Trend Detection in Texas Temperature and Precipitation

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Abstract

Earth's climate is changing and the observed changes are not spatially uniform. Due to regional- and local-scale climate change variability, additional research is needed to assess and document climate change at these scales. Such research is not only beneficial to the scientific community but also to policy makers and adaptation strategies. In an attempt to document the changing climate of Texas, this study uses ordinary least squares linear regression to detect trends in seasonal and annual temperature and precipitation records over the period 1932 -2002. With the aid of geographic information software, this study allows the dual visualization of changes in temperature and precipitation. Results indicate that temperature and precipitation trends are not uniform in Texas and that smaller regions within Texas also exhibit variability.

Keywords: climate change, climate of Texas, temperature trends, precipitation trends.

Introduction

Evidence has accumulated over the last several decades that indicate that Earth's climate is changing and, as a result, awareness to these changes and their potential consequences has spread through the science and policy communities. As used here, climate change refers to any statistically significant change in an indicator of climate over an extended time period, regardless of its attribution. Climate change has been established by the detection of trends in climate change indicators such as surface temperature, precipitation, sea level, atmospheric composition, and extreme weather events, among others.

Perhaps the most commonly referenced information about climate change by the science community, policy makers, and the general public is the temperature increase reported by the Intergovernmental Panel on Climate Change (IPCC). The IPCC's Fourth Assessment Report (AR4, IPCC 2007) reported that global mean temperatures have risen by 0.74°C ± 0.18°C over the period 1906-2005. Temperature changes, along with changes in other climate change indicators, are not uniform across the globe. Rather, observed changes vary by region, meaning that the commonly reported global-scale trends might not be representative of changes experienced by smaller-scale regions.

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Regional variability means that different regions experience climatic changes of different magnitudes, maybe even changes of different signs (i.e. increasing/decreasing trends). Likewise, the impacts of climatic change will vary regionally, not only because of spatial variations in the actual climatic change but also due to variations in the interactions of local residents, ecosystems, and economies with their local climate. Changes in regional and local climate are significant for agriculture, ecosystems, energy use, water demand and availability, various other aspects of the economy, and everyday life within that region (e.g. Norwine et al. 1995; IPCC 2007; Schmandt, North, and Clarkson 2011).

Texas, for instance, is sensitive to temperature and precipitation changes due, in part, to its demand for water, both agriculturally and municipally. In fact, Fehrenbach (1983) stated that the scarcity of water is a dominant feature of Texas. Changes in temperature and precipitation, particularly increasing temperature and decreasing or more variable precipitation, increases the vulnerability of people and ecosystems in water-stressed areas such as Texas (Bates et al. 2008). The demand for water is increased with rising temperatures for agricultural (irrigation) and municipal uses. Rising temperature also reduces ground water availability, resulting from increased evapotranspiration rates and decreased aquifer recharge. Decreased precipitation reduces ground water availability, decreases aquifer recharge, and increases demand through irrigation needs. Adding to the potential problems associated with temperature and precipitation changes, the population of Texas is expected to double by 2060, which would increase water demand by 27% (Texas Water Development Board (TWDB) 2007).

Because climate change and consequent impacts exhibit regional variability, adaptation policies and strategies also vary regionally (Dessai and Hulme 2003). However, policy-makers and risk managers are often unable to use climate information produced by climate models because they are predominately at a global scale whereas adaptation measures typically occur at regional, state, and local levels (Burton et al. 2002). Nonetheless, regional and local climate change studies have predominately taken a top-down approach (Wilbanks and Kates 1999); i.e., using the output from global climate models to assess a smaller region (e.g. Murphy 1999; Boer, Flato, and Ramsden 2000; Robinson, Reudy, and Hansen 2002; Seager et al. 2007; Cayan et al. 2008). The resolution of global general circulation models and continental-scale models is, however, too coarse to make precise inferences about regional and local-scale climatic changes. Thus, additional research is needed documenting past climatic change and modeling potential future changes at the scale at which adaptation measures are developed: regional, state, and local scales (Karl and Trenberth 2003).

One of the most recent comprehensive analyses to assess climate change science, climate change evidence, and climate change impacts that was specifically focused on Texas was *The Impact of Global Warming on Texas*, second edition by the Texas Climate Initiative (TCI) (Schmandt, North, and Clarkson 2011; TCI 2011). In chapter two of this text, Nielsen-Gammon (2011) presented an analysis of temperature and precipitation trends in Texas over the twentieth century. He reported varying rates of warming in the Panhandle, Far West, East, Southeast, and South Texas and varying rates of cooling in West Central, South Central, and North Central Texas. He also reported that these trends were rather uniform across seasons. Regarding precipitation, his major conclusion was that precipitation generally increased, with the greatest rates occurring along and east of the north-south corridor from South Texas to Oklahoma. The trends reported by Nielsen-Gammon (2011) were estimated from regionally-averaged time series and, while this approach is useful when synthesizing trends from multiple stations into a regional trend, it may mask within-region variability.

This study focuses on observed temperature and precipitation changes in Texas. This study is guided by two questions: (1) How have temperature and precipitation in Texas changed during the twentieth century? (2) Has the change been uniform across the state? Surface temperature and precipitation records for thirty-nine locations throughout Texas are analyzed in an attempt to detect long-term trends, both temporally and spatially. Rather than averaging multiple stations to calculate regional trends, this study examines individual locations; however, the regions defined by Nielsen-Gammon (2011) are provided to facilitate comparison. This study is focused on trend detection, which involves the demonstration that a climate change indicator has changed in some defined statistical sense, without providing a reason for the change (IPCC 2007). Therefore, attributing causality to any detected changes is beyond the scope of this study.

Study area

The state of Texas encompasses 692, 000 km^2 of land, spanning nearly eleven degrees of latitude (25.83°N-36.50°N) and more than thirteen degrees of longitude (93.52°W-106.63°W) (Figure 1). Along with latitudinal variations in solar radiation, Texas' climate is substantially influenced by three geographic features (Nielsen-Gammon 2011): (1) the Rocky Mountains, (2) the Great Plains, and (3) the Gulf of Mexico. Given its large expanse and various geographic influences, it is not surprising that Texas is home to multiple climate types. The four major Köppen-Geiger climate types that dominate Texas are humid subtropical with hot summers (Cfa), cold midlatitude desert (BWk), cold midlatitude steppe (BSk), and hot subtropical steppe (BSh) (Figure 1). These climate types indicate that Texas experiences a large range of temperatures and precipitation. The general spatial pattern of temperature in Texas is increasing mean temperature from north to south, except in summer when the pattern becomes more erratic (Bomar 1983; Nielsen-Gammon 2011). Diurnal and seasonal temperature variability decreases near the Gulf of Mexico due to the moderating effect of the relatively warm Gulf surface temperature through-

