

Chapter 2. The Changing Climate of Texas

John W. Nielsen-Gammon

Texas is the second largest state in the United States, with a total land area of 261,914 square miles. Its size and geographical location combine to give it a diverse climate, with a wide variety of local and regional climatic influences. Before discussing the historical record of past climate change in Texas and possible future changes as a result of global warming and other factors, this chapter will give an overview of Texas climate and how the climate is determined by topographic and other characteristics.

OVERVIEW OF TEXAS CLIMATE

Texas's climate is strongly influenced by three large geographical features. The first is the Rocky Mountains, or more broadly, the North American Cordillera. This set of mountain ranges and plateaus, extending from Alaska through western Canada and the United States to Mexico and Central America, presents a formidable barrier to air traveling from west to east or from east to west. Except for El Paso, which lies within the Cordillera, winds from the north and south are much more common in Texas than winds from the east or west.

The other two substantial geographical features are the central and eastern North American continent and the Gulf of Mexico. Both form a barrier-free pathway for transport into Texas, but the characteristics of the air depend on the route taken. The Great Plains form an unbroken, relatively flat land mass stretching from the Arctic Circle to Texas. Cold air masses that appear on the eastern side of the North American Cordillera are channeled southward, traversing the distance between the United States-Canadian border and Texas in about a day and a half. The Gulf of Mexico, on the other hand, serves as a moisture source for Texas. Much of the moisture crossing the coastline originates from the Caribbean Sea or the open Atlantic, but the air picks up additional moisture from the Gulf of Mexico before reaching Texas. The Gulf of Mexico also serves as a moderating influence on temperature, since its surface temperatures do not change nearly as much from day to day or from winter to summer as land surface temperatures.

The basic climatic patterns in Texas are fairly simple: annual mean temperature increases from north to south, and annual mean precipitation increases from west to east. The temperature variations are encapsulated with maps of January normal minimum temperature (Figure 2.1) and July normal maximum temperature (Figure 2.2). Typical daily minimum temperatures in January range from about 20°F in the northern Panhandle to about 50°F near the mouth of the Rio Grande. The north-south contrast is completely absent for maximum temperatures in July. Hotspots are found along the Rio Grande and Red River, while the coolest summertime temperatures are found in the mountains of West Texas.

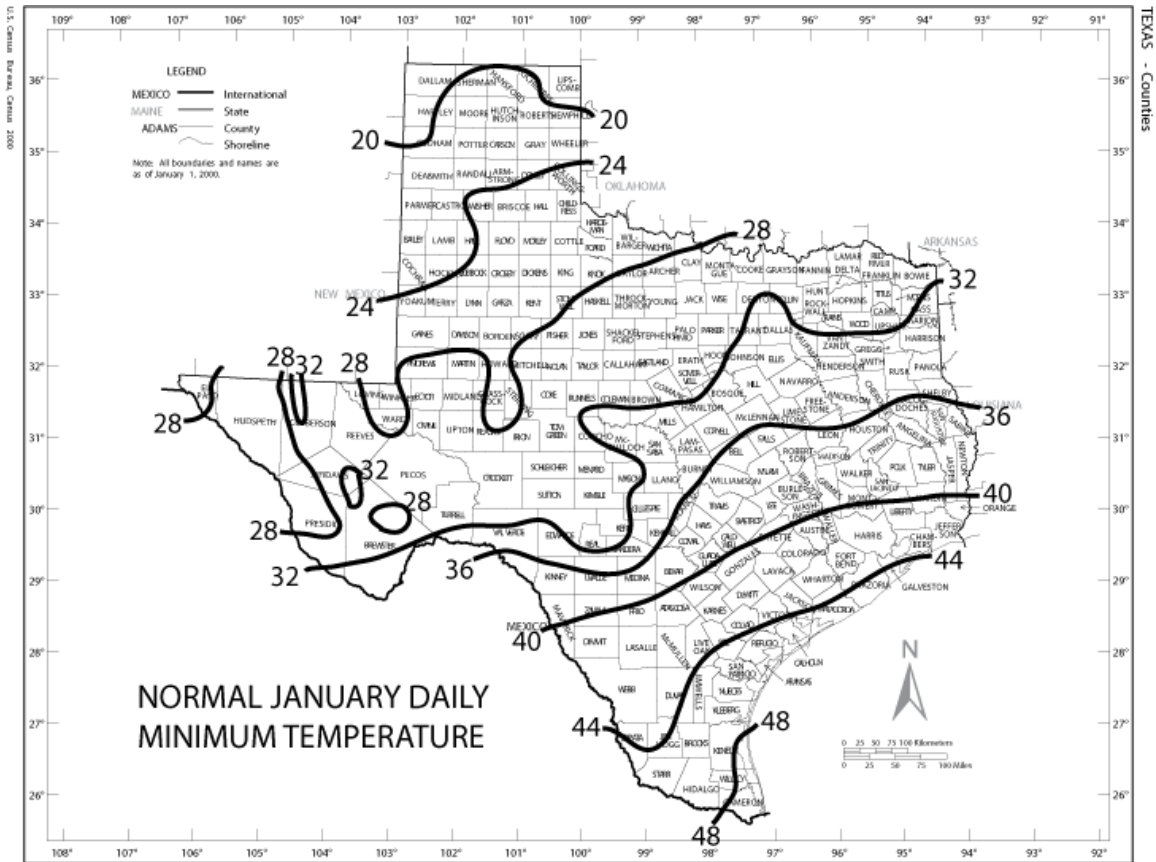


Figure 2.1: Normal January daily minimum temperature (°F), 1971-2000. Redrawn after graphics created Feb. 20, 2004 by the PRISM Group, Oregon State University, <http://prismclimate.org>.

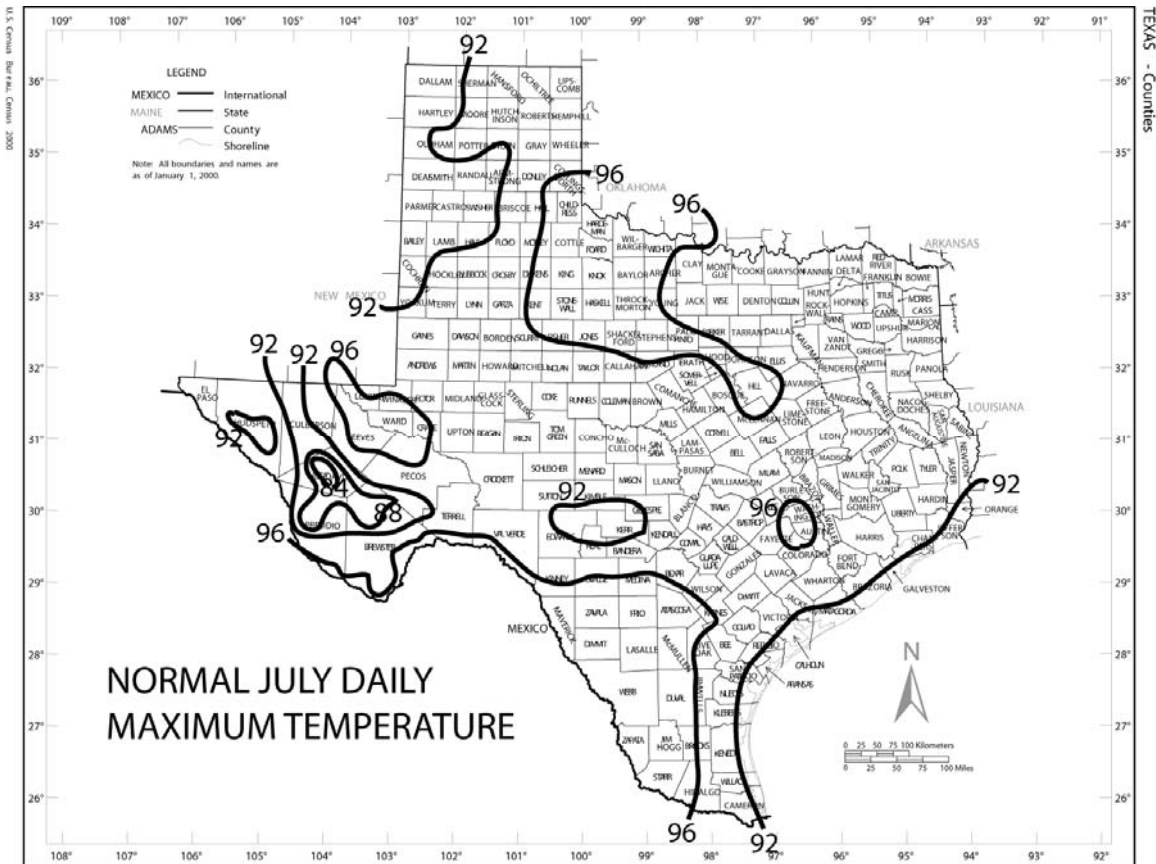


Figure 2.2: Normal July daily maximum temperature (°F), 1971-2000. Redrawn after graphics created Feb. 20, 2004 by the PRISM Group, Oregon State University, <http://prismclimate.org>.

The broad east-west variation in precipitation (Figure 2.3) is caused by the Gulf of Mexico, which can more readily supply moisture to the eastern half of the state than to the western half. Exceptions to this pattern include the Balcones Escarpment, the edge of the Edwards Plateau west of San Antonio, where precipitation is enhanced by air being forced upward by the topography as it travels northward, and West Texas, where precipitation is more common in the higher terrain than the lower due to upslope flow and summertime thunderstorms.

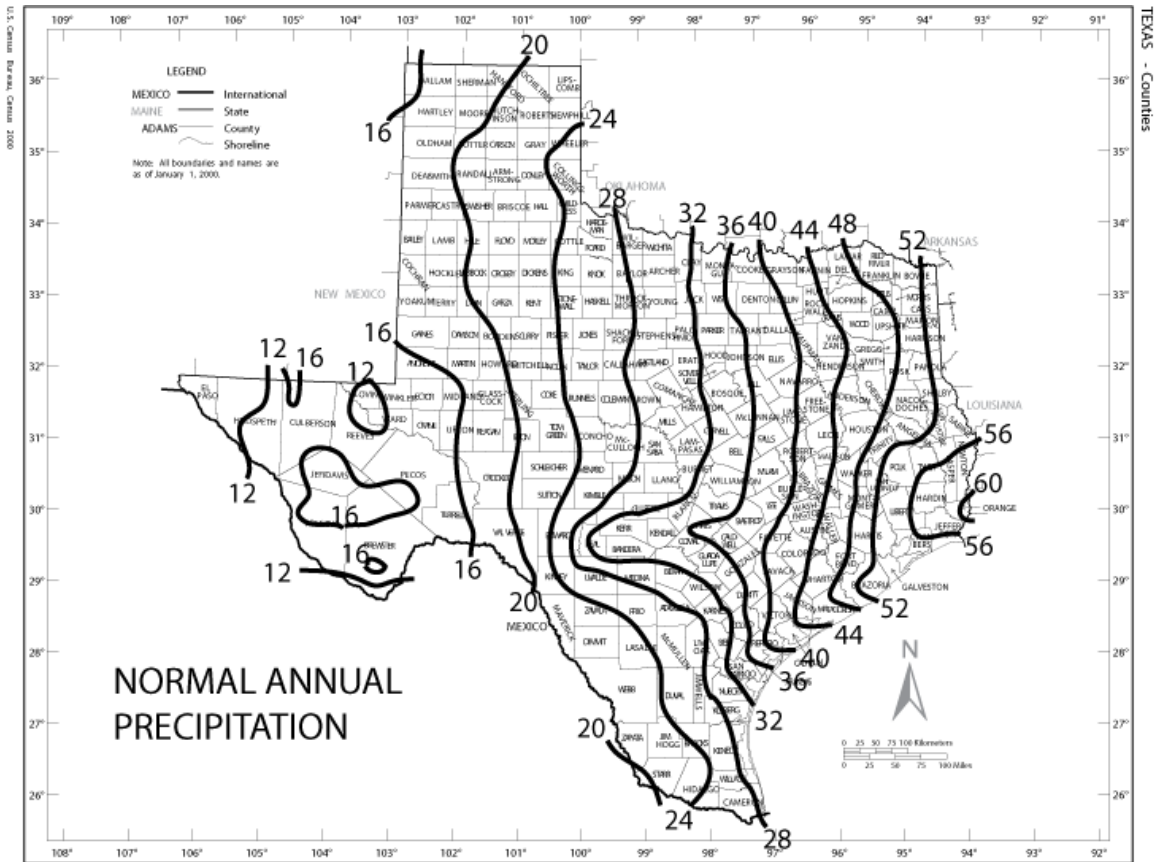


Figure 2.3: Normal annual precipitation (inches), 1971-2000. Redrawn after graphics created Feb. 20, 2004 and June 16, 2006 by the PRISM Group, Oregon State University, <http://prismclimate.org>.

Regional and Seasonal Climatic Variations

For the purposes of this chapter, Texas may be subdivided into eight climatic regions (Figure 2.4), each with its own distinct seasonal weather patterns.

