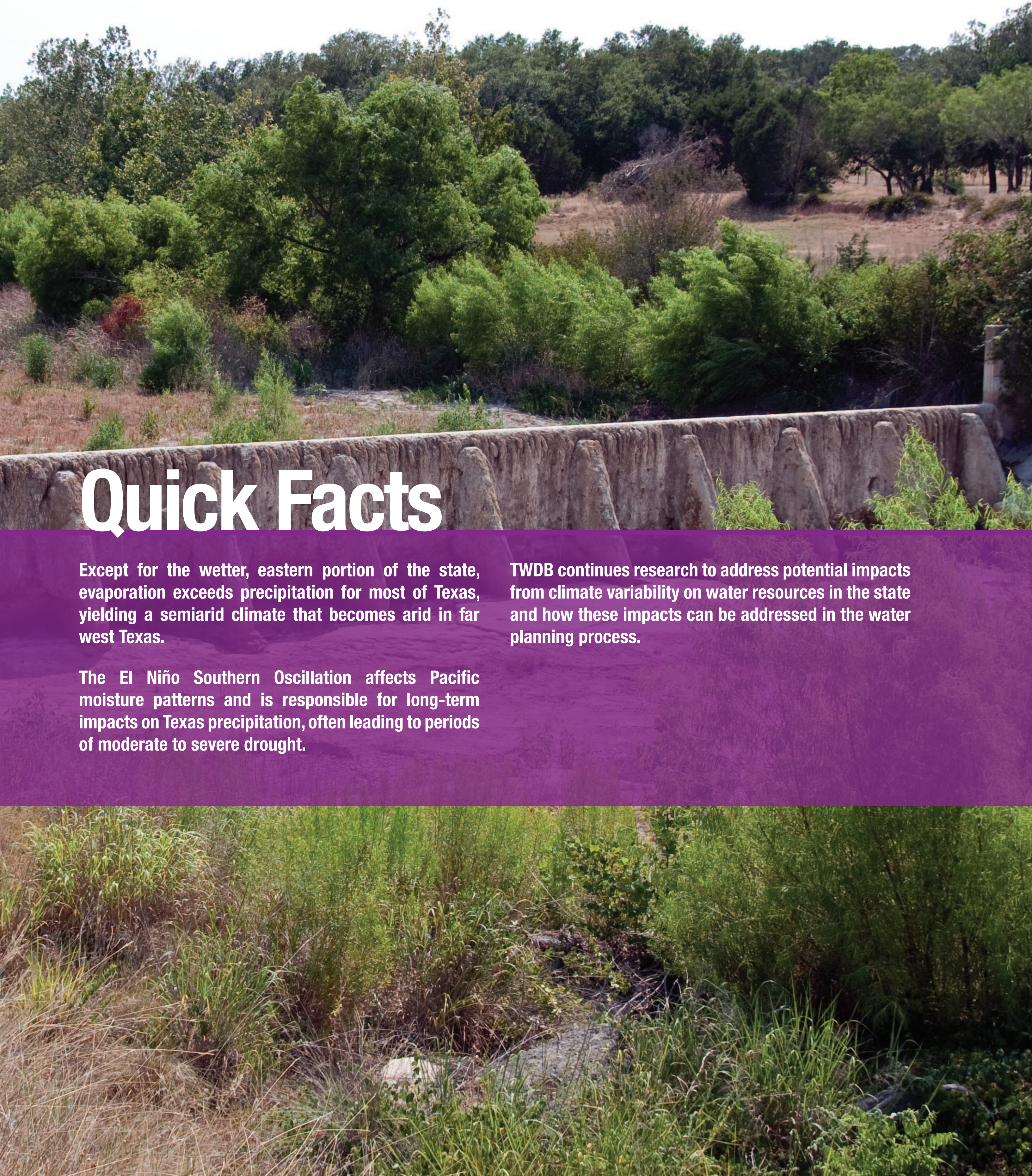


Quick Facts

Except for the wetter, eastern portion of the state, evaporation exceeds precipitation for most of Texas, yielding a semiarid climate that becomes arid in far west Texas.

The El Niño Southern Oscillation affects Pacific moisture patterns and is responsible for long-term impacts on Texas precipitation, often leading to periods of moderate to severe drought.

TWDB continues research to address potential impacts from climate variability on water resources in the state and how these impacts can be addressed in the water planning process.

