land than over the ocean. In Texas, there has been relatively rapid warming over the past three decades, yet over the past century, there has been a negligible temperature change (Fig. 5, TWDB 2007). Warming similar to the global average has occurred over the past century in the subtropical, southern part of the state (Yu et al. 2006).

Climate change projections

Global and regional climate models are improving rapidly, both in terms of geographic resolution and in terms of representing the physical processes of climate. A larger number of model simulations produced for different scenarios exist than in the past, which gives us a greater basis for estimation and assessment of probable future climate conditions. Model projections for the coming century for the interior west of the United States, including west Texas, project up to four times the global average warming that occurred over the 20th century (NRC 2007). Results of climate models from the IPCC (2007a) project that average surface air temperature for Texas will increase by 2-5 °C over the 21st century (Fig. 5). Another manifestation of the projected warming is the larger number of days per year that a given region of Texas will experience temperatures over 100 °F. While in the recent past, approximately 10-20 days per year have been above 100 °F in some regions in Texas, climate models project more than 100 such 100 °F days per year by the end of the century under a high emissions scenario (Fig. 6). The projected temperatures for Texas are dependent on which emissions scenario is ultimately achieved by our society, as illustrated by the range in temperature produced using the A2, A1B, and B1 scenarios (Fig. 5).

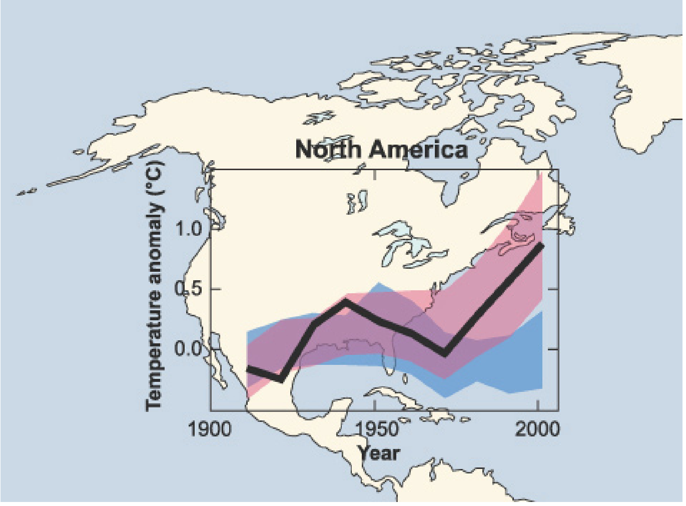

Fig. 4. Twentieth century temperature trend for North America. The black line is the observational trend, the blue band encompasses the range of climate model results that use only natural forcings, and the pink band is the range of model results that use both natural and anthropogenic forcings (Fig. SPM4, IPCC 2007a).

The IPCC concluded in 2007 that the Southwest is likely to experience reduced precipitation in addition to higher temperatures. This conclusion is consistent with projected changes in the large-scale circulation, including an expansion and strengthening of the subtropical high and the associated subsiding motion and retreat of the jet stream and winter storm tracks toward the poles. Observations over the last three decades, as well as climate model simulations, indicate that the descending branch of the Hadley cell has expanded northward. This expansion of Earth's tropics is hypothesized to continue with global warming, which would lead to increased aridity in the Southwest (Hu and Fu 2007; Lu et al. 2007; Frierson et al. 2007; Seidel et al. 2008). Based on an analysis of a series of global climate modeling studies, Texas has been identified as one of three significant climate "hot spots" in North America, in terms of the region's susceptibility to projected changes (Koster et al. 2004; Diffenbaugh et al. 2008).

Several global analyses of climate model results provide projected temperature, precipitation, and runoff information for the Southwest region, which as defined here includes Texas at its eastern end. The analyses compare model results for periods in the 21st century with observations for the 20th century. These include the following:

1. An analysis comparing modeled precipitation minus evaporation for the period 2021–2040 with observations of precipitation minus evaporation for the period 1950–2000 projects pronounced drying of the Southwest (Seager et al. 2007).
2. An analysis comparing modeled runoff for the period 2041–2060 with observed runoff for the period 1900–1970 projects pronounced drying of Southwest, with west Texas experiencing more drying than east Texas (Milly et al. 2005). This study also demonstrated stronger agreement among the different models for the projected results for the western portion of the Southwest than the eastern portion.
3. An analysis comparing modeled temperature and precipitation for the period 2080–2099 relative to observations for the period 1980–1999 projects warmer

temperatures for the Southwest, with strong agreement across different model simulations (Meehl et al. 2007a). For the same periods and model comparisons, precipitation is projected to be lower in the Southwest. These models do not project a pronounced west-east gradient in drying across Texas, and there is more agreement among different model simulations for the result of lower winter precipitation in the western portion of the Southwest than for the result of lower winter precipitation in the eastern portion. Agreement among the different model simulations is significantly weaker for precipitation than for temperature (Meehl et al. 2007a).