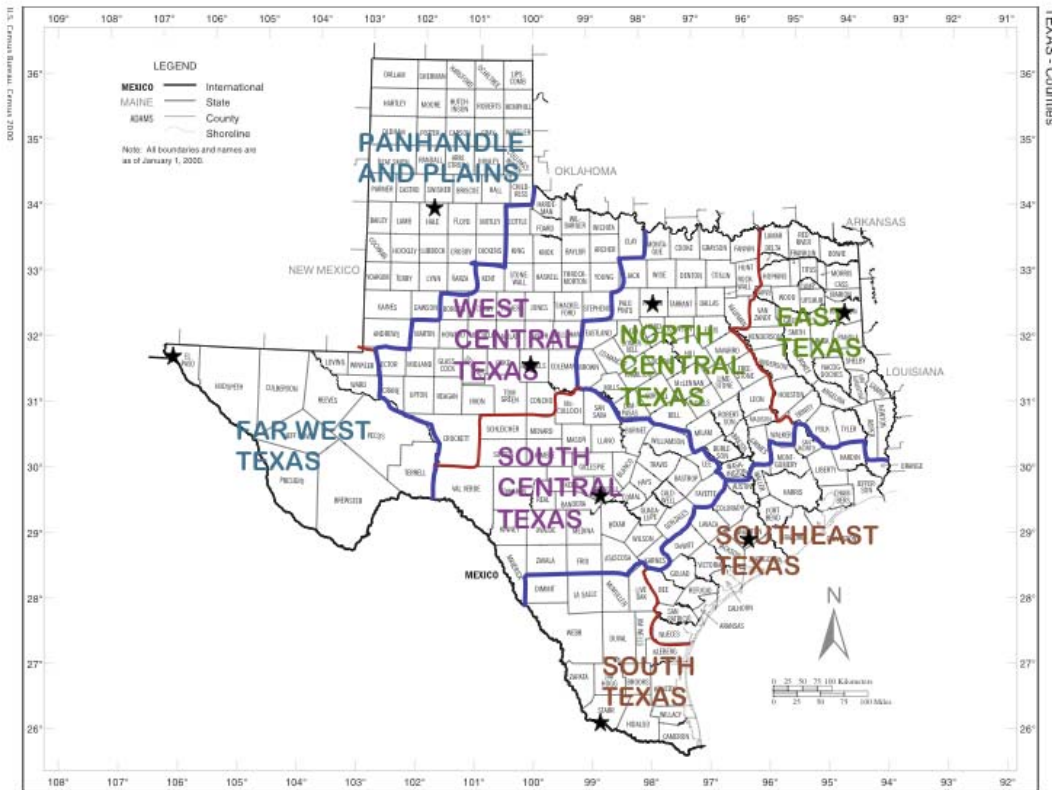


Figure 2.4: Map of Texas climatic regions utilized in this chapter. The locations of representative long-term climate observing stations within each region are plotted as stars.

Seasonal variations in precipitation are depicted for one key long-term station in each region using box-and-whisker charts. These charts show the median monthly precipitation (thick horizontal line), the values between the lowest quarter of all months and the highest quarter of all months (shaded), and the values between the lowest five percent and the highest five percent of all months (vertical lines). For example, in El Paso in June (Figure 2.5), a third of an inch of precipitation or more occurs about half the time (the median line), zero precipitation occurs almost a quarter of the time, and more than five percent of all Junes produce greater than two inches of precipitation.

Because of the skewed nature of precipitation, median precipitation is almost always smaller than average or “normal” precipitation. In other words, precipitation is more likely to be “below normal” than “above normal”.

Far West Texas has a well-defined wet season and dry season (Figure 2.5). The dry season is November through May, and the wet season is June through October. The peak rainfall months of July and August are a consequence of the Southwest Monsoon, a flow pattern that brings moist tropical air and convection to northwestern Mexico, Arizona, New Mexico, and the western edge of Texas. Long-term changes in rainfall in Far West Texas are closely related to changes in the pattern of the Southwest Monsoon. During the dry season, entire months without precipitation are not uncommon.

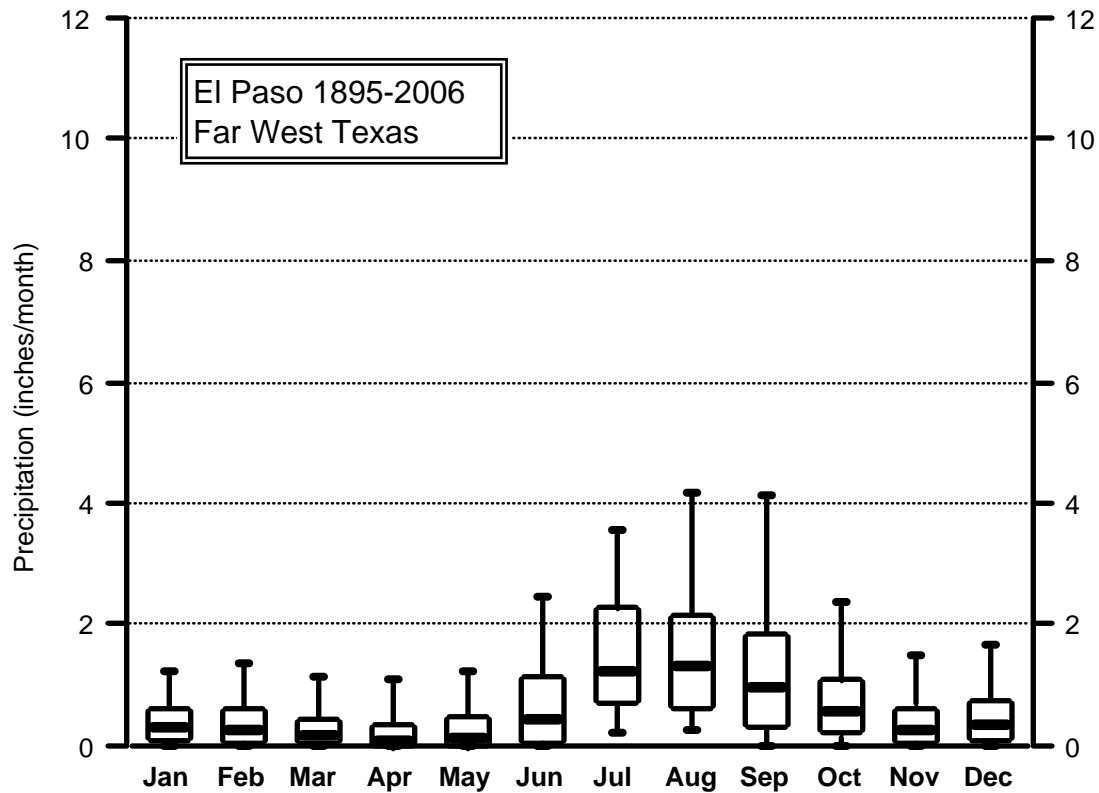


Figure 2.5: Box and whisker plot for monthly precipitation in El Paso, Far West Texas. Bottom and top of box indicate 25th and 75th percentiles of precipitation; bottom and top of whiskers represent 5th and 95th percentiles.

The Panhandle and Plains also receive a share of the July and August Southwest Monsoon precipitation, but even more precipitation falls in May and June (Figure 2.6). This is the period of time when the West Texas Dryline is active. The Dryline marks the boundary between humid, potentially unstable air from the Gulf of Mexico and hot, dry, descending air from the interior Southwest. Severe thunderstorms are favored to form along and to the east of the Dryline, sometimes producing tornadoes and large hail. The Monsoon precipitation is more regular than the Dryline precipitation, as seen by the relatively short shaded bar for August compared to earlier months.

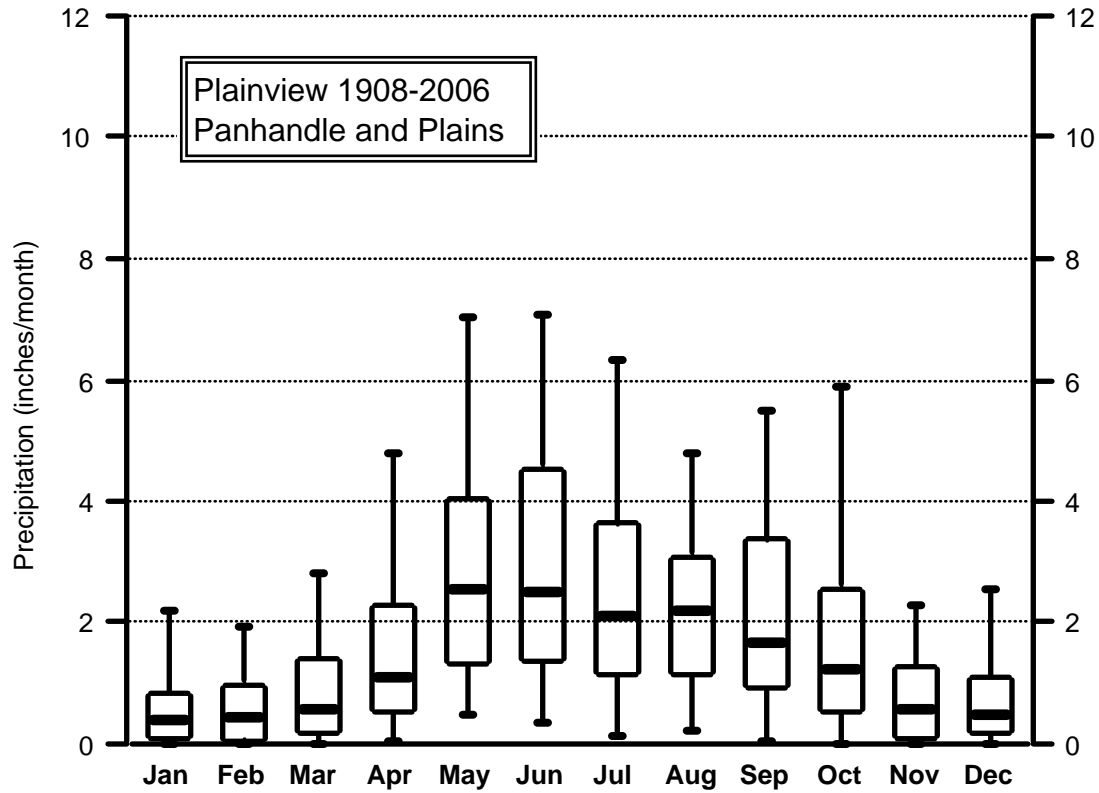


Figure 2.6: Box and whisker plot for monthly precipitation in Plainview, Panhandle and Plains.

In West Central Texas (Figure 2.7), the springtime precipitation maximum occurs squarely in May, a bit earlier than in the Panhandle and Plains. Without moisture from the Southwest Monsoon, July is one of the drier months of the year. This dryness, in terms of precipitation, is exacerbated by the higher temperature during July, making July the driest month of the year in terms of precipitation minus evaporation. Wintertime precipitation, while still much lower than in late spring or early fall, is much higher than in Far West Texas or in the Panhandle and Plains.

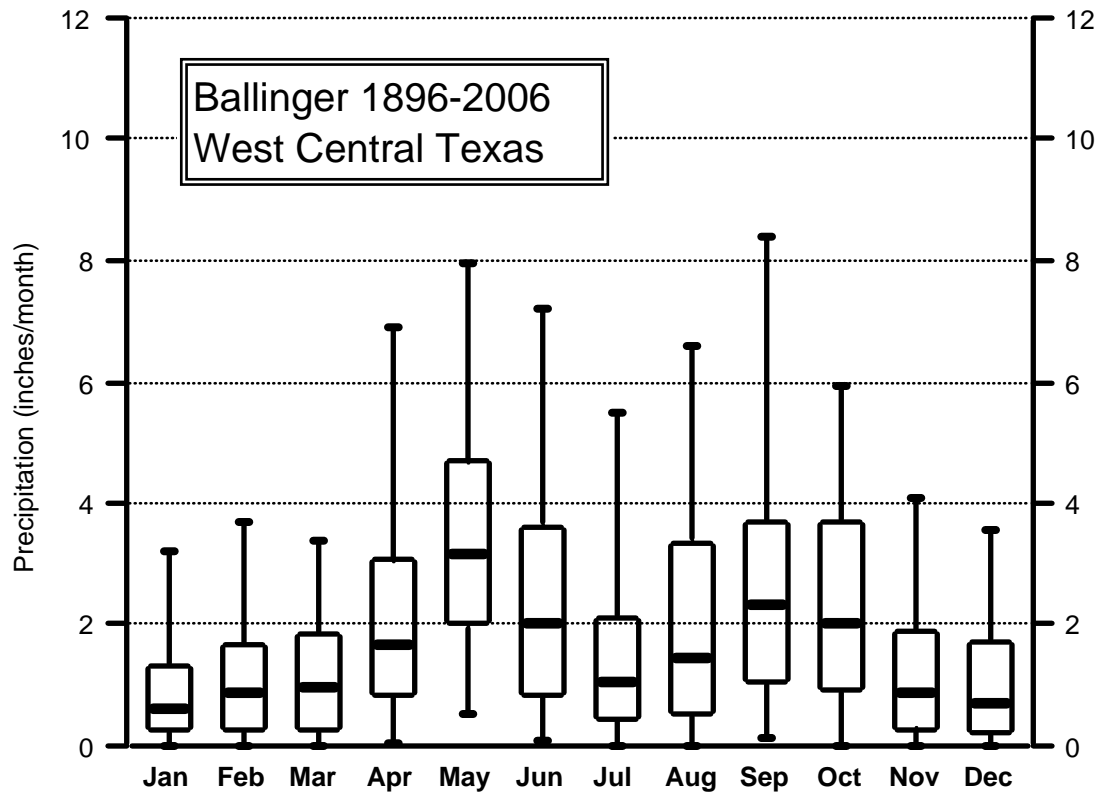


Figure 2.7: Box and whisker plot for monthly precipitation in Ballinger, West Central Texas.