4 Climate of Texas

Average annual temperature gradually increases from about 52°F in the northern Panhandle of Texas to about 68°F in the Lower Rio Grande Valley. Average annual precipitation decreases from over 55 inches in Beaumont to less than 10 inches in El Paso.

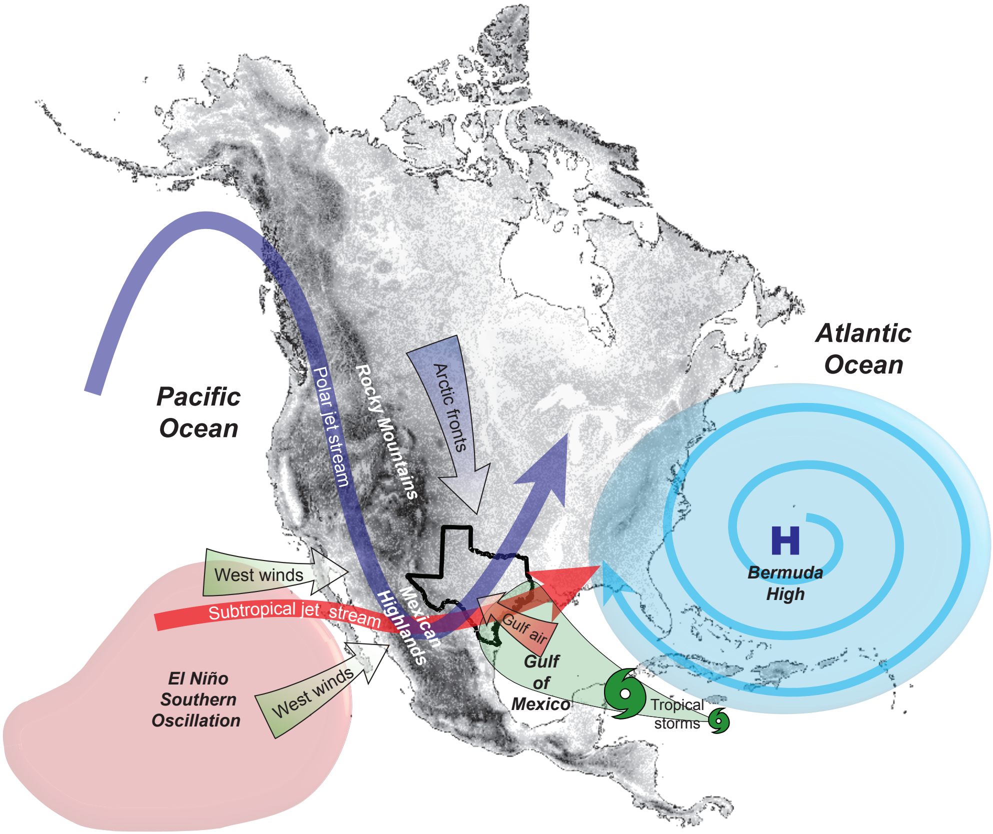
Because of its size—spanning over 800 miles both north to south and east to west—Texas has a wide range of climatic conditions over several diverse geographic regions. Climate is an important consideration in water supply planning because it ultimately determines the state's weather and, consequently, the probability of drought and the availability of water for various uses. The variability of the state's climate also represents both a risk and an uncertainty that must be considered by the regional water planning groups when developing their regional water plans (Chapter 10, Risk and Uncertainty).

4.1 OVERVIEW OF THE STATE'S CLIMATE

The variability of Texas' climate is a consequence of interactions between the state's unique geographic location on the North American continent and several factors that result because of the state's location (Figure 4.1):

- the movements of seasonal air masses such as arctic fronts from Canada
- subtropical west winds from the Pacific Ocean and northern Mexico
- tropical cyclones or hurricanes from the Gulf of Mexico
- a high pressure system in the Atlantic Ocean known as the Bermuda High
- the movement of the jet streams