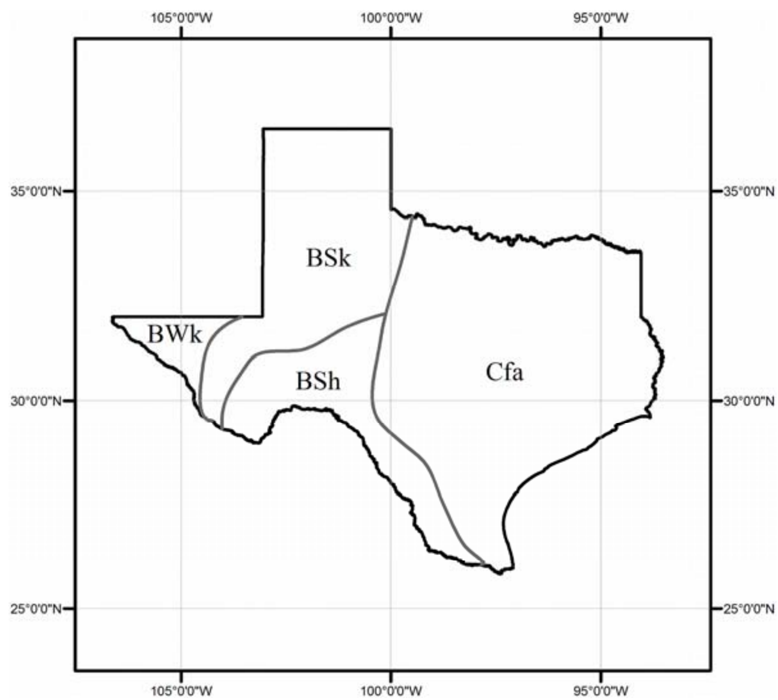


Figure 1. Geographic location and major Köppen-Geiger climate regions of Texas. Köppen-Geiger boundaries are estimated from a map produced by Kottek *et al*. (2006).

out the year. The general spatial pattern of precipitation in Texas is increasing mean precipitation from west to east (Bomar 1983; Nielsen-Gammon 2011). Seasonally, spring is the wettest time of year for most of Texas, besides west Texas where convective storms make summer the wettest season. The eastern half of Texas also has a second peak in precipitation in late summer and early fall, largely due to tropical systems coming ashore from the Gulf (Bomar 1983).

The climate of Texas is exceedingly variable from year-to-year (North 1995a and 1995b). Interannual-to-decadal climate fluctuations in Texas can be partly explained by teleconnections with the El Nino/Southern Oscillation phenomenon in the Equatorial Pacific (North 1995b; Watkins and O'Connell 2006), the North Atlantic Oscillation in the North Atlantic, and the Pacific Decadal Oscillation in the North Pacific (Watkins and O'Connell 2006). The manifestation of teleconnections and other natural cycles in temperature and precipitation time series is relatively short-term fluctuations, which are superimposed on longer-term trends. The various temporal scales of variability that exist in the climate system complicate, or even mask, the detection of statistically significant long-term trends (North 1995b; Salinger et al. 1995; Basher and Thompson 1996; Tebaldi et al. 2005).

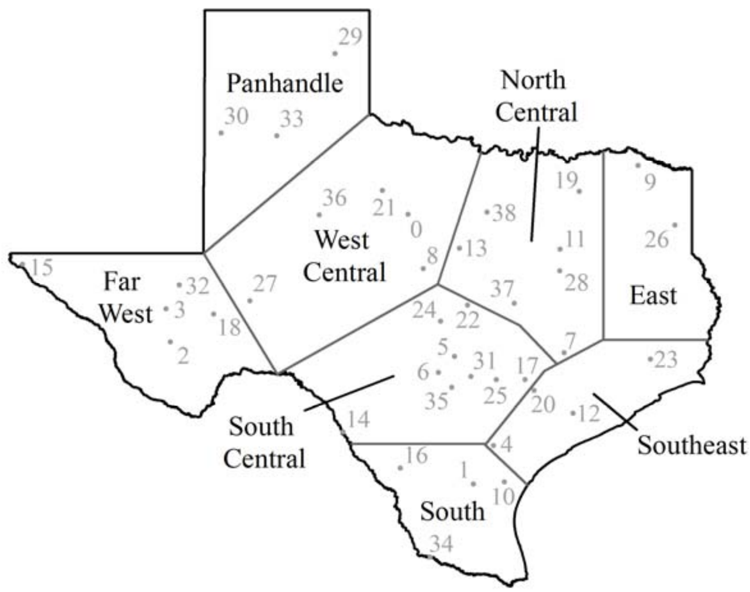
Data source and methodology

A long-term, homogenized data source is needed for accurate trend detection. The United States Historical Climatology Network (USHCN) is perhaps one of the best and most commonly utilized data source for regional temperature and precipitation trend detection (NRC 1998). The USHCN is a high-quality dataset including monthly averaged maximum, minimum, and mean temperature and total monthly precipitation that was developed to assist the detection of regional climate change (NCDC 2010). This network is comprised of United States Cooperative Observing Network stations that were selected based on certain criteria including length of period of record, percent missing data, number of station moves and other station changes that may affect data homogeneity, and spatial coverage (Karl et al. 1990). This study obtained monthly mean temperature (°C) and monthly total precipitation (mm) data from the USHCN (version 1) for thirty-nine stations in Texas over the period 1932−2002 (Figure 2). The stations and time period used in this study were selected with the intent to maximize temporal and spatial coverage and to minimize missing data. The network of USHCN stations, however, does not allow for uniform coverage across Texas. When using the regions defined by Nielsen -Gammon (2011; see Figure 2), it can be seen that portions of all regions in Texas have sparse coverage. This is a clear limitation to any spatial analysis of trends, especially when using station data to represent a region because it is rarely the case that one station is typical of the whole region (Pielke at al. 2002). Other climate data networks are available (e.g. the entire U.S. Cooperative Observing Network or the U.S. Climate Division Dataset) that may create a denser coverage, but these often have shorter data coverage, missing data, and data inhomogeneities such as location moves, changes in the time of observation, and changes in surrounding ground cover, among others. This study, therefore, uses only the USHCN network for consistent data quality.

Seasonal and annual mean temperature and seasonal and annual total precipitation values were calculated from the monthly data. Traditional seasons were used: spring – March, April, and May; summer – June, July, and August; fall – September, October, and November; winter – previous December, January, and February. Anomalies, which represent the deviation of each observed data point from a corresponding average value calculated from a baseline period, are representative of a larger region than absolute numbers (Hansen and Lebedeff 1987). This study, therefore, calculated temperature and precipitation anomalies seasonally and annually to use for the trend analysis. Anomalies are relative to the 1961−1990 base period means to be consistent with the most recent IPCC report (IPCC 2007).