The seasonality in North Central Texas (Figure 2.8) is similar to that in West Central Texas. Peaks in median precipitation occur in May and September. Wintertime precipitation continues to increase as locations farther to the east are considered, and the likelihood of a month without rainfall, or without significant rainfall, is lower than at any other station examined thus far.

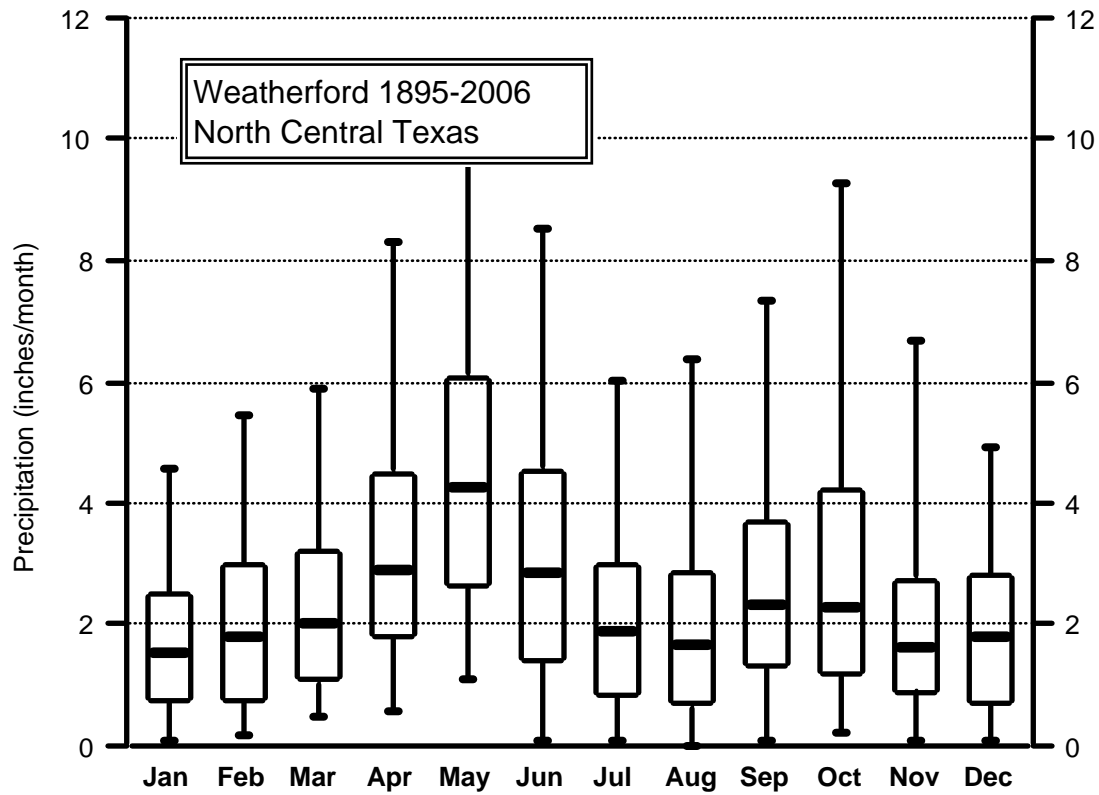


Figure 2.8: Box and whisker plot for monthly precipitation in Weatherford, North Central Texas.

In South Central Texas (Figure 2.9), the precipitation peak in early fall is nearly as prominent as that in late spring. The fall peak increases in prominence closer to the Gulf of Mexico, because tropical disturbances are an important source of moisture and instability.

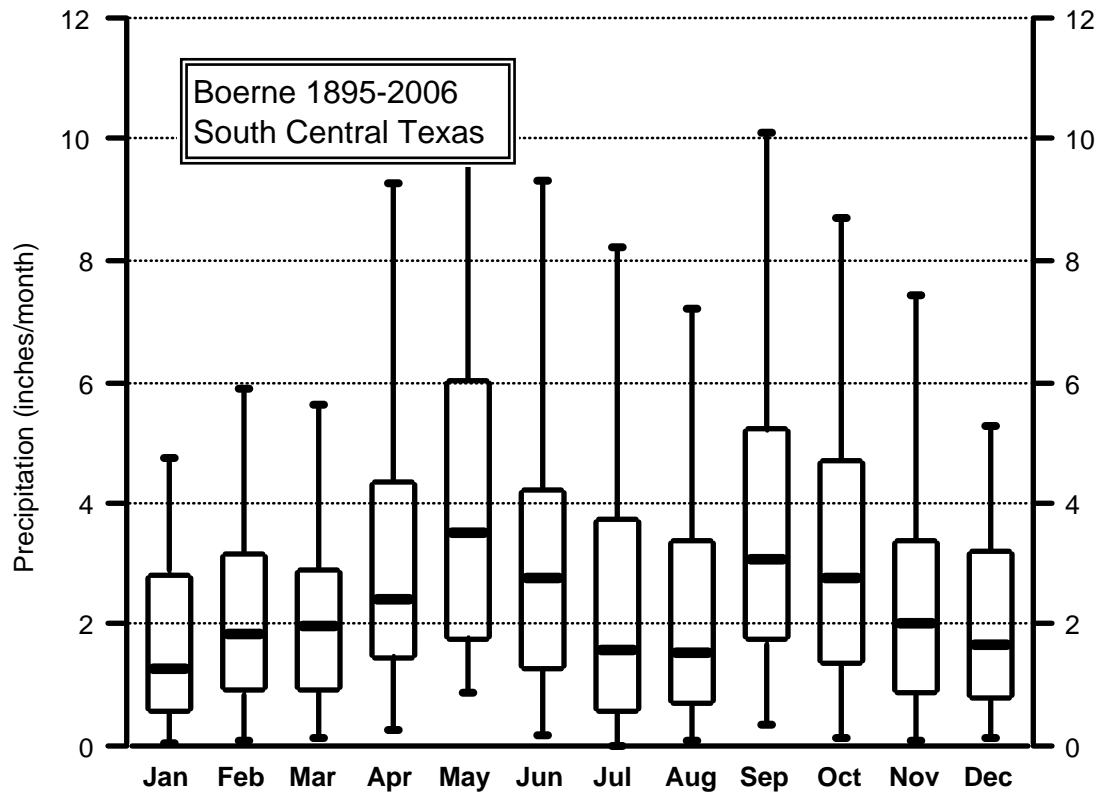


Figure 2.9: Box and whisker plot for monthly precipitation in Boerne, South Central Texas.

South Texas (Figure 2.10) has elements of many other climatic regions in Texas. In common with Far West Texas, it receives very little precipitation during the wintertime. In common with North Central and South Central Texas, it has two precipitation maxima during the year, one in May/June and one in September. The September maximum is especially prominent. These climate variations are due to a combination of geographical location and wind variations. During the wintertime, South Texas lies in the rain shadow of the high terrain of Mexico as disturbances move from west to east. During the time of tropical disturbances, particularly June and September, disturbances tend to move from southeast to northwest, and the easterly winds ahead of storms favor upslope flow and precipitation.

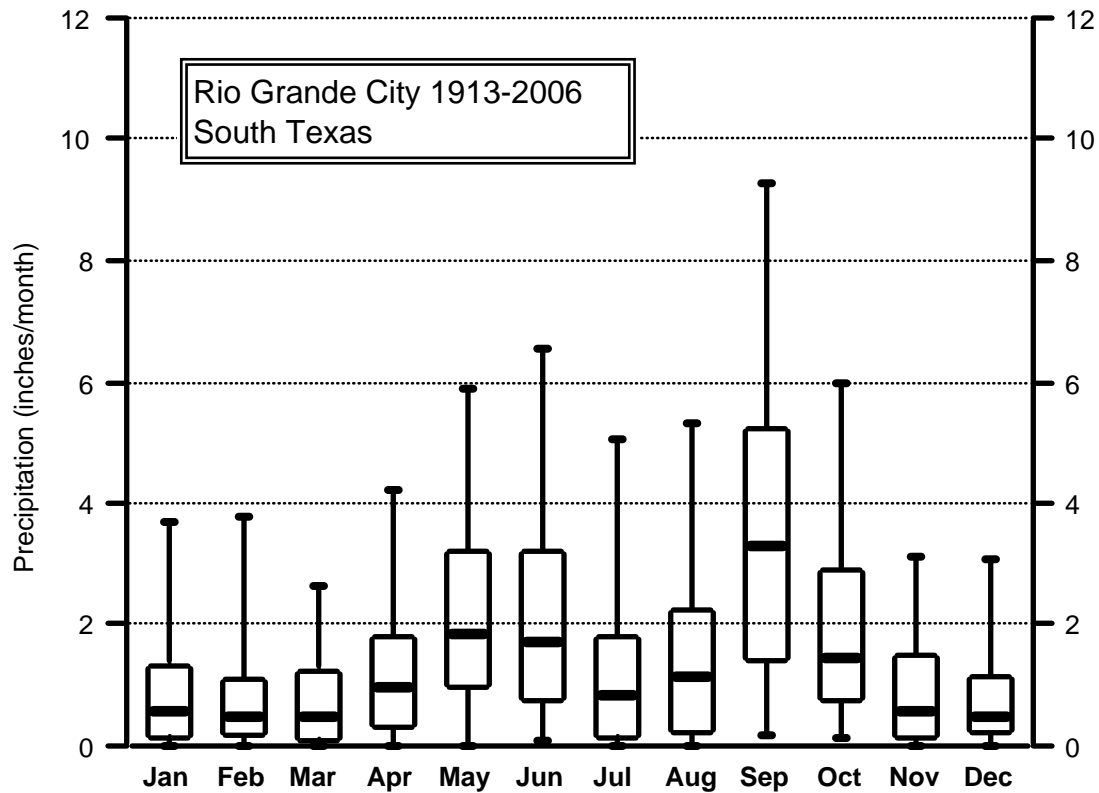


Figure 2.10: Box and whisker plot for monthly precipitation in Rio Grande City, South Texas.

Southeast Texas precipitation (Figure 2.11) has a similar annual pattern to precipitation as South Texas, except that about two inches more precipitation occurs on average in each month in Southeast Texas. The relatively large amount of precipitation in Southeast Texas means that precipitation is able to supply enough moisture to keep the ground damp during most of the year, with significant water stress typical only during July and August.

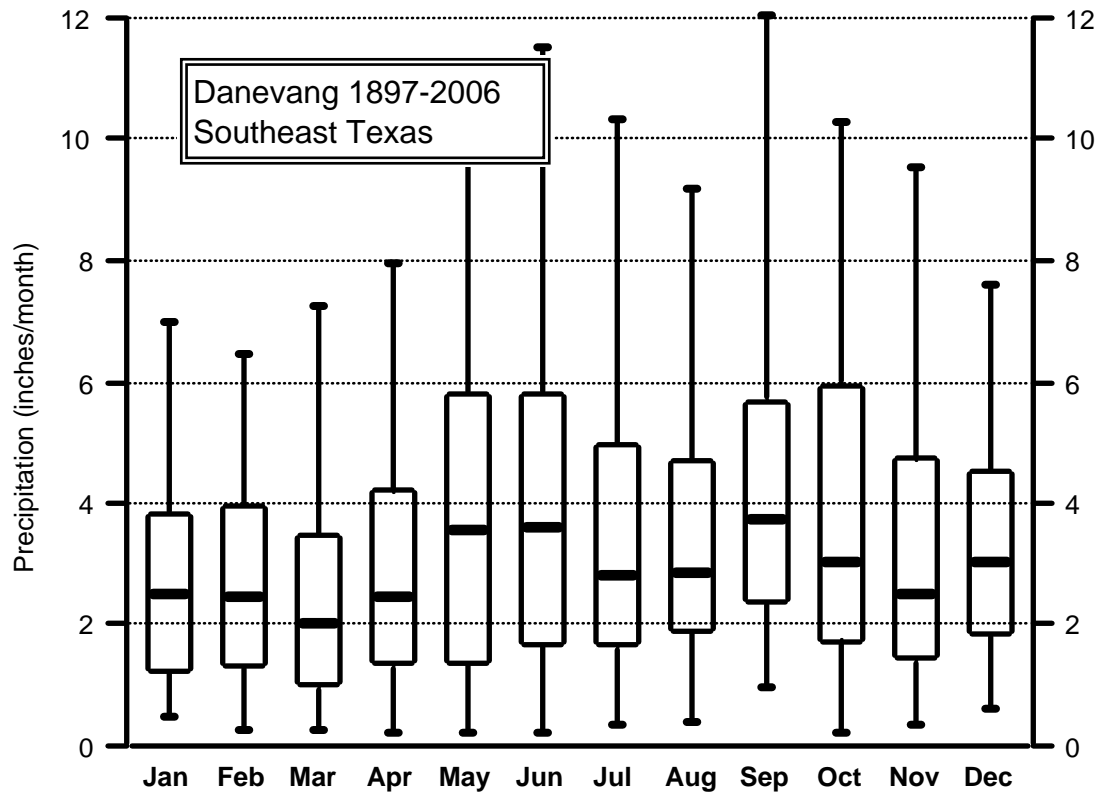


Figure 2.11: Box and whisker plot for monthly precipitation in Danevang, Southeast Texas.