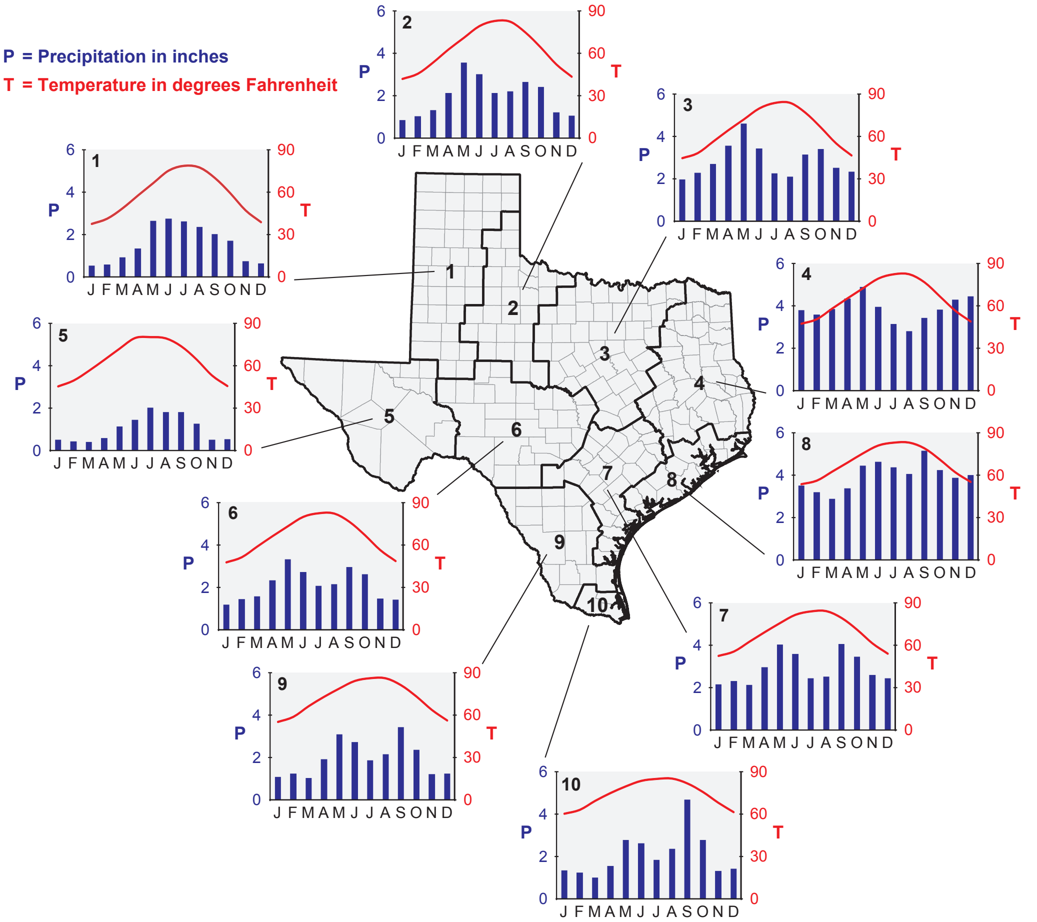
FIGURE 4.1. THE GEOGRAPHIC LOCATION OF TEXAS WITHIN NORTH AMERICA AND ITS INTERACTION WITH SEASONAL AIR MASSES AFFECTS THE STATE'S UNIQUE CLIMATE VARIABILITY (SOURCE DIGITAL ELEVATION DATA FOR BASE MAP FROM USGS, 2000).



The Gulf of Mexico is the predominant geographical feature affecting the state's climate, moderating seasonal temperatures along the Gulf Coast and more importantly, providing the major source of precipitation for most of the state (TWDB, 1967; Larkin and Bomar, 1983). However, precipitation in the Trans-Pecos and the Panhandle regions of Texas originates mostly from the eastern Pacific Ocean and from land-recycled moisture (TWDB, 1967; Slade and Patton, 2003). The 370 miles of Texas Gulf Coast creates a significant target for tropical cyclones that make their way into the Gulf of Mexico during the hurricane season. The Rocky Mountains guide polar fronts of cold arctic air southward into the state during the fall, winter, and spring.

During the summer, the dominant weather feature in extreme west Texas is the North American (or Southwest) Monsoon, as the warm desert southwest draws moist air northward from the Gulf of California and the Gulf of Mexico to produce summertime thunderstorms. In the rest of Texas, summertime thunderstorms form along the sea breeze or in response to tropical or subtropical disturbances. Warm dry air masses from the high plains of northern Mexico are pulled into the state by the jet stream during the spring and fall seasons, colliding with humid air from

FIGURE 4.2. CLIMATE DIVISIONS OF TEXAS WITH CORRESPONDING CLIMOGRAPHS (SOURCE DATA FROM NCDC, 2011).



the Gulf of Mexico, funneled by the western limb of the Bermuda High system—producing destabilized inversions between the dry and humid air masses and generating severe thunderstorms and tornadoes.