In summary, the implications for Texas of these global climate model and observation analyses are that 1) compared with the 20th century, Texas is projected to be warmer and drier for the three different 21st century time periods investigated: 2021–2040, 2041–2060, and 2080–2099; 2) there is stronger agreement among the models regarding the predictions of increasing temperature than for the predictions of decreasing precipitation; and 3) there is not strong consensus regarding 21st century differences across the state in terms of the extent of decreasing precipitation and runoff.

We further focus here on constraining future aridity in Texas by considering projections for the Palmer Drought Severity Index (PDSI) for different climate models and for five different parts of the state (Fig. 3). Future aridity in Texas appears to be significant and comparable to the megadroughts of the past. For example, model projections for west Texas show that nearly every decade from 2040 to 2100 includes a drought of similar or longer duration than the drought of the 1950s (Fig.s 3A, 3B). There are considerable uncertainties in the timing and magnitude of the model projections, illustrated by the differences in results among different climate modeling research groups, and among repeat model runs with different starting conditions within the same research group (Fig. 3B). Climate models are not capable of predicting timing and magnitude of individual drought events. Given these limitations in the models and the differences in their results, some notable similarities among all of the model results exist for the projected increases in aridity (Fig. 3B). While some parts of the state may receive more annual precipitation (Jiang and Yang sub-

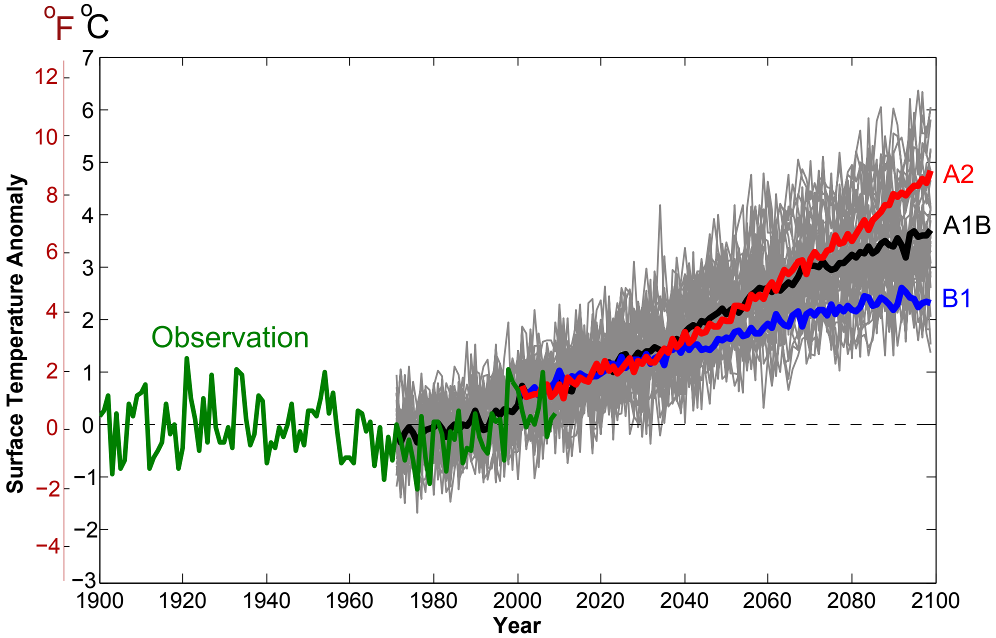

Fig. 5. Observed and modeled surface temperature anomalies for Texas. The observed anomalies are yearly observed departures from the 30-year observed mean climatology from 1971 to 2000. Modeled changes in annual mean surface temperature are averaged over ensemble members for each of the 16 models (and 39 total simulations) that participated in the IPCC Fourth Assessment Report (2007a). The future climate projections are based on three different emissions scenarios, A2, A1B, and B1. For the A1B scenario (balanced energy use) the gray trend represents all model results and the black trend denotes the average. For the B1 (purple trend, rapid economic change and clean and resource efficient technology) and A2 (red trend, business as usual scenario as described in Fig. 3) only the averages are shown. Emissions scenarios described in IPCC (2000). Anomalies for each model are shown relative to that model's mean climatology from 1971–2000. The model data are from downscaled regional outputs from models that participated in the World Climate Research Programme as described in Fig. 3. The source of the observations is the National Climatic Data Center dataset (Guttman and Quayle 1996). From Jiang and Yang (submitted).