One of the most widely used methods of detecting trends in a data set is to determine the least squares best fit linear line within a given time interval (Wigley, 2006; Wu et al. 2011). Thus, this study evaluates temperature and

Selected USHCN Stations in Texas



ID	Station	ID	Station	ID	Station
0	Albany	13	Dublin	26	Marshall
1	Alice	14	Eagle Pass	27	McCamey
2	Alpine	15	El Paso	28	Mexia
3	Balmorhea	16	Encinal	29	Miami
4	Beeville	17	Flatonia	30	Muleshoe
5	Blanco	18	Fort Stockton	31	New Braunfels
6	Boerne	19	Greenville	32	Pecos
7	Brenham	20	Hallettsville	33	Plainview
8	Brownwood	21	Haskell	34	Rio Grande City
9	Clarksville	22	Lampasas	35	San Antonio
10	Corpus Christi	23	Liberty	36	Snyder
11	Corsicana	24	Llano	37	Temple
12	Danevang	25	Luling	38	Weatherford

Figure 2. Spatial distribution of the selected USHCN stations in Texas along with regions adapted from Nielsen-Gammon (2011) to facilitate comparison.

precipitation trends using a linear regression model:

$$y_t = \beta_1 + \beta_2 t + u_t, \quad (1)$$

where y_t is the temperature or precipitation observation at time t, β_1 is the y-intercept of the best-fit linear trend line, β_2 is the slope of the best-fit linear trend line, and u_t is the residual at time t (Wang et al. 2008). This study specifically uses an ordinary least squares (OLS) regression model to detect linear trends and to determine the best-fit of the linear trend lines. The basic idea behind OLS is that the predicted linear trend line will minimize the summation of the squared distance between predicted and observed temperature or precipitation values (residuals). Because of its attempt to minimize the summation of squared residuals, OLS regression is sensitive to outliers. This sensitivity may influence the magnitude of trends, but it is unlikely to influence the sign of the trends. See Wilks (2006) for a more thorough discussion of OLS analysis.

Regression models were run for temperature and precipitation anomalies at the seasonal and annual time scales over the period 1932-2002. The value and sign of β_2, also known as the regression or slope coefficient, from equation (1) indicates the magnitude of the trend (i.e. slope of the trend line) and whether the trend is increasing or decreasing. The magnitude and sign of regression coefficients were recorded for each model run along with the significance level (p-value). This study defines statistically significant trends as those with $p < 0.10$. Similar to Pielke et al. (2002), we chose a rather conservative level of significance to minimize the exclusion of possible trends where one might exist (i.e., we did not want to fail to reject the null hypothesis of no trend when a weak trend might exist); however, those trends with $p < 0.05$ are also distinguished. Significant temperature and precipitation trends were placed in spatial context with geographic information system software (ArcGIS 9, ArcMAP version 9.3 by ESRI) to assess spatial patterns, specifically looking for areas with similar statistically significant trends and areas that are geographically anomalous. Geographic anomalies are areas where neighboring stations have statistically significant and opposite trends (Pielke et al. 2002).

Results

A table of all regression coefficients is located in the Appendix. All temperature and precipitation trends referred to in the Results section are statistically significant ($p < 0.10$).

Spring trends

Fifteen of the thirty-nine stations (38 %) had statistically significant trends in spring temperature, eight of which were warming trends and seven were cooling (Figure 3). The trends ranged from -0.21°C per decade in Albany to +0.35°C per decade in Alpine (Figure 4A). The most substantial cluster of trends was a grouping of five stations with cooling trends in South Central

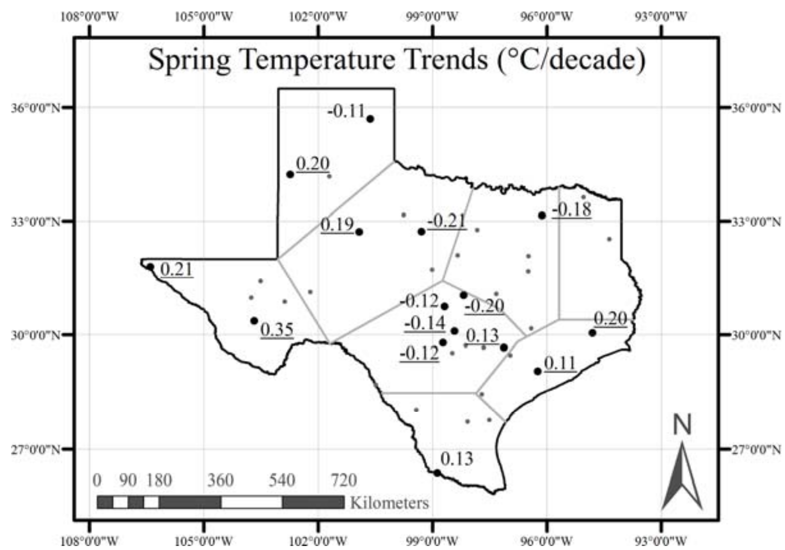


Figure 3. Statistically significant linear trends ($p < 0.10$) in spring temperature anomalies (relative to the 1961-1990 base period mean) over the period 1932-2002. Trend estimates that are underlined are statistically significant at $p < 0.05$.

Texas. Far West Texas and Southeast Texas each had two warming trends and South Texas had an isolated warming trend. Trends in the Panhandle and West Central Texas were geographically anomalous. Each of these regions had one warming and one cooling trend. Only one station had a statically significant trend in spring precipitation; Miami, which is located in the Panhandle, had an increasing trend of +8.83 mm per decade (Figure 4B).

Summer trends

Twenty-two stations (56 %) had statistically significant trends in summer temperature, four of which were warming trends and eighteen were cooling (Figure 5). The trends ranged from -0.29°C per decade in Encinal to +0.16°C per decade in Rio Grande City (Figure 7A).Interestingly, these two stations were both located in South Texas. South Central, North Central, and West Central Texas were dominated by cooling trends. The Panhandle, Far West, South, and Southeast Texas were anomalous, each with one warming and once cooling trend. For instance, in the Panhandle, Muleshoe and Plainview are located only approximately 96 kilometers (60 miles) apart, but had statistically significant trends with opposite signs (+0.08°C per decade and -0.20°C per decade, respectively). Also, in Southeast Texas, Hallettsville and Danevang are separated by approximately 83 kilometers (52 miles), but had statistically significant trends with opposite signs. Four stations located in Far West, South