4.2 CLIMATE DIVISIONS

The National Climatic Data Center divides Texas into 10 climate divisions (Figure 4.2). Climate divisions represent regions with similar characteristics such as vegetation, temperature, humidity, rainfall, and seasonal weather changes. Climate data collected at locations throughout the state are averaged within each of the divisions. These divisions are commonly used to assess climate characteristics across the state:

- Division 1 (High Plains): Continental steppe or semi-arid savanna
- Division 2 (Low Rolling Plains): Sub-tropical steppe or semi-arid savanna
- Division 3 (Cross Timbers): Sub-tropical sub-humid mixed savanna and woodlands
- Division 4 (Piney Woods): Sub-tropical humid mixed evergreen-deciduous forestland
- Division 5 (Trans-Pecos): Except for the slightly wetter high desert mountainous areas, sub-tropical arid desert
- Division 6 (Edwards Plateau): Sub-tropical steppe or semi-arid brushland and savanna

- Division 7 (Post Oak Savanna): Sub-tropical sub-humid mixed prairie, savanna, and woodlands
- Division 8 (Gulf Coastal Plains): Sub-tropical humid marine prairies and marshes
- Division 9 (South Texas Plains): Sub-tropical steppe or semi-arid brushland
- Division 10 (Lower Rio Grande Valley): Sub-tropical sub-humid marine

4.3 TEMPERATURE, PRECIPITATION, AND EVAPORATION

Average annual temperature gradually increases from about 52°F in the northern Panhandle of Texas to about 68°F in the Lower Rio Grande Valley, except for isolated mountainous areas of far west Texas, where temperatures are cooler than the surrounding arid valleys and basins (Figure 4.3). In Far West Texas, the average annual temperature sharply increases from about 56°F in the Davis and Guadalupe mountains to about 64°F in the Presidio and Big Bend areas. Average annual precipitation decreases from over 55 inches in Beaumont to less than 10 inches in El Paso (Figure 4.4). Correspondingly, average annual gross lake evaporation is less than 50 inches in east Texas and more than 75 inches in far west Texas (Figure 4.5).

Although most of the state's precipitation occurs in the form of rainfall, small amounts of ice and snow can occur toward the north and west, away from the moderating effects of the Gulf of Mexico. The variability of both daily temperature and precipitation generally increases inland across the state and away from the Gulf, while relative humidity generally decreases from east to west and inland away from the coast. The range between summer and winter average monthly temperatures increases with increased distance from the Gulf of Mexico. Except for climatic divisions 1 and 5 in far west Texas, the state climate divisions show two pronounced rainy seasons in the spring and fall. Both rainy seasons are impacted by polar fronts interacting with moist Gulf air during those seasons, with the fall rainy season also impacted by hurricanes and tropical depressions.

Most of the annual rainfall in Texas occurs during rain storms, when a large amount of precipitation falls over a short period of time. Except for the subtropical humid climate of the eastern quarter of the state, evaporation exceeds precipitation—yielding a semi-arid or steppe climate that becomes arid in far west Texas.

4.4 CLIMATE INFLUENCES

Texas climate is directly influenced by prominent weather features such as the Bermuda High and the jet streams. These weather features are in turn influenced by cyclical changes in sea surface temperature patterns associated with the El Niño Southern Oscillation, the Pacific Decadal Oscillation, the Atlantic Multidecadal Oscillation, and the atmospheric pressure patterns of the North Atlantic Oscillation.

The Bermuda High, a dominant high pressure system of the North Atlantic Oscillation, influences the formation and path of tropical cyclones as well as climate patterns across Texas and the eastern United States. During periods of increased intensity of the Bermuda High system, precipitation extremes also tend to increase. The jet streams are narrow, high altitude, and fast-moving air currents with meandering paths from west to east. They steer large air masses across the earth's surface and their paths and locations generally determine the climatic state between drought and unusually wet conditions.

The El Niño Southern Oscillation, a cyclical fluctuation of ocean surface temperature and air pressure in the tropical Pacific Ocean, affects Pacific moisture patterns

FIGURE 4.3. AVERAGE ANNUAL TEMPERATURE FOR 1981 TO 2010 (DEGREES FAHRENHEIT) (SOURCE DATA FROM TWDB, 2005 AND PRISM CLIMATE GROUP, 2011).