mitted), the net result of projected increased temperatures is proposed to be drier conditions moving eastward relative to today (Yu et al. 2006). A projected increase in aridity through the 21st century is common to the model results for all regions in Texas (Fig. 3C). It is proposed that on the time scale of years to decades the normal climate of the Southwest may resemble that of the drought of the 1950s (Seager et al. 2007).

The high variability and uncertainty in the precipitation forecasts for Texas over the 21st century (Tebaldi et al. 2006; Meehl et al. 2007a; Jiang and Yang submitted) suggest that climate change impacts on water availability would be difficult to project. Two factors, however, indicate that evaporation may be a more important and more predictable determinant in projections of water availability in Texas. First, there is much stronger agreement between model forecasts of temperature increase and less variability in the forecasted temperature increases (Fig. 5) compared with precipitation projections (Tebaldi et al. 2006; Meehl et al. 2007a). Second, evaporation plays a large role in Texas' hydrologic cycle, as evidenced by Nexrad estimates of precipitation and streamflow data that indicate that nine out of every 10 drops of rain that fall on Texas leave Texas as evaporation rather than as runoff to streams (C. David and others, UT Austin, personal communication). This is based on the assumption that submarine discharge of fresh groundwater is minor relative to streamflow and evaporation, and this assumption is in agreement with global-scale estimates (Burnett et al. 2003). These two factors are consistent with evaporation dominating over precipitation in governing future dryness indices such as expressed by the PDSI.

Different mechanisms are attributed to the proposed future and recorded past droughts in the Southwest. The projected future drying in this region is consistent with the expansion of the Hadley circulation and a poleward shift of the westerlies and storm tracks driven by greenhouse gas forcing (Hu and Fu 2007; Frierson et al. 2007; Lu et al. 2007; Seidel et al. 2008, Cook et al. 2008). The droughts of the past, in contrast, appear to be associated with changes in SSTs in the eastern equatorial Pacific Ocean associated with La Niña episodes and solar forcing (Cook et al. 2007, 2008; Hoerling et al. 2009). As such, the paleorecord is not an ideal analog for future droughts. As noted by Cook et al. (2008), "It is thus disquieting to consider the possibility that drought-inducing La Niña-like conditions may become more frequent and persistent in the future as greenhouse warming increases." Thus, key research areas include improved coverage of regional and temporal variability of past droughts in Texas, downscaled model projections for regional climate change, and an improved understanding of the driving mechanisms of both past and potential future droughts.