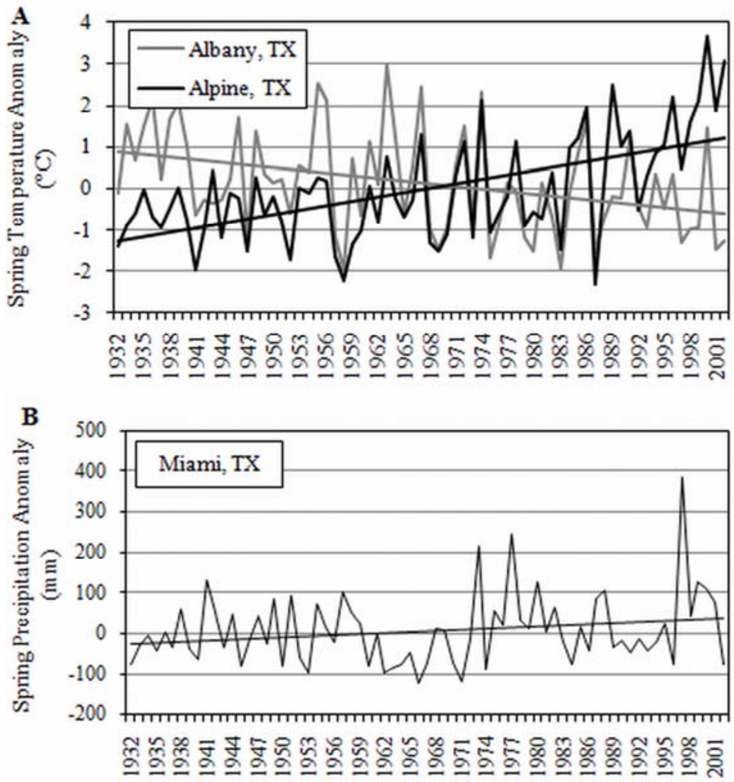


Figure 4. Statistically significant ($p < 0.10$) linear trends in spring temperature (A) and precipitation (B) anomalies, 1932–2002. Anomalies are relative to the 1961-1990 base period mean.

Central, North Central, and East Texas had increasing trends in summer precipitation (Figure 6), the greatest of which was +16.82 mm per decade in Dublin (Figure 7B).

Fall trends

Fourteen stations (36 %) had statistically significant trends in fall temperature, three of which were warming trends and eleven were cooling (Figure 8). The trends ranged from -0.21°C per decade in Brownwood to +0.18°C per decade in Liberty (Figure 10A). Nine of the eleven cooling trends were located in South Central, West Central, and North Central Texas; the other two were in the Panhandle and in South Texas. Geographic anomalies were located in South Texas, where Encinal and Corpus Christi, which are located approximately 191 kilometers (119 miles) apart, had trends of -0.10°C per decade and +0.12°C per decade, respectively.

Seventeen stations (44 %) had statistically significant trends in fall precipitation, all of which were increasing (Figure 9). The greatest increase occurred

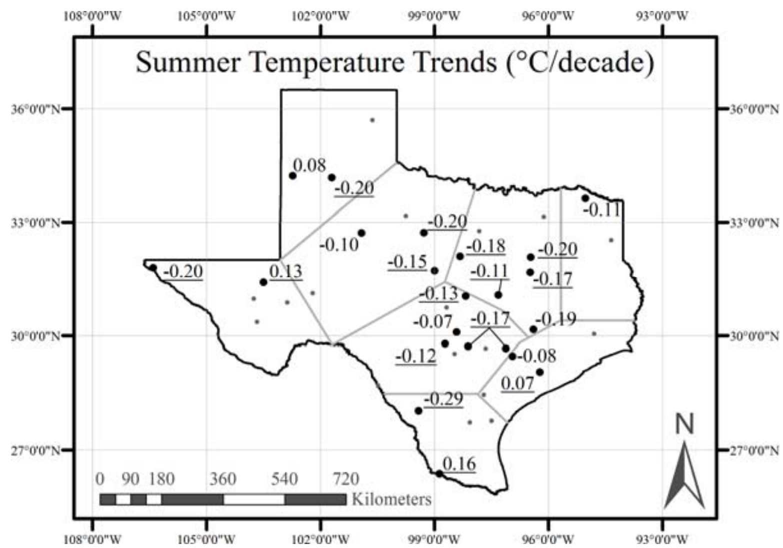


Figure 5. Statistically significant linear trends ($p < 0.10$) in summer temperature anomalies (relative to the 1961-1990 base period mean) over the period 1932-2002. Trend estimates that are underlined are statistically significant at $p < 0.05$.

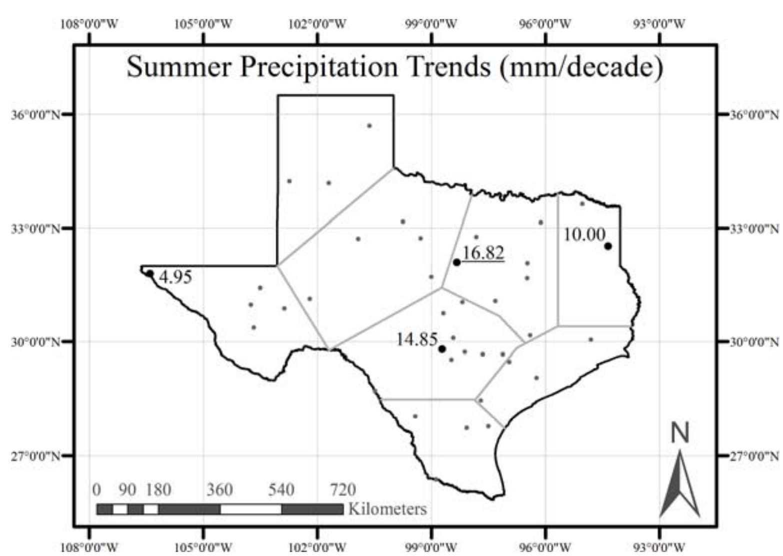


Figure 6. Statistically significant linear trends ($p < 0.10$) in summer precipitation anomalies (relative to the 1961-1990 base period mean) over the period 1932-2002. Trend estimates that are underlined are statistically significant at $p < 0.05$.

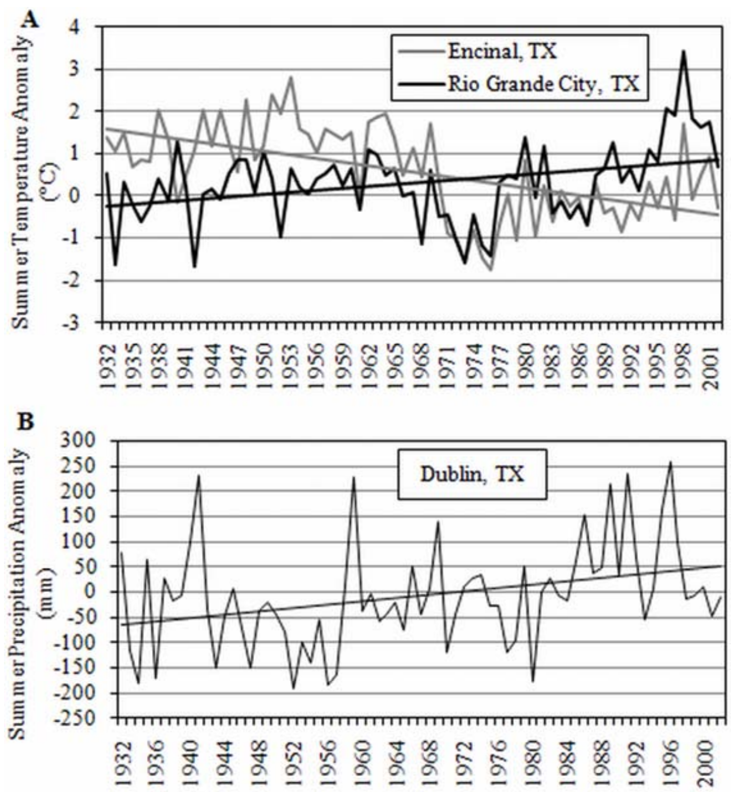


Figure 7. Statistically significant ($p < 0.10$) linear trends in summer temperature (A) and precipitation (B) anomalies, 1932–2002. Anomalies are relative to the 1961-1990 base period mean.

in Liberty, with +33.60 mm per decade (Figure 10B). Most striking is the marked spatial distribution of the trends–all seventeen trends were located east of 99°W longitude, which includes the eastern portions of South Central and South Texas and all of North Central, East, and Southeast Texas. This amounts to 71 % of the stations east of the 99th meridian exhibiting increasing trends. There were no statically significant trends west of 99°W longitude.