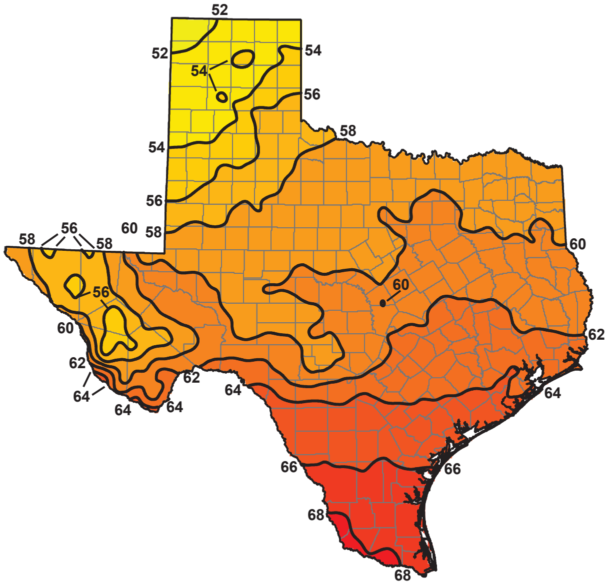


FIGURE 4.4. AVERAGE ANNUAL PRECIPITATION FOR 1981 TO 2010 (INCHES) (SOURCE DATA FROM TWDB, 2005 AND PRISM CLIMATE GROUP, 2011).

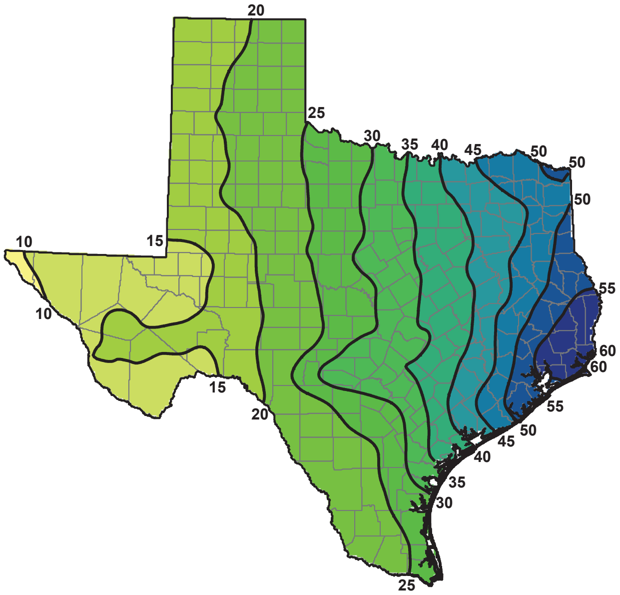


FIGURE 4.5. AVERAGE ANNUAL GROSS LAKE EVAPORATION FOR 1971 TO 2000 (INCHES) (SOURCE DATA FROM TWDB, 2005).

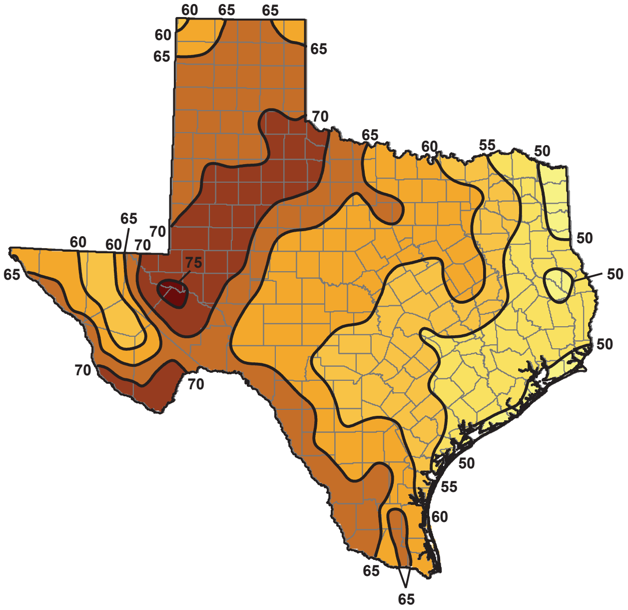


TABLE 4.1. RANKINGS OF PALMER DROUGHT SEVERITY INDICES BASED ON DROUGHT DURATION AND DROUGHT INTENSITY FOR CLIMATE DIVISIONS OF TEXAS