Research is also needed regarding the changes in soil mois-

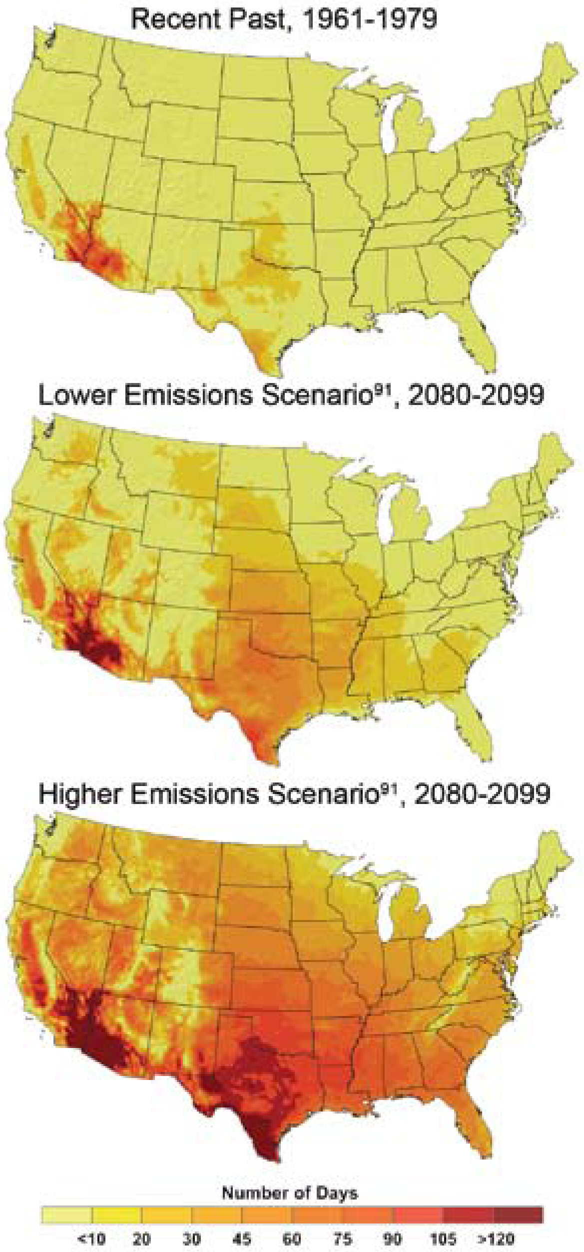

Fig. 6. Recent (1961-1979) and projected future (2080-2099) temperature changes in the US for two emissions scenarios (B1 and A1). Temperature changes expressed as the number of days per year with temperatures above 100 °F. In the higher emissions scenario A1, some regions of Texas will shift from 10-20 days in the recent past to more than 100 days per year in which the temperature exceeds 100 °F. From U.S. Global Change Research Program (2009), following approach of Hayhoe et al. (2004, 2008). Emissions scenarios described in IPCC (2000).

ture and runoff that will accompany these climatic changes. The relatively few studies that have been conducted on the projected impacts of climate change on Texas water resources have significant uncertainties associated with the projections (Muttiah and Wurbs 2002; Wurbs et al. 2005; CH2M HILL 2008). These studies provide estimates of the impacts of changes in temperature and precipitation on the San Jacinto, Brazos, and Colorado River drainage basins. Each estimate is based on assumptions that need to be validated concerning the use of climate-model information on the long-term mean and variability in changes in precipitation and temperature and resulting impacts on streamflows. The San Jacinto River Basin evaluation was the only study to find an increase in streamflow. A 20% increase in flow and 30% increase in variability in a 50-year model projection come from increased flood flows in spring and fall (Muttiah and Wurbs 2002). For the Brazos River Basin, a 50-year model projection finds reduced streamflow and a 5% reduction in reliability of this resource (Wurbs et al. 2005). Multiple climate model projections for 2050 for the Colorado River Basin yield estimates of significantly decreased runoff in the basin in central Texas, with estimates of future streamflow to the Colorado River to decrease by 13% to 34% (CH2M HILL 2008). Water-demand projections for 2100 for Travis, Hays, and Williamson counties in central Texas are 170% to 400% larger than for 2010 (LCRA 2010). Combining the impacts of increased demand on water due to population growth and projections in climate change by 2050, first-order water budget calculations indicate that, under drought conditions, Texas' surface water supply will fail to meet the state's water-use demands (Ward 2010).

SIGNIFICANT UNKNOWNS REGARDING CLIMATE CHANGE IMPACTS ON TEXAS WATER

In this section we consider the main impacts and uncertainties regarding climate change in Texas, with particular emphasis on water resources and more general consideration of impacts on public health and the state's economy. The following are the principal areas of uncertainty regarding the scientific community's understanding of climate change impacts on Texas water resources.

1. Climate models are better at predicting mean climate than climate variability and climate extremes. Climate change projections are based on global circulation models that are best at replicating and projecting global scale climate. Although projections of future temperature are relatively robust in that there is good agreement between different climate models for most regions of the world, projections for precipitation at regional scales contain a higher degree of uncertainty (Meehl et al. 2007a; Deng et al. 2007). The applicability of such projections will be enhanced by an improved understanding of the sources of uncertainty through evaluation of the ability of different models to reproduce observed (e.g., 20th century) climate. Understanding how well physical and dynamic processes are represented and understanding climate feedbacks (i.e., links between processes that can enhance or diminish effects) are important, especially for the regions that influence climate in Texas (Tebaldi and Knutti 2007).
2. In general, there is less confidence in regional scale predictions than those at larger scales. For Texas relative to other regions, there is little agreement on the magnitude of changes in precipitation in the 21st century (Nielsen-Gammon 2010), although pronounced drying trends characterize most model results for the Southwest (Fig. 3; Milly et al. 2005; Seager et al. 2007; Meehl et al. 2007a). Whereas there are uncertainties and approximations in hydrologic models used for watershed management in Texas, larger uncertainties for such management lie in the use of global climate models for predicting regional climate change (Wurbs et al. 2005).
3. Texas is affected by short-term climate phenomena driven by changes in tropical SSTs, such as the El Niño–Southern Oscillation (ENSO). El Niño and its counterpart, La Niña, are not well predicted by global climate models, but they do have a strong correlation to specific climate patterns across the Southwest and in Texas (Wurbs et al. 2005; Kurtzman and Scanlon 2007; Cook et al. 2007; Meehl et al. 2007b; Hoerling et al. 2009). The Pacific Decadal Oscillation is another periodic climate phenomenon associated with the Pacific Ocean and ENSO (Newman et al. 2003) that also shows some correlation with Texas climate patterns, but to a lesser degree than ENSO (Kurtzman and Scanlon 2007).
4. Texas' vulnerability to severe weather from tropical storms and hurricanes is well established, yet there is only limited knowledge for predicting the impact of future climate change on the intensity and frequency of such events for Texas (Deng et al. 2007), as well as the response of water resources to such events. An increase in the frequency of such storms may serve to increase recharge to aquifers and runoff to streams. Negative consequences of such storm activity include damage to water resource infrastructure from flooding and winds, soil erosion, and contamination of aquifers from runoff and coastal storm surges. Although there have been recent advances in our understanding