Winter trends

Eight stations (21 %) had statistically significant trends in winter temperature, three of which were warming trends and five were cooling (Figure 11). The trends ranged from -0.24°C per decade in Brownwood to +0.25°C per decade in Rio Grande City (Figure 12). Four of the five cooling trends were located in the South Central and West Central Texas; the other cooling trend was located in Far West Texas. Far West Texas was also geographically anomalous. For instance, the cooling trend at Balmorhea was within 271 kilometers

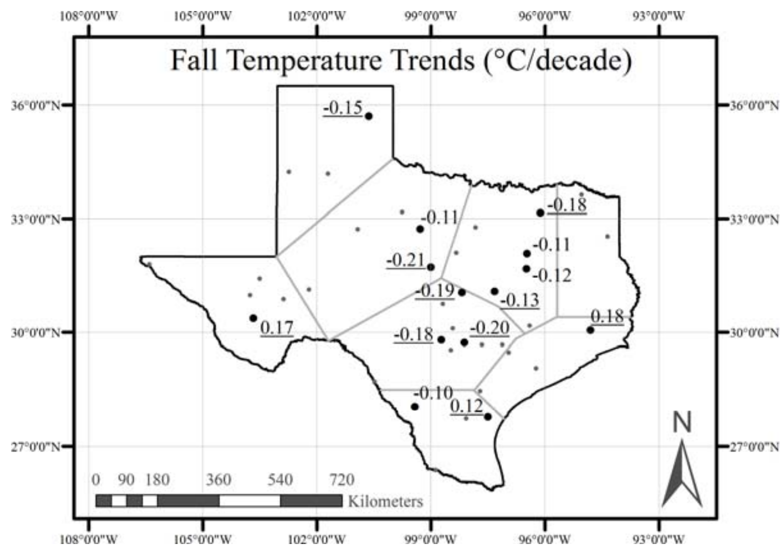


Figure 8. Statistically significant linear trends ($p < 0.10$) in fall temperature anomalies (relative to the 1961-1990 base period mean) over the period 1932-2002. Trend estimates that are underlined are statistically significant at $p < 0.05$.

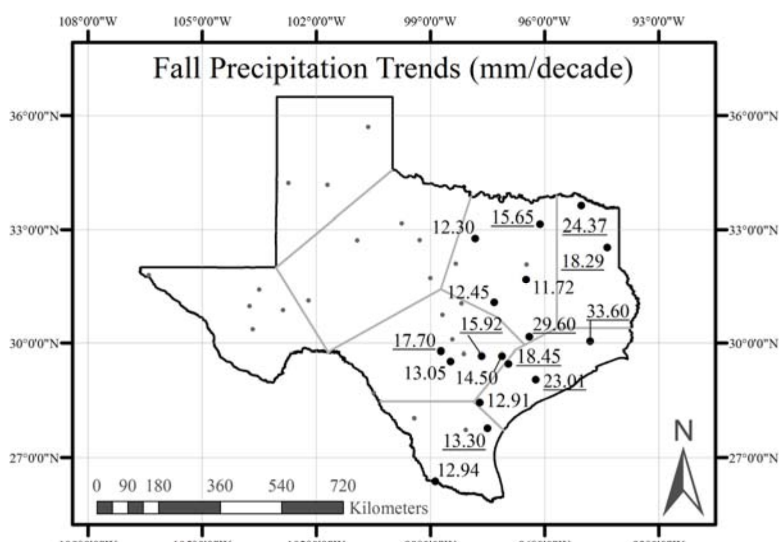


Figure 9. Statistically significant linear trends ($p < 0.10$) in fall precipitation anomalies (relative to the 1961-1990 base period mean) over the period 1932-2002. Trend estimates that are underlined are statistically significant at $p < 0.05$.

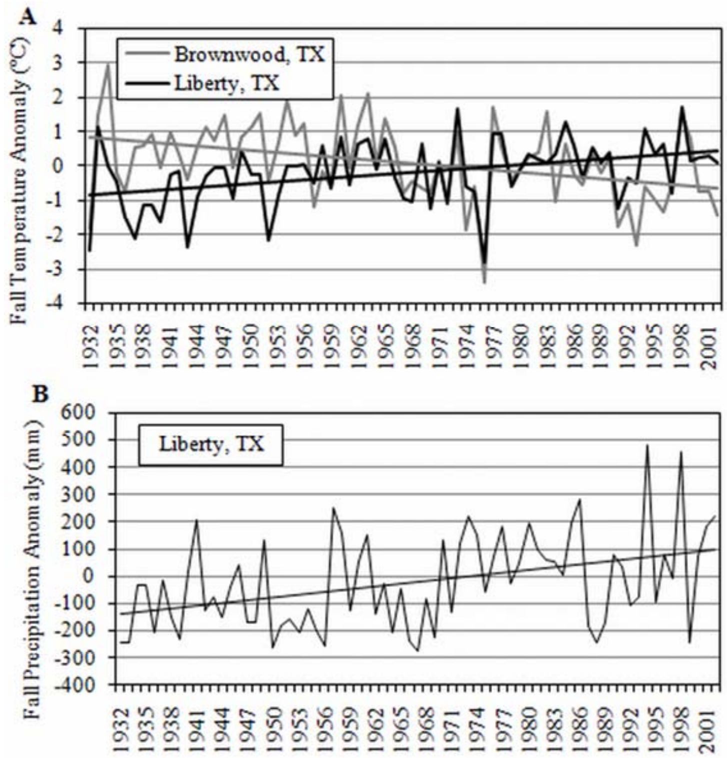


Figure 10. Statistically significant ($p < 0.10$) linear trends in fall temperature (A) and precipitation (B) anomalies, 1932–2002. Anomalies are relative to the 1961-1990 base period mean.

(168 miles) of the warming trend at El Paso and within 70 kilometers (43 miles) of the warming trend at Alpine. An isolated warming trend was also located in South Texas. There were no statistically significant trends in winter precipitation.