In East Texas (Figure 2.12), the precipitation pattern is almost the exact opposite of that in Far West Texas. In East Texas, the climatologically wettest month of the year is December, and the driest months are July, August and September. East Texas is far enough north to be affected by frequent traveling wintertime disturbances, and far enough east that there is generally ample moisture available when the disturbances arrive. Rainfall is least when temperatures are warmest, and in August median precipitation in Marshall is actually lower than median precipitation in Plainview, in the Panhandle and Plains region.

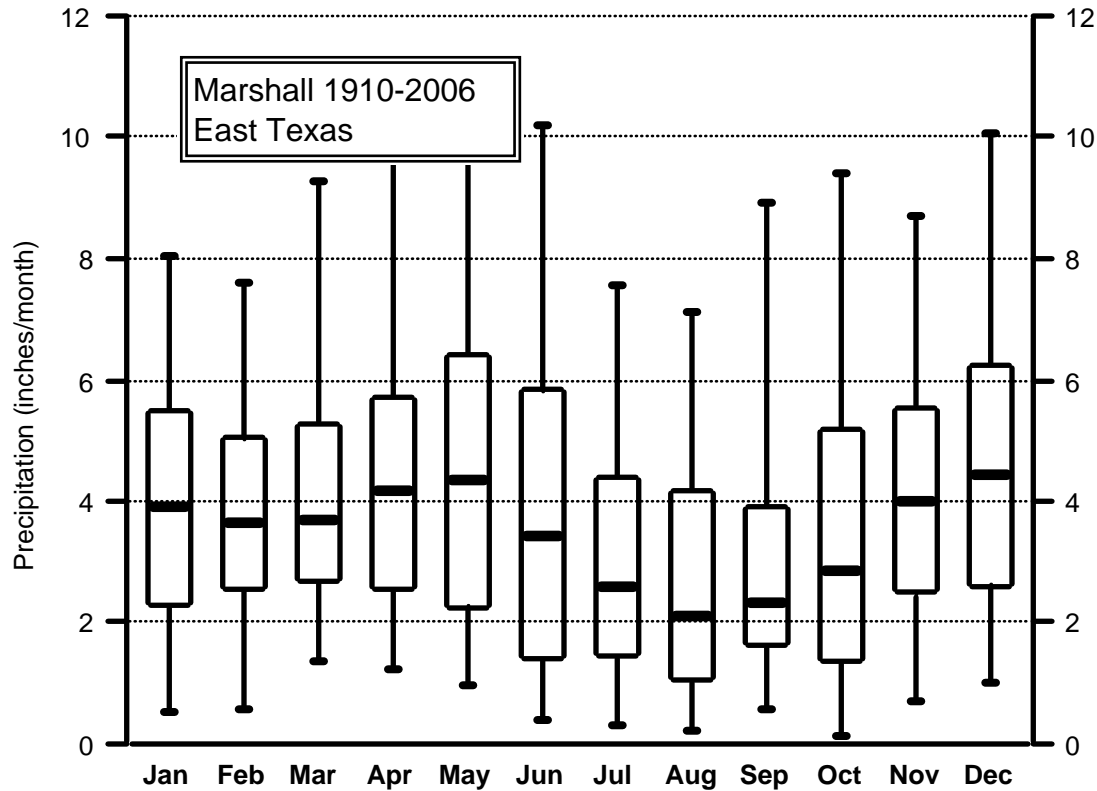


Figure 2.12: Box and whisker plot for monthly precipitation in Marshall, East Texas.

Severe and High-Impact Weather

Texas climate, and the impact of changes in Texas climate, is defined not just by changes in average conditions but changes in weather extremes. One could argue that the state of Texas is the worldwide leader in the combined frequency and variety of severe and high-impact weather.

Severe weather includes tornadoes, hail and damaging thunderstorm winds. The prevalence of all three types of severe weather generally increases in Texas from south to north and from west to east (Figure 2.13). In South Texas and Far West Texas, significant tornadoes (those producing F2 damage or greater) come within 25 miles of any given point less than once every two decades. This does not make significant tornadoes impossible there: one of the deadliest tornadoes in Texas history struck Goliad, Texas.

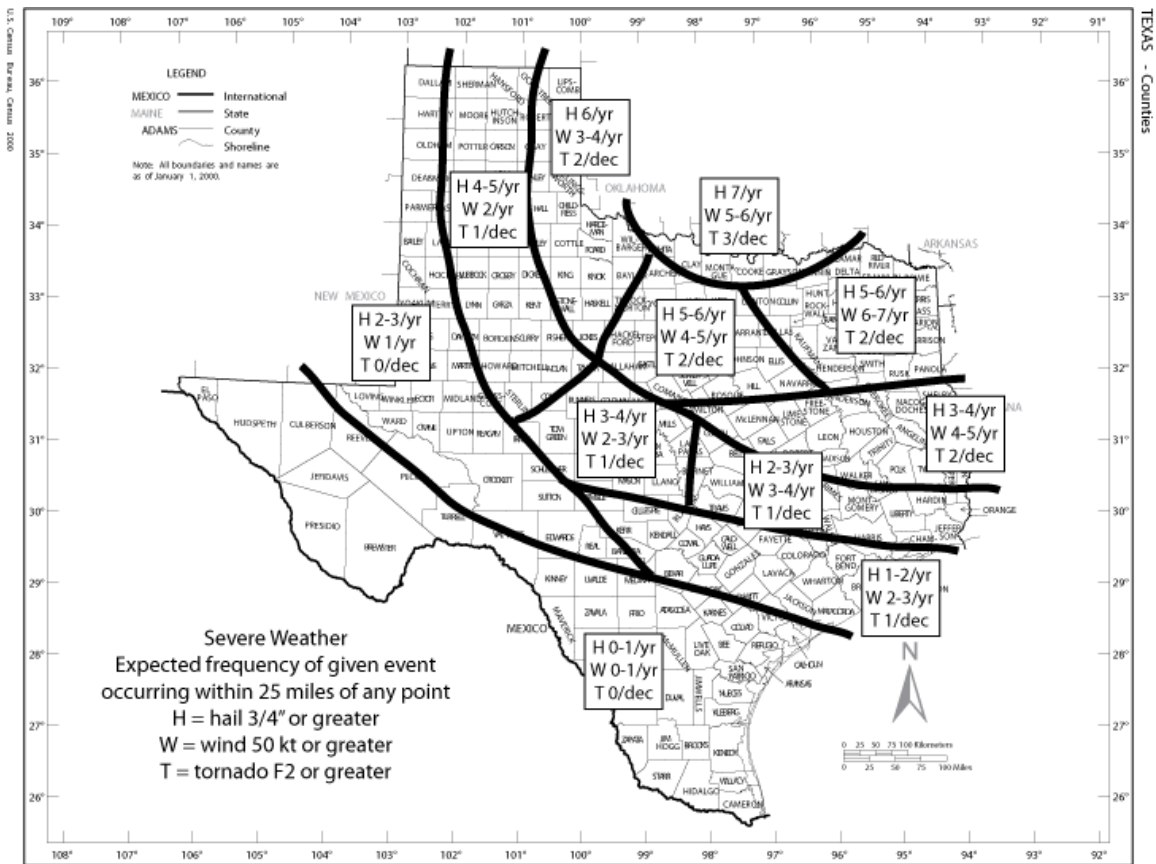


Figure 2.13: Climatological frequency of severe weather in Texas. Indicated are expected frequency of hail (3/4" or larger diameter), strong thunderstorm winds (50 knots or greater), and significant tornadoes (F2 or greater). An event is defined as an occurrence within 25 miles of a given location. Hail and wind frequencies are given as events per year, while tornado frequencies are given as events per decade. Spatial analyses are based on the period 1980-1999 for hail and wind, and 1921-1995 for tornadoes, and were conducted by the National Severe Storms Laboratory (NSSL 2003).

Severe weather is most common along the Red River from Wichita Falls to the Arkansas border. On the whole, hail at least 3/4" in diameter and thunderstorm winds at least 50 knots are equally common, with damaging winds slightly more prevalent in eastern Texas and hail slightly more prevalent in western Texas.

All types of severe weather are most common in the springtime. The peak likelihood of hail is in late April in East Texas; early May in North Central Texas, Southeast Texas, South Central Texas and South Texas; late May in West Central Texas and Far West Texas; and early June in the Panhandle and Plains. The peak likelihood for significant tornadoes is slightly earlier in the year; for thunderstorm winds it is slightly later in the year.

Hurricanes are most common in late August and September, although significant storms have struck Texas as early as June. Overall, the frequency of a hurricane passing within 75 miles of any given coastal location averages once every 7-15 years, according to the National Hurricane Center. Major hurricanes (those category 3 or stronger on the

Saffir-Simpson scale) pass within 75 miles of any given coastal location about once every 25-46 years.

While wind and tornadoes can be major hazards, the greatest damage and loss of life from hurricanes comes from the storm surge. The magnitude of the storm surge depends on the strength, longevity and size of the hurricane, as well as the configuration of the coastline.

Hurricanes can also produce copious amounts of rainfall. For rainfall from hurricanes, the intensity of the hurricane itself matters little, and tropical storms are just as capable of producing major flooding as full-blown hurricanes. Of the 21 rainfall events in Texas between 1948 and 2002 that produced at least 20" of precipitation, four were associated with hurricanes, five were associated with tropical storms, and the remainder were nontropical in origin (Nielsen-Gammon et al. 2005). A memorable recent example of rainfall produced by a tropical storm was Allison in 2001, which flooded downtown Houston and caused more damage than any other tropical storm in United States history. Another tropical storm, Claudette in 1979, produced the greatest 24-hour precipitation total in United States history (45" in Alvin, Texas).

Other heavy rainfall events in Texas are produced by deep, moisture-laden air from the south being forced upward over Texas by a slowly-moving, upper-level disturbances. The unstable air produces strong convection, and the wind patterns are such that thunderstorms form repeatedly over a small area, such as north of a stationary front. The topography of the Balcones escarpment provides additional lift for such air masses, favoring precipitation formation there and leading to enhanced rainfall there (Figure 2.3). In addition, the rugged, rocky soil of the Hill Country inhibits infiltration of water into the soil, producing rapid runoff and contributing to the flash flood potential of the area.

Droughts are also a common high-impact weather event. The drought of the 1950s was the most severe long-term drought in Texas and is usually treated as the drought of record for water planning purposes. More recently, significant droughts have occurred in 1996, 1998, 2000 and 2005-6.

Because potential evapotranspiration far exceeds precipitation in the summertime throughout the state and in all seasons in the western part of the state, most of Texas is vulnerable to short-term variations in rainfall. One or two months without precipitation in the wintertime generally has little impact, but the same rainfall deficit in the summer can be catastrophic because of the high temperatures and evaporation rates. Such short-term summertime water deficits are harmful to agriculture and ranching and can tax the ability of municipal water systems to deliver sufficient water for their customers. Longer-term water deficits, those of six months or more, can also cause significant shortages in the supply of water.

Wildfire frequency and danger are closely tied to weather. Although one might assume that the greatest wildfire danger is associated with the most severe droughts, wildfires are most dangerous when a few months of very wet weather produce heavy vegetation growth and are followed by a few months of very dry weather that cause the fuel to dry out. When the fuel is in place, dangerous wildfires are most likely to occur on days with very strong wind and low humidity. Dust storms are favored under similar weather conditions but with longer-term dryness.

Winter weather is a danger to Texas in part because it is so rare. Except for the Panhandle and Plains and the mountains of Far West Texas, significant snowstorms or ice storms are unusual. As a result, they normally bring traffic to a standstill. Ice storms, in particular, cause damage to trees and power lines and can produce power outages that last for days or weeks, particularly in East Texas. The frequency of winter weather decreases as one goes southward, but snow has been recorded in all corners of the state.

THE HISTORICAL CLIMATE RECORD IN TEXAS

Climate records in Texas go back more than a century. Some individual records exist from the middle of the 18th century, and by 1900 climate records through most of the state were collected as part of the United States Cooperative Observer Program (COOP). A subset of COOP stations with relatively long, homogeneous records has been designated the United States Historical Climatology Network (USHCN) (Easterling et al. 1996; NCDC 2008).