of the relationship between global warming and tropical storm intensity and frequency, the specifics of this relationship and its potential impact on water resources have large uncertainties associated with them (e.g., Emanuel 2005; Webster et al. 2005; Knutson and Tuleya 2004; Pielke et al. 2005; Emanuel et al. 2008).

5. Local factors such as land-use change can significantly affect local climate, yet the role of these factors in climate change in Texas has not been examined in detail (Yang 2004; Scanlon et al. 2005). Feedbacks between climate change and land-use change in this region may be significant, as indicated by analysis of the 1950s and 21st century droughts in Mexico (Stahle et al. 2009).

Unique aspects of Texas water resources and unknowns regarding impacts of climate change

Unique aspects of Texas' groundwater and surface water resources add to the uncertainty associated with the impact of climate change on Texas water. Climate change will likely intensify a number of existing stresses on water supplies in the state.

Across the state, highly variable conditions exist for rates of recharge and storage, and flow regimes. All rivers cross Texas from west to east, discharging in the Gulf of Mexico, and most are not snow-fed. At a state level, Texas precipitation is relatively unique in the strong east-to-west decrease in rainfall (Fig. 1C). Consequently, water supply needs in west Texas are strikingly different from those in east Texas. At one extreme, arid regions in north Texas receive little rainfall and are highly dependent upon groundwater supplies via aquifers that recharge through playa lakes. For example, much of the recharge to the regionally extensive Ogallala Aquifer likely occurred during the last ice age, creating a challenge to this resource's sustainability in the face of increasing usage, changing climate, and slow, persistent decreases in availability over time (Scanlon et al. 2005). At the other extreme, the Edwards Aquifer is recharged by more frequent rainfall with runoff to small rivers, such as Barton Creek, and a fast-moving groundwater system. The resultant conditions of water resource availability can fluctuate rapidly in the Edwards, with the potential to exhibit very low flow and then shift quickly to normal levels (Mahler and Massei 2007). Such karst aquifers that recharge rapidly, as well as shallow, highly permeable clastic aquifers that are responsive to precipitation and drought (such as the Seymour and Lipan-Kickapoo aquifers) will be more susceptible to the impacts of climate change (Mace and Wade 2008; Chen et al. 2001).

Competition for resources, particularly water resources, is aggravated by the growth of the state's population. While population growth alone increases water resource needs, the basic services provided to support the burgeoning populations can compound the overall level of demand. For example, many Texans get electric power from traditional forms of energy generation, which are often water-intensive when compared to emerging energy generation technologies.

Climate change is likely to exacerbate a number of existing stresses in the state. Detailed projections of the impacts of climate change on south Texas agriculture, ecosystems, air quality, and water supply are provided in Norwine and John (2008). The implications of climate change for Texas' unique water resource conditions include the following:

1. With projected warming of Texas' climate, rivers and reservoirs will lose increasing amounts of water to evaporation.
2. The Rio Grande and other rivers are essential for irrigation but could experience a drastic reduction in streamflow or dry up if, as the balance of evidence indicates, droughts become more common. Significantly decreased river flow will damage agriculture, aquatic ecosystems, and the estuaries that depend on fresh–salt water balances for cash crops such as shrimp.
3. A global analysis using observational and model results suggests that more intense rainfall events are associated with global warming (IPCC 2007a, Chap. 3). For the period 2080–2099 relative to 1980–1999, the Southwest is projected to experience both an increase in precipitation intensity (with relatively weak agreement among models) and longer dry periods in between rain events and more heat waves (with relatively strong model agreement; Tebaldi et al. 2006). Implications of such projections for Texas include the potential to increase runoff and lessen the amount of water that infiltrates into the ground and recharges aquifers. Both increased runoff of rainfall and decreased infiltration of rain into soil have the potential to exacerbate water quality problems.
4. Agricultural productivity, already water-limited in much of the state, is vulnerable to an increased frequency of drought and to potential shifts in the locations of optimal growing zones for typical crops. Land-use change driven by agriculture in the High Plains of Texas has been shown to impact recharge and groundwater quality (Scanlon et al. 2005). Groundwater-irrigated agriculture may also be affected by dropping aquifer levels and rising electricity costs for pumping water.
5. Many forms of traditional energy generation require water that, due to climate-induced and other stresses, will be under demand in other sectors. Cooling water for coal-fired, natural gas, and nuclear power plants, for example, represents 40% of freshwater extraction

in the United States (King et al. 2008). The interdependence of energy and water is also evident in the significant amounts of energy expended for purifying and pumping freshwater. Severe drought could cause water-intensive energy generation to shut down, with cascading effects on the economy and health if brownouts or blackouts follow.

Population growth in Texas

Under any of several likely projections, Texas will have a population that is at least twice as large (at 35.8 million projected for 2040) as in 1990 (when it was 17.0 million) and may be more than three times as large, at 51.7 million (OSD 2006). Another projection has the state's population more than doubling between 2000 and 2060 from 20.9 to 45.6 million people, whereby 297 Texas cities are expected to more than double their population during this period (TWDB 2007). A rural-to-urban population shift is projected, with greatest growth in regions encompassing the Dallas, Houston, San Antonio, Austin, and McAllen areas. Such rapid population changes concurrent with climate change would exacerbate water demand and supply problems, particularly in urban areas.

Potential economic and human health impacts of climate change in Texas

Given the projections for warmer temperatures, more extremes (duration, time between occurrences, and intensity) in drought and rainfall, and rising sea level, there are potential economic and human health impacts for Texas. If temperatures rise as projected, human health will likely be affected by more heat-related illnesses, water quality impacts, and the northward spread of tropical diseases and pests. Rising temperatures also suggest that more regions in Texas will not attain EPA ground-level ozone standards (US EPA 2009). Many human health impacts of global climate change are also projected to occur via climate change impacts on water (Shea et al. 2007; Frumkin et al. 2008).

Projected climate changes also have the potential to negatively affect Texas' economy. The state's economy and land-use patterns will likely shift to adjust from traditional energy and agriculture to renewable sources and dryland agriculture (Norwood and Dumler 2002). Under a scenario of increasing aridity, Texas' second largest industry, agriculture, would be significantly impacted and the state's ability to meet electric power demands would be challenged. Rising sea level and changes in stream discharge into Gulf of Mexico estuaries would threaten coastal freshwater aquifers, and the coast's $2.5 billion economic benefit derived from tourism, recreation, and fishing (TWDB 2007). The Texas coast has experienced among the greatest sea level rises in the United States over the past 50 years, and is projected by the end of the century to experience among the greatest rises, including a projected 3.5-foot rise in Galveston (USGCRP 2009). The protection provided by barrier islands and coastal wetlands against storm surges would be significantly reduced or lost. Costs of replacement or replenishment of beaches, bays, and marshes and coastal development and infrastructure will likely be staggering. Developing a funding plan for the anticipated costs of water development and conservation efforts is another significant challenge (Texas Comptroller 2009). As noted by the TWDB (TWDB 2007):

> *"Not only is Texas' population rapidly growing, but it also has one of the world's most robust economies. If Texas were an independent nation, its economy would rank eighth in the world when measured by gross national product. Rapid growth, combined with Texas' susceptibility to severe drought, makes water supply a crucial issue. If water infrastructure and water management strategies are not implemented, Texas could face serious social, economic, and environmental consequences."*

The state of Texas already has a significant stake in, and could further benefit economically from, an expansion of climate-mitigating efforts, including the development of renewable energy resources, such as wind and solar power; underground sequestration of carbon dioxide from coal fired power plants; and energy trading systems. A significant unknown involves determining what the cost to the state will be if no action is taken. If no further climate mitigation efforts are undertaken, if major research programs into the climate change impacts on Texas water resources are not developed, and if no policy changes based on such research are enacted, what will the economic costs to Texas be in 10, 20, or 50 years?