Annual trends

Twenty-one stations (54 %) had statistically significant trends in annual temperature, four of which were warming trends and seventeen were cooling (Figure 13). The trends ranged from -0.17°C per decade in Lampasas to +0.16° C per decade in Alpine (Figure 15A). Similar to the seasonal trends, cooling trends were primarily located in South Central, West Central, and North Central Texas. Two warming trends were located in Far West Texas. Geographic anomalies were located in the Panhandle and South Texas. In the Panhandle, similar to the summer temperature trends, Muleshoe and Plainview had statistically significant trends with opposite signs.

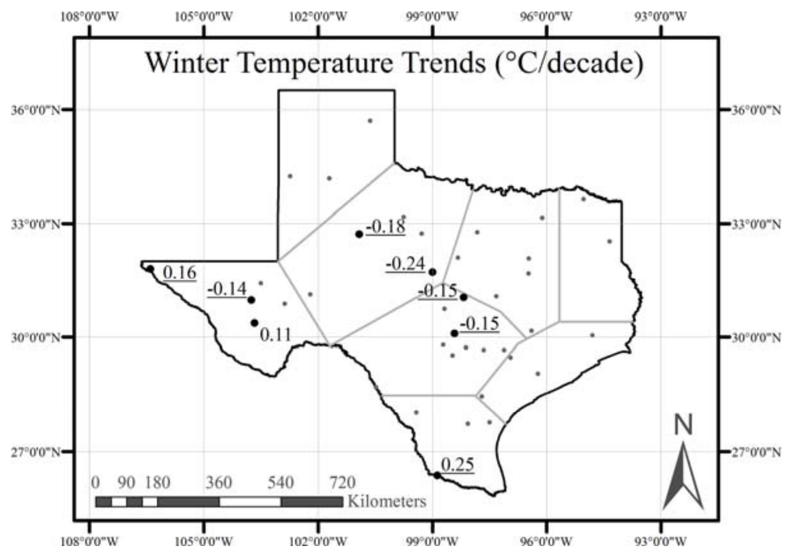


Figure 11. Statistically significant linear trends ($p < 0.10$) in winter temperature anomalies (relative to the 1961-1990 base period mean) over the period 1932-2002. Trend estimates that are underlined are statistically significant at $p < 0.05$.

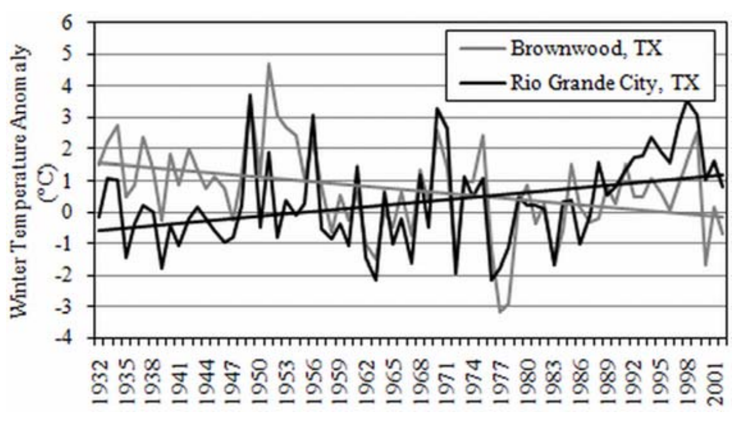


Figure 12. Statistically significant ($p < 0.10$) linear trends in winter temperature anomalies, 1932–2002. Anomalies are relative to the 1961-1990 base period mean.

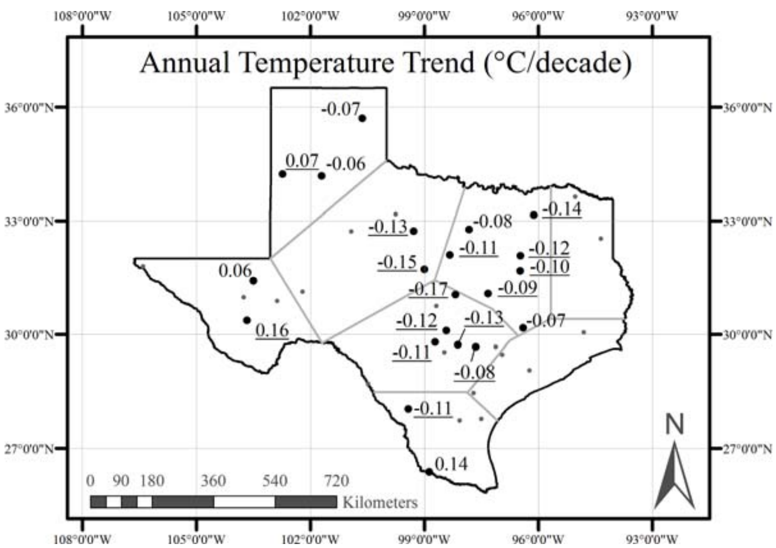


Figure 13. Statistically significant linear trends ($p < 0.10$) in annual temperature anomalies (relative to the 1961-1990 base period mean) over the period 1932-2002. Trend estimates that are underlined are statistically significant at $p < 0.05$.

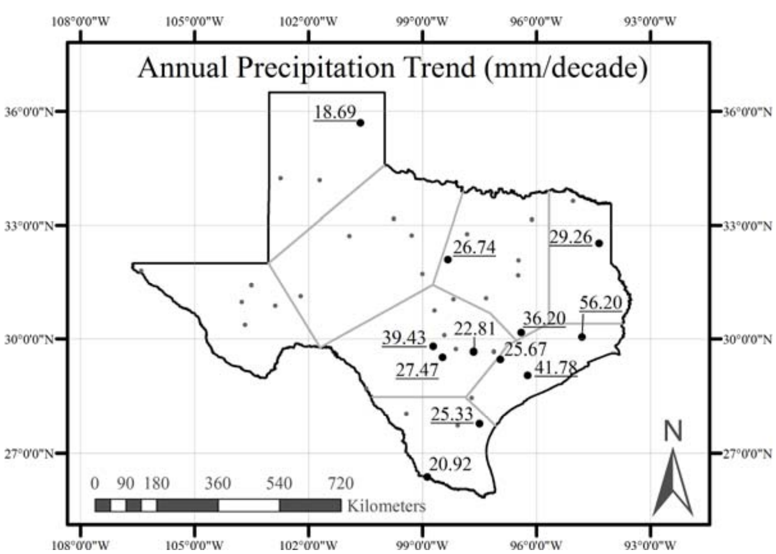


Figure 14. Statistically significant linear trends ($p < 0.10$) in annual precipitation anomalies (relative to the 1961-1990 base period mean) over the period 1932-2002. Trend estimates that are underlined are statistically significant at $p < 0.05$.