Individual stations from the USHCN Version 2 dataset were utilized in the discussion of regional and seasonal climate variations in Texas. For the purposes of examining longer-term climate variations, data from all USHCN V2 stations within each climate region are standardized with respect to long-term means (computed from all available data for 1895-2006) and averaged together. In order to suppress random variability associated with month-to-month changes in weather while preserving information on seasonality, data from multiple months are averaged together and presented here.

CHANGES IN TEMPERATURE

Past Temperature Changes

The most direct manifestation of global warming is a rise in surface temperatures. Although there are many potential sources of error in surface temperature measurements that are not entirely removable through adjustment procedures (Pielke et al. 2007), interannual regional-scale variations of a few tenths of a degree Fahrenheit and century-scale variations of a degree or more Fahrenheit are probably trustworthy. This is particularly true when spatial patterns of temperature change do not correspond to known regional variations of confounding effects.

Local temperature changes are significant for agriculture, ecosystems, energy use, water supply and other aspects of the Texas economy and way of life. Global-scale temperature changes are far from irrelevant: they affect Texas through changes in weather patterns, sea level, moisture, and a variety of indirect influences. However, changes in global temperatures are documented and explained in documents produced by the Intragovernmental Panel on Climate Change (IPCC). Because of the importance of local temperature changes and the relative inattention to them by global panels, this section focuses on temperature changes taking place within Texas itself.

Global-scale temperatures are strongly constrained by balances in the global energy budget, so global temperature changes are relatively easily related to changes in radiative forcing, such as incoming solar radiation, greenhouse gas concentrations and aerosols. 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.

Temperature variations during different times of the year affect society and ecosystems in different ways. Wintertime temperatures (here, December through February) help determine the hardiness required of plants, energy expended on heating, and the survivability of pests. Temperatures during the swing months of March-April and October-November determine the length of the growing season and planting times. Temperatures during the hotter part of the year (May-September) strongly affect evaporation rates, energy spent on cooling, crop survival and the tolerability of the climate.

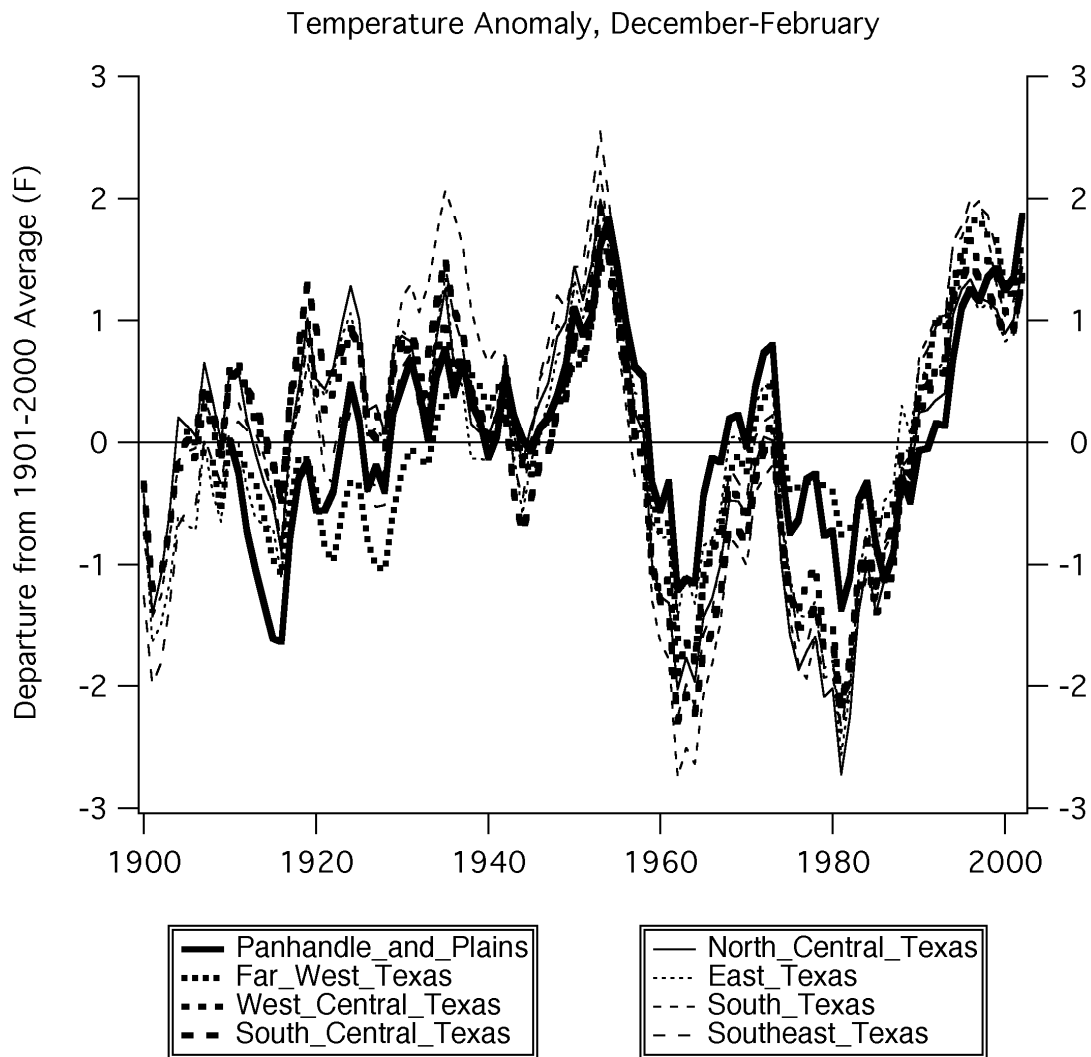


Figure 2.14: Nine-year running mean of average values of December-February mean USHCN V2 temperature departures from long-term mean, in each of eight Texas climate regions.

The wintertime temperatures (Figure 2.14) show considerable variability, even with nine-year averages. Temperatures increased fairly steadily during the first half of

the 20th century, reaching a peak in the early 1950s. Thereafter, temperatures dropped, attaining 20th century minima in the early 1960s and early 1980s, fully 4°F colder than in the early 1950s. Since then, temperatures have warmed, and the past decade and a half have produced temperatures warmer than at any time in the past century except the early 1950s.

Because annual and longer temperature averages vary on a fairly broad spatial scale, the various regional temperatures track each other closely. The time series least like the others is from Far West Texas, which possesses much less decade-scale variability than the other Texas climatic regions and which seems to indicate a greater tendency for a warming trend over the past century.

In contrast, the temperatures during the swing months of March-April and October-November (Figure 2.15) have much less decade-scale variability. In other words, the length of the growing season has undergone very little change from decade to decade. The most anomalous nine-year average temperatures are those at the end of the period, covering 1998-2006, which are several tenths of a degree warmer than any previous temperature maxima in all Texas climatic regions. Aside from the coinciding temperature minima in 1916, there appears to be little or no correspondence between variations in wintertime temperatures and variations in swing season temperatures. As in winter, the Far West Texas temperatures are least similar to the others, again showing a tendency to be relatively cool during the early part of the century and relatively warm during the latter part of the century.

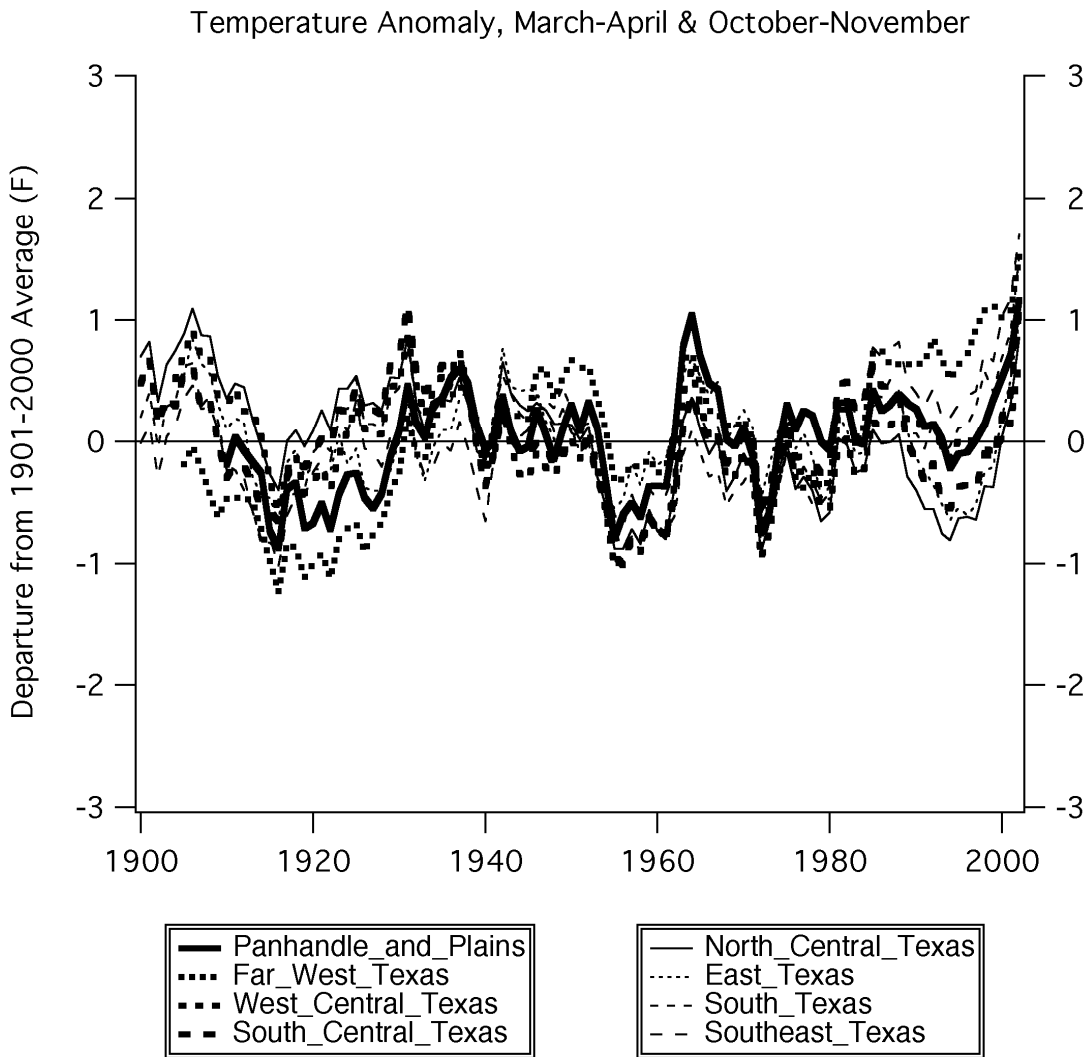


Figure 2.15: Nine-year running mean of average values of March, April, October and November mean USHCN V2 temperature departures from long-term mean, in each of eight Texas climate regions.

During the warm-season months of May through September (Figure 2.16), interdecadal variability is small like the swing months but the overall pattern is similar to the winter months. Temperatures climb to a maximum in the early 1950s, then decline rather sharply. After two relative minima, temperatures increase again, and the most recent temperatures are similar to the historical maximum in the 1950s. Oddly, while maxima and minima correspond rather well between winter and summer during the first half of the 20th century, they are almost precisely opposite during the period 1960-1990. As in the other two periods, Far West Texas shows a clear century-scale warming trend not apparent in the graphs for the other climatic regions.

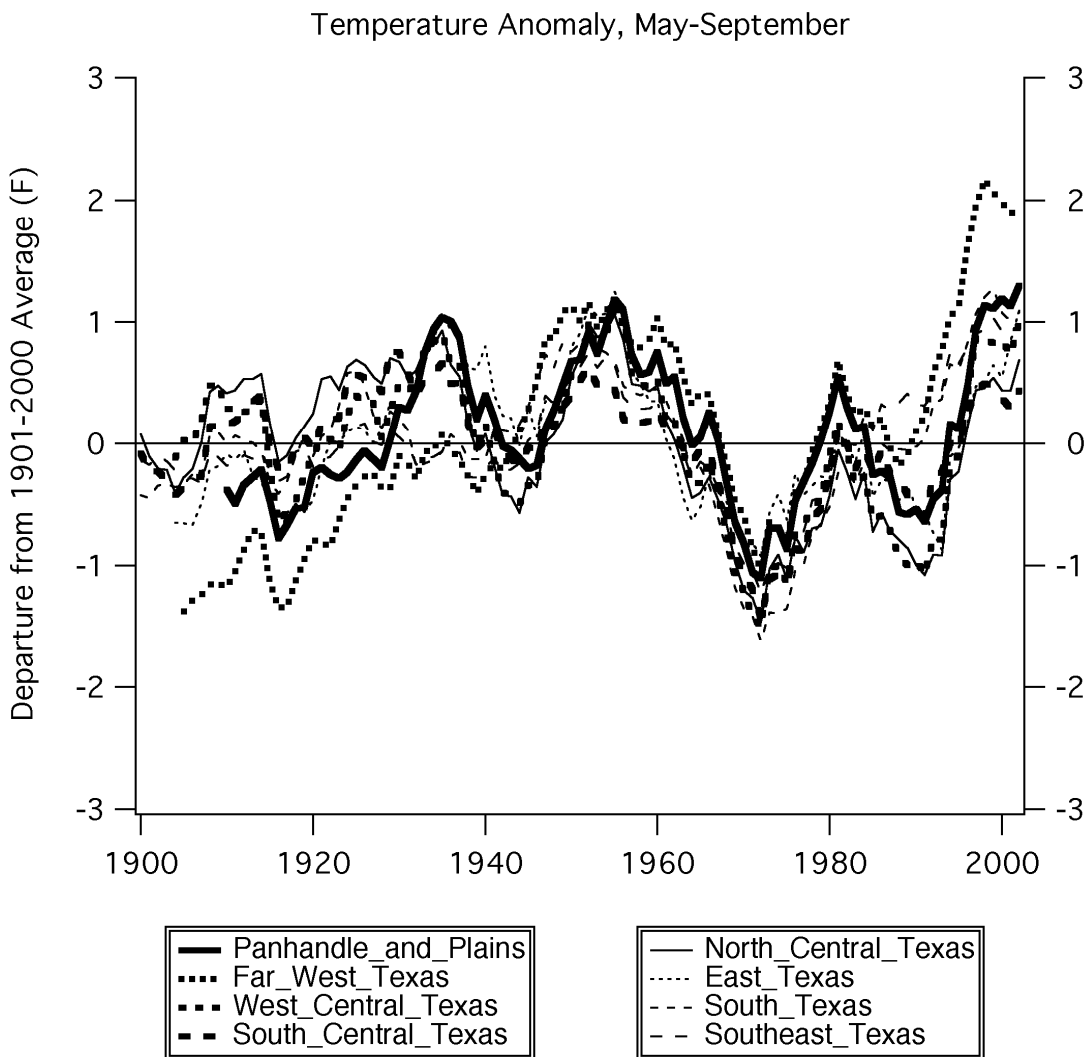


Figure 2.16: Nine-year running mean of average values of May-September mean USHCN V2 temperature departures from long-term mean, in each of eight Texas climate regions.