There have been few attempts at determining the economic costs of climate change. A comprehensive analysis of the global economic costs of global climate change was undertaken by the United Kingdom (Stern 2006). This analysis includes costs of "business as usual" (i.e., assuming no mitigation actions are taken) and mitigation scenarios, and it applies the following three methods: 1) a consideration of the physical impacts of climate change on the economy, human life, and the environment; 2) application of integrated assessment models to estimate economic costs of climate change, and macro-economic models to estimate economic costs of the transition to low-emission energy systems; and 3) a comparison of the costs of social impacts of increased emissions with the costs of achieving emissions reductions. The costs of climate change impacts under a business as usual scenario are a reduction in global consumption per head (the value of goods and services bought by people) in the upper part of the range of 5% to 20%, whereas the costs of emissions mitigation are on the order of

1% of global GDP. The consensus conclusion based on the range of analytical methods is that the benefits of significant and early action will considerably outweigh the costs of no action (Stern 2006).

On a national scale, from 1980 to 2003, there were ten droughts estimated to have cost more than $1 billion dollars each (Ross and Lott 2003, Cook et al. 2007). The TWDB estimates the costs to Texas businesses and workers of a future water shortage similar to the drought of the 1950s, with no change in supply infrastructure or management strategies, to be $9.1 billion in 2010 and $98.4 billion by 2060 (TWDB 2007). Associated lost business taxes are $466 million in 2010 and $5.4 billion in 2060. Given our analysis that the proxy records and model projections indicate that the 1950s drought is not an appropriate worst-case scenario, these estimated costs should be taken as minima. Incorporation of the Stern approach into the TWDB economic models is an important next step in weighing the economic costs of no action for Texas. Integration of expertise from the communities of climate change, hydrology and hydrogeology, land-use change, water resource engineering, and socioeconomics will be essential for a comprehensive understanding of the future of global water resources in general (Vorosmarty et al. 2000) and Texas' water future in particular.

RECOMMENDATIONS

Based on our analysis of the current state of knowledge regarding global climate change, Texas climate change, and the sensitivity of the state's water resources to these changes, we make the following series of recommendations.

1. **Establish a Texas Climate Consortium (TCC).** This proposed consortium will periodically bring together scientists, engineers, policy-makers, and consultants from industry, academia, and government agencies to assess current knowledge of climate change impacts on Texas water. Proposed missions for the TCC are to serve as a state-level IPCC-like resource for investigating and reporting state-of-the-art climate science to help inform policy and management; identify the highest priority science topics and make recommendations for essential research needed, and identify resources needed for research and education. The proposed TCC would be implemented by and report its findings to the TWDB. There are similar organizations in other regions of the United States, such as National Oceanic and Atmospheric Administration's Regional Integrated Sciences and Assessments (http://www.climate.noaa.gov/cpo_pa/risa/), but there is no such organization with a focus on Texas. The proposed TCC will develop the means to engage the science research community with the communities of regional water management, state agencies, industry, and other stakeholders on issues of climate change impacts on Texas water resources. It is proposed that an overarching consortium such as a TCC can best direct progress on the key recommendations below.
2. **Incorporate large droughts of the past into water planning.** Given the evidence for more intense and extended droughts in proxy records of Texas climate relative to the drought of the 1950s, research should be advanced to improve the accuracy, temporal range, and geographic coverage of such proxy records, as well as to improve our understanding of the driving mechanisms of such phenomena. Through improved paleoclimate reconstructions, a more comprehensive drought history can be developed and applied in Texas water planning. Although the climate of the past will not be an exact analogue for the future, natural variability as preserved in paleoclimatic data can be used to help plan for the future, as it will underlie anthropogenic trends. In particular, an understanding of natural, low-frequency climatic variability is essential for future water resource planning.
3. **Establish a statewide, real-time monitoring network of climate and hydrologic variability.** Extensive observations of Texas climate and water will allow scientists and planners to better apply leading-edge scientific understanding to Texas' needs. An extensive network that includes and advances present monitoring systems will allow researchers to better understand the detailed response of hydrologic systems to the onset and nature of extreme climate events. Such a network would be similar to those proposed by The Consortium of Universities for the Advancement of Hydrologic Science (http://www.cuahsi.org/) and The National Ecological Observatory Network (http://www.neoninc.org/).
4. **Improve the applicability of climate models for the Texas region.** This recommendation can be achieved by supporting research in developing methods for using results from global climate models to make predictions for different parts of Texas; and determining how well such models a) simulate the observed variability of Texas climate across time scales (hourly to decadal); b) replicate climate processes that control Texas climate (e.g., tropical storms, winter cold fronts), and c) translate the interactions of the climate system with land surface to produce resultant streamflow, which is a key variable used in water resource planning. Such assessments and improvements are necessary if projections of future climate are to be useful for Texas planners