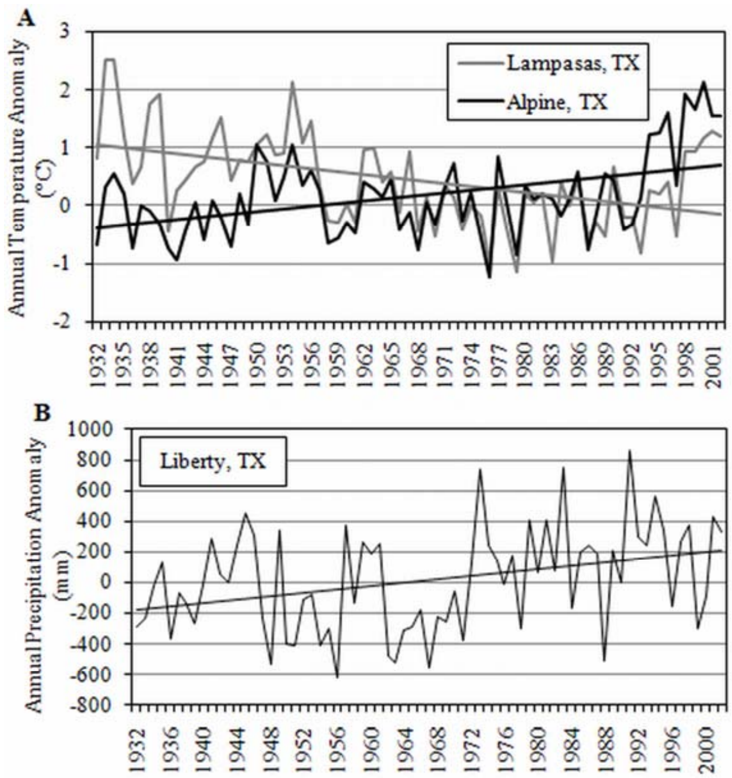


Figure 15. Statistically significant ($p < 0.10$) linear trends in annual temperature (A) and precipitation (B) anomalies, 1932–2002. Anomalies are relative to the 1961-1990 base period mean.

Twelve stations (31 %) had statistically significant trends in annual precipitation and, similar to fall precipitation trends, all were increasing (Figure 14). The greatest increase occurred in Liberty, with +56.20 mm per decade (Figure 15B). Also, similar to the fall precipitation distribution, all but one of the trends were located east of 99°W longitude within South, South Central, North Central, East, and Southeast Texas. One other increasing trend was located in the Panhandle at Muleshoe.

Discussion

Nielsen-Gammon (2011) examined regionally-averaged trends in temperature and precipitation in Texas over the twentieth century. Regarding annual temperature trends, our results are in general agreement with Nielsen-Gammon (2011), especially the cooling that occurred in the West Central, South Central, and North Central portions of the state and the warming that occurred in Far West Texas. However, rather than warming in the Panhandle, South, Southeast, and East Texas, we found that the Panhandle and South Texas were geographically anomalous and that Southeast and East Texas had no statistically significant trends. Also, our results do not indicate that all temperature trends were uniform across seasons, as found by Nielsen-Gammon (2011). While the cooling that occurred in the central regions of the state was rather uniform, trends in the remaining regions varied between seasons. Regarding precipitation trends, our results are also in general agreement with Nielsen-Gammon (2011) who concluded that the greatest increase in precipitation occurred along a north-south corridor from South Texas to Oklahoma. This was especially apparent with fall and annual precipitation trends. However, this study does not support the increasing trend in winter precipitation in the panhandle region reported by Nielsen-Gammon (2011).

By examining individual stations, this study has been able to capture smaller-scale spatial variability that is overlooked when the time series from multiple stations are averaged together to estimate a regional trend. Within-region variability, or geographic anomalies, are especially noticeable features when viewing the spatial distribution of temperature trends across Texas (Figures 3, 5, 8, 11, and 13). There were four cases, for example, when stations located within 100 kilometers (approximately 62 miles) of one another had statistically significant trends with opposite signs (1. Figure 13, Panhandle; 2. Figure 5, Panhandle; 3. Figure 5, Southeast Texas; and 4. Figure 11, Far West Texas). There were also two cases where three stations located within the same region had statistically significant trends, two with increasing (decreasing) trends and the other with a decreasing (increasing) trend (1. Figure 13, Panhandle; and 2. Figure 11, Far West Texas). Such small-scale variability suggests that local forcing may supersede regional and global forcing (Pielke et al. 2002). For instance, land-use and land-cover changes in urban areas have been shown to lead to localized warming; i.e., the urban heat island (Oke 1973; Karl, Diaz, Kukla 1988; Stohlgren et al. 1998; Chase et al. 1999) and increased irrigation has been shown to lead to localized cooling (Lobell, Bonfils, and Faurès 2008). While these are plausible causes for local trend anomalies, there are likely other localized unknown causes that require additional research. Kates and Wilbanks (2003) propose the use of a place-based approach, focused on localities, to investigate the effect of global climate change at the local-scale and to investigate which and how local forcing amplifies or minimizes larger-scale forcing.

Such an investigation could perhaps provide insight into questions that arose from this study. For instance, why did Balmorhea have a statistically significant cooling trend in winter when El Paso and Alpine, which are located approximately 271 kilometers (168 miles) west-northwest and approximately 70 kilometers (43 miles) south-southeast of Balmorhea, respectively, had statistically significant warming trends?

Summary and conclusion

This study evaluated trends in seasonal and annual temperature and precipitation in Texas. Temperature trends exhibited spatial and temporal variability in terms of rate of change and direction of change. In general, stations located in the Panhandle, Far West, South, Southeast, and East Texas exhibited the most variability. Stations in the central Texas regions, particularly South Central Texas, were the most consistent, mostly exhibiting cooling trends or no trends. Precipitation trends were less variable than temperature trends. Most seasons experienced no trends and the trends that were detected indicated no spatial pattern. Fall precipitation trends, however, showed a distinctive east-west pattern. All statistically significant trends were increasing trends and all were east of 99°W longitude, which includes the eastern half of Texas. The dominance of the fall precipitation pattern led to a similar pattern in annual precipitation trends.

Three general conclusions are brought to mind when comparing this study's results with those of Nielsen-Gammon (2011). First, the general agreement regarding the cooling trends in the central Texas regions and the increased precipitation in the eastern half of the state is a form of validation that these regions did experience cooling trends and increased precipitation in the twentieth century. Second, time series trend analysis is sensitive to the time period chosen (Wigley 2006; Liebmann et al. 2010), meaning that the discrepancies found between this study and Neilsen-Gammon (2011) in terms of temperature trends in the Panhandle, Far West, South, Southeast, and East Texas is likely partially due to the different time periods used for trend analysis. Third, this study illustrates that regionally-averaged trends may mask within-region variability. In particular, the regionally-averaged temperature trends reported by Nielsen-Gammon (2011), especially in the Panhandle, Far West, South, Southeast, and East Texas, overlooked trend variability within these regions.