If the temperature observations are taken at face value, temperatures across Texas have increased fairly steadily over the past 20-30 years. However, this temperature increase began during a period of anomalously cold temperatures. It is only during the last 10-15 years that temperatures have become as warm as during earlier parts of the 20th century.

Except possibly for Far West Texas, the historical temperature variations across Texas are affected much more strongly by decadal-scale temperature variations than by longer-term temperature trends. Nonetheless, it is useful to examine the linear trend over the past century. Despite the fundamentally different nature of decade-scale temperature variations throughout the year in Texas, the century-scale trends are quite uniform across seasons. Far West Texas has the largest trend, 1.1-2.2°F per century. The warming trends are more moderate, 0.4-0.9°F, in the Panhandle and Plains and Southeast Texas. Only a very slight warming is present in East Texas and South Texas, and a very slight cooling is present in West Central Texas and South Central Texas. The cooling in North

Central Texas is -0.1 to -0.7°F per century. All trends except for Far West Texas are smaller than the global mean temperature trend over the same period.

Future Temperature Changes

What does the present relative lack of warming imply for projections of future climate change in Texas? Knutson et al. (2006) examined the spatial patterns of temperature change throughout the globe and their reproducibility in an advanced coupled climate model. An area of negative century-long temperature trends extends from central Texas across the southeastern United States. This region is one of the few areas of cooling over the entire globe. While ensemble runs of the coupled climate model, including both anthropogenic and natural forcing, produced realistic historical simulations over most of the globe, they completely failed to reproduce the observed cooling in the south-central and southeastern United States.

Robinson et al. (2002) took a close look at this anomaly. The climate model they used was able to reproduce the anomaly, whether or not anthropogenic forcings were included, as long as the atmospheric model was driven by observed sea surface temperature patterns. Through a series of experiments, Robinson et al. (2002) found that the key region for driving the cooler temperatures in the south-central and southeastern United States was the eastern equatorial Pacific Ocean, where warm sea surface temperatures led to increased water vapor and cloud cover over the southern United States, thereby reducing temperatures throughout the year.

While these studies provide interesting evidence, they are far from conclusive. If portions of the Pacific Ocean are indeed responsible for the suppressed warming in Texas, it is still not known whether those sea surface temperature variations are part of a natural cycle or are themselves a response to global warming. Alternatively, the mechanisms in the climate model and the real atmosphere may be different, and the actual cause of the suppressed global warming response in Texas may be a consequence of cloud-aerosol interactions, land use changes, or other natural or anthropogenically-forced regional climate modes.

At this point, there is no evidence that the climate patterns responsible for the lack of a century-long temperature trend in Texas and the southeastern United States are caused by anthropogenic influences, and natural processes, particularly those driven by variations in ocean circulation, are likely to be cyclical. Furthermore, recent temperatures in Texas are among the highest on record. Thus, it seems prudent to assume that the relative lack of 20th century warming in Texas is a temporary climate phenomenon, and that temperatures are likely to rise significantly in Texas over the coming decades.

The amount of warming has been estimated by the RCPM method (Regional Climate-change Projection from Multi-model ensembles) (Tebaldi et al. 2005; NCAR 2008), courtesy of Seth McGinnis of the National Center for Atmospheric Research. This particular estimation uses the archived set of climate simulations for the A1B emissions scenario and computes changes over a ten-grid-cell domain covering Texas (Figure 2.17). The technique produces probability distributions of future climate, assuming the emissions scenario is accurate, by weighting the climate models according

to their ability to simulate current climate and their similarity to other models in terms of long-term trends.

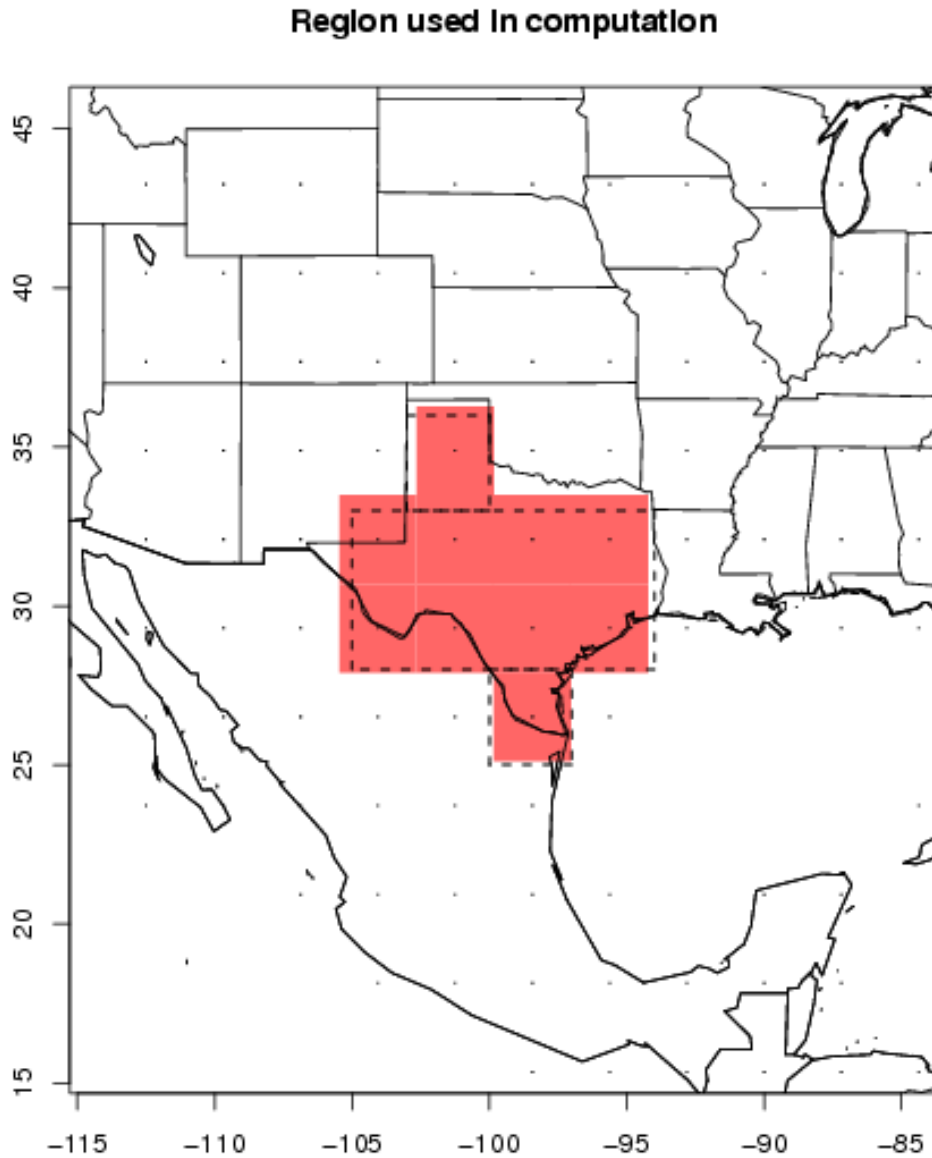


Figure 2.17: Averaging area used for estimation of projected temperatures and precipitation from A1B scenario.

The RCPM data and analyses are provided by the Institute for the Study of Society and Environment (ISSE) at NCAR, based on model data from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (WCRP CMIP3) multi-model dataset. More information about the RCPM analysis can be found at

<http://rcpm.ucar.edu>. RCPM data and analyses are (c) 2006 University Corporation for Atmospheric Research (All Rights Reserved).

The projected temperature trends (Figure 2.18) are computed relative to a simulated 1980-1999 mean. The projections indicate an increase of about 1 °F for the 2000-2019 period, 2 °F for the 2020-2039 period, and close to 4 °F for the 2040-2059 period. With the first eight years of the 2000-2019 period being the warmest such period on record, the projection for that period is well on its way to reflecting reality. By 2020-2039, the chances of temperatures in Texas actually being cooler than 1980-1999 is less than five percent, according to the climate models, and most of the projections fall well outside the range of natural variability.

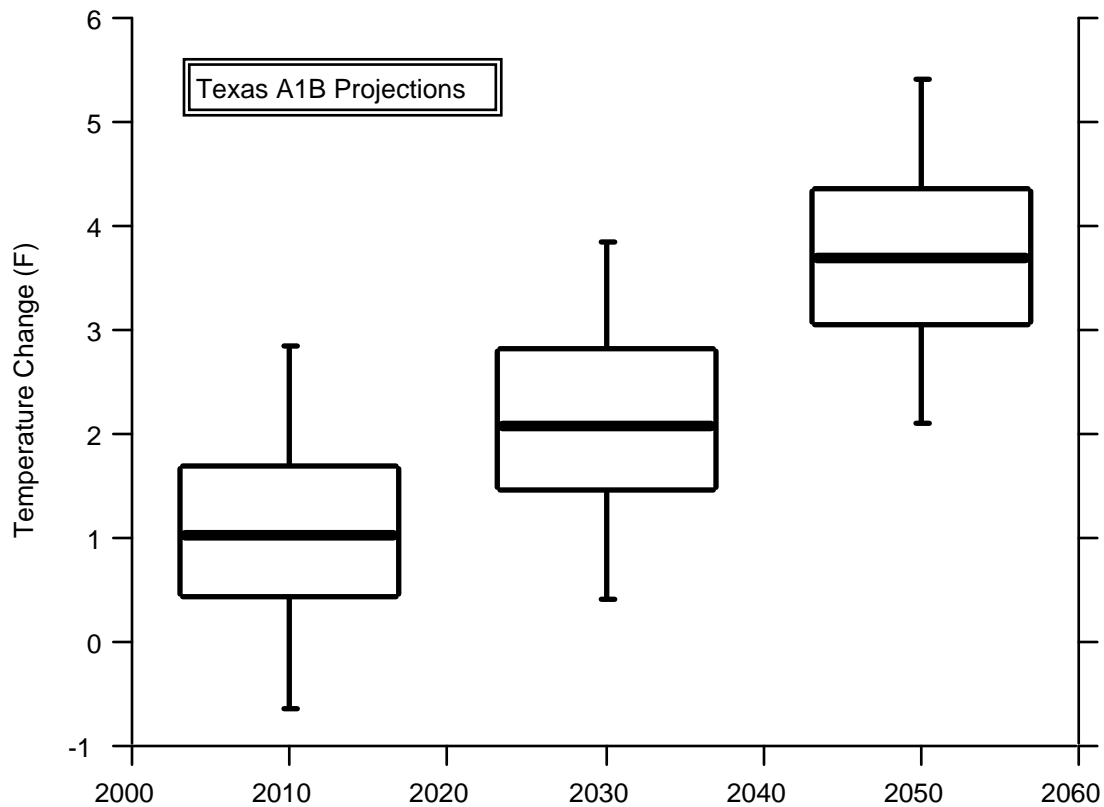


Figure 2.18: Statistical estimates of ranges of future temperatures in Texas relative to 1980-1999 baseline, according to Bayesian analysis of global climate models driven by the A1B forcing scenario. Each estimate is for a 20-year average.

It should be kept in mind that these projections assume no massive volcanic eruptions, sudden decreases in solar output, or other such events that would have a cooling effect on temperatures. Also, the projections assume no explicit action to combat global warming through reduction of greenhouse gas emissions, but reductions of the magnitude being presently contemplated would have little effect on global temperatures over the next 30 years.