Climate Division	Duration Ranking			Intensity Ranking		
	1	2	3	1	2	3
1	1950 to 1956	1962 to 1967	1933 to 1936	1950 to 1956	1909 to 1911	1933 to 1936
2	1950 to 1956	1909 to 1913	1963 to 1967	1950 to 1956	1909 to 1913	1916 to 1918
3	1951 to 1956	1909 to 1913	1916 to 1918	1951 to 1956	1916 to 1918	2005 to 2006
4	1962 to 1967	1915 to 1918	1936 to 1939	1915 to 1918	1954 to 1956	1951 to 1952
5	1950 to 1957	1998 to 2003	1962 to 1967	1950 to 1957	1933 to 1937	1998 to 2003
6	1950 to 1956	1909 to 1913	1993 to 1996	1950 to 1956	1916 to 1918	1962 to 1964
7	1948 to 1956	1909 to 1912	1896 to 1899	1948 to 1956	1916 to 1918	1962 to 1964
8	1950 to 1956	1915 to 1918	1962 to 1965	1950 to 1956	1915 to 1918	1962 to 1965
9	1950 to 1956	1909 to 1913	1962 to 1965	1950 to 1956	1916 to 1918	1988 to 1990
10	1945 to 1957	1960 to 1965	1988 to 1991	1945 to 1957	1999 to 2002	1988 to 1991

and is responsible for long-term impacts on Texas precipitation, often leading to periods of moderate to severe drought. During a weak or negative oscillation, known as a La Niña phase, precipitation will generally be below average in Texas and some degree of drought will occur. (The State Climatologist and the National Atmospheric and Oceanic Administration both attribute drought conditions experienced in Texas in 2010 and 2011 to La Niña conditions in the Pacific.) During a strong positive oscillation or El Niño phase, Texas will usually experience above average precipitation.

The Pacific Decadal Oscillation affects sea surface temperatures in the northern Pacific Ocean, while the Atlantic Multidecadal Oscillation affects the sea surface temperature gradient from the equator poleward (Nielson-Gammon, 2011a). These two long-term oscillations can enhance or dampen the effects of the El Niño Southern Oscillation phases and therefore long-term patterns of wet and dry cycles of the climate. Generally, drought conditions are enhanced by cool sea surface temperatures of the Pacific Decadal Oscillation and also warm sea surface temperatures of the Atlantic Multidecadal Oscillation.

FIGURE 4.6. ANNUAL PRECIPITATION BASED ON POST OAK TREE RINGS FOR THE SAN ANTONIO AREA (DATA FROM CLEAVELAND, 2006).

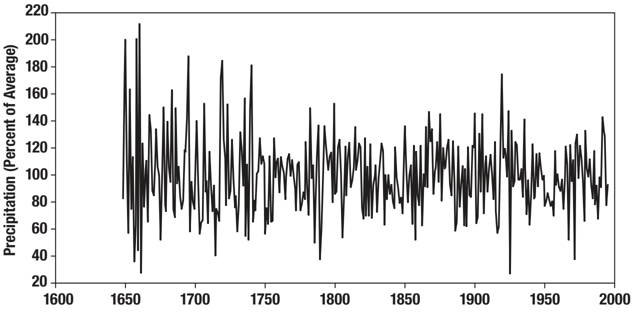
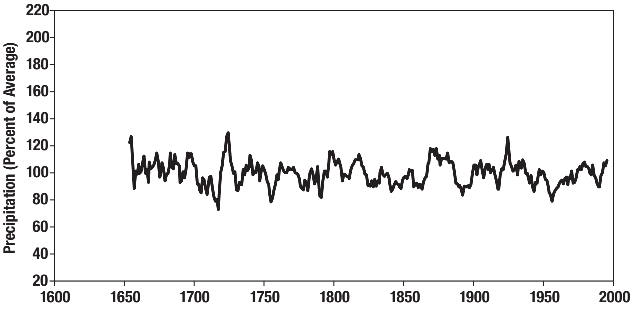


FIGURE 4.7. SEVEN-YEAR RUNNING AVERAGE OF PRECIPITATION BASED ON POST OAK TREE RINGS FOR THE SAN ANTONIO AREA (DATA FROM CLEAVELAND, 2006).



4.5 DROUGHT SEVERITY IN TEXAS

Droughts are periods of less than average precipitation over a period of time. The Palmer Drought Severity Index is often used to quantify long-term drought conditions and is commonly used by the U.S. Department of Agriculture to help make policy decisions such as when to grant emergency drought assistance. The severity of drought depends upon several factors, though duration and intensity are the two primary components. The drought of record during the 1950s ranks the highest in terms of both duration and intensity (Table 4.1). However, it should be noted that drought rankings can be misleading since a single year of above average rainfall can interrupt a prolonged drought, reducing its ranking. Nonetheless, on a statewide basis, the drought of the 1950s still remains the most severe drought the state has ever experienced based on recorded measurements of precipitation. Other significant droughts in Texas occurred in the late 1800s and the 1910s, 1930s, and 1960s. At the end of 2011, the 2011 drought may rank among the most intense one-year droughts on record in many climatic divisions.