This study illustrates that changes in temperature and precipitation vary on multiple spatial scales. Thus, it is imperative that researchers be cognizant of this when averaging multiple locations into a regional trend and when inferring local trends from global- and regional-scale trends. Further, the geographic anomalies detected in this study suggest that local forcing may, in some cases, be more influential than the surrounding regional- and global-scale forcing on the changes that a specific location experiences, as noted by Pielke et al. (2002). Regionally- and globally-averaged trends are practical for viewing the big picture, but they often mask smaller-scale variability, where many of the adaptation policies and strategies are implemented (Burton et al. 2002; Dessai and Hulme 2003). Thus, additional research should be focused on detecting local-scale changes and, if the detected changes are geographically anomalous, what are the possible causes of the anomalous change; i.e., why do the detected changes in this location differ from the changes in the surrounding region?

Acknowledgments

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Appendix

			Spring		Summer		Fall		Winter		Annual	
Region	**ID**	**Station Name**	**T**	**P**	**T**	**P**	**T**	**P**	**T**	**P**	**T**	**P**
PH	29	Miami	**-0.11**	**8.83**	-0.04	1.93	**-0.15**	5.33	0.03	1.84	**-0.07**	**18.69**
	30	Muleshoe	**0.20**	-2.00	**0.08**	1.27	-0.06	2.08	0.10	-1.20	**0.07**	0.79
	33	Plainview	-0.02	1.35	**-0.20**	0.82	-0.05	1.26	0.03	-0.92	**-0.06**	3.00
FW	02	Alpine	**0.35**	-0.85	0.02	3.09	**0.17**	1.77	**0.11**	-1.23	**0.16**	2.98
	03	Balmorhea	0.06	-1.02	-0.02	1.37	0.07	-1.22	**-0.14**	-0.05	0.00	-1.38
	15	El Paso	**0.21**	-0.22	**-0.20**	**4.95**	0.03	-0.02	**0.16**	0.96	0.05	6.39
	18	Fort Stockton	-0.04	-2.28	-0.07	1.14	0.03	3.16	0.02	-2.22	-0.02	-0.35
	32	Pecos	0.03	-0.75	**0.13**	4.29	0.02	0.29	0.05	0.79	**0.06**	4.29
WC	00	Albany	**-0.21**	0.28	**-0.20**	3.50	**-0.11**	4.74	0.00	3.28	**-0.13**	12.10
	08	Brownwood	0.02	-5.20	**-0.15**	6.01	**-0.21**	4.94	**-0.24**	-0.03	**-0.15**	6.14
	21	Haskell	0.04	0.40	-0.07	-1.75	0.00	3.22	-0.04	2.08	-0.02	4.68
	27	McCamey	0.05	-3.15	-0.08	-2.99	-0.03	7.57	0.00	-0.35	-0.02	0.87
	36	Snyder	**0.19**	1.31	**-0.10**	4.17	0.00	2.12	**-0.18**	1.50	-0.03	9.17

			Spring		Summer		Fall		Winter		Annual	
Region	**ID**	**Station Name**	**T**	**P**	**T**	**P**	**T**	**P**	**T**	**P**	**T**	**P**
NC	07	Brenham	-0.09	3.61	**-0.19**	4.32	0.00	**29.60**	-0.02	-3.56	**-0.07**	**36.20**
	11	Corsicana	-0.08	-3.03	**-0.20**	2.81	**-0.11**	11.34	-0.08	3.26	**-0.12**	16.26
	13	Dublin	-0.07	1.17	**-0.18**	**16.82**	-0.06	7.81	-0.11	0.36	**-0.11**	**26.74**
	19	Greenville	**-0.18**	1.18	-0.10	-0.50	**-0.18**	**15.65**	-0.09	2.98	**-0.14**	20.31
	28	Mexia	-0.04	-0.79	**-0.17**	2.13	**-0.12**	**11.72**	-0.05	1.68	**-0.10**	15.16
	37	Temple	-0.06	-5.64	**-0.11**	3.21	**-0.13**	**12.45**	-0.06	-3.41	**-0.09**	7.45
	38	Weatherford	0.00	-2.21	-0.10	8.09	-0.09	**12.30**	-0.11	-0.88	**-0.08**	17.73
SC	05	Blanco	**-0.14**	1.83	**-0.07**	3.52	-0.09	10.30	**-0.15**	-6.71	**-0.12**	10.60
	06	Boerne	**-0.12**	6.33	**-0.12**	**14.85**	**-0.18**	**17.70**	-0.02	-0.64	**-0.11**	**39.43**
	14	Eagle Pass	0.01	-3.20	-0.02	-1.48	0.04	7.42	0.08	-2.61	0.02	0.64
	17	Flatonia	**0.13**	-3.03	**-0.17**	-0.67	0.01	**14.50**	-0.08	-1.26	-0.03	11.55
	22	Lampasas	**-0.20**	-7.48	**-0.13**	4.30	**-0.19**	1.20	**-0.15**	-1.61	**-0.17**	-2.02
	24	Llano	**-0.12**	-3.71	-0.02	1.30	0.03	1.47	-0.03	0.40	-0.04	0.13
	25	Luling	-0.06	5.17	-0.04	-0.08	-0.09	**15.92**	-0.12	0.80	**-0.08**	**22.81**
	31	New Braunfels	-0.05	-0.85	**-0.17**	6.00	**-0.20**	11.11	-0.09	-2.22	**-0.13**	15.98
	35	San Antonio	-0.07	3.34	0.06	7.80	0.08	**13.05**	-0.09	2.03	0.00	**27.47**

			Spring		Summer		Fall		Winter		Annual	
Region	**ID**	**Station Name**	**T**	**P**	**T**	**P**	**T**	**P**	**T**	**P**	**T**	**P**
S	01	Alice	-0.04	-1.15	0.01	1.20	-0.07	6.44	-0.01	-2.84	-0.03	3.82
	10	Corpus Christi	0.07	2.92	0.02	10.04	**0.12**	**13.30**	-0.03	-2.97	0.04	**25.33**
	16	Encinal	-0.01	-2.05	**-0.29**	0.07	**-0.10**	3.94	-0.02	-4.43	**-0.11**	-2.03
	34	Rio Grande City	**0.13**	0.05	**0.16**	4.80	0.03	**12.94**	**0.25**	2.17	**0.14**	**20.92**
SE	04	Beeville	-0.03	2.04	0.04	6.19	0.03	**12.91**	0.05	-2.12	0.02	17.99
	12	Danevang	**0.11**	9.57	**0.07**	5.81	0.02	**23.01**	-0.08	1.20	0.03	**41.78**
	20	Hallettsville	0.00	3.85	**-0.08**	3.02	-0.07	**18.45**	-0.01	-0.20	-0.05	**25.67**
	23	Liberty	**0.20**	9.12	-0.06	12.94	**0.18**	**33.60**	-0.13	-3.88	0.04	**56.20**
E	09	Clarksville	-0.07	-2.86	**-0.11**	-1.70	0.01	**24.37**	0.05	-2.50	-0.03	18.97
	26	Marshall	0.01	0.65	0.03	**10.00**	0.06	**18.29**	-0.02	-1.38	0.02	**29.26**

Regional names appearing in the first column: PH = Panhandle; FW = Far West; WC = West Central; NC = North Central; SC = South Central; S = South; SE = Southeast; and E = East