CHANGES IN PRECIPITATION

Past Precipitation Changes

Unlike temperature, precipitation is not expected to increase globally. As shown in Chapter 1, climate model simulations indicate precipitation should generally increase along the equator and at high latitudes, and generally decrease in other parts of the tropics and subtropics. This banded pattern of precipitation changes corresponds fairly closely to the pattern of observed changes, with one exception. Around 30 °N, the global climate models predict that a decrease in precipitation should have occurred, but the observed change of precipitation at this latitude has been positive (Zhang et al. 2007). Texas lies within this latitude band.

For examination of the precipitation record in Texas, months are grouped according to similar long-term precipitation trends. To enable comparison of similar impacts in different regions of the state, precipitation is expressed as a fraction of the local mean for the period of record, defined as for temperature above. Nine-year averages are plotted.

Precipitation for December-March has increased substantially throughout the state (Figure 2.19). The largest percentage increase, 47 percent per century, took place in the Panhandle and Plains, but since this is the dry season for that area, the impact on water supplies is minimal. The steadiest increase, with the least decadal variation, has been in East Texas, which receives a greater amount of precipitation during December-March than any other Texas climatic region, in both absolute and relative terms. There, the increase has been 15 percent per century.

Wet spells and dry spells tend to coincide throughout the state over most of the period of record. The primary exception is the most recent decade, when far western and southern Texas received close to their long-term average amount of precipitation while northern and eastern Texas received 20-50 percent more than their long-term average. Note that the use of nine-year averages masks shorter-term precipitation variations. The Panhandle and Plains, for example, alternated very wet and dry years during this period.

Precipitation Anomaly, December-March

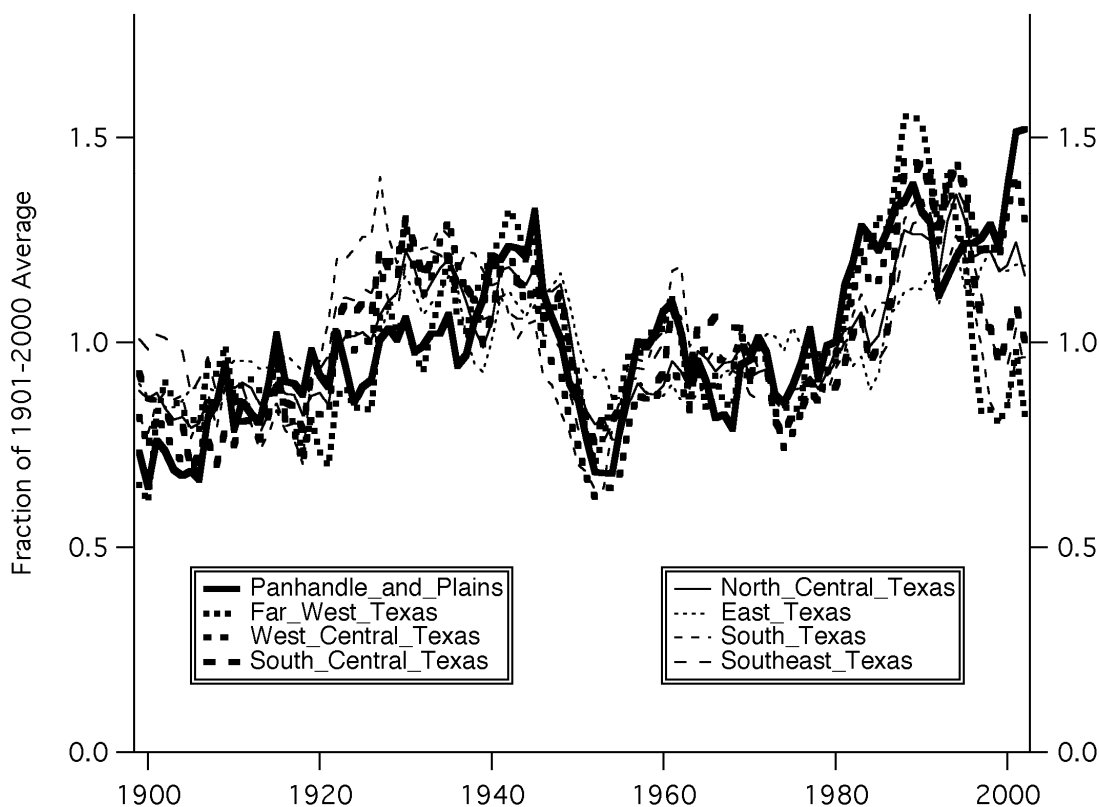


Figure 2.19: Nine-year running mean of average values of December-March USHCN V2 precipitation, as a proportion of the long-term mean, in each of eight Texas climate regions.

During the period April-July, precipitation shows little long-term trend and less interdecadal variability than in December-March (Figure 2.20). Unlike the wintertime, the southern and northern parts of the state seem to vary nearly independently over most of the past century. The decrease in precipitation over the past few years has brought the nine-year averages down to levels otherwise seen only in the 1910s and 1950s.

Precipitation Anomaly, April-July

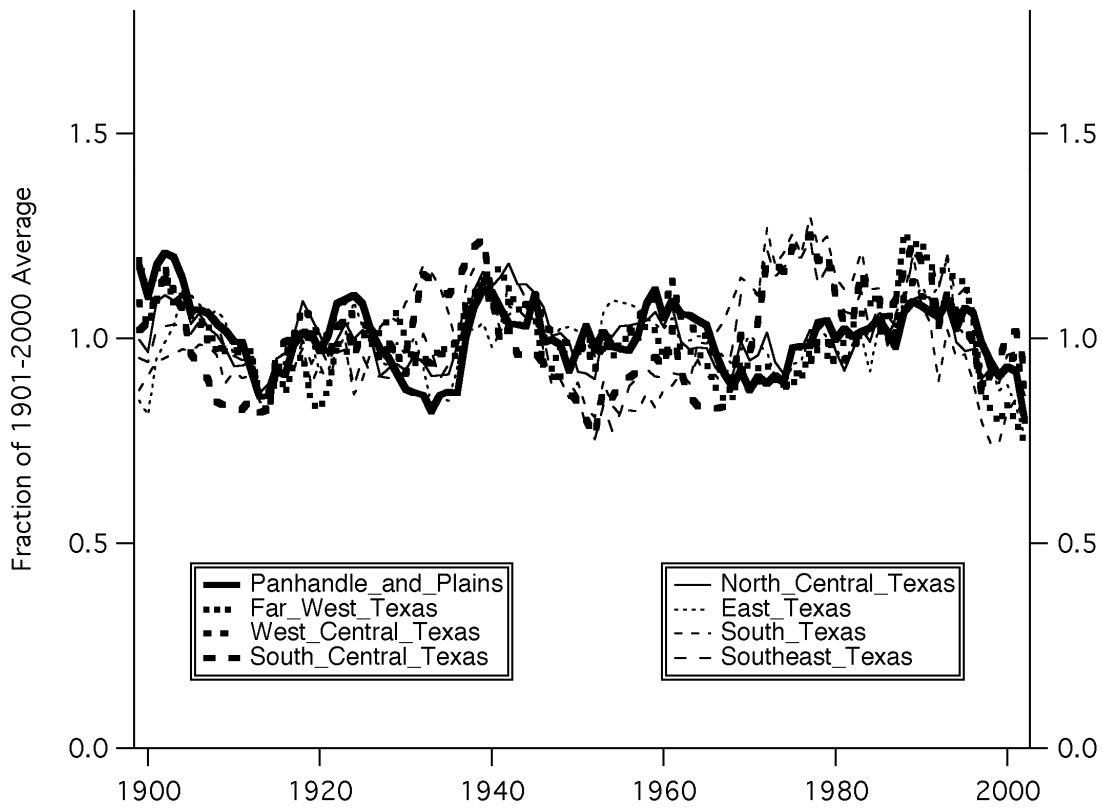


Figure 2.20: Nine-year running mean of average values of April-July USHCN V2 precipitation, as a proportion of the long-term mean, in each of eight Texas climate regions.

The period August-November (Figure 2.21) shows a clear upward trend in precipitation. Precipitation during the last 30 years has been about 20 percent greater than what occurred during the first half of the 20th century. The greatest increase has occurred in the eastern and southern parts of Texas, opposite the spatial pattern of long-term trends in December-March.

Precipitation Anomaly, August-November

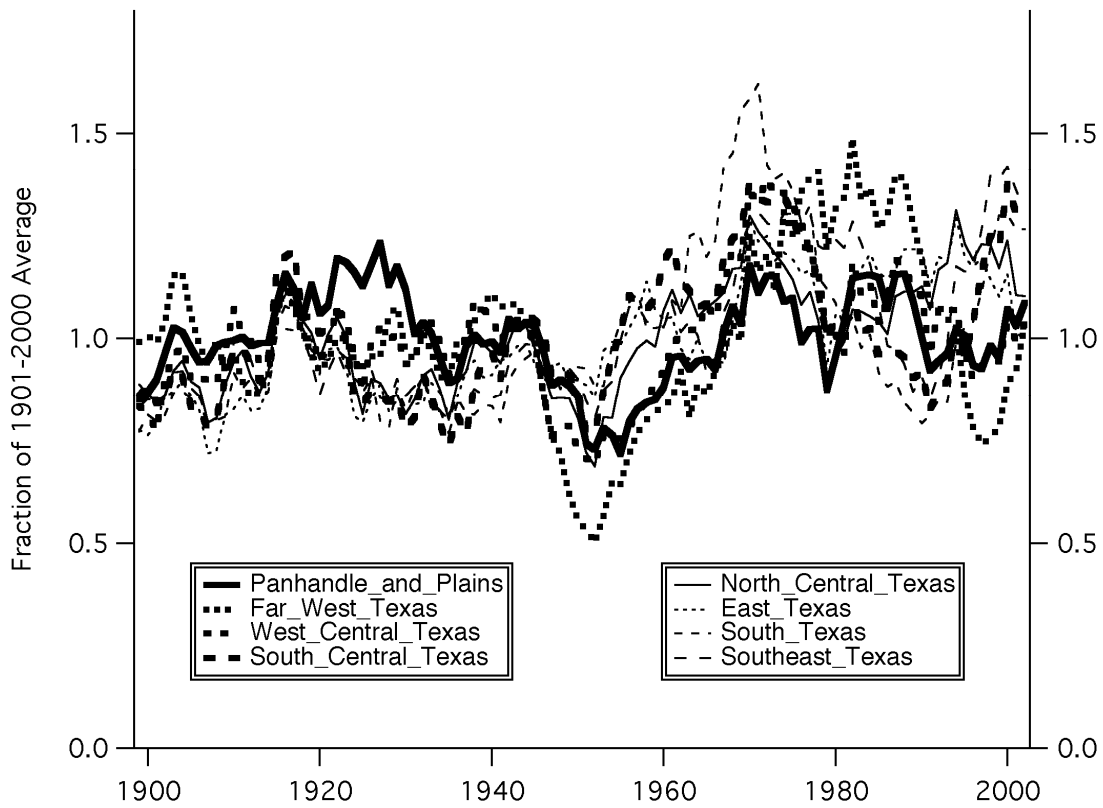


Figure 2.21: Nine-year running mean of average values of August-November USHCN V2 precipitation, as a proportion of the long-term mean, in each of eight Texas climate regions.

Overall, long-term precipitation trends range from about five percent per century in the Panhandle and Plains and Far West Texas to about 20 percent per century in South Texas and Southeast Texas. A sense of the spatial pattern of long-term trends is given by a map of the trends from individual long-term USHCN stations in Texas and surrounding states (Figure 2.22): the greatest increase in precipitation has occurred along a north-south corridor from South Texas to Oklahoma.