4.6 CLIMATE VARIABILITY

The climate of Texas is, has been, and will continue to be variable. Since variability affects the availability of the state's water resources, it is recognized by the regional water planning groups when addressing needs for water during a repeat of the drought of record. More discussion on how planning groups address climate variability and other uncertainties can be found in Chapter 10, Challenges and Uncertainty.

Climate data are generally available in Texas from the late 19th century to the present, but this is a relatively short record that can limit our understanding of long-term climate variability. Besides the variability measured in the record, historic variability can be estimated through environmental proxies by the study of tree rings, while future variability can be projected through the analysis of global climate models. Annual tree growth, expressed in a tree growth ring, is strongly influenced by water availability. A dry year results in a thin growth ring, and a wet year results in a thick growth ring. By correlating tree growth ring thickness with precipitation measured during the period of record, scientists can extend the climatic record back hundreds of years.

In Texas, scientists have completed precipitation data reconstructions using post oak and bald cypress trees. In the San Antonio area (Cleaveland, 2006), reconstruction of precipitation using post oak trees from 1648 to 1995 (Figure 4.6) indicates that the highest annual precipitation was in 1660 (about 212 percent of average) and the lowest annual precipitation was in 1925 (about 27 percent of average).

Drought periods in this dataset can also be evaluated with seven-year running averages (Figure 4.7). The drought of record that ended in 1956 can be seen in this reconstruction, with the seven-year precipitation during this period about 79 percent of average. This record shows two seven-year periods that were drier than the drought of record: the seven-year period that ended in 1717 had precipitation of about 73 percent of average, and the seven-year period that ended in 1755 had a seven-year average precipitation of about 78 percent. There have been about 15 seven-year periods where precipitation was below 90 percent of average, indicating an extended drought.

4.7 FUTURE VARIABILITY

Climate scientists have developed models to project what the Earth's climate may be like in the future under certain assumptions, including the composition of the atmosphere. In simple terms, the models simulate incoming solar energy and the outgoing energy in the form of long-wave radiation. The models also simulate interactions between the atmosphere, oceans, land, and ice using well-established physical principles. The models are capable of estimating future climate based on assumed changes in the atmosphere that change the balance between incoming and outgoing energy. These models can provide quantitative estimates of future climate variability, particularly at continental and larger scales (IPCC, 2007). Confidence in these estimates is higher for some climate variables, such as temperature, than for others, such as precipitation.

While the climate models provide a framework for understanding future changes on a global or continental scale, scientists have noted that local temperature changes, even over decades to centuries, may also be strongly influenced by changes in regional climate patterns and sea surface temperature variations, making such changes inherently more complex. According to John W. Nielsen-Gammon, "If temperatures rise and precipitation decreases as projected by climate models, droughts as severe as those in the beginning or middle of the 20th Century would become increasingly likely" (2011b). However, the temperature increase began during a period of unusually cold temperatures. It is only during the last 10 to 15 years that temperatures have become as warm as during earlier parts of the 20th century, such as the Dust Bowl of the 1930s and the drought of the 1950s.

Climate scientists have also reported results of model projections specific to Texas, with the projected temperature trends computed relative to a simulated 1980 to 1999 average. The projections indicate an increase of about 1°F for the 2000 to 2019 period, 2°F for the 2020 to 2039 period, and close to 4°F for the 2040 to 2059 period (Nielsen-Gammon, 2011c).

Precipitation trends over the 20th century are not always consistent with climate model projections. The model results for precipitation indicate a decline in precipitation toward the middle of the 21st century. However, the median rate of decline (about 10 percent per century) is smaller than the observed rate of increase over the past century. Furthermore, there is considerable disagreement among models whether there will be an increase or a decrease in precipitation prior to the middle of the 21st century. While the climate models tend to agree on the overall global patterns of precipitation changes, they produce a wide range of precipitation patterns on the scale of Texas itself, so that there is no portion of the state that is more susceptible to declining precipitation in the model projections than any other.