and policy-makers. An unmet basic research need is to learn which of the many global climate models used are most accurate at representing Texas climate and its variability, and to determine the optimal approach to downscaling from global to regional climate modeling. We must also identify what is most uncertain about current climate predictions for Texas so that resources can be invested toward minimizing that uncertainty. Paleoclimate records should also be improved as means to assess climate models for future projections.

5. **Continue to advance the use of adaptive management strategies for Texas' water resources.** Although many scientific uncertainties remain regarding the details of the extent and rate of climate change and its impact on Texas water resources, we have enough knowledge to act now. The TWDB's adaptive water planning framework is well positioned to incorporate adjustments to respond to climate change. Adaptive management needs include improved, strategic monitoring of climate in operational real-time. Water quality changes resulting from climate change impacts should be anticipated, including the impacts of increased water temperatures, reduced base flows, more intense storms, fire, dust, and sediment. With regard to water quantity, adaptive strategies must maximize options, such as conservation, that have double benefits—from both an energy and water perspective—and fewer environmental impacts. The complexity of climate change processes in Texas and the resulting impacts indicate that the development of effective adaptive strategies would require resource managers and decision makers to work closely with scientists from across many disciplines.
6. **Determine the impact and calculate the costs of projected climate change to the state's economy, including the costs of taking no action.** If we continue with a business as usual approach, and do not develop new research and management programs regarding the climate change impacts described in this white paper, what are the potential costs to Texas' economy? Potential costs of water shortage impacts for Texas include those to businesses and workers estimated to be $9.1 billion in 2010 and $98.4 billion by 2060. Following the approach of the United Kingdom (i.e., Stern 2006) and the TWDB (2007), an integrated assessment should be undertaken to determine costs of no action if water shortages on the order of the most significant historical and projected droughts occur (Fig. 3).
7. **Advance research on the connection of water supply and energy use.** There is a continuing need for connecting water and energy in a water management context. Significant volumes of water are required to generate energy by most conventional means, mostly for cooling, as well as by many alternative means, such as biofuels. Additionally, energy is required to pump, treat, and deliver water, and to treat and reuse wastewater. In fact, water and wastewater management are two of the largest users of energy in most states (approximately 30% of the total energy produced by power plants in California). Impacts on the available freshwater supply have immediate bearing on our ability to generate electricity from hydropower, coal, nuclear, and gas. Many water supply options being discussed as technology fixes for the future are energy-intensive, including interbasin transfers, desalination, cloud seeding, dry cooling, and expanded groundwater pumping. The large potential for solar power in the Southwest will be maximized by developing technologies that do not require significant amounts of water for cooling (King and Webber 2010). Therefore, capital (infrastructure) and water rights decisions need to be evaluated regarding short- and long-term energy and emissions impacts. Texas should continue to be a leader in pursuing alternative energy sources such as wind and solar, as well as improving existing energy technologies, to gain the multiple benefits of conserving water and reducing emissions.
8. **Encourage and support development of K-12 and university-level education programs.** Innovative educational programs focused on the science and policy of climate change and water resources are needed to train and inspire future researchers and policy-makers. In a comparison among 17 nations of the percentage of 24-year-olds who earn degrees in natural sciences or engineering vs. other majors, the United States ranks 16th (NA 2007). This nationwide trend of fewer students choosing careers in science, combined with the need for new interdisciplinary approaches to training future water resource scientists, managers, and policy-makers, indicates that new and innovative educational efforts are essential. New interdisciplinary degree programs are needed to integrate traditional disciplinary strengths of Texas universities in climate science, water science and engineering, and public policy (Banner and Guda 2004). Scholarships for university students and engaging K-12 curricula on these topics would provide incentives for young learners to follow such programs.

The investments that we make today in such recommendations to anticipate and adapt to these impacts of climate changes may not be visible in our lifetimes, but they will improve the lives of our children and grandchildren.

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