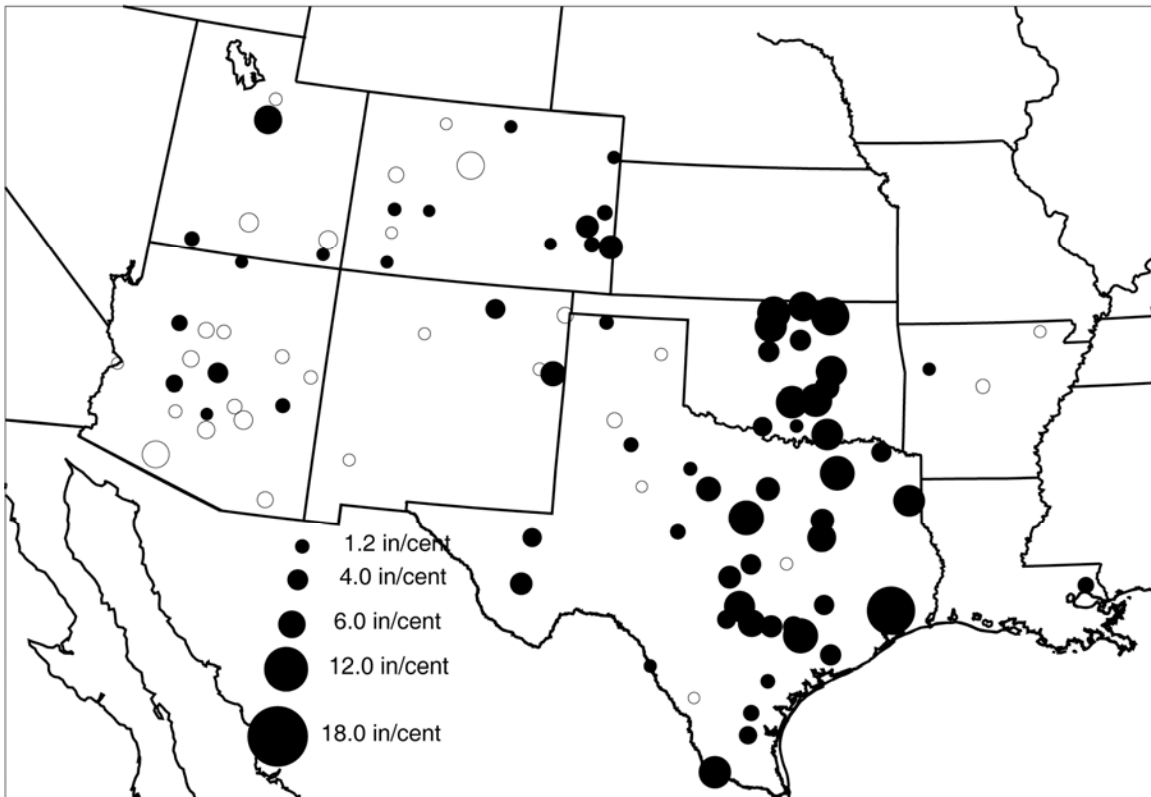


Figure 2.22: Precipitation trends at long-term USHCN V2 stations, in inches per century. Solid circles represent increases; open circles represent decreases.

Future Precipitation Trends

The precipitation trends shown above are not consistent with expectations under global warming scenarios. The RCPM results for precipitation projections are shown in Figure 2.23. They 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, and there is considerable disagreement among models over the sign of the precipitation change 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, such that there is no portion of the state that is more susceptible to declining precipitation in the model projections than any other.

There has been less research directed toward understanding discrepancies between precipitation trends and model projections than toward discrepancies between temperature trends and model projections. In part, this may be because model simulations driven by observed sea surface temperature variations have not yet been able to reproduce the observed substantial variations in precipitation patterns over the past century. Thus, a wide range of factors may have contributed to the observed precipitation increase.

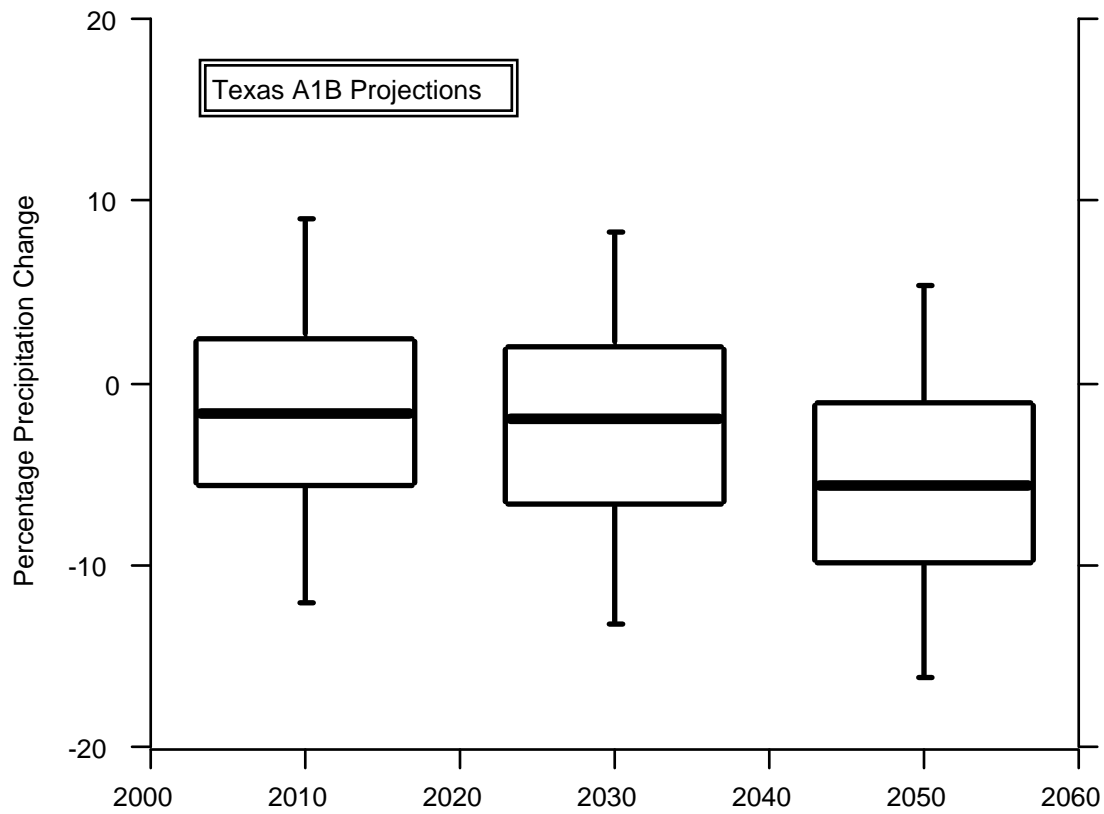


Figure 2.23: Statistical estimates of ranges of future accumulated precipitation in Texas relative to 1980-1999 baseline, according to Bayesian analysis of global climate models driven by the A1B forcing scenario. Each estimate is for a 20-year average.

An examination of these factors lends some indication of whether the increasing trend should be expected to continue. One possibility is that the increased precipitation is a direct response to global warming, albeit one that models have so far been unable to simulate. If so, precipitation would be likely to continue to increase. Another possibility is that the precipitation increase is a response to increased pollution from particulates and aerosols, either directly through changes in the precipitation formation process or indirectly through changes in weather patterns. If so, the trend should reverse itself as particulate pollution decreases. Another possibility is that the increased precipitation is a response to changes in land cover, such as irrigation, surface water storage, and urbanization. An irrigation mechanism seems unlikely, because the precipitation trend is absent precisely during the main agricultural growing season when irrigation is most common. Enhancement of precipitation near Houston, Texas, has been attributed to Houston urbanization (Burian and Shepherd, 2005). A final possibility is that, like surface temperatures, precipitation changes are largely attributable to patterns of sea surface temperature changes. If so, future trends depend on whether the sea surface temperature changes themselves are primarily due to natural variability (in which case the

precipitation trend would reverse itself) or primarily due to anthropogenic effects (in which case the precipitation trend would continue).

Absent any solid knowledge of the cause of the precipitation trends in Texas over the past century, it is impossible to say with confidence what the trends should be over the next half-century. Unlike temperature, where the expected temperature effect is much larger than natural variability, the model consensus for precipitation projections has a change by mid-century that is smaller than past observed rates of change. The models suggest that the odds are tilted in favor of a precipitation decrease, but the models' ability to accurately simulate precipitation changes over a relatively small area such as Texas has not been demonstrated. Within the realm of possibility are an even more rapid increase of precipitation or a catastrophic reversal of the precipitation trend. About the only thing that can be said with confidence is the following: it is not appropriate to assume that the precipitation climatology has been or will be steady over time.

COMBINED CHANGES IN TEMPERATURE AND PRECIPITATION

Much of the Texas natural environment is highly sensitive to soil moisture and water availability, and the Texas human environment (both urban and agricultural) is becoming increasingly sensitive to water supply and demand. These parameters all depend on the effect of simultaneous changes of temperature and precipitation.

The sharp seasonal contrasts in Texas extend to the relationship between temperature and precipitation. During the wintertime in most of Texas, increased precipitation is often accompanied by neutral or increased temperatures, all associated with increased transport of heat and moisture from the Gulf of Mexico. Typically, more rain and snow falls than can evaporate, so even if temperatures are unusually warm there is an ample supply of environmental moisture. This lends a relative stability to cool-season water supplies. West Texas is a quite a bit drier than the rest of the state during the winter, and increased moisture is typically accompanied by cool weather.

In the summertime, cooler weather and increased rainfall go hand in hand. Summertime surface temperatures are strongly affected by variations in soil moisture and cloud cover. Dry summertime conditions are also typically hot summertime conditions, so a lack of water supply (rainfall) is typically aggravated by an increase of water demand (evaporation).

The projected increase in temperatures across Texas implies warmer conditions when it's sunny as well as warmer conditions when it's cloudy. Thus, for a given amount of precipitation, water demand and evaporation will increase and water supply (in the form of reservoir storage, streamflow, and aquifer recharge) will decrease. So, even though precipitation projections are uncertain, it is likely that environmental and human water systems will be under increased stress due to changes in both water supply and water demand. If precipitation actually increases, the gains in precipitation will be partially or wholly offset by increased evaporation and evapotranspiration. If precipitation decreases, the decline in precipitation will be compounded by the increase in evaporation to yield an even greater reduction in water supply and an even greater increase in water demand.

CHANGE IN SEVERE AND HIGH-IMPACT WEATHER

The challenge of predicting future changes in severe and high-impact weather is threefold. First, such weather events are by their nature rare, so it is difficult to tell from observations within a single geographical area whether a true long-term trend is present. Second, observations of such weather events are much less consistent over time than conventional climate parameters such as temperature and rainfall, making it difficult to distinguish changes caused by the atmosphere from changes caused by observing and reporting practices. Third, all such weather events occur on a much smaller scale than climate models can directly simulate, requiring indirect techniques to infer changes in severe and high-impact weather from the climate model output.

One example of such a weather phenomenon is the tornado. A tornado is much too small to be simulated by present-day short-range forecasting models, let alone by global climate models. The large-scale meteorological conditions conducive to tornado formation are understood only in general terms, with much sensitivity to low-level frontal structure and other such atmospheric features, so no studies have been able to infer tornado frequencies from global climate simulations. Finally, the tornado records themselves are spatially inhomogeneous and unreliable, particularly for the weak tornadoes that are most common (Brooks and Doswell, 2001).

It is worth noting that strong tornadoes in the United States show no detectable long-term trends (Brooks and Doswell, 2001), and neither do most other types of severe weather, with the exception of heavy rainfall events (Balling and Cerverny 2003). As water vapor content increases with global temperatures, the amount of precipitation produced per storm should increase as well, and such a change has been observed. Inferences of changes in other types of severe weather likelihood under global warming scenarios are just beginning; initial results suggest an increase (Trapp et al. 2007).

Hurricane counts in the Atlantic fluctuate considerably from year to year and decade to decade. The quality of the Atlantic hurricane database prior to the satellite and aircraft reconnaissance eras is under active scientific debate; whether the recent increase in Atlantic hurricane activity is attributable to global warming or temporary sea surface temperature variations is also a matter of debate. Since global climate models cannot simulate hurricanes directly, recent studies have used a variety of techniques to embed direct simulations of hurricanes within a climate model simulation. Results here too have been mixed, and it seems that the global climate projections admit a wide range of possible changes to future hurricane activity (Emanuel et al. 2008; Knutson et al. 2008).

Despite this uncertainty, one can confidently predict that the likelihood of a major hurricane striking the Texas coast will increase over the coming half-century. The basis for this forecast is the following: landfalling hurricanes in the United States show insignificant trends over the past century or more (Wang and Lee, 2008), yet, for no obvious reason, Texas has had fewer than its share of major damaging hurricanes over the past half-century. According to Blake et al. (2007), of the ten strongest hurricanes to strike Texas in the past 150 years, only one (Rita) occurred within the past 25 years, and even that storm made landfall in Louisiana. Of the 25 storms estimated to have been capable of causing the most damage, based on present-day population and infrastructure, four have hit Texas but none since 1961. The return period for a major hurricane to strike Houston is 21 years, yet none has done so since 1941. Even Ike (2008), which caused

widespread damage in the Houston area, did not reach the major hurricane threshold for wind speed. So, while it is not quite correct to say that Texas is overdue for more major hurricanes, it is correct to say that the expected frequency of very damaging hurricanes during the next few decades is higher than the actual frequency of very damaging hurricanes over the past few decades.

The last form of high-impact weather to be considered in this chapter is drought. 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. In Texas, temperatures are likely to rise, and future precipitation trends are difficult to call, so it is likely that drought frequency and severity will increase in Texas. 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.

CONCLUDING REMARKS

Climate projection is inherently more difficult for a small sub-area of the globe than for the globe as a whole. This is particularly true for Texas, the nature of whose climate changes throughout the year. The wide range of weather conditions that have significant impacts on Texas further complicates matters.

Partially because of this complexity, climate variations over the past century in Texas do not correspond to changes expected from global warming, according to present-day climate models. Local temperature changes due to global warming are likely to soon become strong enough to overwhelm natural variability, leading to temperatures in the neighborhood of 4°F warmer than recent decades by the middle of this century. In the case of precipitation, observed variations over the past century are larger than most future climate projections of precipitation change by mid-century, and are also unexplained. Thus, it cannot be said whether future precipitation will be more or less than present-day precipitation in Texas.

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