Climate scientists have reported that drought is expected to increase in general worldwide because of the increase of temperatures and the trend toward concentration of rainfall into events of shorter duration (Nielsen-Gammon, 2011c). In Texas, temperatures are likely to rise; however, future precipitation trends are difficult to project. If temperatures rise and precipitation decreases, as projected by climate models, Texas would begin seeing droughts in the middle of the 21st century that are as bad or worse as those in the beginning or middle of the 20th century.

While the study of climate models can certainly be informative during the regional water planning process, there is a considerable degree of uncertainty associated with use of the results at a local or regional scale. The large-scale spatial resolution of most climate models (typically at a resolution of 100 to

200 miles by 100 to 200 miles) are of limited use for planning regions since most hydrological applications require information at a 30-mile scale or less. Recent research, including some funded by TWDB, has been focused in the area of "downscaling" climate models, or converting the global-scale output to regional-scale conditions. The process to produce a finer-scale climate model can be resource-intensive and can only be done one region at a time, thus making it difficult to incorporate the impacts of climate variability in local or region-specific water supply projections.

4.8 TWDB ONGOING RESEARCH

TWDB has undertaken several efforts to address potential impacts from climate variability to water resources in the state and how these impacts can be addressed in the water planning process. In response to state legislation, TWDB co-hosted a conference in El Paso on June 17, 2008, to address the possible impact of climate change on surface water supplies from the Rio Grande (Sidebar: The Far West Texas Climate Change Conference). The agency also hosted two Water Planning and Climate Change Workshops

THE FAR WEST TEXAS CLIMATE CHANGE CONFERENCE

As a result of legislation passed during the 80th Texas Legislative Session, TWDB, in coordination with the Far West Texas Regional Water Planning Group, conducted a study regarding the possible impact of climate change on surface water supplies from the portion of the Rio Grande in Texas subject to the Rio Grande Compact. In conducting the study, TWDB was directed to a convene a conference within the Far West Texas regional water planning area to review

- any analysis conducted by a state located west of Texas regarding the impact of climate change on surface water supplies in that state;
- any other current analysis of potential impacts of climate change on surface water resources; and
- recommendations for incorporating potential impacts of climate change into the Far West Texas Regional Water Plan, including potential impacts to the Rio Grande in Texas subject to the Rio Grande Compact, and identifying feasible water management strategies to offset any potential impacts.

The Far West Texas Climate Change Conference was held June 17, 2008, in El Paso. Over 100 participants attended, including members of the Far West Texas Regional Water Planning Group and representatives from state and federal agencies, environmental organizations, water providers, universities, and other entities. TWDB published a report on the results of the conference in December 2008. General policy recommendations from the conference included

- continuing a regional approach to considering climate change in regional water planning;
- establishing a consortium to provide a framework for further research and discussion;
- reconsidering the drought of record as the benchmark scenario for regional water planning; and
- providing more funding for research, data collection, and investments in water infrastructure.

in 2008 and 2009 to address the issue of climate on a state level. The workshops convened experts in the fields of climate variability and water resources planning to discuss possible approaches to estimating the impact of climate variability on water demand and availability and how to incorporate these approaches into regional water planning efforts.

In response to recommendations from these experts, TWDB initiated two research studies. The *Uncertainty and Risk in the Management of Water Resources* (INTERA Incorporated and others, 2010) study developed a generalized methodology that allows various sources of uncertainty to be incorporated into the regional water planning framework. Using estimates of the probability of specific events, planners will be able to use this model to analyze a range of scenarios and potential future outcomes. A second, on-going research study assessing global climate models for water resource planning applications is comparing global climate models to determine which are most suitable for use in Texas. The study is also comparing regionalization techniques used in downscaling of global climate models and will provide recommendations on the best methodology for a given region.

The agency also formed a staff workgroup that leads the agency's efforts to

- monitor the status of climate science, including studies for different regions of Texas;
- assess changes predicted by climate models;
- analyze and report data regarding natural climate variability; and
- evaluate how resilient water management strategies are in adapting to climate variability and how regional water planning groups might address the impacts.

Until better information is available to determine the impacts of climate variability on water supplies and water management strategies evaluated during the planning process, regional water planning groups can continue to use safe yield (the annual amount of water that can be withdrawn from a reservoir for a period of time longer than the drought of record) and to plan for more water than required to meet needs, as methods to address uncertainty and reduce risks. TWDB will continue to monitor climate policy and science and incorporate new developments into the cyclical planning process when appropriate. TWDB will also continue stakeholder and multi-disciplinary involvement on a regular basis to review and assess the progress of the agency's efforts.

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